Environmental and economic performance evaluation of municipal wastewater treatment plants in India: a life cycle approach

Sheetal Kamble, Anju Singh, Absar Kazmi and Markus Starkl

ABSTRACT

Life cycle assessment (LCA) was used to evaluate the environmental impacts associated with wastewater treatment plants (WWTPs). Moreover, an economic evaluation was also addressed using life cycle cost (LCC) approach. Emissions associated with electricity production for operating the WWTPs, emissions from the treated effluent and hazardous heavy metals emissions have been identified as the main contributors to the overall environmental impact. Among the WWTPs considered, soil biotechnology (SBT) obtained the lowest environmental impact in all the evaluated impact categories, except for eutrophication potential. While the aerated lagoons (AL) system presented the worst results due to the high electricity and chemicals consumption. Moreover, the results obtained from the evaluation of benefit from treated effluent reuse clearly indicate that there is a drop in the toxicity potential when the rate of effluent reuse is increased. On the other hand, the present worth of SBT was estimated to be Rs. 40 million/millions of litres per day (MLD) which is the highest as compared to other technologies. Membrane bioreactor (MBR) is the second highest (Rs. 24.7 million/MLD), which is mainly contributed by civil, electro-mechanical and membrane cost. The results of LCA and LCC provide specific insights about the factors which play a major role during the life cycle of wastewater treatment technology and its associated impacts.

Key words | environmental impacts, life cycle assessment, life cycle costs, wastewater treatment, wastewater treatment technologies

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INTRODUCTION

Economic losses from inadequate sanitation may slow down economic growth, as costs from pollution and health impacts were estimated as 6.4% of gross domestic product (WHO & UNICEF 2010). The generation of wastewater is increasing because of population growth and improved living standards in many countries. Wastewater treatment plants (WWTPs) have been designed and operated to reduce the pollution of wastewater and to minimize the adverse impacts on environmental quality and human health (Wang *et al.* 2012). Advanced wastewater treatment (WWT) and the associated reclamation of water is a necessary and critical function to protect both human health, the natural/aquatic environment providing for reduced overall water demand through reuse. Nevertheless, WWTPs have substantial environmental impacts during their life cycle due to energy consumption, chemical usage and gas emissions, as well as sludge generation which requires additional treatment.

Many technologies have been developed for WWT (such as membrane bioreactor, sequencing batch reactor, etc.). The evaluation of technology is important for obtaining better economic efficiency, as well as for reducing the life cycle environmental impacts (Corominas *et al.* 2013a, 2013b). When selecting or managing a water treatment approach, it is crucial to perform a comprehensive systems analysis to understand environmental and cost trade-offs of different options (Cashman *et al.* 2018).

Wastewater generation and treatment in India

The urban centres generate about 61,754 MLD of municipal wastewater. However, the treatment capacity available for

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municipal wastewater is only 22,963 MLD (CPCB 2016). Because of the hiatus in WWT capacity, about 38,791 MLD of untreated wastewater (62% of the total wastewater) is discharged directly into nearby water bodies, leaving a big gap in the treatment of municipal wastewater. In the near future, there is a need for extensive sewerage network for collecting and transporting the sewage generated to the WWTP for the treatment. The stricter implementation of policies, examination of latest technology and regular observations and measurements (O&M) of existing WWTPs, promoting decentralized treatment plants for treatment of households, rural, and urban sewage and reuse of treated sewage for non-potable purposes like flushing, gardening, etc. would surely help the municipal authorities to achieve better wastewater management (Singh *et al.* 2018).

Life cycle assessment (LCA) and life cycle costs (LCC) applied to wastewater treatment and management

