The importance of mass balance in life cycle assessment of nature-based solutions for wastewater treatment: key learning points from a case study

Karine Dufossé, Nicolas Forquet, Pascal Molle, Marilys Pradel, Eléonore Loiseau

Blue-Green Systems

Blue-Green Systems Vol 00 No 0, 1 doi: 10.2166/bgs.2024.023

The importance of mass balance in life cycle assessment of nature-based solutions for wastewater treatment: key learning points from a case study

Karine Dufossé [a,b], Nicolas Forquet [c], Pascal Molle[c], Marilys Pradel [d] and Eléonore Loiseau [a,b,*]

[a] ITAP, University of Montpellier, INRAE, Institut Agro, Montpellier, France
[b] ELSA, Research Group for Environmental Lifecycle & Sustainability Assessment, Montpellier, France
[c] INRAE, UR REVERSAAL Centre de Lyon-Grenoble Auvergne-Rhône-Alpes, France
[d] Université Clermont Auvergne, INRAE, UR TSCF, Montoldre, France
*Corresponding author. E-mail: eleonore.loiseau@inrae.fr

KD, 0009-0007-0912-3268; NF, 0000-0003-1154-5498; MP, 0000-0003-2053-6366; EL, 0000-0003-1331-8715

ABSTRACT

This study aims to perform a comprehensive life cycle assessment (LCA) of nature-based solutions (NBS) for wastewater treatment (WWT), specifically focusing on a French vertical flow (VF) wetland. The LCA encompasses the construction phase, operational phase, and end-of-life management, with a particular emphasis on achieving a balanced mass flow for carbon, nitrogen, and phosphorus across air, water, and soil compartments. The VF wetland is evaluated for its environmental impacts and compared to a conventional activated sludge system. The key findings reveal that the VF wetland achieves substantial reductions in resource use, yet requires significantly more land and exhibits higher impacts on greenhouse gas emissions and in categories sensitive to water emissions. The results underline the importance of complete mass balances in LCAs of NBS to accurately identify environmental hotspots. Recommendations for methodological improvements and system boundary definitions are provided to enhance the definition of mass balance within NBS.

Key words: environmental impact, French vertical flow wetland, life cycle assessment, mass balance, wastewater treatment, water management

HIGHLIGHTS

- A life cycle assessment (LCA) of French vertical flow (VF) wetland was carried out to include mass balance and indirect emissions.
- The results were compared with a reference for water treatment and activated sludge (AS), with similar size.
- French VF wetland has higher impacts on climate change (due to N_2O emissions), land use, and marine and freshwater eutrophication.
- Mass balance of N, P, and C flows play a major role in LCA results.

1. INTRODUCTION

Nature-based solutions (NBS) are approaches that use natural processes and ecosystems to address various environmental, social, and economic challenges (European Commission 2015). These solutions aim to protect, sustainably manage, and restore natural or modified ecosystems to provide benefits such as enhancing biodiversity, improving water quality, reducing flood risks, mitigating climate change, and promoting human well-being. NBS include a wide range of strategies, such as green infrastructure, ecosystem restoration, and the sustainable use of natural resources, tailored to meet specific local needs and conditions (Nesshöver *et al.* 2017). For the last several decades, various new NBS technologies have been developed across all continents (Castellar *et al.* 2021). In particular, NBS are being promoted as a way of improving the resilience and sustainability of cities in the face of a wide range of environmental challenges (Ershad Sarabi *et al.* 2019). In the field of urban water management, they are seen as an alternative to more centralized and 'grey' treatment in order to move towards more sustainable management of water and biogeochemical cycles (Masi *et al.* 2018; Flores *et al.* 2019).

In NBS for water management, certain installations prevent flooding by diverting stormwater flow or enabling faster infiltration into the soil. This is particularly the case for infiltration basins, retention ponds, swales, and rain gardens (Woods-Ballard *et al.* 2015; URBANGREENUP 2018; UNALAB 2019). Treatment wetlands can also improve urban water management and treat wastewater before its discharge into the natural environment by replicating natural processes occurring in natural wetlands involving vegetation, soils, and the associated microbial assemblages (Dotro *et al.* 2017; Stefanakis 2019).

To accurately assess the environmental impacts of NBS technologies, it is crucial to consider both local impacts during the 'use phase' (e.g., water quality improvement) and impacts from other life cycle phases (e.g., construction and end-of-life management) (Corominas *et al.* 2020; Larrey-Lassalle *et al.* 2022; Babí Almenar *et al.* 2023). Life cycle assessment (LCA) is a standardized and widely used method for evaluating the environmental impacts of products and services from a life cycle perspective (Hellweg & Milà i Canals 2014). It is a reference method for the environmental assessment of technologies in the field of water management (Corominas *et al.* 2020; Parra-Saldivar *et al.* 2020; Larrey-Lassalle *et al.* 2022). Numerous water-related NBS technologies have been analysed using LCA, including swales and ponds (Byrne *et al.* 2017; Bixler *et al.* 2019), rain gardens for rainwater or stormwater management (Flynn & Traver 2013; Petit-Boix *et al.* 2015; Vineyard *et al.* 2015), and treatment wetlands for wastewater treatment (WWT) (Roux Boutin & Risch 2010; Fuchs *et al.* 2011; Pan Zhu & Ye 2011; Flores *et al.* 2019; Resende *et al.* 2019; Risch Boutin & Roux 2021).

When focusing on the studies for WWT, system boundaries always encompass the life cycle stages related to construction, maintenance operations, and end-of-life of materials, as well as emissions to water in the water exiting the system. Therefore, input and output water qualities are assessed. Greenhouse gas (GHG) emissions (CO_2, CH_4, N_2O) during the use phase are sometimes included, based on measurements or the International Panel on Climate Change (IPCC) emission factors (Fuchs Mihelcic & Gierke 2011; Pan Zhu & Ye 2011; Resende Nolasco & Pacca 2019). Some rare studies also include sludge spreading, with its fertilizing effect, and the related soil and air emissions (Roux Boutin & Risch 2010; Flores *et al.* 2019; Risch Boutin & Roux 2021). However, these studies highlight a lack of harmonization in the definition of system boundaries, and of robustness in the calculation of mass balances, as noticed in most literature review papers (Corominas *et al.* 2020; Parra-Saldivar *et al.* 2020; Larrey-Lassalle *et al.* 2022) that proposed a set of guidelines for carrying out the LCA of WWT technologies. It is thus essential to carry out a complete mass balance to estimate the environmental impacts of a technology for all the environmental compartments, i.e. air, water, and soil (Corominas *et al.* 2020; Larrey-Lassalle *et al.* 2022) as it is widely acknowledged in grey technologies for WWT (Heimersson *et al.* 2016).

This paper aims to implement a complete LCA of an NBS water treatment technology, from the construction phase to end-of-life and sludge management. Particular attention will be paid to calculating a balanced mass flow for carbon, nitrogen, and phosphorus in the three environmental compartments. A French vertical flow (VF) wetland (treatment wetland) for WWT is used as proof of concept. Comparing data and methodological choices regarding system boundaries will enable the formulation of recommendations for evaluating NBS versus grey technologies in WWT.

2. MATERIAL AND METHOD

The environmental assessment approach is based on the following four standardized phases of the LCA framework (ISO 2006): (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results with a focus on the challenges of taking into account a complete mass balance of C, N, and P flows in LCA of NBS for WWT.

2.1. Goal and scope definition

This study aims to carry out a complete LCA of an NBS for WWT and discusses methodological choices related to system boundaries and data collection related to C, N, and P mass balance. A comparison with a grey technology is also proposed for interpretation and discussion.

