Comparing environmental impacts of tertiary wastewater treatment technologies for advanced phosphorus removal and disinfection with life cycle assessment

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ABSTRACT

Different technologies for tertiary wastewater treatment are compared in their environmental impacts with life cycle assessment (LCA). Targeting very low phosphorus concentration (50–120 μg/L) and seasonal disinfection of wastewater treatment plant (WWTP) secondary effluent, this LCA compares high-rate sedimentation, microsieve, dual media filtration (all with UV disinfection), and polymer ultrafiltration or ceramic microfiltration membranes for upgrading the large WWTP Berlin-Ruhleben. Results of the LCA show that mean effluent quality of membranes is highest, but at the cost of high electricity and chemical demand and associated emissions of greenhouse gases or other air pollutants. In contrast, gravity-driven treatment processes require less electricity and chemicals, but can reach significant removal of phosphorus. In fact, dual media filter or microsieve cause substantially lower specific CO_2 emissions per kg P removed from the secondary effluent (180 kg CO_2-eq/kg P, including UV) than the membrane schemes (275 kg CO_2-eq/kg P).

Key words | advanced phosphorus removal, environmental footprint, life cycle assessment, tertiary wastewater treatment

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INTRODUCTION

Triggered by the EU Water Framework Directive (WFD) (EU 2000), new requirements for improving water quality of rivers and lakes are being imposed throughout Europe. Following a comprehensive assessment of the status quo in water quality and emissions across river basins, new targets for emission reduction into surface water have been set in river basin management plans to improve the chemical quality of rivers and lakes. In the Berlin-Brandenburg area in eastern Germany, a concept for reduction of nutrient emissions into surface water has been elaborated by water authorities, targeting a further decrease of phosphorus emissions, which are a major cause of eutrophication (SenStadt/MUGV 2011). According to this concept, a further reduction of phosphorus concentration in wastewater treatment plant (WWTP) effluents of Berlin will be required to reach the goals of the WFD. Consequently, the Berlin water authorities have demanded a future implementation of a tertiary treatment stage for advanced removal of phosphorus for the WWTP Berlin-Ruhleben treating the wastewater of 1.6 million population equivalents (PE). However, the resulting new discharge standard has not been fixed, with discharge limits of 120, 80 or even 50 μg/L total phosphorus (TP) (85%ile of grab samples) as possible options depending on the applied technology for tertiary treatment.

In addition, further requirements arise from the discharge of the effluent of WWTP Ruhleben into the river Spree/Havel, affecting the hygienic quality of highly frequented bathing waters downstream (Berlin Wannsee). The EU Bathing Water Directive (BWD) defines a minimum hygienic quality to be guaranteed in these bathing waters during the summer season of April–September (EU 2006). For historical reasons (division of Berlin into eastern and western sector), a pressure pipeline of 18 km is currently in operation during the summer period to discharge the effluent of WWTP Ruhleben further downstream, thus bypassing Lake Wannsee. However, an upgrade of the WWTP with a desinfection step operating during the summer season would enable the discharge of the effluent into the river Spree/Havel throughout the entire year, thus ending the need for costly operation and maintenance of the pressure pipeline.

Hence, the WWTP Ruhleben will be upgraded with a tertiary treatment stage to reach the targets of advanced

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phosphorus removal and seasonal disinfection. As different technological processes are principally suitable to fulfill these targets, several research projects have been initiated to validate the process performance and stability of the different options in pilot trials. The tested technologies for tertiary treatment include coagulation of phosphorus followed by separation of particulate matter with high-rate sedimentation, microsieve, dual media filtration, or membranes. However, these technologies differ in their P removal efficiency, investment and operational costs, and energy and material demand for construction and operation of the processes. From an environmental point of view, additional impacts due to energy and chemical demand for tertiary treatment should be carefully balanced against the environmental benefits in terms of improved effluent quality, to end up with a sustainable solution for the entire system. In particular, local environmental benefits of improved surface water quality (less P emissions) will come at the cost of additional demand for resources (fossil fuels, ores) and environmental emissions (greenhouse gases (GHG), air pollutants) caused by the advanced treatment process. Having this in mind, water authorities demanded quantitative information on environmental trade-offs of the specific processes to support the decision for a specific discharge limit of TP and the respective treatment process.

