LCA in wastewater treatment - Applicability and limitations for constructed wetland systems: using vertical Reed Bed Filters

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Abstract Over the past decades in Europe, man-made ecosystems such as constructed wetland systems have been successfully harnessed to treat sewage and other pollutants in waste waters. This work presents a comparative Life Cycle Assessment (LCA) study between (i) a 2-stage vertical Reed Bed Filter, and (ii) a conventional activated sludge system, both designed following usual French guidelines in domestic sewage treatment. The first LCA applicability challenge is to get an equilibrated mass balance between wastewater inputs in Nitrogen, Phosphorus, Carbon and systems outputs. The second LCA challenge overcome in this work is to provide grounds for comparison in terms of treatment efficiency between the two systems. Results show the poor efficiency of vertical Reed Bed Filters in removing nitrates, organic nitrogen and phosphates which highlight the need to pursue other avenues in the all important reduction of eutrophication in waterways.

1 Introduction

Wetland ecosystems are known for their physical, chemical and biological microbial processes at play in pollutant breakdown and removal from water passing through these systems. Over the past decades in Europe, man-made ecosystems such as constructed wetland systems (CW) have been successfully harnessed to treat sewage and other pollutants in wastewater. Several authors have published Life Cycle Assessment (LCA) studies on classic wastewater treatment plants (WWTP) [1] and wastewater sanitation systems [2] but as yet little attention has been given to LCA studies on constructed wetlands (CW) systems [3][4][5].

Most of the existing studies assess different CW systems without comparing them to classic wastewater treatment technologies or paying attention to the system's end-of-life by-products, wastes and final water discharges.

In LCA, a model of the system is first constructed, with a selected flow rate of environmentally relevant substances between the technical system and the environmental compartments. This systemic approach enables the assessment of changes in wastewater treatment efficiencies with changing input parameters, and a comparison between different technical solutions in terms of the estimated environmental footprint related to emissions and resource use. For a general description of LCA, see the relevant ISO standard [6].

2 Materials and method

2.1 Functional unit and LCIA method

To enable a comparison between different solutions in the treatment of domestic sewage, a comparative LCA is carried out in this study. For this purpose, the functional unit which quantifies the performance of the studied systems has to be carefully defined in the first phase of a LCA study. The chosen functionality is the treatment to French legal standards for discharge to surface waters of "a kilogram of daily organic load" ($kgBOD_5$) of domestic origin. This is consistent with the main purpose of the WWTPs being to reduce emissions of nutrients and BOD to acceptable levels.

The WWTPs are modelled under SimaPro 7.2 software, using inventory data from ecoinvent v2.0 database and technical data from French guidelines. The LCA study comprises the production of components, construction and assembly, operation and maintenance, dismantling and final disposal of the WWTP components.

Regarding the impact categories to be assessed, the ReCiPe methodology [7] for Life Cycle Impact Assessment (LCIA) was chosen. This method yields eighteen relatively robust midpoint indicators with three complimentary (but relatively more uncertain) endpoint indicators. The decision whether to use midpoints or endpoints should be based on the goal of the study and its target audience.

2.2 Systems overview

A complete wastewater treatment system involves the collection and transport of domestic sewage from the serviced households via the sewer network, to the wastewater treatment plant whose capacity is theoretically adapted to the population serviced. Fig. 1 presents a general overview of a conventional wastewater system. The sewer network is excluded from the system boundaries since it is assumed that the collection and transportation of wastewater would be the same for the alternative wastewater treatment processes compared in this study. It can be noted that the post-treatment of solid wastes from the preliminary treatment stage is excluded from the system boundaries. Indeed, it is assumed that the solid wastes for all studied systems will share the same end of life. The wastewater treatment plants included in the scope of the present LCA study are (i) a vertical flow reed bed filter (vRBF), and (ii) an activated sludge process (AS) featuring an enhanced phosphate elimination involving precipitating agents and flocculants in the sludge conditioning process. All WWTP infrastructures are modelled with a lifetime of 30 years.