The LCA was applied to a French VF wetland, consisting of two treatment stages, one with gravel-based filters and the other with sand-based filters, both planted with common reeds (Phragmites Australis) (see Figure 1). It is a widely distributed technology in France (Morvannou *et al.* 2015). More specifically, French VF wetlands are designed for the treatment of raw wastewater for small communities. The studied case in this paper is sized for WWT for 1,000 PE (population-equivalent), with a daily wastewater emission of 150 L PE^{-1}, polluted with 60 g BOD_5, and built for a 30-year lifespan. This technology shows substantial removal rates for chemical

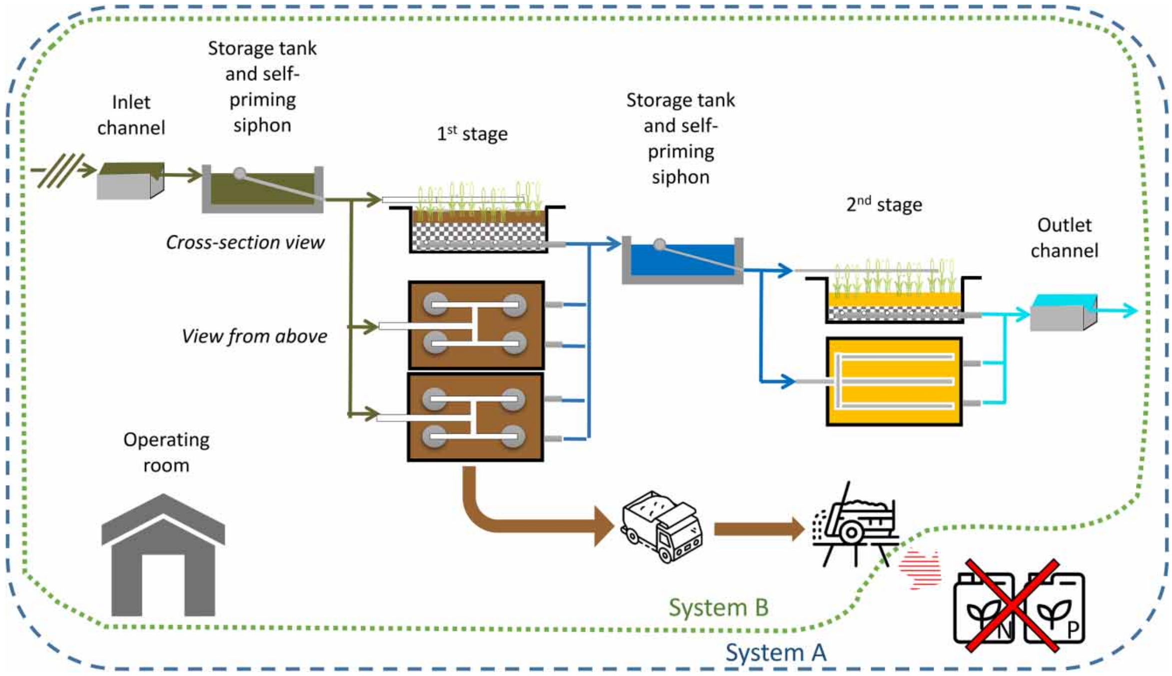

Figure 1 | Constructed wetland facilities and system boundaries, adapted from Risch & Boutin (2020), presenting the system boundaries including (System A in blue) or excluding (System B in green) the substitution of mineral fertilizers due to sludge spreading.

oxygen demand (COD), total suspended solids (TSS), and total Kjeldahl nitrogen (TKN), reaching 87, 93, and 84%, respectively, between the incoming water to the system and the treated water exiting it (Morvannou *et al*. 2015).

The functional unit (FU) was 'to treat 1 m^3 of raw wastewater in France, with an abatement rate of 80% on the COD'. This corresponds to an FU conventionally used for WWT, integrating the regulatory requirements of small treatment plants in France (Directive Eau Résiduaire Urbaine 1991). Therefore, the rationale for this choice is to ensure comparisons with conventional solutions, i.e. grey technologies, such as activated sludge.

According to the recommendations of Corominas *et al*. (2020) and INRAE Transfert (2022), a wide perspective is adopted for system boundaries that encompass the WWT technology, and sludge treatment, transport, and application (Figure 1, System B). Since sludge is regarded as a coproduct of WWT, ISO 14044 recommends that system expansion be applied to estimate the impacts of this coproduction, including the integration of avoided mineral fertilizer production (Figure 1, System A). For WWT technology, construction, including excavation, materials for the filters and surrounding equipment, and operation and maintenance of the filters during the entire lifetime, up to the dismantlement of the NBS are considered. A particular focus is placed on the use phase through N, P, and C flow mass balances and sludge spreading.

2.2. Data collection and LCI

2.2.1. General information about the French VF wetland

Figure 1 illustrates the sequential treatment phases of the French VF wetland (two stages, with three and two compartments, respectively), while Table 1 summarizes the key structural properties of the construction for the first and second stages. The presence of filters in parallel for each treatment step allows rotation in feeding, leaving some filters resting. Indeed, wastewater is poured during a feeding period (3.5 days) in a first filter. Then, a technician changes the flow direction to feed another filter. The resting period is essential not only to complete the treatment of the interstitial water remaining in the filter, but also to partially degrade and mineralize the surface deposit formed during the feeding period, thus partially restoring the infiltration capacity. The second stage has only two compartments, which are successfully fed for 7 days and then let to rest for 7 days. Both are covered with a geomembrane and a geotextile to ensure waterproofing.

Table 1 | Main characteristics of the constructed wetland (French system) studied

	1st stage	2nd stage	Surrounding area
Area (m^2)	1,200	800	3,000
Number of parallel filters	3	2	
Total depth (m)	1.1	0.85	
Depth filled with materials (m)	0.6	0.6	
Composition (depth in m)	Gravel (0.6)	Sand (0.3) + gravel (0.3)	
Construction characteristics			
Filing (Gravel) (t)	1,224	408	538
Filing (Sand) (t)	0	384	
Geomembrane (PEHD) (kg)	1,957	1,333	
Geotextile (PP) (kg)	2,221	1,512	271
Distribution pipes (kg)	(stainless steel) 1,533	(PEHD) 700	
Drainage pipes (PVC) (kg)	512	342	(evacuation) 296
Partition walls (Glass fibre) (kg)	84	20	
Excavated volume (m^3)	4,800	3,200	
Excavation time (h)	44	29	
Dosing system	Self-priming siphon	Self-priming siphon	
Operating room (concrete) (t)			25
Storm overflow (concrete) (t)			4.4
Storage tank (concrete) (t)			8.8
Inlet and outlet channels (concrete) (t)			8.8

Table 2 | Main assumptions of origin and end-of-life treatment for raw materials used in the inventory

Material	Local or imported	End-of-life treatment
Stainless steel	Imported	95% recycling + 5% landfill
Concrete	Local	100% landfill
PEHD	Imported	25% incinerated + 75% landfill
PP	Imported	25% incinerated + 75% landfill
PVC	Imported	25% incinerated + 75% landfill
Gravel	Local	100% landfill
Sand	Local	100% landfill
Glass fibre	Imported	25% incinerated + 75% landfill

2.2.2. Construction hypothesis

The lifespan of such a constructed wetland is 30 years. It is assumed that the previous land occupation was pasture or meadow. After the dismantlement, the land occupation would come back to this initial state. The volume of excavated soil, computed from the filters geometry, was used to estimate machine operation and energy consumption for construction and dismantlement, assuming an excavation rate of 110 $m^3\,h^{-1}$ (ACV4E Software 2018; Risch Boutin & Roux 2021). Each hour of construction or dismantling makes use of a dump truck for 0.7 h, a mechanical shovel for 0.7 h, a dumper for 0.3 h, and an excavator for 0.3 h (ACV4E Software 2018; Risch Boutin & Roux 2021).

