Life cycle-based environmental assessment of municipal wastewater treatment plant in India

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Abstract: The environmental footprint of wastewater treatment plant (WWTP) can be assessed using a life cycle assessment (LCA) approach. Life cycle impacts are computed according to the CML 2 baseline 2000 methodology. An LCA study was carried out for WWTP treating municipal wastewater. Results show that the construction phase contributes to nearly 1% for the impacts when compared to overall life cycle impact of the plant and hence can be neglected. This work attempts to achieve significantly transparent results using LCA in limited availability of data. Original data was collected and analysed by the authors as part of this study through visits to wastewater treatment plants and on-site surveys. The lack of national life cycle inventories and computerised databases in India limits the wide application of LCA in the context of environmental decision making.

Keywords: life cycle assessment; LCA; environmental assessment; wastewater treatment; sequencing batch reactor; SBR; CML methodology; India.

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1 Introduction

Wastewater treatment is one of the challenges faced by developing countries like India. As per the report published by Central Pollution Control Board, Ministry of Environment and Forests, Government of India, there is a huge gap in the wastewater generation and available treatment capacity (CPCB, 2009). Due to this gap, large quantity of untreated, partially-treated and treated wastewater is discharged to surface and coastal water bodies. In any type of discharge large amount of nutrients are discharged into these water bodies which results in eutrophication. Indian urban centres and metro cities are growing rapidly and the sanitation facilities are not sufficient to cater to the population load which also results in discharge of wastewater into water bodies.

Many technological alternatives are available for wastewater treatment. Conventional wastewater treatment technologies such as activated sludge process (ASP), up-flow anaerobic sludge blanket react (UASB) and other land-based treatment technologies are presently used in India. However, recently advanced technologies such as sequencing batch reactor (SBR) and membrane bio-reactor (MBR) are preferred due to less land requirement and which also produce better quality of effluent compared to conventional activated sludge process (Kalbar et al., 2012). Therefore, there is a need to evaluate these new alternatives. For environmental assessment of products, technologies and services, life cycle assessment (LCA) is best available tool. LCA has been successfully applied for evaluating commonly used products such as packaging products and materials (Foolmaun and Ramjeawon, 2008; Xie et al., 2011), building products and materials (Koroneos and Dompros, 2009), agricultural and food products (Gillani et al., 2010), and biofuels (Larson, 2006). LCA has also been employed for wastewater treatment technologies assessment (Tillman et al., 1998; Hospido et al., 2004; Gallego et al., 2008).

Considerable numbers of studies have been carried out worldwide addressing environmental footprint and resource consumption of wastewater treatment plants (WWTPs) using LCA approach during the past decade. It was Tillman et al. (1998) who first applied LCA to municipal planning in the context of wastewater systems for evaluating three alternatives. The first alternative was existing wastewater system consisting of centralised wastewater treatment. The second alternative was to use existing piping in the area but with local pre-treatment system, digestion or drying of solid fractions and treatment of liquid fractions in sand filter beds. The third alternative included separation of urine, faeces and grey water conducting them out of the building and managing them separately. The study concluded that based on carbon dioxide emissions the third alternative can be more preferred than the second alternative. The first alternative (the existing system) was least preferred based on carbon dioxide emissions.