LCA is a standardized and sophisticated tool to 'compile and evaluate the inputs, outputs and the potential environmental impacts of a product/process/service system throughout its life cycle' (ISO 2006a). LCA has been used in the field of wastewater treatment for two decades. Several studies applied LCA to conventional activated sludge (CAS) based technologies (Kalbar *et al.* 2013a, 2013b, 2014; Holloway *et al.* 2016), natural based systems (Garfi *et al.* 2017; Kamble *et al.* 2017; Lutterbeck *et al.* 2017), sewage sludge treatment and disposal (Murray *et al.* 2008; Xu *et al.* 2014). Very few studies have carried out economic assessment along with LCA (Rebitzer *et al.* 2003; Nogueira *et al.* 2009; García-Montoya *et al.* 2016; Pretel *et al.* 2016; Starkl *et al.* 2018). Only a handful of studies have applied LCA to evaluate the environmental impacts of MBR systems treating urban wastewater (Hospido *et al.* 2012; Ioannou-Ttofa *et al.* 2016). To date, there are very few studies in Indian context dealing with LCA and wastewater treatment (Kalbar *et al.* 2012a, 2012b; Kalbar *et al.* 2014; Kamble *et al.* 2017; Raghuvanshi *et al.* 2017; Singh *et al.* 2017). Garfi *et al.* (2017) carried out LCA comparing a CAS with two nature-based technologies (i.e. hybrid constructed a wetland and high rate algal pond). Lutterbeck *et al.* (2017) investigated the performance of a WWT system with constructed wetland as a technology in a rural scenario. Singh *et al.* (2017) estimated environmental impacts associated with the construction and seven operational phases of an integrated fixed-film activated sludge reactor. Moreover, Lin *et al.* (2016) investigated the economic and environmental profiles of three alternative nitrogen removal and recovery routes integrated into WWTPs, including conventional nitrification–denitrification, anammox, and ion exchange. There are few other studies that used LCA and economic analysis methods for investigating WWT systems and processes (Meneses *et al.* 2015).

The goal of this study was to evaluate environmental impacts of six WWT technologies, namely: sequencing batch reactor (SBR), membrane bioreactor (MBR), moving bed biofilm reactor (MBBR), activated sludge process (ASP), soil biotechnology (SBT) and aerated lagoons (AL) using LCA. Another objective was to carry out LCC of six technologies under consideration.

MATERIALS AND METHODS

Brief description of the analysed WWTPs

SBR

In this study, a small-scale, 2.5 MLD capacity SBR plant designed for greater organic, as well as nutrient, removal was selected for the analysis.

MBR

A 0.8 MLD capacity plant was selected. Low-pressure membrane filtration, either microfiltration or ultrafiltration is used to separate effluent from activated sludge. The membrane is immersed in the reactor.

MBBR

A 2 MLD MBBR plant was selected. MBBR technology provides cost-effective treatment with minimal maintenance since MBBR processes self-maintain an optimum level of productive biofilm. Additionally, the biofilm attached to the mobile bio-carriers within the system automatically responds to load fluctuations.

ASP

The ASP is one of the most commonly used technologies for the secondary treatment of sewage in India. In this study, 1 MLD capacity plant was selected.

SBT

A 1.5 MLD plant designed to recycle sewage was studied. The plant consists of a treatment bed made from specially prepared soil with required mineral additives. The bed is of about 2.5 m in height spread over an area of about 1,700 m^2. The floor and the walls of the containment are waterproofed with HDPE sheets with side anchoring.

AL

A 1.4 MLD plant was selected. Artificial aeration is provided to oxidize the organic matter. In aerobic lagoons, all the suspended solids present in the wastewater are in suspension, and complete mixing takes place.

The unit processes and operations of the analyzed WWTPs are depicted in Table 1.

METHODOLOGY OF THE STUDY

The LCA modelling was carried out with the help of GaBi software (v.6.2). The LCA methodology used in this study is in accordance with the international standards ISO 14040-44 series (ISO 2006a, 2006b). The ISO 14040-44 determines four stages for LCA as follows: goal and scope definition, life cycle inventory, life cycle impact assessment, interpretation for the study. The following sections provide a brief description of the four LCA procedures utilized in this study.

Functional unit

In the current study, 1 m^3 of treated wastewater was chosen as a functional unit which is the most commonly used functional unit (Corominas *et al.* 2013a).

System boundaries and assumptions made in this study

Previous studies have shown that construction and demolition phases of mechanized WWTPs have negligible impacts (less than 5% of impacts compared with overall life cycle impacts of the WWTP) compared with the operation phase (Pasqualino *et al.* 2009). Thus, this study has taken into account only the operation phase. The system boundary of the present study comprised unit processes related to wastewater treatment, sludge treatment, sludge disposal and transportation to a landfill site. The inputs were influent, electricity, chemicals, and diesel. The data for electricity consumption were collected from plant operators, and background data were used from the Ecoinvent database to assess the environmental impacts. The energy process used for modelling was Indian electricity grid mix, medium voltage. Direct process emissions which are biogenic in nature were excluded from the analyses because they belong to the short CO_2 cycle and do not contribute to climatic change (Coats *et al.* 2011). For transportation of sewage sludge to the landfill site, the distance of 50 km was assumed.