A suitable tool for a comprehensive assessment of the total environmental impacts of a technological system is the method of life cycle assessment (LCA). This tool enables the systematic and comprehensive quantification of all direct and indirect environmental impacts with environmental indicators, following a standardised framework as defined in ISO 14040/44 (ISO 14040 2006; ISO 14044 2006). LCA has been used extensively in previous studies to systematically assess the environmental impacts of wastewater treatment (Corominas *et al.* 2013a), also with a focus on nutrient removal strategies (e.g. Corominas *et al.* 2013b). However, LCA of advanced tertiary treatment has only been applied for processes targeting the removal of organic and inorganic micropollutants (e.g. Hoibye *et al.* 2008; Wenzel *et al.* 2008; Muñoz *et al.* 2009; Igos *et al.* 2013), but so far not for processes for advanced phosphorus removal to very low effluent limits and disinfection.

OBJECTIVES

The present paper will provide results of a comparative LCA case study of tertiary treatment processes for advanced P removal and disinfection, based on data of long-term pilot trials at a large WWTP. Due to expected stricter effluent limits for nutrients and disinfection in many WWTPs following recent legislation (WFD, BWD), the methods and results of this study will also be valuable to provide decision support for future upgrades of other WWTPs which have to comply with stricter effluent standards. Beyond the factual results of the comparative LCA, the suitability of the LCA approach for quantifying the environmental benefits and additional impacts of tertiary wastewater treatment will be discussed.

DEFINITION OF GOAL AND SCOPE FOR LCA

The goal of this LCA is the comparison of different technologies for tertiary treatment at WWTP Berlin-Ruhleben in terms of their environmental impacts. The system functions are defined by the two requirements for advanced P removal and disinfection: (1) to eliminate TP from secondary effluent down to at least 120 μg/L TP (85%ile of grab samples) and (2) to safely reach 'good bathing water quality' during the bathing season (Apr–Sep) as defined by the BWD. The functional unit of this LCA is set as 'the treatment of secondary effluent per population equivalent and year ($(PE*a)^{-1}$)', referring to the organic load at the WWTP inlet (120 g chemical oxygen demand/(PE*d) (ATV 2000)). System boundaries include the construction of the tertiary treatment stage (infrastructure) and its operation, including the demand for electricity, chemicals, and other materials (Figure 1).

The hydraulic load caused by returning the filter backwash water to the WWTP inlet is accounted for in the substance flow model as additional flow in the tertiary treatment stage, which is required not to exceed 5% of the peak hydraulic capacity of the WWTP (7 m^3/s). Quality of the return flow (sludge with retained TP and coagulation chemicals) is assumed not to alter the quality of the secondary effluent owing to its small contribution compared to the WWTP influent load. While gravity-driven treatment technologies (high-rate sedimentation, dual media filter, microsieve) are capable of treating the maximum peak flow due to their high hydraulic flexibility, membrane filtration options are generally designed for dry weather peak flow only (=4.5 m^3/s) to prevent high investment costs. At peak flow conditions, excess volume (2.7% of annual volume) is bypassed without membrane filtration and just treated by UV disinfection in summer to guarantee full disinfection performance.

In detail, the following scenarios are evaluated within this LCA (Figure 2).

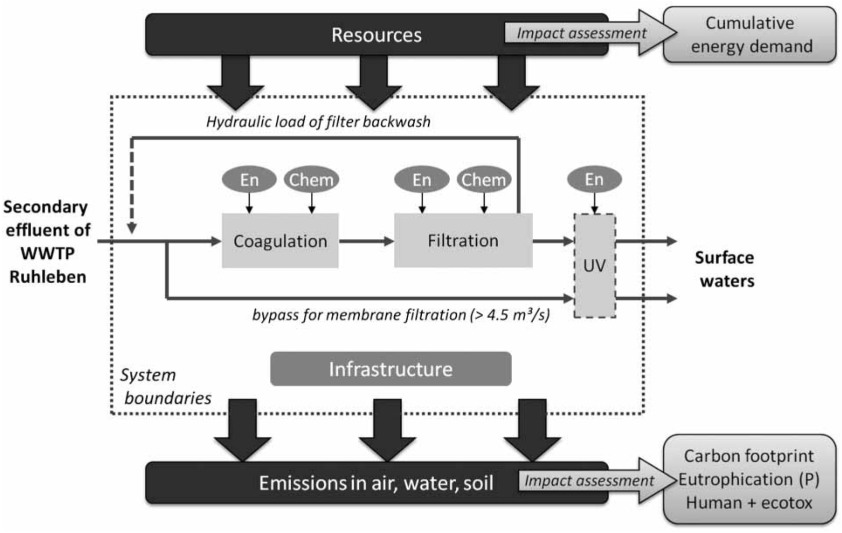

Figure 1 | System boundaries for LCA (En: energy, Chem: chemicals, final UV disinfection or bypass depending on treatment technology).