Table 1 Studies on LCA of water and WWTPs

Sr. no.	*Evaluated technologies*	*Functional unit*	*LCIA method*	*Software*	*Reference*
1	Conventional water treatment method, and membrane filtration technology	1 kL of potable water	CML 2000	GaBi 3.0	Friedrich (2002)
2	Industrial water recycling plant	1 kL of water supplied to industry	CML 2000	GaBi 3.0	Pillay et al. (2002)
3	Horizontal flow reedbed system, and package bio-filtration plant.	Number of 'population equivalents'	NA	SimaPro	Dixon et al. (2003)
4	Scenario 1: Reference (No treatment), Scenario 2: Biofilter+Biogas+Incineration, Scenario 3: UF+Biogas+Incineration, Scenario 4: Biofilter+Sandblasting, Scenario 5: UF+Sandblasting, Scenario 6: Biofilter+Sludge bed	Washing of 1,000 tonnes of coloured workwear per year, including generation and treatment of wastewater for water recycling and the handling of the residues in agreement with current Danish legislation.	Environmental Design of Industrial Products (EDIP), 1997 method	NA	Jørgensen et al. (2004)
5	Wastewater treatment plant consisting of preliminary, physico-chemical and biological treatments.	The amount of wastewater treated at the WWTP per day with the subsequent sludge disposal	CML Methodology, 2002	SimaPro 5.0	Hospido et al. (2004)
6	Continuous microfiltration (CMF) with ozonation as a pretreatment disinfection step, membrane bioreactor (MBR) followed by reverse osmosis (RO) as a metals and organics removal step, and wastewater stabilisation pond (WSP) system.	Delivery of 1 mL of recycled water to be used for irrigation of sensitive crops	NA	GaBi 3.0 version 2.0	Tangsubkul et al. (2005)

Notes: NA – not applicable, CML – Centre of Environmental Sciences (University of Leiden, The Netherlands), LCIA – life cycle impact assessment, the reduction and assessment of chemical and other environmental impacts (TRACI).

Table 1 Studies on LCA of water and WWTPs (continued)

Sr. no.	*Evaluated technologies*	*Functional unit*	*LCIA method*	*Software*	*Reference*
7	20 technologies suitable for treating extensive volumes of water produced during the oil and gas extraction processes are evaluated	Process water flow of 10,000 m^3/day for a time period of 15 years (system design life)	CML 2 baseline 2000 v2.1	Simapro 6.0	Vlasopoulos et al. (2006)
8	CAS, CAS-TF, external MBR, and immersed MBR	Production on average of 3,000 m^3/day of water during 25 years	CML 2 baseline 2000, Eco-Points 97 and Eco-Indicator 99	SimaPro 5.1	Ortiz et al. (2007)
9	Constructed wetlands, slow rate infiltration, and Conventional one activated sludge process	Population equivalent (p.e.)	CML 2 baseline 2000	Simapro 7.0	Machado et al. (2007)
10	Extended aeration biodenipho treatment aerobic-anoxic treatment	p.e.-year	CML 2 baseline 2000	Simapro 6.0	Gallego et al. (2008)
11	EcoSan system	Treatment of the wastewater generated by 40 persons working in the building for 220 days per year.	Cumulative Exergy Demand (CExD)	Umberto 5.5	Benetto et al. (2009)
12	High-rate anaerobic treatment, microbial fuel cells, and microbial electrolysis cells	Wastewater flow rate of 2,200 m^3/d at a strength of 4,000 mg COD/L, over 10 years of operation.	IMPACT 2002 + (v.2.03)	SimaPro 7, v.7.1.8	Foley et al. (2010)
13	Treatment plant achieving biological nutrient removal treatment plant achieving biological phosphorous removal with chemical addition/filtration to further remove phosphorus	Production of 37,854 m^3 (10 mil gal) of treated effluent meeting minimum prescribed water quality criteria	TRACI	TRACI	Coats et al. (2011)
14	Membrane bio-reactors having various configurations	One cubic metre (m^3) of permeate produced	CML 2.05	SimaPro 7.3	Hospido et al. (2012)

Notes: NA – not applicable, CML – Centre of Environmental Sciences (University of Leiden, The Netherlands), LCIA – life cycle impact assessment, the reduction and assessment of chemical and other environmental impacts (TRACI).