Life cycle inventory

Following the goal and scope definition, life cycle inventory analysis was conducted. Life cycle inventories were generated based on several on-site visits to WWTPs. Table 1 presents a summary of the operation phase life cycle inventory for WWT technologies.

Life cycle impact assessment (LCIA)

LCIA represents the third phase. In this study, the CML 2001 (November 2013) method was used for LCIA as it gives a separate score for each type of environmental impact. The results of the LCIA of WWTPs for different selected impact categories are presented below in Table 2. The results of the comparative assessment of six plants are shown in Figure 1.

RESULTS OF THE COMPARATIVE LCA STUDY

Interpretation of results

Finally, the interpretation of the results allows identifying the hot spots in the process as well as recommending options to reduce the environmental burdens.

Impacts were mainly caused by consumption of fossil-based electricity and chemicals, as well as wastewater effluents from WWTPs are major contributors due to the remaining nutrients emissions and the emission of heavy metals from disposed sludge.

The total energy consumption (per MJ/m^3) over the life cycle of the plants has been found to be AL (3.39) > MBBR (2.51) > MBR (1.69) > SBR (0.913) > ASP (0.682) > SBT (0.131) which is in the range of the similar studies carried out in India (Singh & Kazmi 2017) and other countries (0.36 MJ/m^3 to 5.4 MJ/m^3). Singh & Kazmi (2017) reported the specific power consumption values between 0–3.6 MJ/m^3 (MBBR > MBR > SBR) for different WWTPs under study which is line with the results of the present study.

Concerning impact indicator results, it is found that electrical consumption by the WWTPs makes the most significant contribution to global impact categories such as abiotic depletion potential (ADP), global warming potential (GWP), acidification potential (AP) and photochemical

Table 1 | Summary of the operation phase life cycle inventory for inputs and outputs of WWTPs (functional unit: 1 m^3 of treated wastewater)

Sr. no.	Parameter	Unit	SBR	MBR	MBBR	ASP	SBT	AL	Data source and LCA process/flow
1	**Total electricity consumption**	MJ	**0.913**	**1.69**	**2.51**	**0.682**	**0.131**	**3.39**	Plant operators IN: electricity, medium voltage
1.1	Wet well	MJ	0.111	–	0.246	–	–	–	
1.2	Primary clarifier	MJ	–	–	–	0.031	–	–	
1.3	Aeration tank	MJ	–	0.833	–	1.01	–	–	
1.4	Sedimentation tank	MJ	–	–	–	0.0349	–	–	
1.5	Secondary reactor	MJ	0.756	0.822	1.08	–	0.0591	3.1	
1.6	Flocculation chamber	MJ	–	–	0.404	–	–	0.0771	
1.7	Sand filter	MJ	–	–	0.311	–	–	0.0771	
1.8	Chlorination	MJ	0.00786	0.0211	0.00276	0.0504	–	–	
1.9	Ozonation	MJ	–	–	0.469	–	–	–	
1.10	Discharge tank	MJ	–	–	–	–	0.0358	0.1	
1.11	Collection tank	MJ	–	–	–	–	0.0358	0.0357	
1.12	Sludge thickener	MJ	–	0.0117	–	0.217	–		
1.13	Centrifuge	MJ	0.0379	0.0468	–	0.0238			
2	**Chemical consumption**								Plant operators
2.1	Alum	kg	–	–	0.00553	–	–	0.0507	
2.2	Lime	kg	–	–	0.0502	–	–		
2.3	Sodium hypochlorite	kg	0.02	0.0205	0.052	0.012	–	0.0179	
3	**Sludge generated**	kg	**0.008**	**0.004**	**0.0255**	**0.051**	**0.001**	**0.0104**	Plant operators
3.1	Transportation of sludge	km	50	50	50	50	50	50	Plant operators
3.2	Type of truck used for transportation								Truck-trailer; diesel driven, Bharat stage IV, cargo; consumption mix; up to 28 t gross weight/12.4 t payload capacity
4	**Emissions to air**		**4.26**	**6.19**	**11.6**	**2.5**	**0.103**	**13.4**	Indirect emissions due to total electricity consumption and transportation of sludge to landfill. Taken from Gabi database
4.1	CO_2	kg	0.43	0.701	1.19	0.283	0.0504	1.47	
4.2	SO_2	kg	0.00225	0.00411	0.00642	0.00166	0.000318	0.00858	
4.3	NO_X	kg	0.00167	0.00291	0.0046	0.00123	0.00013	0.00598	
4.4	CO	kg	0.000234	0.000341	0.000648	0.000138	2.64E-005	0.000747	
4.5	**Heavy metals**	kg	**2.69E-006**	**4.79E-006**	**7.42E-006**	**1.93E-006**	**3.7E-007**	**97E-006**	
4.5.1	Zinc	kg	8.76E-007	1.58E-008	2.41E-006	6.4E-007	1.22E-007	3.02E-006	