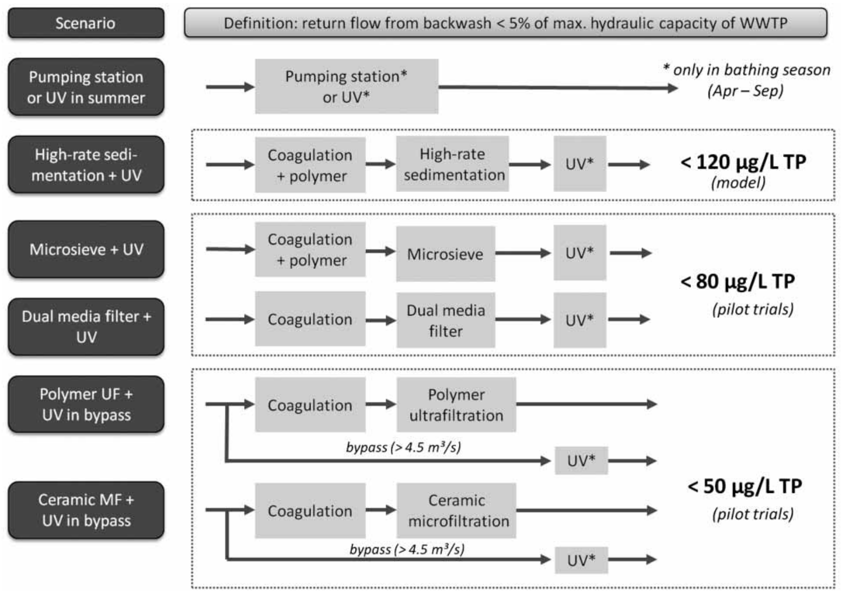

Figure 2 | Selected technology scenarios for tertiary treatment at WWTP Berlin-Ruhleben.

(a) Pumping station or UV in summer (status quo): direct discharge in winter, UV disinfection (1 m^3/s) or pumping of dry weather flow (<4.5 m^3/s) via pressure pipeline in summer.

(b) High-rate sedimentation + UV: dosing of coagulant ($FeCl_3$) and polymer, dosing of microsand (120 µm) for improved settling, sedimentation with lamella clarifier, recycling of microsand via hydro-cyclone, final disinfection with UV in summer.

(c) Microsieve + UV: dosing of coagulant (polyaluminium chloride, which showed better performance in pilot trials than $FeCl_3$ in terms of effluent TP quality and residual coagulant (KWB 2013)) and polymer, filtration in microsieves (10 µm mesh) using continuous backwash, final disinfection with UV in summer.

(d) Dual media filter + UV: dosing of coagulant ($FeCl_3$) in-line, filtration in dual media filter (1.1 m anthracite, 0.6 m sand) with periodic backwash, final disinfection with UV in summer.

(e) Polymer UF + UV in bypass: dosing of coagulant ($FeCl_3$) in-line, filtration in ultrafiltration membrane modules (polymeric membrane, hollow-fibres, inside-out) with periodic backwash and regular chemical cleaning, designed for dry weather peak flow, excess volume of rain weather flow bypasses membrane stage and is treated with UV disinfection in summer.

(f) Ceramic MF + UV in bypass: dosing of coagulant ($FeCl_3$) in-line, filtration in microfiltration membrane modules (ceramic membranes, monolithic, inside-out) with periodic backwash and regular chemical cleaning, designed for dry weather peak flow, excess volume of rain weather flow bypasses membrane stage and is treated with UV disinfection in summer.

For the substance flow model, quality of secondary effluent is defined by regular monitoring data of WWTP Ruhleben. Data of effluent quality and process parameters (layout of infrastructure, electricity demand, chemicals) of tertiary treatment technologies are extrapolated from extensive pilot trials in Berlin for the processes of dual media filtration (Sperlich *et al.* 2012), UV disinfection, microsieve and membrane filtration (KWB 2013). For high-rate sedimentation, supplier data of energy and chemical demand are used along with conservative projections of expected effluent quality based on suspended solids (SS) removal (supplier data: <5 mg/L SS) and estimated TP content of SS.

