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Assessment of wastewater treatment technologies: life cycle approach

Pradip P. Kalbar, Subhankar Karmakar & Shyam R. Asolekar

Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay, Mumbai, India

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activated sludge process; constructed wetlands; life cycle assessment; sequencing batch reactor; up-flow anaerobic sludge blanket reactor–facultative aerobic lagoon; wastewater treatment plant.

Correspondence
Shyam R. Asolekar, Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India. Email: asolekar@iitb.ac.in

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Abstract

Four municipal wastewater treatment plants (WWTPs) in India based on different technologies are compared by conducting Life Cycle Assessment (LCA) using field data. CML 2 baseline 2000 methodology is adopted in which eight impact categories are considered. SBRs ranked highest in energy consumption and global warming potential (GWP) but also produced the best effluent with respect to organics and nutrients. Constructed wetlands have negligible energy consumption and negative GWP because of carbon sequestration in the macrophytes. Emissions associated with electricity production required to operate the WWTPs, emissions to water from treated effluent and heavy metal emissions from waste sludge applied to land are identified as main contributors for overall environmental impacts of WWTPs. This comparison of technologies suggests that results from LCA can be used as indicators in a multicriteria decision-making framework along with other sustainability indicators.

Introduction

Wastewater treatment is one of the major issues faced by the developing countries like India. Selection of appropriate technologies for wastewater treatment is another challenge faced by urban local bodies (ULBs). The decision-makers in ULBs, however, do not have a rational framework to compare wastewater treatment technologies. Therefore, in this study, environmental footprints of most commonly used sewage treatment technologies in India namely: activated sludge process (ASP), sequencing batch reactor (SBR), up-flow anaerobic sludge blanket reactors followed by facultative aerobic lagoon (UASB–FAL) and constructed wetlands (CWs) have been compared using the life cycle approach.

Historically, Life Cycle Assessment (LCA) has been a useful tool for computation of the environmental footprint of a given wastewater treatment technology (Tillman *et al*. 1998; Hospido *et al*. 2004; Gallego *et al*. 2008). The environmental footprint of a given wastewater treatment plant (WWTP) depends on the choice of technology because any given treatment technology has a characteristic consumption of resources, energy and chemicals. The footprint is also determined by the treatment objective (e.g. disposal of treated wastewater after mere compliance with the prescribed regulatory norms or production of high-quality water for recycle and reuse applications).

In the Indian context, there are no national databases available for carrying out LCA and it becomes rather difficult to generate a material or emission inventory. The standard methodology as prescribed in ISO 14040 series (ISO 1997) is employed for conducting the LCA. This work intends to provide a decision support for decision-makers by providing estimates of environmental footprint of WWTPs. The LCA is based primarily on data collected during several field visits to actual municipal WWTPs [sewage treatment plants (STP)]. In the present study, the operation and maintenance (O&M) phases of the earlier four WWTPs used in India are studied using LCA.

Methodology

The LCA methodology used in this work is as per the ISO 14040 series (ISO 1997) as described in the operational guide to ISO 14040 by Guinee *et al*. (2001). In order to perform technology assessment, it is essential to bring all the technologies on a common platform, so that there can be parity in comparison. The following assumptions are made in this study for technology comparison:

(1) The inlet biochemical oxygen demand (BOD) for all the treatment plants is assumed to be 200 mg/L, which is the average BOD_5 value in India (CPCB 2009).

(2) Energy consumption for the pumping of sewage to the plant is not considered because of variation in the pumping distances at each location, which may affect results of the study.

(3) Each technology produces different quality and quantity of sludge and requires different sludge management options.

It is necessary to evaluate the wastewater treatment technology in combination with suitable sludge management options. In this study, the best suitable sludge management options for each of the technology are evaluated, and accordingly, system boundaries have been decided. This assumption makes technology assessment truly unbiased, and due credit is given to intrinsic properties of the technology.

(4) Treated sludge is to be used as manure for agricultural land. Sludge transportation distance is assumed to be 100 km for all WWTPs.