Surrounding the French VF wetland, a grass area of 3,000 m^2 has a buffer role and holds an operating room, a storm overflow, inlet and outlet channels, and some storage tanks. These structures are made of 25 t of reinforced concrete and 22 t of lean concrete, assuming that there are local materials for the transportation.

The various stage feed structures (self-priming siphons), as well as the manual bar screen, have been taken into account through the consumption of raw materials. They do not entail any power consumption. In addition, there is no lift station to feed the filters.

The distance hypotheses were as follows:

- For local materials: 20 km by truck between the quarry and the wetland site.
- For imported materials: 200 km by train and 50 km by truck between the manufacture and the wetland site.
- The landfill and recycling sites are located 30 km by truck from the wetland for all materials.
- The incineration site is located 50 km by truck from the wetland for all incinerated materials.

2.2.3. Operation and maintenance

This life cycle stage takes into consideration all maintenance operations that occur on the French VF wetland in its entire lifetime. It is modelled as 1 average year of maintenance, repeated 30 times to cover the whole lifespan of the filter. A twice-weekly routine check (changing the flow direction to parallel filter) is carried out, by car, with a distance of 20 km one-way and 17 travels happen for exceptional maintenance and operation, with the same distance, per year. The exceptional maintenance includes the following:

- Grass mowing around the wetland three times per year (6 working days and travels per year);
- Reed harvesting once a year (10 working days and travels per year);
- Sludge removal, every 10 years, but with an annual build-up of 24 t on the whole wetland (10 working days and travel in 10 years, so 1 working day and travel per year).

A daily accumulation of 24.7 g of sludge (or surface deposit) for 1,000 PE was estimated in the 1st stage. No sludge gets accumulated in the 2nd stage, as all suspended elements are collected in the 1st stage. Further, 100% of the collected sludge is spread on fields, transferring emissions to the soil due to its chemical composition (trace metal elements (TMEs)), indirect gaseous emissions (N_2O and NH_3), as well as some emissions to water through lixiviation (NO_3^- and PO_4^{3-}). These indirect emissions were estimated using agricultural references for fertilization emissions (IPCC 2006; Prasuhn 2006). The storage area is located 35 km away from the filter and the fields are 2 km from the storage (ECODEFI 2011). The sludge is transported by lorry, before being spread using a tractor and a spreader, considering a dose of 9.01 tMS ha^{-1}. This dose was calculated using barley as the reference crop, one of France's main cereal crops (Ministère de l'Agriculture et de la Souveraineté alimentaire 2023). Barley cultivation in central France requires 115.4 kg N ha^{-1}, 131.5 kg P_2O_5 ha^{-1}, and 100.25 kg K_2O ha^{-1} for correct fertilization (Pradel Pacaud & Cariolle 2009). The dose was estimated considering the P and N content in the removed sludge, with both elements considered fully bioavailable for long-term fertilization.

An annual harvest of 1 kg/m^2 was considered for the reed biomass. This biomass was then composted in the industrial site. The cut-off grass is left on site, without any impact considered beyond the mowing.

2.2.4. Focus on mass balance for C, N, and P flows

French VF wetland is a treatment technology that primarily aims to reduce the organic pollution (measured by the COD or BOD content) and the pollution associated with reduced forms of nitrogen, depending on the size of the treatment plant. As a small-scale installation (1,000 PE), the case study must comply with current regulations and ensure 80% removal of COD from incoming wastewater before it is released into the natural environment. No particular threshold is set on N removal. Although not specifically targeted, P is also partially removed through assimilation and adsorption. Following the first rule of thermodynamics, 'nothing is lost, nothing is created, everything is transformed', it was crucial to gather a complete picture of the mass balance happening daily in the different stages and compartments of the French VF wetland. Figure 2 reports the main C, N, and P flows occurring in the compartments of the French VF wetland.

The input wastewater quality was determined through experts' knowledge, starting from the regulatory value of 60 g BOD day^{-1} PE^{-1} and assuming that the wastewater production is 150 L PE^{-1} day^{-1}, the wastewater composition was estimated as shown in Table 3. A summary of this mass balance is presented in Table 3, and detailed calculations and references are available in the Supplementary material. The outputs were calculated by experts and using compilation of multiple references on equivalent technologies. The complete procedure is available in the Supplementary material. To ensure the balance of elements between input and output when necessary,

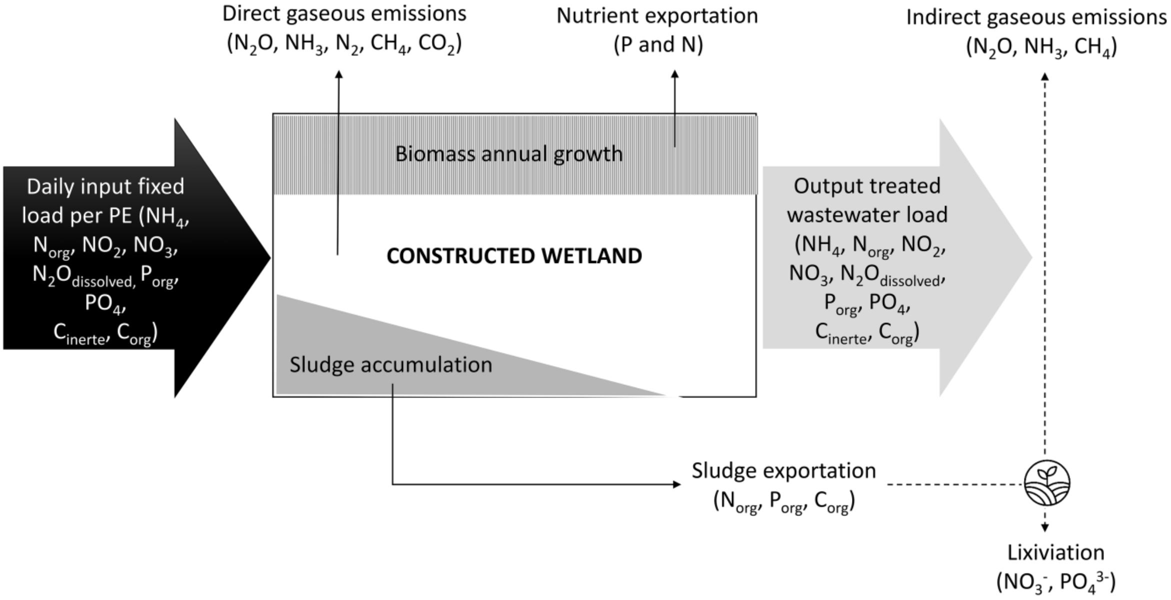

Figure 2 | Schematic representation of a mass balance for a French VF wetland.

Table 3 | Mass balance for a French VF wetland for 1,000 PE, on nitrogen, phosphorus, and carbon flows, from input wastewater load (1st column) to the repartition between the different categories of outputs as direct water and air emissions, or sludge and reed accumulation

		Input (g·PE^{-1}·day^{-1})	Outputs (g·PE^{-1}·day^{-1})			
			Direct emissions		By-products	
		Wastewater	Water	Air	Sludge	Reed
Nitrogen	N-NH_4	11.47	1.96			
	N_{org}	4.03	0.52		0.25	0.36
	N-NO_2	0	0.05			
	N-NO_3	0	7.39			
	N-$N_2O_{dissolved}$	0	0.07			
	N-NH_3			0		
	N-N_2O			0.12		
	N-N_2			4.82		
	Total	15.50	9.99	4.94	0.25	0.36
Phosphorus	P_{org}	0.53	0		0.39	0.03
	P-PO_4	1.58	1.68			
	Total	2.10	1.68		0.39	0.03
Carbon	$C_{inerte-soluble}$	2.10	2.10			
	$C_{inerte-particulate}$	13.10	0			
	C_{org}	37.20	4.72		6.91	
	C-CO_2			38.43		
	C-CH_4			0.24		
	Total	52.40	6.82	38.67	6.91	0

The grey cells indicate that the molecule is not considered in this compartment, while the zeros mean that the molecule could be present but the assumption is made that it is absent.

adjustment variables are used, derived from the subtraction between the total element entering the system and the different outputs measured in different forms. These adjustment variables are N_2 and CO_2.