For the impact assessment, two mid-point environmental indicators are calculated based on the LCA impact assessment methodology ReCiPe 2008 (Goedkoop *et al.* 2009): global warming potential (GWP) for 100 years (IPCC 2007) and eutrophication potential of freshwaters (accounting only for P emissions into surface waters). Additionally, cumulative energy demand of fossil and nuclear resources (VDI 2012) is calculated to reflect the depletion of non-renewable fuels. Finally, the indicator results are normalised to the annual mean environmental impact of a European inhabitant (EU-27 (27 EU member states) basic year 2000) to reveal the quantitative contribution of tertiary treatment to the total environmental impacts of society.

DATA OF LIFE CYCLE INVENTORY

Secondary effluent of WWTP Ruhleben amounts to an annual volume of 87.6 million m^3/a, with an even split of 50% in summer (Apr–Sep) and 50% in winter (Oct–Mar) period. The cumulative volume above dry weather peak flow (4.5 m^3/s) accounts for 2.4 million m^3/a (2.7% of annual volume). The quality of secondary effluent is estimated from 24 h mixed samples during dry weather conditions (annual mean: 320 μg/L TP) and rain weather peak flow (annual mean: 350 μg/L TP), noting that SS in secondary effluent are very low in normal operating conditions (<10 mg/L SS). During extensive peak flow events (>5 m^3/s), a temporary increase in TP effluent concentration to 440 μg/L TP is estimated from online data. Underlying process data for layout of tertiary treatment units and operational demand for electricity and chemicals are listed in Table 1, while detailed results of pilot trials and LCA input data can be found elsewhere (KWB 2013).

Inventory datasets for industrial processes relevant for constructing and operating tertiary treatment (background processes such as production of electricity, chemicals, materials, transport) have been extracted from the database ecoinvent v2.2 (Ecoinvent 2010). For the substance flow model, the LCA software tool Umberto v5.6 (IFU and IFEU 2009) has been used.

RESULTS OF IMPACT ASSESSMENT

The various options for tertiary treatment are compared for their potential environmental impacts for each of the specific environmental indicators. For an overall comparison, indicator results are then normalised to the total environmental impacts per person and year in Europe to gain insight into the relative contribution of the tertiary treatment stage. This normalisation indicates the quantitative relevance of environmental impacts caused by tertiary treatment.

Water quality: eutrophication

All options for tertiary treatment will reduce the phosphorus loads to surface waters considerably (Figure 3). The annual P emissions of WWTP Ruhleben (28.2 t TP/a, equivalent to >97% P elimination from influent wastewater) are further reduced by 66% with high-rate sedimentation, 81% with microsieve, 83% with dual media filter, and 90% with the membrane processes, respectively. In this study, the high effluent quality of the membrane effluent is partially compromised by the bypass at rain weather peak flow, which is not treated for P removal. This effect results in a calculated mean annual effluent concentration of 33 μg/L TP for the membrane processes, compared to 55 μg/L TP for the dual media filter, 63 μg/L TP for the microsieve, and 105 μg/L TP for the high-rate sedimentation process. Industrial background processes (electricity and chemical production) have only a minor contribution to the overall impact on

Table 1 | Process data of tertiary treatment processes for life cycle inventory

	Pumping station or UV[a]	High-rate sedimentation + UV	Microsieve + UV	Dual media filter + UV	Polymer UF + UV in bypass	Ceramic MF + UV in bypass
Layout	–	50 m/h (Q_{rw})	10 μm mesh	10 m/h (Q_{dw}) 15 m/h (Q_{rw})	75 L/(m^2*h) (Q_{dw}) recovery 95%	90 L/(m^2*h) (Q_{dw}) recovery 95%
Return flow (%)	–	4	1.8	4	5	5
Chemicals (g/m³)	–	5.5 (Fe) 0.3 (polymer)	2 (Al) 0.6 (polymer)	4 (Fe)	8 (Fe) + cleaning chemicals	8 (Fe) + cleaning chemicals
Electricity (w/o UV) (Wh/m³)	155[a]	31[b]	35[b]	42[b]	88	88
UV dose[a] (J/m²)	1000	850	700	700	1000 (bypass)	1000 (bypass)
Electricity for UV[a] (Wh/m³)	50	42	35	35	50 (bypass)	50 (bypass)
Mean effluent quality (μg/L TP)	330	105[c]	63	55	23	23
Discharge limit[d] (μg/L TP)	500	120[c]	80	80	50	50

[a]Only operated in summer (April–September).
[b]Incl. water lifting.
[c]Model.
[d]For 85%ile of grab samples.
Q_{dw} = dry weather peak flow, Q_{rw} = rain weather peak flow.