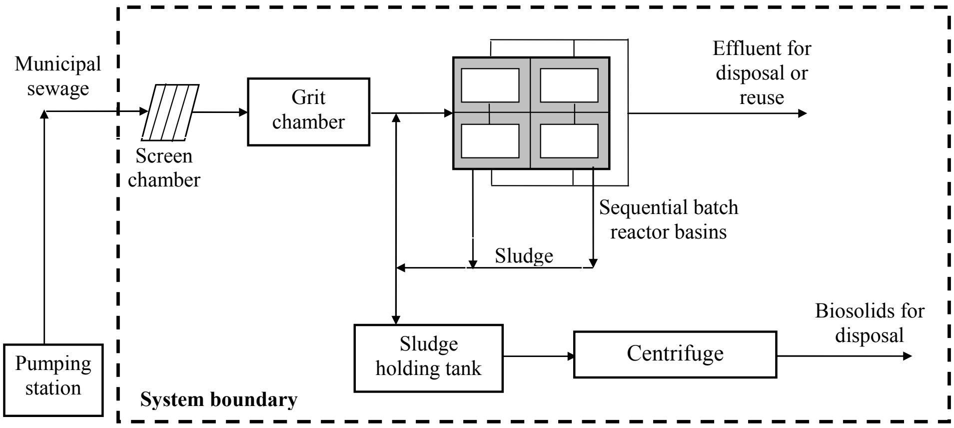
Lundin et al. (2000) studied the influence of system boundaries and the scale on the LCA of wastewater systems. Based on the life cycle inventory (LCI) results, the environmental loads of conventional wastewater systems were compared with those of segregating systems. The LCIs for wastewater systems were generated for base system which excluded production of electricity and production of fertilisers. In the extended system, productions of resources were included. The study concluded that the segregating systems have clear environmental advantage when compared to conventional ones. Also, this study underlined that if the environmental consequences of changing conventional wastewater systems to segregation technologies are assessed, system boundaries excluding fertiliser production and agricultural practice are not appropriate. Such, narrow system boundaries favour existing technologies and systems since positive features of the new solutions would not be taken into account.

There are many other studies which broadly covered the municipal water and WWTPs, industrial WWTPs and water recycling facilities. Table 1 presents a brief summary of published literature categorically addressing comparison of technologies for water and wastewater treatment using LCA. It can be concluded from Table 1 that CML 2 baseline 2000 methodology developed by Centre of Environmental Science (CML), University of Leiden, The Netherlands has been the most commonly used life cycle impact assessment (LCIA) methodology for evaluating wastewater treatment technologies.

Further, from the studies listed in Table 1, it can be seen that in most of the cases, the data required for generating material and emissions inventory were typically obtained from 'ready to use' databases provided by commercial softwares. It was precisely for this reason the commercially available databases led to building of complex process flow models in a variety of situations in the Western World. As a result, the decision support thus obtained has become the integral part of the 'decision making exercise'. In the Indian context, where there are no national databases available for carrying out LCA, it becomes very difficult to generate materials or emissions inventory. This, work intends to provide the decision support to the policy makers as well as decision makers through identification of the important components that influence the life cycle impacts as well as through providing a reasonable estimation of environmental footprint of the wastewater treatment technology. This has been achieved by adapting the so called process-based approach for LCA. A standard methodology has been employed for conducting the LCA of WWTP. Finally, the different phases of life cycle of WWTP have been compared.

In the current study, an engineered designed case study of SBR has been considered for evaluation due to unavailability of the data of actual field-scale SBR plant. Figure 1 shows the envisaged treatment scheme of the SBR plant having 25 MLD ($\approx$ 0.1 millions pe) capacity. The plant was designed for higher organic as well as nutrient removal as per the standard design procedures (Metcalf and Eddy, 2003; Arceivala and Asolekar, 2007). Based on the unit and equipment sizing the materials inventory was generated. Field visits were made to the different WWTPs to collect the actual data from field regarding equipments and civil units. Wherever primary data from field work could not be obtained; the secondary data available in literature have been used. The present effort aims at the development of an LCA platform which is applicable to Indian scenarios and at quantifying the environmental impact of a given WWTP. This step might be very nascent stage on performing LCA of WWTP, but in India this is the first comprehensive effort on LCA.

Figure 1 Units considered in the studied WWTP



Source: Kalbar et al. (2012)

2 Methodology

The LCA methodology followed in this work is as per the ISO 14040 (1997) series, which is described in operational guide to ISO 14040 by Guinee et al. (2001). Life cycle impacts have been computed using Microsoft excel spreadsheet according to the 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, is applied. The CML 2001 characterisation factors were used from Ecoinvent data base v2.1 (Swiss Centre for Life-Cycle Inventories, 2009).