It is assumed that 5% of the input wastewater is lost through evaporation (Risch *et al.* 2014).

2.2.5. Trace metal elements, hypothetic mass balance

To have a broader picture on the environmental impacts generated from the French VF wetland, TMEs mass balance has to be included in the study. Quantities of TME are derived from Catel *et al.* (2017) as follows: cadmium

(2.86×10^{-5} g PE^{-1} day^{-1}), mercury (9.11×10^{-4} g PE^{-1} day^{-1}), nickel (6.85×10^{-4} g PE^{-1} day^{-1}), lead (1.18×10^{-3} g PE^{-1} day^{-1}), cobalt (1.58×10^{-4} g PE^{-1} day^{-1}), arsenic (6.27×10^{-4} g PE^{-1} day^{-1}), molybdenum (4.40×10^{-4} g PE^{-1} day^{-1}), zinc (2.23×10^{-2} g PE^{-1} day^{-1}), barium (6.28×10^{-3} g PE^{-1} day^{-1}), copper (8.19×10^{-3} g PE^{-1} day^{-1}), chromium (4.46×10^{-4} g PE^{-1} day^{-1}), and vanadium (2.45×10^{-4} g PE^{-1} day^{-1}).

The following assumptions, based on expert's knowledge, is made regarding the distribution of TME in the different outputs: 50% of the trace metals is found in the water exiting the filter, 25% remains in the sludge that will be spread, and 25% is captured by the reeds that will be composted. Thus, the latter two contribute to the emission of TME to the soil.

2.2.6. Avoided products: mineral fertilization

In order to have a complete picture of all the effects of a French VF wetland, it is necessary to take into consideration the fertilizing and amendment effect due to the sludge spreading, as a coproduct of the WWT. An extension of the system boundaries is then considered to include the avoided mineral fertilizers.

The avoided mineral fertilization is based on the amount of nitrogen and phosphorus that is supplied to the soil through the sludge, and therefore will not be provided by mineral forms of fertilizers. Spreading the accumulated sludge over 15 years allows for organic fertilization of 9 ha of barley crops, with a total of 131.5 kg P_2O_5 ha^{-1} and thus 66.7 kg N ha^{-1}, as the limitation factor to calculate the spreading dose, was the P content in the sludge. The same amounts of fertilization were substituted from the system using average mineral fertilizers for France from the Ecoinvent database. Additionally, the emissions associated with these fertilizers were calculated using the same frameworks as for sludge (IPCC 2006; Prasuhn 2006) to substitute them in the system as well. Thus, 116.14 kg N_2O, 17.47 kg NH_3, 191.13 kg NO_3^-, and 3.822 kg P would have emitted from this mineral fertilization, which will not occur thanks to the spreading of the sludge.

2.2.7. Reference for comparison

In order to interpret and discuss the results, a comparison of the environmental impacts of the NBS technology and a grey technology is performed. A grey process is selected for a small-scale WWT plant (806 PE) from the Ecoinvent database. This plant relies on three water treatment stages (mechanical, biological, and chemical), and the sludge is digested before being spread and incinerated. Emissions associated with this technology include direct emissions from WWT, emissions from incineration and spreading of sludge, as well as certain emissions related to sewer overload discharge. This reference was then slightly modified to adapt to the French context: the origin of electricity was changed to French, as well as the water source. The system boundaries are comparable except for the avoided products from the grey technology (substitution of mineral fertilization by sludge spreading and energy recovery from sludge incineration) that are not included within the reference boundaries. The System B boundaries (Figure 1) for the French VF wetland were thus used for the comparison, based on the same volume of wastewater treated within both technologies (1 m^3).

3. LIFE CYCLE IMPACT ASSESSMENT

The software SimaPro 9.5 was used with the ecoinvent 3.9.1 allocation, cut-off by classification and the EF 3.1 method (Andreasi Bassi *et al*. 2023) to characterize the environmental impacts as this is the LCIA method recommended by the European Commission.

4. RESULTS AND DISCUSSION

4.1. Analysis of the French VF wetland including the mineral fertilization substitution

4.1.1. Overview

Figure 3 reports the results of the contribution analysis of the French VF wetland according to the impacts of the construction and end-of-life stage, the operation and maintenance stage, and the direct emissions related to the use phase computed from the mass balance for N, P, and C flows, as well as TME. For better understanding and visibility of the different contributions, the life cycle stage of operations and maintenance was divided into two categories: the 'Emissions' category includes only the emissions to water, air, and soil related to the operation and maintenance of the filter, while the 'Operation and Maintenance' category encompasses all elements necessary for the operation of the filter, including the end-of-life of coproducts (sludge and reed biomass) but excluding maintenance-related emissions. The contribution of substitution of mineral fertilization due to the spreading of sludge is also highlighted.

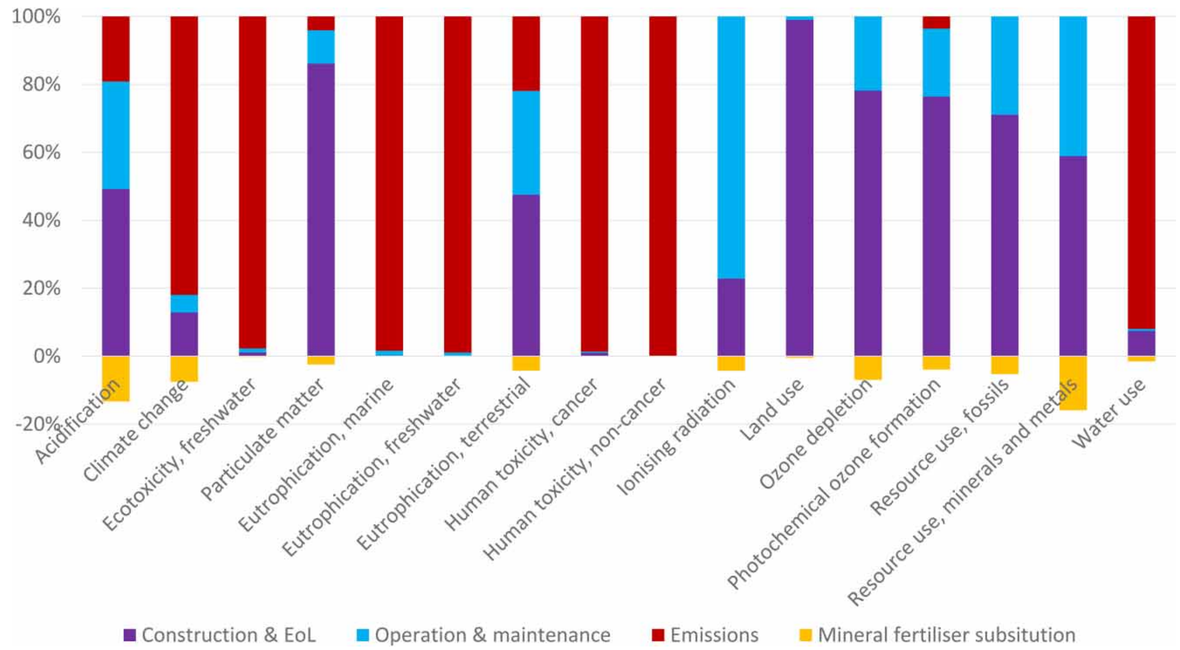

Figure 3 | Analysis of the French VF wetland using the EF 3.1 method, over 16 categories of environmental impacts and the single score. The main life cycle steps are presented: construction and end-of-life (purple), operation and maintenance without the emissions linked (blue), emissions from operation and maintenance (red), and the substitution of mineral fertilizer (orange).