(5) Studies on LCA of WWTPs report that primary production processes have major contribution in the impacts over a life cycle and secondary processes such as construction of manufacturing plant and manufacture of vehicles and chemicals, etc. are estimated to contribute less than 5% of the total impacts of the treatment plant (Emmerson *et al*. 1995; Gaterell *et al*. 2005; Hospido *et al*. 2008). A similar approach is used in this study where only primary processes (electricity production, emissions to water and soil from treatment plant) are considered. Chemical production has not been included in the analysis. The impact of chlorine production on the O&M phase has been validated using a European database, which contributes to additional 2% in global warming potential (GWP), acidification potential (AP) and terrestrial ecotoxicity (TE) impact categories and negligible change in other impact categories. Hence, the assumption of neglecting production of chemicals will not influence the results of this comparative assessment study.

Goal and scope definition

The goal of this study is to compare environmental footprints of municipal WWTPs based on various technologies. Studies on LCA of WWTPs have shown that construction and demolition phases of WWTPs have negligible impacts compared with the operation phase (Emmerson *et al*. 1995; Tillman *et al*. 1998; Lundin *et al*. 2000; Karrman & Jonsson 2001; Gaterell *et al*. 2005; Machado *et al*. 2007). Based on these studies, Kalbar *et al*. (2012) carried out LCA of WWTPs using Indian inventories and confirmed the findings of the earlier studies and shown that the construction phase of WWTP in India accounts for about 1% of impacts compared with overall life cycle impacts of the WWTP. Therefore, the current study focuses on the O&M phase of the WWTPs. System boundaries considered for LCA affect largely on the final results and hence shall be judiciously selected (Tillman *et al*. 1994). Energy required for operation of the plant and emissions during the O&M phase are considered in the current study. Process emissions that are biogenic in nature (i.e. CO_2 associated with microbial activity in the treatment reactors) are excluded from the analyses, because they belong to the short CO_2 cycle and do not contribute to climatic change (Eggleston *et al*. 2006; Hospido *et al*. 2008; Coats *et al*. 2011). This approach is in agreement with similar studies on WWTP assessment (Gallego *et al*. 2008; Hospido *et al*. 2008).

The system boundaries considered for the assessment for various WWTPs are shown in the Fig. 1. In this research, person equivalent (p.e.) for a period of 1 year is chosen as functional unit which is most commonly used in similar studies (Tillman *et al*. 1998; Lundin *et al*. 2000; Hospido *et al*. 2008). In India, 1 p.e. represents 50 g of BOD_5 load per day (Arceivala & Asolekar 2007).

Life cycle inventory

Life cycle inventories are generated based on-site visits to WWTPs. Energy and chemicals [polyelectrolyte, disinfectant (chlorine), etc.] are primarily used in the O&M phase. In order to estimate effluent and sludge emissions from the plant, actual data are collected from each WWTP. To complete the emission inventory, it is necessary to estimate the emissions from per unit of energy generation. In this study, it is assumed that all the power generation is from coal-based thermal power plants. The emission inventory for electricity production is generated using secondary data (Garg *et al*. 2001; Nag 2006; NEERI 2006; Chakraborty *et al*. 2008). The following subsections provide more details on each of the WWTP and their inventories.

ASP

The ASP is one of the most commonly used technologies for the secondary treatment of sewage in India. Therefore, all technologies considered in this study are compared against this 'baseline' ASP technology. In the current study, material and emission inventory is generated by studying a 50-MLD (≈ 0.2 millions p.e.) STP based on ASP at Erandvane, Pune, State of Maharashtra. The plant was selected for evaluation based on its consistent performance and well-documented O&M record. The Erandvane STP treatment train consists of primary treatment, aeration tanks (with coarse bubble aeration) and blowers, dosing system, sludge handling units and other utilities (e.g. compressor, service water pumps, instrument air compressor). Figure 1(a) shows the process flow diagram of the plant. All these units are included in the scope of the current study. The emission inventory summary is given in Table 1. Aeration accounted for 55% of the total energy consumption. Other parts of the treatment like primary and sludge treatment contribute to 4 and 28% of energy consumption, respectively. These results are consistent with values of 46.9% for aeration, 5.8% for primary treatment and 22.3% for sludge treatment as reported by Zhang & Wilson (2000) for large-scale WWTPs. The detailed energy consumption pattern for various subsystems for this STP is shown in the Fig. 2.