In the present study, for evaluation of life cycle impacts, operational life of WWTP has been considered as 50 years for both mechanical as well as civil units after consulting with water infrastructure construction companies in India. The construction phase (CP) and operation and maintenance (O&M) phase of the WWTP have been included in the scope of present research. However, end-of-life or dismantling phase has not been included in the scope of this study since its contribution to environmental impact is typically rather low compared to overall environmental impact of the plant (Emmerson et al., 1995; Tillman et al., 1998; Lundin et al., 2000; Karrman and Jonsson, 2001; Machado et al., 2007).

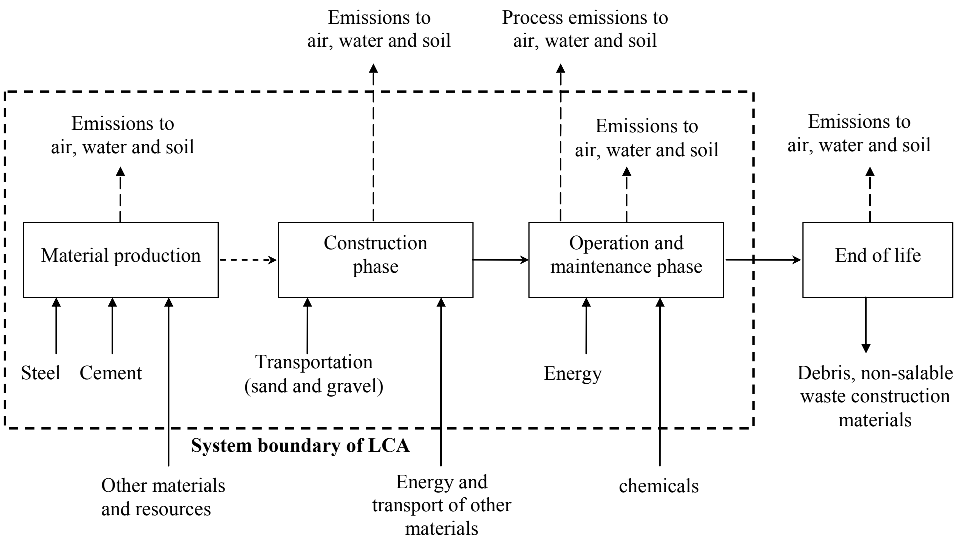
2.1 Goal and scope definition

The goal of this study is to assess environmental impact of WWTP based on the 'process based' LCA. The environmental footprint of CP and O&M phase is estimated. The scope of the present study is limited to conducting LCA for WWTP treating sewage generated by municipalities in India.

2.1.1 System boundary

LCA is subjective decision making tool in which system boundaries are defined based on personal opinion, which essentially determines transparency of the final results. The system boundary definition should always be relevant to goal of the study. There can be number of practical aspects that limit how a large and complex system can be analysed, for example, resources and data availability for the study (Tillman et al., 1994). The system boundary considered for this work is shown in Figure 2. The system boundary is chosen keeping in mind the objective of the study and data availability limitations on the processes.

Figure 2 System boundaries for LCA of WWTPs



In the present study, manufacturing of steel and cement which are the major contributors in the CP are considered. Also, emissions associated with transportation of sand and gravel is also included assuming 100 km as transportation distance for each trip. Other emissions from the CP activities were not considered due to limitations of the data availability. In the O&M phase energy required for operation of the plant and emissions during O&M phase are considered in the present study. However, process emissions and chemicals required for operation of the plant are not taken into consideration in the system boundary due to the data availability and negligible impact. The impact of chlorine production on O&M phase has been validated using European database. Chlorine production contributed to additional 2% impact 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 study. As mentioned earlier, end-of-life phase is not included in the scope of present study.

2.1.2 Functional unit

There can be many ways in which functional unit can be defined for a given problem. In the case of LCA of WWTPs, it is important that the functional unit should represent service provision which differs somewhat from more common product-orientated LCAs in which emphasis is placed on a more rigid end-point of function provided by, typically, a manufactured product or material (Vlasopoulos et al., 2006). For example, in the case of WWTPs based on activated sludge process where there will be minimal evaporation loss but in the case of waste stabilisation ponds there will be considerable evaporation loss. Therefore, quantity of effluent generated from the WWTPs based on various technologies can be different. It is emphasised in this study that functional unit should account for this variability of quantity of wastewater generated. In this context, the functional unit for present study is chosen as population equivalents (pe) for a period of one year. In India, one person represents 50 g of BOD5 load per day (Arceivala and Asolekar, 2007).