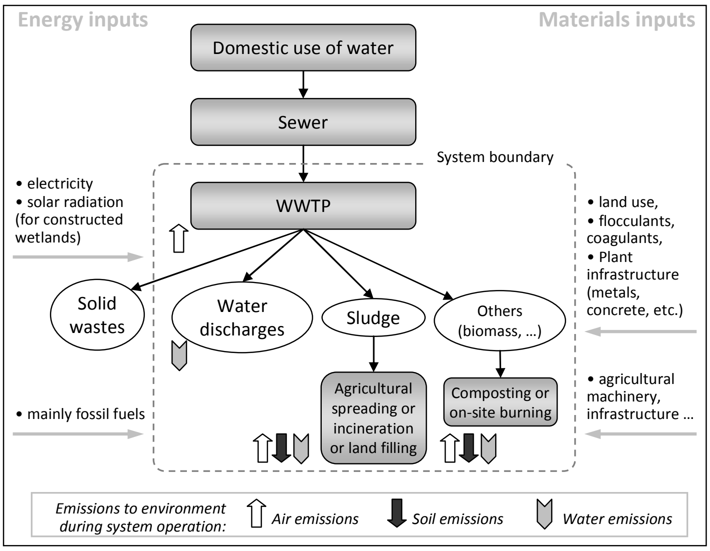

Fig. 1: Flow chart of the wastewater system

Tab. 1 gives detailed compositions of influent (domestic sewage) treated by the systems under study, and compares it with the available ecoinvent data for a Class 5 WWTP. It can be noted that the sewage composition from ecoinvent is quite similar to the French one, while the hydraulic load is significantly higher.

Tab. 1. Input sewage composition in the studied systems

System input		ecoinvent Class 5 AS (CH)	vRBF (FR)	AS (FR)
Nominal Organic load ($kgBOD_5.d^{-1}$)		48,36		312
Nominal hydraulic load ($m^3.day^{-1}$)		446	145	936
Treatment capacity		806 PE	967 Hab.	6240 Hab.
Concentration ($mg.L^{-1}$)	BOD_5	103.6	333	
	COD	155.4	800	
Flows ($g.day^{-1}$)		**per P.E.** (a)	**per Hab.** (b)	
BOD_5		60,0	50,0	
COD		90,0	120,0	
$N\text{-}NH_4$		8,27	7,5	
N-org(c)		6,46	2,5	
$N\text{-}NO_2$		0,22	0,0	
$N\text{-}NO_3$		0,58	0,0	
Total N		***15,53***	***10,0***	
P-Part		0,34	0,4	
$P\text{-}PO_4$		1,36	1,6	
Total P		***1,70***	***2,0***	

(a) **P.E.**: Person-Equivalent – One person-equivalent has a daily biodegradable organic load of 60g of oxygen per day expressed on a five-day biochemical oxygen demand ($BOD_5.d^{-1}$) (European Council Directive [8])
(b) **Hab.**: French P.E., organic load equivalent to 50g$BOD_5.d^{-1}$
(c) N-org is the sum of particulate nitrogen and dissolved organic nitrogen

It is assumed that the influent is made up exclusively of domestic sewage, collected from French rural communities. French PE units used in this study are defined according to Cemagref guidelines issued following data collected on French rural communities.

2.2.1 CW system

The WWTP model representing a CW system is based on a 2-stage vRBF plant designed for a daily nominal load in BOD_5 of 48kg.d^{-1}. The vRBF design follows the usual French recommendations [9][10] with three filters on the first stage (60m x 20m) and two filters on the second stage (56m x14m). Fig. 2 presents an overview of the vRBF process modelled in this study.