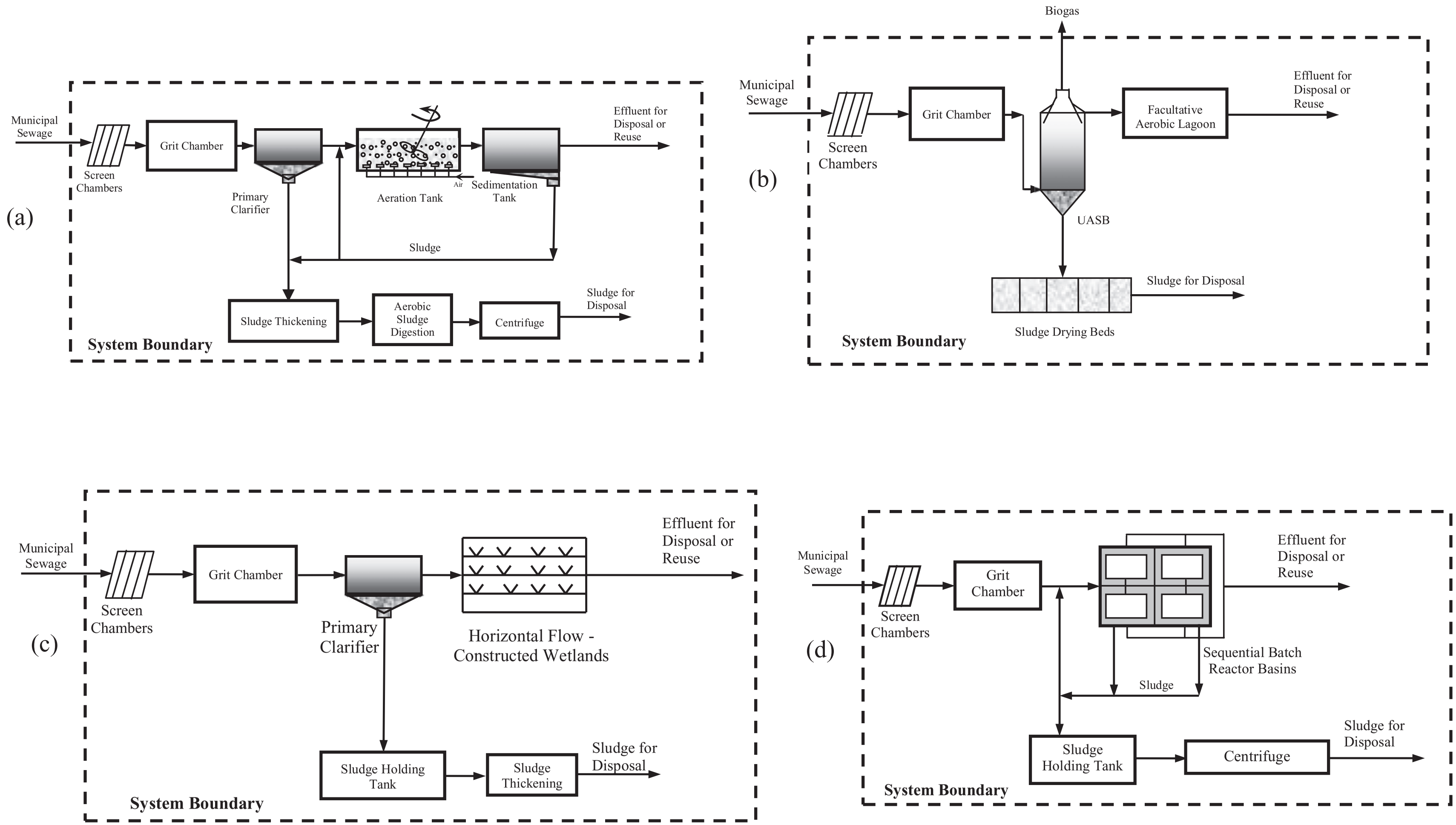

Fig. 1. Units considered in the comparison of the wastewater treatment plants (a) activated sludge process, (b) sequencing batch reactor, (c) up-flow anaerobic sludge blanket reactor (UASB)–facultative aerobic lagoon and (d) constructed wetlands.