3 Life cycle inventory

LCIs have been generated from the primary data collected from studying publicly owned WWTPs based on various technologies situated in India. Any WWTP is a big engineered system involving many unit operations and processes in which many types of civil and mechanical equipments being used and connected to each other by use of different types of pipes. In addition, there are other sophisticated electrical and instrumentation equipment is fitted in plant to make the plant more mechanised. Generating LCIs of all these units is very difficult task. In India, no national database is available on such types of inventories. All the data related to construction of the WWTP have been collected by personally visiting the sites. The data regarding the technical specifications of mechanical units and data regarding civil units was gathered in a standard format after reviewing daily records of construction contractors. After studying this information, it was concluded that the major materials involved in manufacturing WWTP were steel and concrete (cement, sand and gravels) required for civil works, and steel used to manufacture mechanical equipments. Therefore, in this study only manufacturing of steel and cement is considered. The emissions inventory for steel production is generated from Tata Steel plant, India (Tata Steel Limited, 2008) and emissions inventory for cement is referred from ACC cement plant, India (ACC, 2007).

The O&M phase of WWTP involves use of energy and chemicals [coagulants, carbon source, polyelectrolyte, disinfectant (chlorine), etc.]. Production of chemicals is excluded from this study due to unavailability of Indian database on production of these chemicals. As mentioned earlier, the chlorine production has an additional 2% impact in O&M phase on GWP, AP and TE impact categories and negligible change in other impact categories and hence, the assumption of neglecting production of chemicals will not influence the results of this study. Energy consumption of the WWTP was estimated based on the equipment sizing. Appropriate efficiencies of the equipments and operation hours per day were obtained from field WWTPs. Further, 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 was generated using secondary (Garg et al., 2001; Nag, 2006; NEERI, 2006; Chakraborty et al., 2008). The summary of phase wise emissions inventory is given in Table 2.

Table 2 Summary of LCI of WWTP

Sr. no.	*Parameter*		*Unit*	*Construction phase*	*O&M phase*	*Total*
1	Resource consumption					
	1.1	Electricity	kWh	0.07	28.14	28.21
	1.2	Coal (used for production of electricity)	kg	0.05	20.5	20.55
	1.3	Gypsum	g	20.81	0.00	20.81
	1.4	Sand and gravels	kg	1.89	0.00	1.89
2	Emissions to air					
	2.1	Particulates	g	0.26	66.14	66.40
	2.2	CO_2	kg	0.43	31.72	32.15
	2.3	SO_2	g	0.70	262.18	262.89
	2.4	NO_x	g	0.72	112.60	113.32
	2.5	CO	g	0.27	146.58	146.85
	2.6	Mercury	mg	0.02	4.00	4.01
3	Emissions to water					
	3.1	COD	g	0.69	4562.50	4563.19
	3.2	N-total	g	0.39	1323.13	1323.52
	3.3	P-total	g	0.28	91.25	91.53
	3.4	Heavy metals*	g	0.66	88.01	88.67
4	Emissions to soil					
	4.1	N-total	g	1.70	255.50	257.20
	4.2	P-total	g	0.61	63.88	64.48
	4.3	Heavy metals*	g	1.39	16.10	17.49

Notes: All the values are expressed per pe-year.
*Heavy metals includes zinc, tin, nickel, lead, copper, cobalt, chromium, cadmium and arsenic.