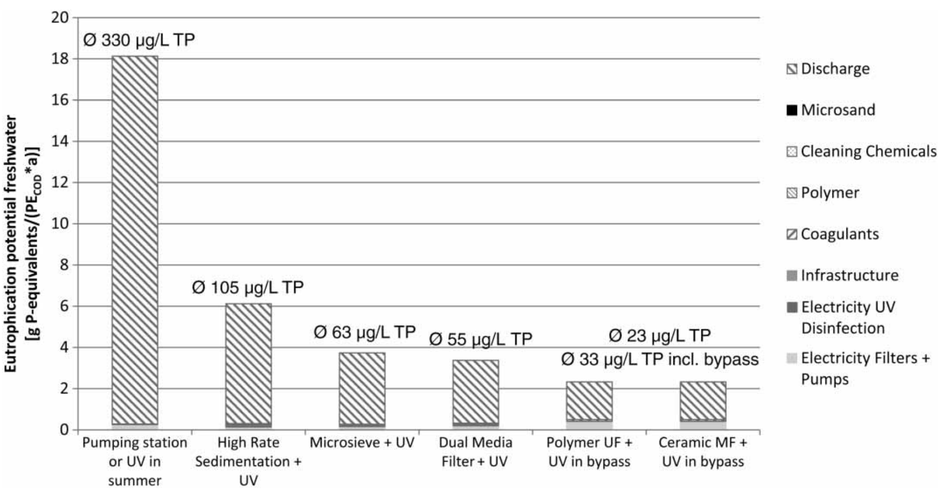

Figure 3 | Reduction in eutrophication potential (freshwater) with tertiary treatment schemes (calculated annual mean TP concentration in WWTP effluent indicated as Ø μg/L TP).

freshwater eutrophication within the life cycle, which is dominated by direct emissions at the WWTP.

Cumulative energy demand

The cumulative energy demand of tertiary treatment technologies is calculated as between 39 and 69 MJ/(PE*a) (Figure 4). Low-energy processes such as high-rate sedimentation, microsieve and dual media filtration require 30–33 MJ/(PE*a) plus an additional 9–11 MJ/(PE*a) for downstream UV disinfection. Membrane processes need more energy for pressure pumps and backwash, totalling at around 68 MJ/(PE*a). UV disinfection of the small bypass volume requires only 0.4 MJ/(PE*a) for the membrane scenarios. Compared to the total net energy demand of WWTP Ruhleben without tertiary treatment (ca. 323 MJ/(PE*a) including sludge treatment and disposal), tertiary treatment technologies will account for a surplus of 12–21%. Surprisingly, the existing

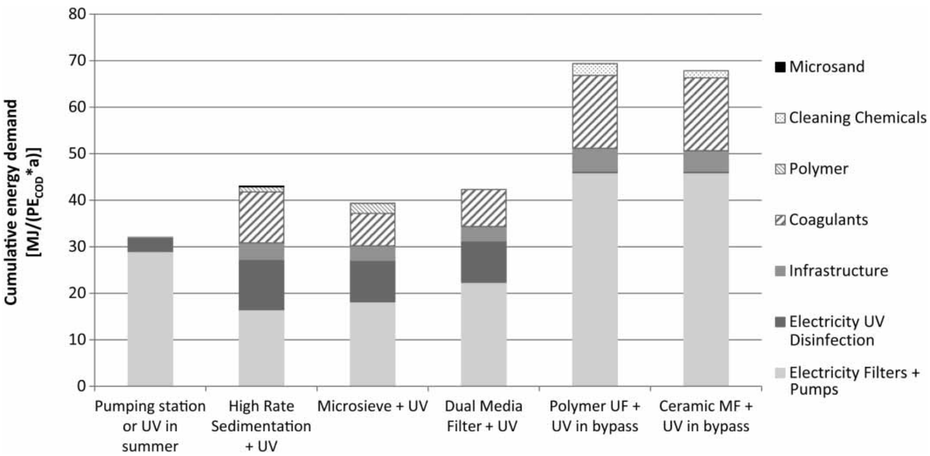

Figure 4 | Increase in cumulative energy demand with tertiary treatment schemes due to electricity and chemical consumption and materials for infrastructure.

discharge management with pumping station or UV disinfection in summer already has a comparatively high energy demand at 32 MJ/(PE*a) although only operating during April–September. Hence, the new tertiary treatment stage will effectively lead to an increase of only 7–11 MJ/(PE*a) in the case of low-energy treatment or 36 MJ/(PE*a) with membranes compared to the existing system.