Table 1 Summary of the operation and maintenance phase life cycle inventory of wastewater treatment plants (all values expressed per p.e.-year)

Serial no.	Parameter	Unit	ASP	SBR	UASB–FAL	CWs
1	Energy consumption	kWh	15.76	28.14	3.02	1.83
2	Emissions to air					
2.1	Particulates	g	37.14	66.14	8.72	4.70
2.2	CO_2	kg	18.06	31.72	7.56	–3.89
2.3	SO_2	g	147.60	262.18	39.61	19.93
2.4	NO_x	g	63.78	112.60	22.41	9.94
2.5	CO	g	85.04	146.58	56.85	20.02
2.6	Mercury	mg	2.24	4.00	0.43	0.26
3	Emissions to water					
3.1	COD	kg	6.39	4.56	9.13	5.48
3.2	N-total	kg	2.69	1.32	9.13	2.14
3.3	P-total	kg	0.55	0.09	0.73	0.55
3.4	Heavy metals[a]	g	208.96	88.01	227.11	178.94
4	Emissions to soil					
4.1	N-total	g	164.25	255.50	319.38	91.25
4.2	P-total	g	41.06	63.88	79.84	22.81
4.3	Heavy metals[a]	g	10.35	16.10	20.12	5.75

[a]Heavy metals include zinc, tin, nickel, lead, copper, cobalt, chromium, cadmium and arsenic.
ASP, activated sludge process; CWs, constructed wetlands; SBR, sequencing batch reactor; UASB–FAL, up-flow anaerobic sludge blanket reactor–facultative aerobic lagoon.

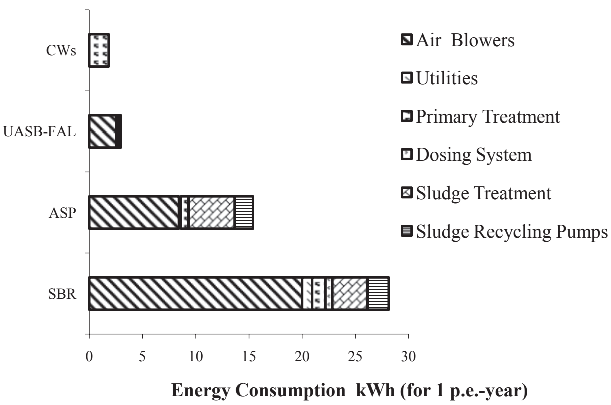

Fig. 2. Energy consumption distribution of the wastewater treatment plants. ASP, activated sludge process; CWs, constructed wetlands; SBR, sequencing batch reactor; UASB–FAL, up-flow anaerobic sludge blanket reactor–facultative aerobic lagoon.

UASB–FAL

UASB reactors are fast becoming a preferred treatment system because of their robustness and little or no energy dependence because of biogas production. Although the effluent quality from UASB will not meet regulatory standards, a subsequent final polishing unit or FAL or extended aeration process can provide the additional treatment to meet these compliance standards. In the current study, UASB followed by FAL (UASB–FAL) is considered for comparison as a stand-alone technology.

A 78-MLD (≈ 0.3 millions p.e.)-capacity STP at Tapovan, Nashik, State of Maharashtra, is selected as the UASB–FAL system, again based on its consistent performance and well-documented O&M record. The STP has mechanical screening and grit removal mechanisms followed by six UASB reactors each of 13 MLD capacities. Figure 1(b) shows the process flow diagram of the plant. Effluent from FAL is additionally treated in a polishing pond and discharged into the Godavari River. Sludge from the UASB is taken to sludge drying beds and subsequently used for agricultural purposes. The emission inventory summary is given in Table 1. Figure 2 shows the comparison of energy distribution pattern of UASB–FAL with ASP.

CWs

CWs are natural wastewater treatment systems with a great potential for application in the Indian context. The 7.8-MLD (≈ 30 000 p.e.)-capacity STP at Jaipur, State of Rajasthan, uses ASP for secondary treatment followed by a physico-chemical phosphorous removal process. Following this, CWs are used for tertiary treatment. The data for this CW-based STP are collected through number of site visits. Figure 1(c) shows the process flow diagram of the plant. The CW STP at Jaipur uses 21 CW tanks with *Phragmites karka* (*P. karka*) to treat the sewage. Four saplings were planted per m^2 of area with a harvesting time of 6 months. Each CW tank is 65 m in length and 20 m in width (1300 m^2 area) and is designed to handle a flow of 0.3714 m^3/day.

Because the other three technologies evaluated in this study are used as secondary treatment, it is necessary to transform the tertiary treatment CWs to an equivalent secondary treatment system so that all the four technologies can be compared on an equivalent basis. CWs are converted to an equivalent secondary treatment by increasing the number of CW tanks without actually changing the tank dimensions. The equivalent CWs are designed according to Arceivala & Asolekar (2007) for a BOD_5 of 200 mg/L and the inventories are generated for this equivalent CW plant using the actual data collected from studying STP based on the CWs.