Emissions into the air, water, and soil contribute to 11 out of 16 impact categories according to the EF 3.1 method (Figure 3). While their contribution is relatively moderate for four categories, it is significantly predominant for seven impact categories: climate change (82%), water use (92%), freshwater ecotoxicity (98%), marine eutrophication (98%), freshwater eutrophication (99%), human toxicity cancer (99%), and non-cancer (100%).

Wastewater management (inflow and outflow of the system, along with 5% evaporation) is addressed in the emissions stage, making this stage the largest contributor to the overall impact. The land use category is primarily influenced by the construction stage, as land occupation is accounted for in this phase of the inventory.

4.1.2. Construction and end-of-life stage

The construction and end-of-life stage (in purple in Figure 3) dominates terrestrial eutrophication (48% of the total impact), acidification (49%), resource use impacts (59 and 71%), photochemical ozone formation (77%), ozone depletion (78%), and particulate matter (86%).

Raw materials, notably gravel and in a secondary manner sand, stainless steel, and plastics (PET, PP, and PVC), contribute the most to these impacts as presented in Figure 4. Earthwork also contributes to most impact categories, due to the intensive use of combustion-motorized engine.

4.1.3. Contribution of operation and maintenance, without emissions

Looking at the contributions of the operation and maintenance stage (in bright blue in Figure 3), the impact categories to which they contribute significantly are ionizing radiation (77%), mineral and metals resource use (41%), acidification (32%), terrestrial eutrophication (31%), fossils resource use (29%), ozone depletion (22%), and photochemical ozone formation (20%).

The primary sources of these impacts are the use of motorized equipment, primarily for regular maintenance and secondarily for sludge spreading. Additionally, the composting of biomass significantly contributes to acidification and terrestrial eutrophication. The other processes (reed mowing, mechanical weeding, and sludge dredging) comprising the operations and maintenance have very low to negligible contributions to the impacts. It is important to highlight that emissions to water, air, and soil (except for diesel combustion) are not accounted for in this stage; they are studied separately in the 'emission' category.

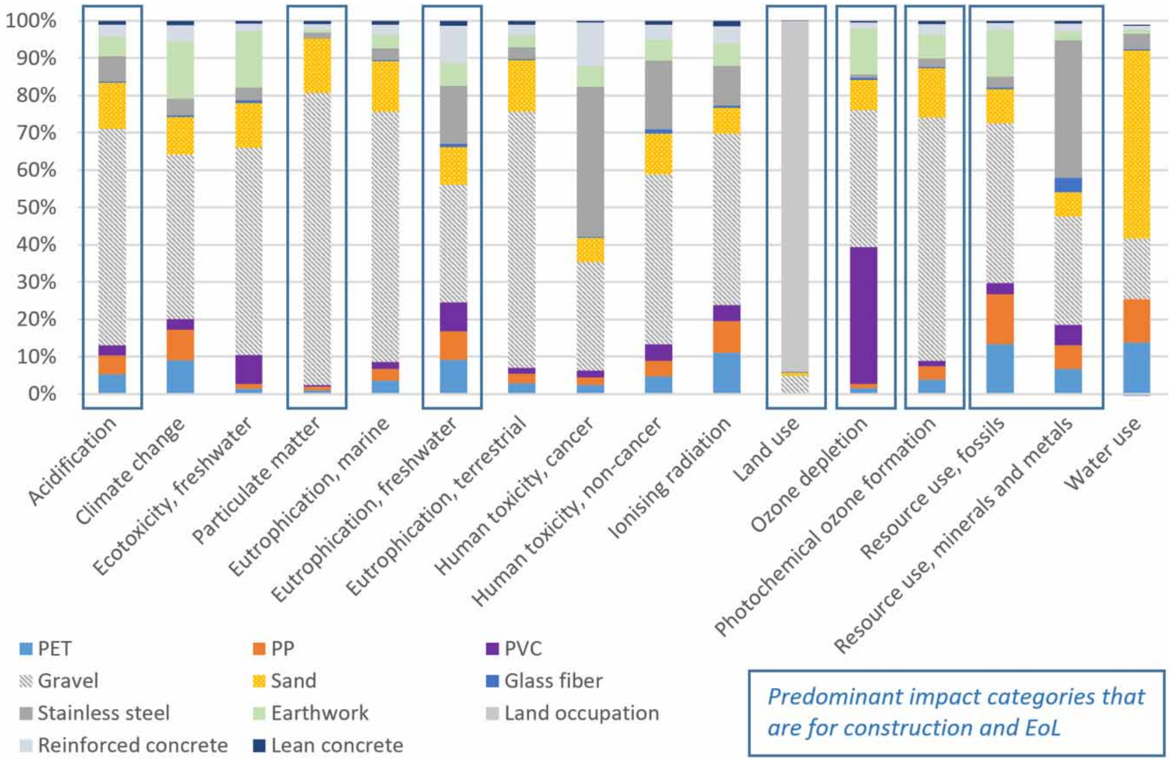

Figure 4 | Construction step analysis, using the EF 3.1 method and presenting the raw material used to build the French VF wetland.

4.1.4. Contribution of the emissions occurring during operation and maintenance

The emissions into the air during the filter operation contribute to 92% of the climate change impact, with 69% attributed to N_2O, 13% to CH_4, and 10% to CO_2. The remaining contribution to climate change from emissions comes from sludge fertilization (8%). The impacts of aquatic eutrophication and ecotoxicity are due to the composition of the water treated by the technology returning to the ecosystem. Marine eutrophication is attributed to the quantity of NO_3^- (75% of the emissions impact) and NH_3 (20%). Freshwater eutrophication stems from the quantity of PO_4^{3-} (100% of the impact). Lastly, freshwater ecotoxicity arises from NH_3 emissions (61%) and the presence of zinc (38%). TME into the soil through sludge spreading and biomass composting are responsible for all human toxicity impacts (especially mercury for more than 90% of both impacts), whereas the same elements emitted into the water have a negligible impact on these human toxicity impact categories.

4.1.5. Substitution of mineral fertilizers

Substitution of mineral fertilizers (in orange in Figure 3) has a moderate effect on impact categories. It significantly reduces the impacts of mineral resources use (−16%), acidification (−13%), and climate change (−8%). Its contribution is lower (<7%) or even negligible for other categories.

While emissions in the field are relatively similar for both types of fertilization, the mechanized operations for fertilization are vastly different. Sludge, being a viscous substance, requires more resources for handling, whereas mineral fertilizers are concentrated in fertilizing elements and optimized for easy spreading. However, mineral fertilizers have impacts related to their production, while sludge introduces trace metals into the soil.

Taking into account the substitution of mineral fertilizers by sludge spreading helps offset some of the impacts associated with sludge spreading. This offset is moderate for acidification (53% of what is emitted by sludge spreading) but becomes significant in terms of climate change (87%) for the sludge emissions only. For mineral resource use, the impact is almost twice as high for mineral fertilizer use as for sludge spreading.