Emission of GHG

Tertiary treatment schemes require electricity and chemicals for operation and materials for infrastructure, causing additional emissions of GHG during the production of these inputs. In general, results for GWP are strongly correlated to cumulative energy demand: low-energy processes with downstream UV cause a GWP of 2.5–2.8 kg CO_2-eq/(PE*a), while high-energy membrane treatment causes a GWP of 4.3 kg CO_2-eq/(PE*a) (Figure 5). Major contributors to GWP are electricity production for filtration (40–70% of total GWP) and UV disinfection (1–26%), followed by chemical production (15–23%) and infrastructure (8–11%). Compared to the GWP of the existing WWTP without tertiary treatment (ca. 34 kg CO2-eq/(PE*a)), tertiary treatment accounts for an increase of 7–13% in total GWP. Again, the existing management practice with pumping station/UV already has a GWP of 2.1 kg CO2-eq/(PE*a), so that the effective increase by implementing tertiary treatment would be lower.

Normalisation

Normalisation of all environmental indicators to the total environmental impacts per person in Europe (reference year: 2000) gives quantitative information on the contribution of tertiary treatment processes to each category of environmental impact (Figure 6). As expected, discharge

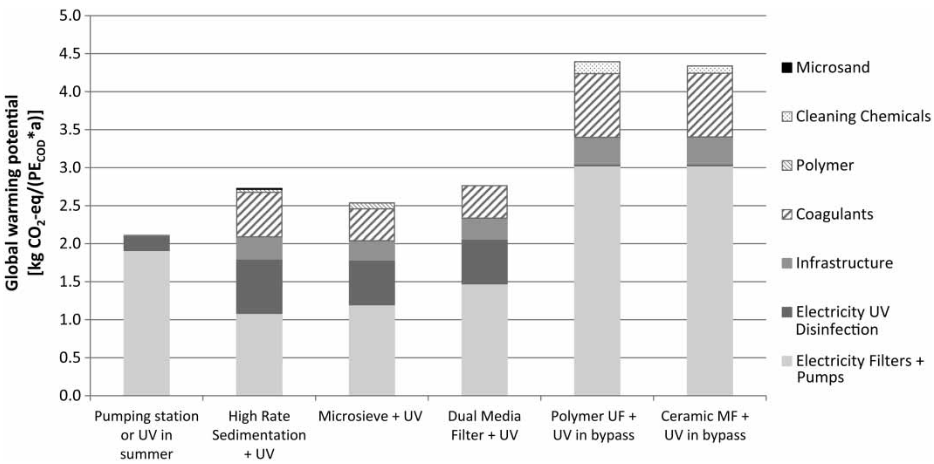

Figure 5 | Increase in GWP with tertiary treatment schemes due to electricity and chemical consumption and materials for infrastructure.