While estimating the environmental impact of the CWs over the life cycle, it is necessary to account for the carbon sequestration achieved by harvesting *P. karka*. Vanyarkho & Arkebauer (1995) reported a carbon sequestration of 3.3 kg/m^2/year which was used by Dixon *et al*. (2003) in an LCA study. The carbon sequestration capacity of the CW STP at Jaipur is also assumed to be 3.3 kg/m^2/year.

For the equivalent CW system (1 p.e.-year capacity, 200 mg/L of influent BOD), the estimated area is calculated to be 657 m^2. All the other parameters such as plant type (*P. karka*) used for treatment, sand and gravel used, and the dimensions of the CW tanks are kept the same as for the Jaipur CWs. The emission inventory summary is given in Table 1.

SBR

SBR technology is emerging as a promising technology in the Indian market. It is mostly suitable in the urban settlements owing to its lower land requirement compared with ASP. Also, SBR can achieve good nutrient removal with minor design changes. In an urban area where surface water bodies are under stress and cannot take any more nutrient load, SBR is the best possible solution. This brings the need to compare this new solution with conventional solutions.

In this study, because of the unavailability of actual plant data, we have considered an engineered design case study of SBR plant. Figure 1(d) shows the treatment scheme of this SBR plant. A medium-scale, 25-MLD ($\approx$ 0.1 millions p.e.)-capacity SBR plant is designed for greater organic as well as nutrient removal as per the design procedures given in Metcalf and Eddy (2003) and Arceivala & Asolekar (2007). The energy consumption for the plant is estimated based on unit and equipment sizing and assuming appropriate equipment efficiencies. The summary of emission inventory is shown in Table 1. Figure 2 shows the comparison of energy distribution pattern of SBR with ASP.

Life cycle impact assessment (LCIA)

The impact assessment phase of the LCA is comprised of mandatory elements, viz. *selection of impact categories*, *classification* (assignment of the inventory data to the chosen impact category), *characterization* (calculation of impact categories using characterization factors), as well as optional elements, viz. *normalization* [calculation of category indicator results relative to reference value(s)] and *grouping and/or weighting* the results (Pennington *et al*. 2004). The current study does not include normalization, because there are no reference values available because of a lack of LCA studies in India.

Impact categories in this study are selected based on data availability and significance of a particular impact category with respect to the goal of the study. Life cycle impacts are computed using Microsoft Excel worksheets according to CML 2 baseline 2000 methodology, developed by Centre of Environmental Science (CML), University of Leiden, the Netherlands, which gives a separate score for each type of environmental impact. Globally applicable CML 2001 characterization factors from the Ecoinvent database v2.1 (Swiss Centre for Life-Cycle Inventories 2009) are used in the LCIA to estimate impact potentials of each category. Eight impact categories, viz. AP, GWP, TE, eutrophication potential (EP), freshwater aquatic ecotoxicity (FWAT), human toxicity (HT), marine aquatic ecotoxicity (MAET) and abiotic resources depletion potential (ADP) are considered. The results of the LCIA are given in Table 2.

Results

LCA results of the ASP, SBR, UASB–FAL and CWs technologies are based on studies carried on various field-scale STPs, and wherever data were not available, secondary data were used. Table 1 gives the life cycle inventory for WWTPs. Table 2 shows life cycle impacts in various categories of WWTPs for the O&M phase.

Energy consumption

The energy consumption of mechanized WWTPs varied from 28.14 kWh/p.e.-year for SBR and 15.76 kWh/p.e.-year for ASP which is in the range of the similar studies carried out in other countries; Tillman *et al*. (1998) reported 46.4 kWh/p.e.-year, Lundin *et al*. (2000) reported 33 kWh/p.e.-year; Gallego *et al*. (2008) reported an average value of 60.5 kWh/p.e.-year for 15 small-scale WWTPs and Hospido *et al*. (2008) reported an average value of 28.3 kWh/p.e.-year for three large-scale WWTPs having ASP as secondary treatment.

SBR (28.14 kWh/p.e.-year) was found to be more energy consuming than ASP (15.76 kWh/p.e.-year), UASB–FAL (3.02 kWh/p.e.-year) and CWs (1.83 kWh/p.e.-year). Reasons for higher energy requirements of SBR compared with ASP include:

(1) SBRs are typically designed for both organic and nutrient removal, which requires more oxygen and hence more energy.