(*continued*)

Table 1 | continued

Sr. no.	Parameter	Unit	SBR	MBR	MBBR	ASP	SBT	AL	Data source and LCA process/flow
4.5.2	Tin	kg	8.75E-008	1.5E-007	2.41E-007	6.07E-008	1.16E-008	3.04E-007	
4.5.3	Nickel	kg	1.4E-007	2.39E-007	3.92E-007	9.65E-008	1.85E-008	4.91E-007	
4.5.4	Lead	kg	3.5E-007	6.16E-007	9.63E-007	2.49E-007	4.76E-008	1.25E-006	
4.5.5	Copper	kg	4.49E-008	7.55E-008	1.24E-007	3.05E-008	5.84E-009	1.54E-007	
4.5.6	Cobalt	kg	2.69E-008	4.59E-008	7.41E-008	1.85E-008	3.55E-009	9.27E-008	
4.5.7	Chromium	kg	6.77E-011	8.88E-012	1.92E-010	5.93E-008	1.13E-008	2.97E-007	
4.5.8	Cadmium	kg	2.48E-008	4.58E-008	6.82E-008	1.85E-008	3.55E-009	9.24E-008	
4.5.9	Arsenic	kg	1.54E-007	2.83E-007	4.24E-007	1.14E-007	2.19E-008	5.71E-007	
5	**Emissions to water**	kg	**1.04E003**	**1.78E003**	**2.86E003**	**719**	**138**	**3.68E003**	
5.1	COD	kg	0.000188	0.000245	0.000511	9.9E-005	1.9E-005	0.000616	Analysed in laboratory, APHA (2005) method
5.2	N-Total	kg	9.85E-010	6.38E-010	2.71E-009	2.58E-010	4.94E-011	2.05E-009	Analysed in laboratory, APHA (2005) method
5.3	P-Total	kg	3.49E-007	1.29E-009	9.1E-007	7.29E-010	3.43E-009	3.53E-007	Analysed in laboratory, APHA (2005) method
5.4	**Heavy metals**	kg	**0.000278**	**0.000469**	**0.000761**	**0.000189**	**3.53E-005**	**0.00097**	Analysed by ARCOS, simultaneous ICP (inductively coupled plasma) spectrometer
5.4.1	Zinc	kg	2.88E-008	2.71E-008	7.99E-008	1.1E-008	2.1E-009	7.16E-008	
5.4.2	Tin	kg	3.51E-051	2.18E-015	9.71E-015	8.84E-016	1.69E-016	7.27E-015	
5.4.3	Nickel	kg	2.37 – 008	2.77E-008	7.69E-008	1.12E-008	2.15E-009	7.92E-008	
5.4.4	Lead	kg	1.26E-008	7.69E-009	4.11E-008	3.11E-011	8E-009	3.27E-008	
5.4.5	Copper	kg	1.19E-008	1.03E-008	6.66E-008	4.17E-009	2E-009	3.69E-008	
5.4.6	Cobalt	kg	1.21E-010	5.29E-013	3.15E-010	2.86E-013	4.09E-014	1.23E-010	
5.4.7	Chromium	kg	1.51E-009	4.75E-008	4.05E-009	1.92E-008	3.68E-009	1.43E-007	
5.4.8	Cadmium	kg	2.95E-009	2.02E-009	1.76E-008	8.2E-010	1.56E-010	1.69E-008	
5.4.9	Arsenic	kg	9E-009	5.7E-009	4.68E-008	2.31E-009	4.4E-010	4.3E-008	
6	**Emissions to soil**	kg	**1.63E-006**	**2.96E-006**	**4.47E-006**	**1.2E-006**	**2.29E-007**	**5.99E-006**	Taken from Gabi database
6.1	**Heavy metals**	kg	**1.63E-006**	**2.96E-006**	**4.47E-006**	**1.2E-006**	**2.29E-007**	**5.99E-006**	
6.1.1	Zinc	kg	6.02E-007	1.08E-006	1.65E-006	4.37E-007	8.37E-008	2.2E-006	
6.1.2	Nickel	kg	4.55E-009	3.08E-009	1.21E-008	1.25E-009	2.39E-010	9.02E-009	
6.1.3	Lead	kg	3.96E-008	5.95E-008	1.08E-007	2.4E-008	4.6E-009	1.27E-007	
6.1.4	Copper	kg	2.16E-007	3.97E-007	5.94E-007	1.6E-007	3.07E-008	8.01E-007	
6.1.5	Chromium	kg	7.55E-007	−5.31E-014	2.07E-006	7.45E-014	−4.11E-015	2.82E-006	
6.1.6	Cadmium	kg	5.05E-009	8.64E-009	1.38E-008	3.49E-009	6.69E-010	1.78E-008	
6.1.7	Mercury	kg	7.57E-009	1.4E-008	2.08E-008	5.66E-009	1.08E-009	2.82E-008	