4.2. Comparison of the French VF wetland and a grey reference

Figure 5 provides a comparison between the environmental impacts of the green technology system, French VF wetland, and a grey technology reference, activated sludge based on the FU. To make the results comparable, the

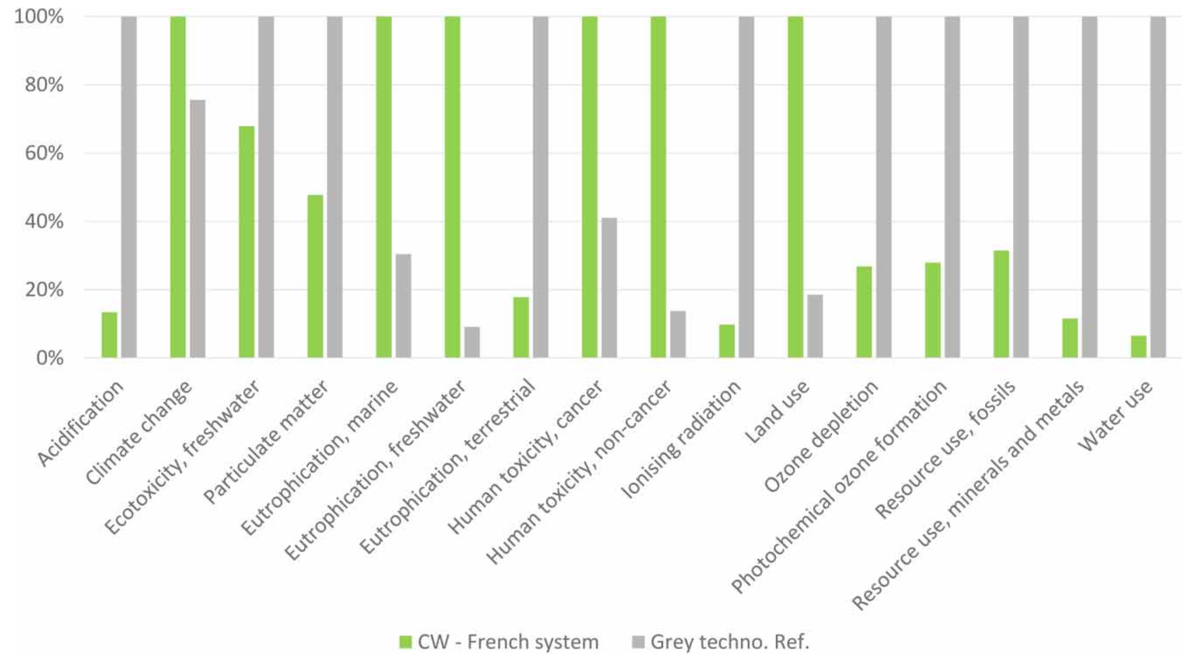

Figure 5 | Comparison of green NBS technology for WWT (French VF wetland) and grey equivalent technology (activated sludge), using the EF 3.1 method.

same system boundaries are used and the substitution of mineral fertilizers was not included in the French VF wetland (System B in Figure 1). However, the mass balance as presented previously, along with trace metal emissions and sludge spreading, are included. The French VF wetland technology achieves better results for 10 impact categories out of the 16 categories of the EF 3.1 method.

The activated sludge technology emits more emissions (notably NH_3, NOx, and SO_2) than the French VF wetland, which significantly contributes to impact categories such as acidification, particulate matter, terrestrial eutrophication, ozone depletion, and photochemical ozone formation. Additionally, this technology requires the use of electricity, predominantly derived from nuclear sources in France, thus explaining the impact of ionizing radiation 10 times higher than for the French VF wetland. This green technology also allows a mitigation of 32% on the freshwater ecotoxicity impacts.

In terms of land footprint, the French VF wetland utilizes significantly more space than the grey technology for the same amount of treated water. This results in a land use impact over 80% higher for the French VF wetland. The impacts on marine and freshwater eutrophication, as well as on human toxicity, can be explained by N and P emissions to the output water source, as well as the TME emitted to the soil, as described previously. N_2O emissions associated with the operation of the filter amplify the impact on climate change, making it 22% greater than the GHG emissions related to the grey technology reference.

4.3. Data for mass balance

Through this detailed study, it is evident that the LCA results of the French VF wetland are dominated by air emissions during operation, the treated water output from the filter, and the trace metal emissions into the soil from sludge spreading and composting. The impacts related to the construction and end-of-life of the filter, as well as maintenance operations, are secondary according to the impact categories. Therefore, it is necessary to perform a complete mass balance, especially for C, N, and P flows, to obtain results that highlight the system hotspots, to avoid missing out important pollution and to allow for comparison with other technologies (Corominas *et al.* 2020; Larrey-Lassalle *et al.* 2022).

Regarding GHG emissions, IPCC is providing emissions factors that can help to fill incomplete mass balance (IPCC 2014, 2019; Table 4). These factors are only available for some WWT NBS, especially treatment wetlands. While they provide a good estimate of CH_4 emission, the proposed calculations for CO_2 remained incomplete if DCO in output treated water or C content in exported sludge remains unknown. For N_2O emissions, the estimate diverges greatly from the value proposed in the case study and from values in the literature. There is significant

Table 4 | Comparison of GHG emissions from the French VF wetland case study with IPCC emission factors

Mass balance element	Proposed value in this paper	Estimation using IPCC methodology	Recommendations for missing value
CH_4	0.241 g CH_4 day^{-1} PE^{-1}	0.393 g CH_4 day^{-1} PE^{-1}	IPCC emission factors allow a fair estimation of CH_4 emissions, based on DCO in the input wastewater. Emissions factors are available only for generic treatment wetlands.
CO_2	Adjustment value of C mass balance	Adjustment value of C mass balance	It is obtained by subtracting the total incoming carbon with all other carbon fluxes exiting the system (sludge, treated water, and CH_4). Note that biomass fixes carbon through photosynthesis and does not take carbon from the filter. A COD or BOD abatement rate for the outgoing water is usually available for the technology, but assumptions need to be made for the carbon content in the sludge.
N_2O	0.12 N-N_2O·day^{-1}·PE^{-1}	0.003565 g N-N_2O·day^{-1}·PE^{-1}	IPCC emission factors tend to underestimate greatly the N_2O emissions, applied to the case study. Other references in the literature provide emission factor 30 times higher than the ratio proposed by the IPCC for similar wetlands (Filali *et al.* 2017). Due to its high contribution to climate change, sensitivity analysis has to be carried out if measurements are not available.

uncertainty regarding N_2O emission factors due to a limited number of studies and *in situ* measurements (IPCC 2014; Corominas *et al.* 2020). Therefore, it is essential to emphasize that more research and measurements are crucial to improve estimation of N_2O emissions, regardless of the NBS used for wastewater, as it can contribute enormously to climate change impacts.

In this study, no indirect gas emissions were taken into account. Indirect emissions, originating from nitrogen discharged into surface waters and nitrogen in the form of NH_3 from sludge spreading that is released into the atmosphere and then redeposited, will undergo nitrification and denitrification processes in the receiving environments (Hélias 2019). Using the inventories provided within this study and the emissions factors from Hélias (2019), the N indirect emissions would increase the GHG of the whole French VF wetland by 14% or by 19% if the substitution of mineral fertilizers by sludge is included (higher NH_3 emissions from sludge). Similarly, the COD contained in the treated water can release CH_4. Thus, additional emissions of N_2O and CH_4 should be accounted for, depending on the receiving environment (IPCC 2019; INRAE Transfert 2022).

Regarding sludge exports, there are very few references in the literature to obtain generic reference data according to the filters. Some data can be found in Canle (2009) and Brockmann Pradel & Helias (2018). The latter reference provides the necessary elements for calculating emissions related to sludge spreading. Therefore, it is feasible to incorporate this element within the system boundaries. It will also be interesting to consider carbon storage in the soil related to sludge spreading to achieve a more comprehensive balance.