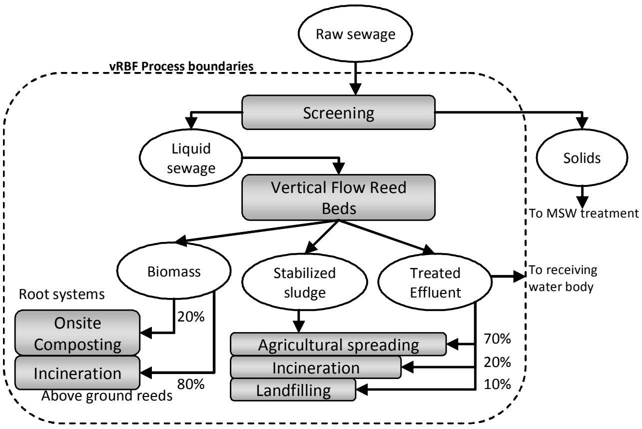

Fig. 2. Flow chart of the constructed wetland (vRBF) system

2.2.2 AS system

The LCA base model for an AS system is defined for a low-load activated sludge technology with a selective chemical precipitation of phosphates with iron (III) chloride (see Fig. 3 for an overview of the process). A conventional sludge conditioning process with flocculation and coagulation and dewatering is then applied to obtain a stabilized, dry-cake sludge. Model design is based on technical reports issued for regional French WWTPs.

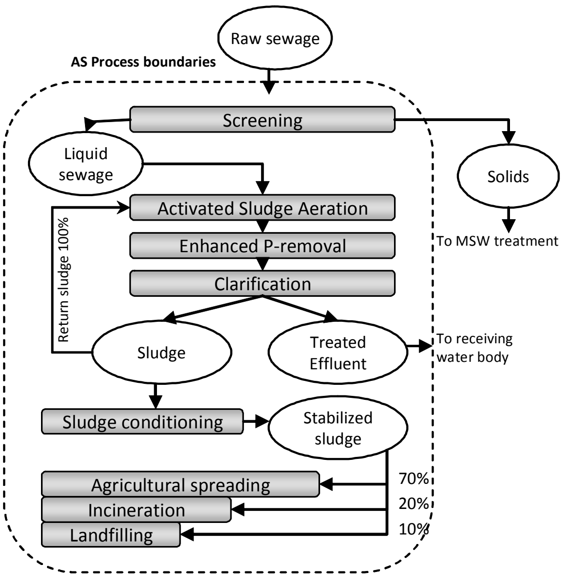

Fig. 3. Flow chart of the activated sludge system

3 Life Cycle Inventory

The present chapter summarises the life cycle inventory (LCI), but as it is not realistic to supply a full LCI in a conference paper, supporting information will be available upon request to the corresponding author.

3.1 Inventory of resources required for facilities construction, operation and maintenance

The materials used in the construction phase were considered to last for the whole lifetime of the plants (30 years), with no replacement being considered.

Besides the usual end-of-life options available for most of all components and raw materials inventoried in the construction of the WWTPs, in this study the end-of-life options for the by-products and wastes generated during the operation of the plants are also considered.

Usual French practice in sludge handling can be estimated as follows for the excess sludge purged from the treatment process: 70% of agricultural spreading (soil improvement), 20% of incineration in municipal solid waste facility, and 10% of land filling. Concerning the harvested biomass from the planted macrophyte beds in a vRBF, it is assumed that of 1 kg of plant biomass, 0,8 kg is burned at a municipal incineration facility and 0,20 kg composted onsite. Electricity consumption was taken from the actual French electrical mix available in ecoinvent (with a large share of nuclear power).

3.2 Inventory of emissions to environment

The material input-output balance reflecting the efficiency of the vRBF system is shown in Tab. 2. Balancing such a table is a quite complex task which calls for specialist expertise and access to measurements data. This table is based on Cemagref expertise and available data [10] and is really to be considered as a first basis to conduct this LCA of vRBF. In fact, most of the previous LCA approaches on CW systems [3][4] do not investigate such a precise input-output balance. In a comparative LCA study between different treatment technologies, the efficiencies of the studied processes (i.e. the discharged water) are not equivalent. In order to find common ground for this type of comparison, it is thus necessary to include effluents, but also the produced excess sludge which can displace mineral fertilizers use to a certain extent when considering agricultural soil improvement.