Table 2 Results of life cycle impact assessment of wastewater treatment plants for the operation and maintenance phase (all values expressed per p.e.-year)

Impact category	Unit	ASP	SBR	UASB–FAL	CWs
Acidification potential (AP)	kg SO_2-Eq	0.19	0.34	0.06	0.03
Global warming potential (GWP)	kg CO_2-Eq	18.20	31.97	7.67	–3.86
Eutrophication potential (EP)	kg PO_4^{3-}-Eq	3.76	1.38	5.85	3.40
Freshwater aquatic ecotoxicity (FWAT)	kg 1,4-DCB-Eq	155.03	62.21	129.23	101.22
Human toxicity (HT)	kg 1,4-DCB-Eq	5.45	3.39	3.98	3.66
Marine aquatic ecotoxicity (MAET)	kg 1,4-DCB-Eq	509.89	206.15	419.85	330.95
Abiotic resources depletion potential (ADP)	kg antimony-Eq	0.15	0.28	0.03	0.02
Terrestrial ecotoxicity (TE)	kg 1,4-DCB-Eq	0.05	0.08	0.09	0.03

ASP, activated sludge process; CWs, constructed wetlands; DCB, dichlorobenzene; SBR, sequencing batch reactor; UASB–FAL, up-flow anaerobic sludge blanket reactor–facultative aerobic lagoon.

(2) Removal efficiencies of the SBRs are greater than ASP and hence the effluent quality is typically better than ASP.
(3) Typically, there is no primary sedimentation tank provided before SBR. Therefore, BOD removal (say 30%) expected during primary treatment will not be achieved. SBRs are therefore designed for larger total organic loading and hence require more energy for aeration as compared to the ASP.
In sum, it can be said that the impact of WWTP is more dependent on design and how a plant is operated. Even for similar technologies, there can be a huge difference in the performance depending upon the operation of the plant; this fact has already been reported by Gallego *et al*. (2008). If SBR and the ASP are compared only on the basis of carbonaceous BOD removal, then energy efficiencies of SBR may be equal to or greater than the ASP.

CO_2 emissions and GWP

Energy consumption for the operation of WWTPs is found to be the largest contributing parameter for CO_2 emissions. CWs have negative CO_2 emissions and hence negative GWP because a large amount of CO_2 is sequestered during wastewater treatment. The fact that CW biomass acts as a carbon sink, locking away atmospheric CO_2, has been reported by Dixon *et al*. (2003) and Machado *et al*. (2007). The energy consumption of UASB–FAL can also be reduced if energy from biogas is utilized (not practised currently at the Nashik STP).

The GWP is evaluated using the baseline method outlined in Guinee *et al*. (2001) with a time horizon of 100 years. The GWP potential of ASP, SBR and UASB–FAL is found to be 18.02 kg of CO_2 equivalents (kg CO_2-Eq), 31.97 kg CO_2-Eq and 7.67 kg CO_2-Eq, respectively. In a similar study of four WWTPs by Hospido *et al*. (2008) of the same scale in Spain, an average value of 19.9 kg CO_2-Eq has been reported, with 30 kg CO_2-Eq as highest and 11.1 kg CO_2-Eq as lowest value. GWP of CWs (–3.86 kg CO_2-Eq) is negative, which shows that natural treatment systems can mitigate global warming.

Acidification and ADP

AP is mainly because of SO_2 and NO_x emissions from coal combustion, which generates electricity for operating the plants. Coal consumption has major contribution in ADP. SBR is found to have the highest AP (0.34 kg SO_2-Eq) and ADP (0.28 kg antimony-Eq) as compared with other technologies. ASP is the next highest in both categories, followed by UASB–FAL and CWs.

EP

Nitrogen and phosphorus emissions to the water are primarily contributors to EP. UASB–FAL system had the highest EP (5.85 kg PO_4^{3-}-Eq) because there is negligible removal of nutrients in the UASB–FAL system. The ASP had the second highest EP (3.76 kg PO_4^{3-}-Eq), because of its capability to remove 40–50% of nutrients. The EP of CWs (3.40 kg PO_4^{3-}-Eq) is about the same as for ASP because macrophytes (plants) used in treatment have the capability to recycle nutrients. The SBR had lowest EP value of 1.38 kg PO_4^{3-}-Eq, which matches with values (1.29 to 0.10 kg PO_4^{3-}-Eq for nutrient removing systems) reported by Gallego *et al*. (2008). This lowest EP of SBR is because of its intrinsic nutrient removal (70–80%) capacity.