Finally, TMEs play a significant role in the LCA results of NBS. However, there is limited knowledge about these elements and their impact on ecotoxicity. In the absence of rapid improvement in the robustness of toxicity and ecotoxicity indicators, it is crucial to better understand their distribution among sludge, biomass, and treated water to enhance the inventory of WWT technologies.

5. CONCLUSION

The French VF wetland could achieve significant reductions in the use of electrical energy and mineral, metal, and fossil resources. However, due to the GHG emissions during the operation phase, and especially the N_2O emissions, the French VF wetland contributes more to climate change. This study also highlighted a gap in the literature regarding measurement of N_2O emissions from constructed wetlands, despite their potential to tip the balance GHG. In addition, when considering more impact categories, these results must be weighed against poorer performance in impact categories sensitive to water emissions due to the absence of denitrification and dephosphatation. Additionally, it is important to consider that the land footprint is much higher for this NBS technology compared with conventional technology. Therefore, integrating all these elements into a single score does not favour the NBS technology. However, this result must be put into perspective because some of the impact categories that carry the most weight are based almost exclusively on the mass balance of TMEs, which is done approximately, and these impact indicators are also quite weak.

This lack of information or uncertainties can be a critical barrier limiting the adoption of NBS by decision makers (Ershad Sarabi *et al.* 2019). Risch *et al.* (2015) conducted a study that included both sewer systems and WWT plants. They have shown that the sewer system contributes significantly to several midpoint indicators: human health, ecosystems, and resources. This study highlights the potential benefits of implementing a decentralized WWT approach, which limits the extent of the sewer network. The present study focused exclusively on the technology but further study should place the NBS technology within its context of use. However, besides environmental impacts, NBS support multiple ecosystem services and address many urban challenges (Castellar *et al.* 2021). These services and challenges should be thoroughly assessed in further research in order to provide a better guidance for decision makers.

FUNDING

This document has been prepared in the framework of the European project MULTISOURCE. This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement no. 101003527.

The sole responsibility for the content of this publication lies with the authors. It does not necessarily represent the opinion of the European Union. Neither the EASME nor the European Commission are responsible for any use that may be made of the information contained therein.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

K.D.: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Data Curation, Writing – original draft. N.F.: Methodology, Data Curation, Formal analysis, Validation, Writing – Review & Editing. P.M.: Investigation, Data Curation, Formal analysis, Validation, Writing – Review & Editing. M.P.: Data Curation, Formal analysis, Writing – Review & Editing. E.L.: Conceptualization, Methodology, Validation, Writing – Review & Editing, Supervision.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

ACV4E Software (2018) *Hypothèses Pour la Modélisation des Filières Extensives de Traitement des Eaux Usées*. Available at: https://www.elsa-pact.fr/ressources/logiciel-acv4e/contenu-support-et-documents-a-telecharger (Accessed 28 May 2024).

Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S. & Ardente, F. (2023) *Updated Characterisation and Normalisation Factors for the Environmental Footprint 3.1 Method*. Luxembourg: Publications Office of the European Union. JRC130796.

Babí Almenar, J., Petucco, C., Sonnemann, G., Geneletti, D., Elliot, T. & Rugani, B. (2023) Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: An application to urban forests, *Ecosystem Services*, **60**, 101506. https://doi.org/10.1016/j.ecoser.2022.101506.

Bixler, T. S., Houle, J., Ballestero, T. & Mo, W. (2019) A dynamic life cycle assessment of green infrastructures, *Science of The Total Environment*, **692**, 1146–1154. https://doi.org/10.1016/j.scitotenv.2019.07.345.

Brockmann, D., Pradel, M. & Helias, A. (2018) Agriculture use of organic residues in life cycle assessment: Current practices and proposal for the computation of field emissions and of the nitrogen mineral fertilizer equivalent, *Resources, Conservation and Recycling*, **133**, 50–62. https://doi.org/10.1016/j.resconrec.2018.01.034.

Byrne, D. M., Grabowski, M. K., Benitez, A. C. B., Schmidt, A. R. & Guest, J. S. (2017) Evaluation of life cycle assessment (LCA) for roadway drainage systems, *Environmental Science & Technology*, **51**, 9261–9270. https://doi.org/10.1021/acs.est.7b01856.

Canle, J.-P. (2009) Guide technique sur les Matières de Vidange issues de l'assainissement non collectif: Caractérisation, collecte et traitements envisageables (Technical guide on drainage materials from non-collective sanitation: Characterization, collection, and possible treatments), *FNDAE*, 1–69.

Catel, L., Boutin, C., Dubois, V. & Roux, P. (2017) *Inventaires du Cycle de vie de Filières de Traitement des Eaux Usées en Assainissement Non Collectif, Rapport ONEMA (Inventories of the Life Cycle of Wastewater Treatment Systems in Non-Collective Sanitation, ONEMA Report)*. Published on the ACV4E-ELSA-PACT Website. Available at: https://www.elsa-pact.fr/ressources/logiciel-acv4e/acv4e-fait-parler-de-lui2 (Accessed 28 May 2024).

Castellar, J. A. C., Popartan, L. A., Pueyo-Ros, J., Atanasova, N., Langergraber, G., Säumel, I., Corominas, L., Comas, J. & Acuña, V. (2021) Nature-based solutions in the urban context: Terminology, classification and scoring for urban challenges and ecosystem services, *Science of The Total Environment*, **779**, 146237. https://doi.org/10.1016/j.scitotenv.2021.146237.

Corominas, L., Byrne, D. M., Guest, J. S., Hospido, A., Roux, P., Shaw, A. & Short, M. D. (2020) The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review, *Water Research*, **184**, 116058. https://doi.org/10.1016/j.watres.2020.116058.

Directive Eau Résiduaire Urbaine (DERU) 91/271/CEE du 21 mai (1991) Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment.

Dotro, G., Langergraber, G., Molle, P., Nivala, J., Puigagut, J., Stein, O. R. & von Sperling, M. (2017) *Treatment Wetlands. Biological Wastewater Treatment Series, Volume 7*. London, UK: IWA Publishing, p. 172. eISBN: 9781780408774. Available at: http://wio.iwaponline.com/content/16/9781780408774.

ECODEFI 2011 (2011) *Guide D'éco-Conception des Matériels D'épandage (Guide for the eco-Design of Spreading Equipment) – Technical Report*. Available at: https://www.cetim.fr/content/download/48356/1445883/version/1/file/GUIDE_ECODEFI_Version_finale_.pdf.

Ershad Sarabi, S., Han, Q., L. Romme, A. G., de Vries, B. & Wendling, L. (2019) Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: A review, *Resources*, **8**, 121. https://doi.org/10.3390/resources8030121.

European Commission (2015) *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on Nature-Based Solutions and Re-Naturing Cities*. Brussels, Belgium: European Commission.

Filali, A., Bollon, J., Molle, P., Mander, Ü. & Gillot, S. (2017) High-frequency measurement of N_2O emissions from a full-scale vertical subsurface flow constructed wetland, *Ecological Engineering*, **108**, 204–248. https://doi.org/10.1016/j.ecoleng.2017.08.037.

Flores, L., García, J., Pena, R. & Garfí, M. (2019) Constructed wetlands for winery wastewater treatment: A comparative life cycle assessment, *Science of The Total Environment*, **659**, 1567–1576. https://doi.org/10.1016/j.scitotenv.2018.12.348.

Flynn, K. M. & Traver, R. G. (2013) Green infrastructure life cycle assessment: A bio-infiltration case study, *Ecological Engineering*, **55**, 9–22. https://doi.org/10.1016/j.ecoleng.2013.01.004.