Tab. 2. Material input-output balance for the use phase of a vRBF

Input wastewater content			**vRBF outputs ($g.d^{-1}.hab^{-1}$) -** effluents and other outputs (<< stands for negligible quantities)						
			Emissions and direct discharges			**By-products**			**Total output**
Substances		**$g.d^{-1}.hab^{-1}$**	**Air**	**Soil**	**Water**	**Sludge**	**Reeds**	**Filter matrix**	
N	N-NH4	7,50			0,25	<<		0,10	
	N-org	2,50			1,80	0,75	0,76		
	N-NO2+3	0			6,23			<<	
	N-NH3		<<						
	N-NO		<<						
	N-N_2O		0,11						
	N-N_2		<<						
	Total N, in	***10,0***	***0,11***	**-**	***8,28***	***0,75***	***0,76***	***0,10***	***10,0***
P	P-org	0,40				0	0,05	<<	
	P-PO4	1,60			1,50	0	<<	0	
	P-P2O5	0			0	0,44	<<	0,01	
	Total P, in	***2,00***	**-**	**-**	***1,50***	***0,44***	***0,05***	***0,01***	***2,00***
C	C_{org}	45,0			1,87	13,1	<<	<<	
	C-CO2		29,8						
	C-CH4		0,16						
	$C_{mineral}$	5,00			2,00	3,00			
	Total C, in	***50,0***	***30,0***	**-**	***3,87***	***16,1***	**-**	**-**	***50,0***

The environmental flows to air and water from the two studied processes are inventoried in Tab. 3. Soil emissions are considered in a specific agricultural spreading module where transfer coefficients from the sludge to air and water have been calculated, as well as avoided synthetic (mineral) fertilizers [11] based on common French fertilization practices. Further background data may be available upon request to corresponding author. Work is underway to include trace metals in effluents and by-products, as well as persistent trace organics.

Tab. 3. Inventory flows to the environment (g. $Hab.day^{-1}$)

System output	**vRBF**	**AS**
Emissions to water		
COD, Chemical Oxygen Demand	12,0	10,8
HCO_3^-, Carbonate **(*)**	10,0	10,0
NH_4^+, Ammonium ion	0,32	0,39

N, Nitrogen total (organic)	1,80	0,60
NO_2^-, Nitrite	0,00	0,00
NO_3^{2-}, Nitrate	27,6	1,33
P, Phosphorus (Particulate P)	0 ,00	0,14
PO_4^{3-}, Phosphate	4,60	0,15
Cl^-, Chloride	-	4,27
Emissions to air		
CO_2, Carbon dioxide, biogenic	109	46,5
CH_4, Methane, biogenic	0,22	0,08
N_2O, Dinitrogen monoxide	0,35	0,47
Emissions to soil		
None. Agricultural spreading of sludge modelled with transfer coefficients to air and water. Trace metals are being considered in future research.		
(*) As a proxy for the mineral C-fraction in effluent		

4 Results and Discussions

The following results are expressed in relation to the functional unit of 1 kgBOD5 of domestic sewage treated to French legal standards for discharge to surface waters.
Tab. 4. presents the list of abbreviations used to refer to the ReCiPe midpoint categories.