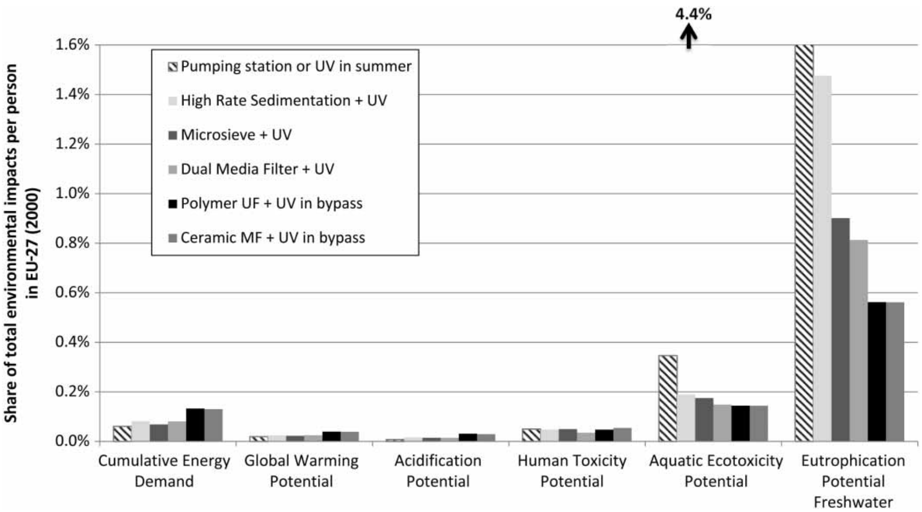

Figure 6 | Normalisation of LCA results by relating the contribution of tertiary treatment processes to total environmental impacts per person in EU-27 (reference year: 2000).

of secondary effluent (representing the direct impact of the WWTP on the environment) has a relatively high contribution in the respective impact category, namely in eutrophication (>4%). This reflects the primary function of the WWTP, which is in fact the reduction of emissions of nutrients and pollutants in surface waters. Naturally, the effluent of a WWTP is still responsible for a relatively high share of these environmental impacts, compared to the overall emissions into surface waters. In contrast, energy-related indicators such as cumulative energy demand and GWP of tertiary filtration processes have only a minor share, accounting for less than 0.13% of the total environmental impacts per person. From this perspective, an upgrade of WWTP with a tertiary treatment stage seems reasonable from an environmental point of view. Nevertheless, indirect effects of the different options for tertiary treatment vary heavily between technologial options as shown above, and they should be kept in mind while taking a decision on an appropriate technology for WWTP upgrade.

DISCUSSION

Impact assessment results show that membrane processes are superior in effluent quality to gravity-driven processes of dual media filtration, microsieve, or high-rate sedimentation in terms of phosphorus removal. However, the additional benefits of membranes in terms of reduced annual emission loads are relatively small (−8%), and indirect environmental effects such as consumption of fossil energy resources or emission of GHG are substantially higher (65–74%) for membrane processes than for low-energy filtration. This can be underlined by calculating a relative 'environmental efficiency' of tertiary treatment as emitted CO_2-equivalents against the removed P load for each treatment scheme. Gravity-driven processes have a higher environmental efficiency with only 180 kg CO_2-eq/kg $P_{removed}$ for dual media filtration or microsieve and 235 kg CO_2-eq/kg $P_{removed}$ for high rate sedimentation (all including UV disinfection). In contrast, membrane schemes cause 275 kg CO_2-eq/kg $P_{removed}$ due to their high energy and chemical demand. Based on this efficiency, gravity-driven processes such as dual media filtration or microsieve seem preferable from an environmental point of view, as they provide a substantial decrease in P effluent loads with a reasonable investment of energy and chemicals. However, the weighting between energy demand and related GHG emissions and decrease in P emissions to surface water is always subjective and cannot be based on scientific evidence. Nevertheless, the results of this LCA will assist the Berlin water authorities in setting a suitable new discharge limit for TP at WWTP Berlin-Ruhleben to be reached with the respective tertiary treatment technology.

CONCLUSIONS

From the results and experiences gained in this extensive LCA case study of tertiary wastewater treatment processes, some general conclusions can be extracted to assist other stakeholders (water utilities, legal authorities, and operators) in deciding for a specific treatment process to improve the effluent quality of large WWTPs.

- LCA is a suitable tool to quantify direct and indirect environmental impacts of tertiary treatment. With this method, the intrinsic environmental trade-off of each WWTP upgrade (less direct emissions on-site, but higher indirect emissions for production of electricity, chemicals, and infrastructure) can be systematically assessed and quantified for taking a well-informed decision on the type of process to be implemented.
- Process data for the LCA inventory should be ideally based on pilot trials on-site and be validated with project partners to strengthen the validity and credibility of the results.
- Electricity and chemical demand and related emissions of GHG and air pollutants show high differences based on the technology assessed. Thus, technologies have a distinct environmental efficiency in terms of reduced pollutant loads related to invested energy or associated GHG emissions.
- Political targets for improving both water quality and reducing energy demand and related GHG emissions have to be carefully balanced to reach a reasonable outcome in the decision process and decrease the overall environmental impacts of wastewater treatment. LCA does not provide a scientifically based weighting between environmental impacts, which is always based on subjective judgement of the relevant stakeholders.

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