Fuchs, V. J., Mihelcic, J. R. & Gierke, J. S. (2011) Life cycle assessment of vertical and horizontal flow constructed wetlands for wastewater treatment considering nitrogen and carbon greenhouse gas emissions, *Water Research*, **45**, 2073–2081. https://doi.org/10.1016/j.watres.2010.12.021.

Heimersson, S., Svanström, M., Laera, G. & Peters, G. (2016) Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems, *International Journal of Life Cycle Assessment*, **21**, 1197–1212. https://doi.org/10.1007/s11367-016-1095-8.

Hélias, A. (2019) At the boundary between anthropogenic and environmental systems: The neglected emissions of indirect nitrous oxide, *International Journal of Life Cycle Assessment*, **24**, 412–418. https://doi.org/10.1007/s11367-018-1564-3.

Hellweg, S. & Milà i Canals, L. (2014) Emerging approaches, challenges and opportunities in life cycle assessment, *Science*, **344**, 1109–1113. https://doi.org/10.1126/science.1248361.

INRAE Transfert (2022) Recommandations méthodologiques pour la réalisation des ACV des systèmes d'assainissement non collectif (Methodological recommendations for conducting Life Cycle Assessments (LCAs) of non-collective sanitation systems), 202105-571/DV001501-1506. Available at: https://atep-france.fr/fr/recommandations-methodologiques-pour-la-realisation-des-acv-des-systemes-d-assainissement-non-collectif/.

IPCC (2006) N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. (eds.) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Hayama, Japan: Institute for Global Environmental Strategies (IGES).

IPCC (2014) Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. In: *2013 Supplement to the 2002 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Available at: http://www.ipcc-nggip.iges.or.jp.

IPCC (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. In: *Chapter 6. Wastewater Treatment and Discharge*, Vol. 5, pp. 7–65.

Larrey-Lassalle, P., Armand Decker, S., Perfido, D., Naneci, S. & Rugani, B. (2022) Life cycle assessment applied to nature-based solutions: Learnings, methodological challenges, and perspectives from a critical analysis of the literature, *Land*, **11**, 649. https://doi.org/10.3390/land11050649.

Masi, F., Rizzo, A. & Regelsberger, M. (2018) The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm, *Journal of Environmental Management, Sustainable Waste and Wastewater Management*, **216**, 275–284. https://doi.org/10.1016/j.jenvman.2017.11.086.

Ministère de l'Agriculture et de la Souveraineté alimentaire (2023) *Infographie – Palmarès des Produits Agricoles et Agroalimentaires Français (Infographic – Ranking of French Agricultural and Agri-Food Products)*. Available at:

https://agriculture.gouv.fr/infographie-palmares-des-produits-agricoles-et-agroalimentaires-francais (Accessed 29 May 2024).

Morvannou, F. N., Michel, S., Troesch, S. & Molle, P. (2015) Treatment performances of French constructed wetlands: Results from a database collected over the last 30 years, *Water Science & Technology*, **71** (9), 1333–1339. https://doi.org/10.2166/wst.2015.089.

Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., van Dijk, J., Inge Vistad, O., Wilkinson, M. E. & Wittmer, H. (2017) The science, policy and practice of nature-based solutions: An interdisciplinary perspective, *Science of The Total Environment*, **579**, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106.

Pan, T., Zhu, X.-D. & Ye, Y.-P. (2011) Estimate of life-cycle greenhouse gas emissions from a vertical subsurface flow constructed wetland and conventional wastewater treatment plants: A case study in China, *Ecological Engineering*, **37**, 248–254. https://doi.org/10.1016/j.ecoleng.2010.11.014.

Parra-Saldivar, R., Bilal, M. & Iqbal, H. M. N. (2020) Life cycle assessment in wastewater treatment technology, *Current Opinion in Environmental Science & Health*, **13**, 80–84. https://doi.org/10.1016/j.coesh.2019.12.003.

Petit-boix, A., Sevigné-itoiz, E., Rojas-gutierrez, L. A., Paceli, A. P., Josa, A., Rieradevall, J. & Gabarrell, X. (2015) Environmental and economic assessment of a pilot stormwater infiltration system for flood prevention in Brazil, *Ecological Engineering*, **84**, 194–201. https://doi.org/10.1016/j.ecoleng.2015.09.010.

Pradel, M., Pacaud, T. & Cariolle, M. (2009) *Fertilisation des Systems de Cultures par des Boues de Station D'épuration: Description des Systems et Calcul des Doses de Fertilisants à Apporter (Fertilization of Crop Systems with Sewage Sludge: Description of Systems and Calculation of Fertilizer Doses to be Applied)*. Cemagref – Technical Report. Available at: https://hal.inrae.fr/hal-02592600

Prasuhn, V. (2006) *Erfassung der PO_4-Austräge für die Ökobilanzierung (Estimation of Phosphate (PO_4) Emissions for Ecological Balance Assessment)*. Switzerland: Salca-Phosphor: Agroscope, p. 20.

Resende, J., Nolasco, M. & Pacca, S. (2019) Life cycle assessment and costing of wastewater treatment systems coupled to constructed wetlands, *Resources, Conservation and Recycling*, **148**, 170–177. https://doi.org/10.1016/J.RESCONREC.2019.04.034.

Risch, E. & Boutin, C. (2020) *Mise en œuvre de l'ACV en Assainissement non Collectif – Diagnostic Préliminaire (Mplementation of Life Cycle Assessment (LCA) in Non-Collective Sanitation – Preliminary Diagnosis)*.

Risch, E., Loubet, P., Núñez, M. & Roux, P. (2014) How environmentally significant is water consumption during wastewater treatment?: Application of recent developments in LCA to WWT technologies used at 3 contrasted geographical locations, *Water Research*, **57**, 20–30. https://doi.org/10.1016/j.watres.2014.03.023.

Risch, E., Gutierrez, O., Roux, P., Boutin, C. & Corominas, L. (2015) Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems, *Water Research*, **77**, 35–48. https://doi.org/10.1016/j.watres.2015.03.006.

Risch, E., Boutin, C. & Roux, P. (2021) Applying life cycle assessment to the environmental performance of decentralised versus centralised wastewater systems, *Water Research*, **196**, 116991.

Roux, P., Boutin, C., Risch, E. & Heduit, A. (2010). 'Life cycle environmental assessment (LCA) of sanitation systems including sewerage: Case of vertical flow constructed wetlands versus activated sludge', *Proceedings 12th IWA International Conference on Wetland Systems for Water Pollution Control*, pp. 1–11.

Stefanakis, A. I. (2019) The role of constructed wetlands as green infrastructure for sustainable urban water management, *Sustainability*, **11**, 2–19. https://doi.org/10.3390/su11246981.

UNALAB (2019) *Nature Based Solutions – Technical Handbook (Part II)*. Available at: https://unalab.eu/en/publications (Accessed 29 May 2024).

URBANGREENUP (2018) *NBS Catalogue*. Available at: https://www.urbangreenup.eu/insights/deliverables/d1-1--nbs-catalogue.kl (Accessed 29 May 2024).

Vineyard, D., Ingwersen, W. W., Hawkins, T. R., Xue, X., Demeke, B. & Shuster, W. (2015) Comparing green and grey infrastructure using life cycle cost and environmental impact: A rain garden case study in Cincinnati, OH, *Journal of the American Water Resources Association*, **51**. https://doi.org/10.1111/1752-1688.12320.

Woods-Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scot, T., Acheley, R. & Kellagher, R. (2015) *The SUDS Manual*. London: Ciria.

First received 30 May 2024; accepted in revised form 18 October 2024. Available online 25 November 2024