Tab. 4. Abbreviations of the ReCiPe midpoint categories

Abbr.	Impact category	Unit of the indicator result
CC	Climate change	kg (CO_2 to air)
OZ	Ozone depletion	kg (CFC-11 to air)
HT	Human toxicity	kg (14DCB to urban air)
POF	Photochemical oxidant formation	kg (NMVOC to air)
PMF	Particulate matter formation	kg (PM10 to air)
IR	Ionising radiation	kg (U235 to air)
TA	Terrestrial acidification	kg (SO2 to air)
F-Eu	Freshwater eutrophication	kg (P to freshwater)
M-Eu	Marine eutrophication	kg (N to freshwater)
TET	Terrestrial ecotoxicity	kg (14DCB to industrial soil)
FET	Freshwater ecotoxicity	kg (14DCB to freshwater)
MET	Marine ecotoxicity	kg (14DCB to marine water)
ALO	Agricultural land occupation	$m^2. yr^{-1}$ (agricultural land)

ULO	Urban land occupation	m². yr^{-1} (urban land)
NLT	Natural land transformation	m² (natural land)
WD	Water depletion	m^3 (water)
MD	Metal depletion	kg (Fe)
FD	Fossil depletion	kg (oil)

4.1 Contribution analysis

Considering the whole life cycle of the wastewater treatment systems and the relative contribution of each phase – construction, operation and maintenance (O&M), dismantling and final disposal – their environmental impacts are presented in Fig. 4. In the present study, the greatest quantities of materials used for plant construction were concrete, steel and plastics (piping in both systems and the geotextile membrane used in the lining of the CW).

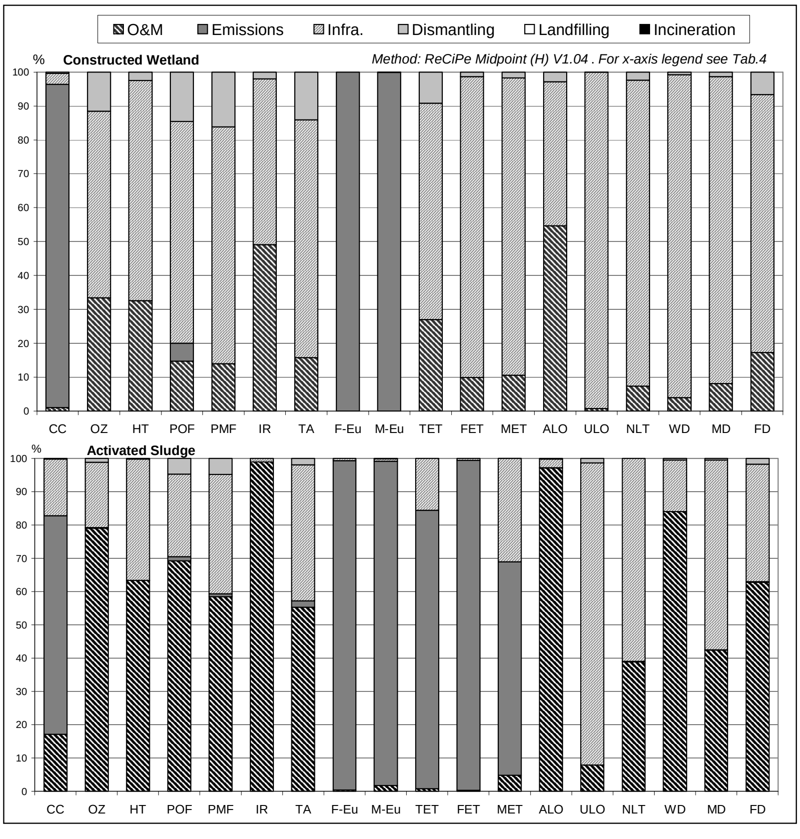

Fig. 4. Contribution analysis of life cycle phases of wastewater systems

4.2 Systems comparison

Fig. 5 presents a comparative Life Cycle Impact Assessment (LCIA) of the systems of interest, using the ReCiPe Characterisation method. The CW system outperforms the AS system in all impact categories with the exception of Eutrophication (Marine and Freshwater) and Urban Land Occupation. In both systems, Eutrophication is caused by the water discharges (as shown in Fig. 4).