4 Life cycle impact assessment

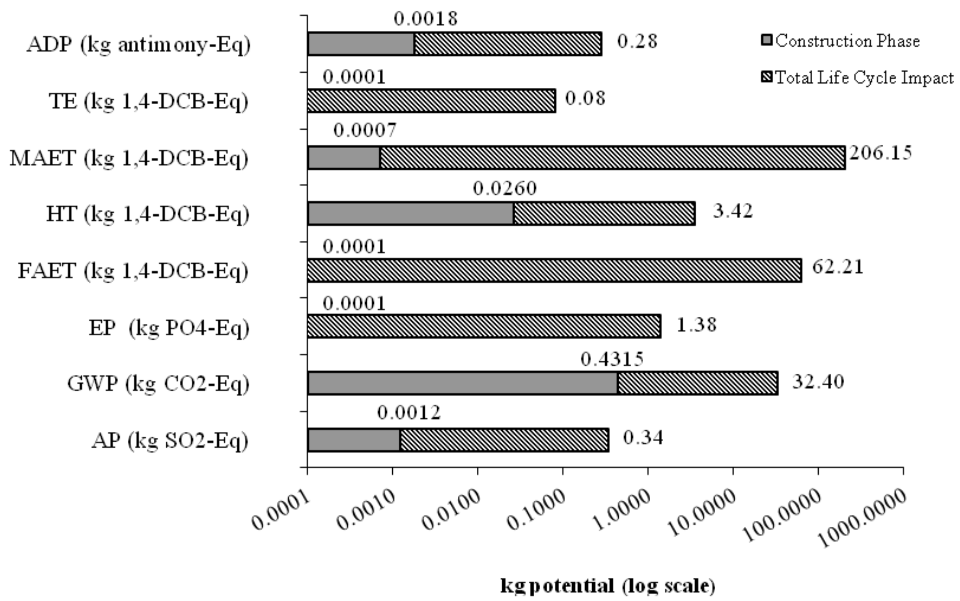
The impact assessment phase of the LCA is comprised of mandatory elements, viz., *selection of impact categories*, *classification* (assignment of the inventory data to the chosen impact category), *characterisation* (calculation of impact categories using characterisation factors), as well as optional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

In this study, impact categories were selected in considerations with data availability and significance of particular impact category with respect to the goal of the study. Life cycle impacts were computed using Microsoft excel spreadsheet according to the 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, is applied. Eight impact categories viz., AP, GWP, eutrophication potential (EP), freshwater aquatic ecotoxicity (FWAT), human toxicity (HT), marine aquatic ecotoxicity (MAET), abiotic resources depletion potential (ADP), TE, were considered to compute life cycle impacts. To estimate potentials in each impact category following generic equation is used (Guinee et al., 2001):

$$Potential\ (for\ any\ impact\ category) = \sum_i Characterisation\ \ Factor_i \times m_i \tag{1}$$

where m is the mass of the i^{th} substance (or pollutant). For example, in the case of GWP, relative contributions of different gases to climate change are commonly compared in terms of carbon dioxide equivalents (kg CO_2-Eq) using GWPs. Methane has characterisation factor for GWP 100 indicator of 25 kg CO_2-Eq., which implies that 1 kg of the methane has the same cumulative climate change effect as 25 kg of carbon dioxide over a 100 year time period. Characterisation factors for all other pollutants were obtained from Ecoinvent database v2.1, (Swiss Centre for Life-Cycle Inventories, 2009). A similar approach was used to estimate potentials for other impact categories. The results of the LCIA are presented in Figure 3.

Figure 3 Results of LCIA of WWTP



Notes: All the values expressed per pe-year.
AP – acidification potential; GWP – global warming potential; EP – eutrophication potential; FWAT – freshwater aquatic ecotoxicity; HT – human toxicity; MAET – marine aquatic ecotoxicity; ADP – abiotic resources depletion potential; TE – terrestrial ecotoxicity

5 Results and discussion

As stated earlier, the LCI (see Table 2) in this study addresses the primary treatment as well as secondary treatment using sequential batch reactor technology. This inventory, however, does not incorporate pumping of sewage to the primary treatment facility. It can be seen from Table 2, the LCIs that have been generated are concurrent with the deliberately chosen system boundaries and assumptions made in this study, e.g., the energy used for operation of the plant is produced by coal-based thermal power plant. The total energy consumption over the life cycle of the plant has been found to be 28.21 kWh/pe-year out of which 99.7% is operational phase energy. This result is comparable with the 33 kWh/pe-year value reported by Lundin et al. (2000). The emissions to air, water and soil listed in Table 2 are in agreement with the findings of other researchers (Tillman et al., 1998; Lundin et al., 2000; Gallego et al., 2008; Hospido et al., 2008).