Toxicity potentials

Toxicity potentials are measured in terms of kilogram equivalent of 1,4-dichlorobenzene (DCB). During the field study, it was observed that the digested sludge (after thickening) is sent for land application, which is main cause of the TE because of the presence of heavy metals in the sludge. SBR and UASB–FAL are found to have the highest TE (0.09 kg 1,4-DCB-Eq) followed by ASP (0.05 kg 1,4-DCB-Eq) and CWs (0.03 kg 1,4-DCB-Eq). The TE for CWs is almost negligible because lesser amount of sludge is generated during wastewater treatment. The amount of sludge generated depends on the technology used for wastewater treatment and how it is being operated. Sludge treatment also decides the quantity and quality of sludge generation. These facts suggests that the results of TE should be used carefully, keeping in mind the entire treatment scheme of the WWTP.

In the current study, the FWAT and MAET are primarily because of heavy metals released from the treated wastewater into natural water bodies. FWAT and MAET are not very different for the four treatment technologies. This result is not surprising considering that none of the four technologies are designed to remove heavy metals. HT is because of the release of heavy metals in water, air and the soil environment. Results showed that UASB–FAL, ASP, CWs and SBR have comparable HT as shown in Table 2.

These results suggests that toxicity potentials by themselves do not tell the whole story of impacts; the environment in which the treated effluent is released (species diversity, sensitive population, etc.) has distinct role in defining the actual impact. From the past LCA studies on WWTPs, it can be seen that there is the need to revisit the characterization models dealing with toxicological impact categories (Larsen *et al*. 2004; Gallego *et al*. 2008).

Discussion

The results of impact assessment show that any given technology may perform well in one particular impact category and poorly in another impact category, and hence, it is difficult to compare the technologies based only on the impact categories. There are many issues like effect of scale, operating conditions, technology design, capability of technology to remove particular pollutants and regional as well as local priorities to be resolved before judging the overall performance of any technology. LCIA methodologies like CML 2 baseline 2000 (midpoint approach) and Ecoindicator 99 (end-point approach) are not designed to capture such technological or socioeconomic-specific issues (Bare *et al*. 2000). Also, local and regional priorities cannot be accommodated in the present LCIA methodologies and hence require amendments; such as modifications in characterization factors to account for regional differences in sensitivities of environmental receptors and regional and local weightages for impact categories. The need for regional LCA methodologies has been recognized by some researchers and efforts have been made to modify the existing LCIA methodologies (Mutel & Hellweg 2009).

Conclusions

To the best knowledge of authors, this is the first LCA conducted in India of WWTPs, and therefore, no specific comparison with results from other locations is possible.

(1) Four most commonly used wastewater treatment technologies are evaluated using life cycle approach. Emissions associated with electricity production required to operate the WWTPs, emissions to water from treated effluent and heavy metal emissions from waste sludge applied to land are identified as main contributors for overall environmental impacts of WWTPs.

(2) SBRs rank highest in energy consumption and GWP but also produced the best effluent with respect to organics and nutrients (low EP). UASB–FAL has highest EP because of almost negligible nutrient removal capacity. CWs found to have overall lowest environmental footprint compared with other technologies. In addition, CWs proved to be mitigating global warming because of the carbon sequestering capability of macrophytes used for treating sewage.

(3) Selection of appropriate wastewater treatment technologies is essential for developing countries like India to be able to manage wastes in sustainable manner.

(4) Technology selection in India is mainly skewed towards handful criteria such as compliance with stipulated regulatory standards and technology cost. Many other essential criteria like location, socioeconomic condition and the environmental receptor (air, soil, stream, river, lake, etc.) are not considered while making choices on appropriate technology for a given situation.

(5) Long-term wastage of resources like energy and chemicals and misallocation of limited financial resources are an unintended consequence of such decision-making. In order to develop a comprehensive framework for technology assessment, it is necessary to incorporate indicators from LCA and life cycle costing as well as sustainability indicators based on regional and local priorities. The comprehensive framework developed in the process will help formulate a suitable decision-making methodology to select the appropriate wastewater treatment technology for a given scenario.

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