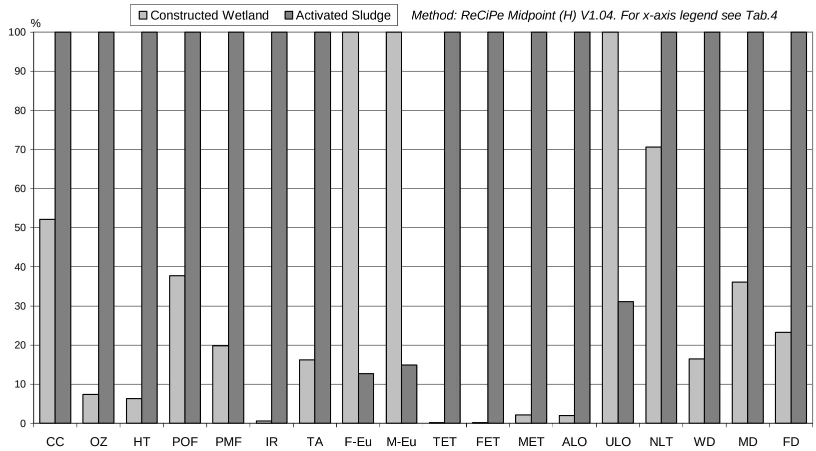

Fig. 5. Comparison of two treatment technologies for 1 kg of BOD_5.day^{-1}

Eutrophication. The CW system has a weaker phosphate removal efficiency compared to the AS system (which features an enhanced phosphate removal via $FeCl_3$ precipitation). This generates a great Freshwater Eutrophication impact for P-limited inland waters. On the other hand, the CW system captures all remaining particulate phosphorus, whereas the AS process effluents have more particle-bound phosphorus (total suspended solids) despite the good phosphate removal. In ReCiPe, particulate phosphorus is known to contribute to Ecotoxicity (Marine, Freshwater and Terrestrial). Marine waters being N-limited, the poor removal efficiencies in nitrates (NO^{3-}) and organic nitrogen of the CW system yield a high impact score in Marine Eutrophication.

Urban Land Occupation (ULO). The CW system being by definition an extensive system which requires about 2-2,5 sqm of reed bed filter per capita for a vRBF [10], it is not surprising for this system to score a high ULO impact whereas the AS technology is engineered with more process intensification namely in the aeration tank.

Other categories. From the LCI, it is expected that the civil engineering of an AS system, which requires a higher materials intensity (concrete, steel, PP, PE, sand, etc.) and transportation needs for these materials to the construction site will contribute to most of the resource depletion impacts. The aeration equipment makes up for most of the energy usage in the AS system, in accordance with the results reported in [3]. The CW system does not require any chemical agent and only requires a small input of electricity in the preliminary treatment (shredding of gross solids). The CO_2 emissions are directly related to the energy consumption, thus the AS system exceeds the CW score in the climate change category.

5 Conclusion

This study reveals the importance of global impacts (concerning climate change, fossil fuel consumption) incurred during the daily operation of a WWTP in order to attain a certain level of treatment in effluents (resulting in local impact categories such as eutrophication, ecotoxicity and land use). Clearly, there is a need to find tradeoffs between process technology performances and operation in terms of environmental costs, i.e. local impacts versus global impacts as suggested in [12].

The challenge in LCA to enable grounds for such comparisons can be met through the balancing between systems inputs and outputs in nitrogen, phosphorus and carbon compounds, and taking into account the fate of wastes and by-products. As shown in [5] it is particularly important to investigate the gaseous emissions from the wastewater treatment process.

LCA results for a vRBF show that the CW treatment technology can outperform conventional technologies in global impacts. It is anticipated that with design optimization for better phosphorus capture and increased denitrification this technology can be environmentally superior in both local and global impact categories. Work is underway to include trace metals in effluents and by-products, as well as persistent trace organics, which will help in making decisions concerning safe and sustainable resource recovery.

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