Figure 3 shows that, as reported by Coats et al. (2011), by and large wastewater treatment cause mainly impacts on global warming and acidification (both due to energy consumption), and EP (due to effluent release to receiving surface water bodies). The contribution of the CP compared to overall impact of WWTP is 1.33% in GWP, 0.65% in ADP and 0.35% in AP, which can be mainly attributed to emissions from steel and cement manufacturing. In other impact categories CP contribution is insignificant, this result is congruent with results reported by other researchers (Karrman and Jonsson, 2001; Machado et al., 2007; Pillay et al., 2002). Contribution of CP in the EP, FWAT, HT, MAET and TE impact categories was almost negligible compared to overall impact of the WWTP. The contribution of CP across all the eight impact categories was nearly 1% of overall life cycle impact of the WWTP and can therefore be neglected in the ultimate analysis, which is also reported by many researchers in other parts of the world (Tillman et al., 1998; Lundin et al., 2000; Karrman and Jonsson, 2001; Gaterell et al., 2005; Machado et al., 2007).

The GWP is mainly contributed by coal combustion due to electricity production. The GWP potential was found to be 32.40 kg of CO_2 equivalents per pe-year. Karrman and Jonsson (2001) reported GWP potential of 12 kg of CO_2 equivalents per pe-year for conventional WWTP. EP is directly related to nutrients discharged to water and soil environment, for which the WWTP based on sequential batch reactor studied in the present work, has better nutrient removal capacity than the conventional activated sludge process. The EP for SBR was found to be 1.38 kg PO_4-Eq. Gallego et al. (2008) reported an average value of 0.45 kg PO_4-Eq for 15 WWTPs. Table 2 shows that disposal of biosolids containing heavy metals contributed substantially to the ecotoxicty and HT impact categories. Ecotoxicity potential is mostly dependent on the heavy metals released in the water and soil environment from the WWTP, for which in the considered WWTP there is no special provision for heavy metal removal, however, some removal take place through the physico-chemical and biological processes of the WWTP.

The Excel spreadsheet application developed in this research was instrumental in analysing the limited available data to yield results that are transparent and useful in decision-making. The results are more reliable owing to the primary data collection exercise carried out for generating LCI. However, from the studies listed in Table 1 it can be seen that, in most of the cases, the data required for generating material and emissions inventory were typically obtained from databases provided by commercial software. Such 'ready to use' databases, have imparted ease and speed to adopting the LCA as the chosen approach in the field of environmental decision making. In comparison with many other potential approaches to decision making lot of analytical work was done in redefining and standardising the methodology for LCA in western world. Because of these favourable conditions LCA has been adopted by the western word as the chosen methodology for the environmental decision making. However, the LCIs have not been developed in India and for that matter in most of the developing world. It is becoming increasingly clear that the need of the hour is development of region-specific datasets and characterisation factors (e.g., Indian sub-continent) and adapting and calibrating the LCA methodologies in the context of socio-economic reality of the region and bio-geo chemical realities of the tropical environmental systems. The results obtained through such LCA studies can be used in the decision making framework developed for selection of appropriate wastewater treatment technology by considering LCA results as one of the attributes along with other attributes like life cycle costing.

6 Conclusions

The life cycle approach is applied in this study to obtain environmental footprint of municipal WWTP. The LCA framework comprising of deliberately chosen system boundaries has been combined with primary data collected from field WWTPs situated in India. In spite of limited availability of the data defendable results have been obtained (which are comparable with published literature). This study illustrates that the LCA can be applied productively to obtain transparent results with the help of detailed primary data collection pertaining to specific case study to generate Indian inventory. The contribution of the CP across all the eight impact categories was found to be nearly 1% of overall life cycle impact of the WWTP and therefore be neglected in the ultimate analysis.

Broadly, the results of LCA can be used in the decision making framework developed for selection of appropriate wastewater treatment technology by considering LCA results as one of the attributes along with other attributes such as life cycle costing. Finally, it is necessary for a country like India to create its own LCIs to improve the environmental decision making process and the present study is the nascent step towards this goal.

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