Table 2 | LCIA results of WWTPs for 11 impact categories

Impact categories	SBR	MBR	MBBR	ASP	SBT	AL
Abiotic depletion potential (ADP) elements (Kg CO_2-Eq)	5.76E-07	2.69E-08	1.47E-06	1.12E-08	2.08E-09	5.7E-07
ADP fossil (MJ)	4.849445	7.822005	12.19931	3.161791	0.605226	16.9
Acidification potential (AP) (Kg SO_2-Eq)	0.003621	0.006524	0.009297	0.002636	0.000505	0.0136
Eutrophication potential (EP) (Kg phosphate-Eq)	0.000157	2.91E-05	0.000388	0.000816	0.000224	0.000576
Freshwater aquatic ecotoxicity potential (FAETP) (Kg DCB-Eq)	0.000806	0.001199	0.001993	0.0043	0.000156	0.014164
Global warming potential (GWP) (Kg CO_2-Eq)	0.448299	0.728398	1.134242	0.294416	0.05636	1.53
Human toxicity potential (HTP) (Kg DCB-Eq)	0.142729	0.105697	0.261565	0.356138	0.020238	0.529
Marine aquatic ecotoxicity potential (MAETP) (Kg DCB-Eq)	488.1626	650.7335	1,208.061	1,619.911	93.47352	2430
Ozone depletion potential (ODP) (Kg R11- Eq)	1.32E-11	1.70E-11	3.58E-11	6.87E-12	1.32E-12	4.21E-11
Photochemical ozone creation potential (POCP) Kg Ethene-Eq	0.000185	0.000324	0.000479	0.000131	2.51E-05	0.000682
Terrestrial ecotoxicity potential (TETP) (Kg DCB-Eq)	0.00463	0.00626	0.0115	1.56E-02	0.000886	0.0232

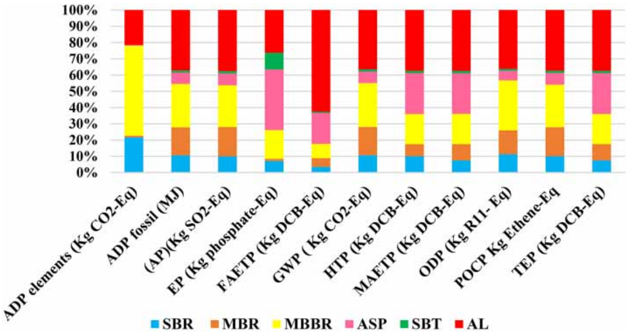

Figure 1 | LCIA results of six WWTPs under this study.

ozone creation potential (POCP). The WWTP itself does not impose a direct impact on the local environment. Its environmental impact is ascribed to the production of the electricity (Ioannou-Ttofa *et al.* 2016). This was owing to the extraction and burning of fossil fuels, which releases pollutants and carbon dioxide to the environment.

GWP

The energy consumption for the operation of WWTPs is found to be the largest contributing factor for CO_2 emissions and GWP. Being the technology with the highest electricity demand, AL reported worst on this impact category followed by MBBR. Reasons for the higher energy requirements of AL are because this system processing 1 m^3 of wastewater consumes more electricity and chemicals than others. Next, due to the high consumption of electricity and chemical dosing, the CO_2 and GHG emissions to air and hence the emissions related GWP has been found to be more for the MBBR plant under study. Further, sometimes, due to the use of aerators or mechanical stirrers in MBBR to ensure that the beds are moving for uniform treatment make the energy consumption.

AP and ADP

AP is mainly because of SO_2 and NOx emissions from coal combustion, which generates electricity for operating the plants. Coal consumption also has a major contribution to ADP (fossil). Similarly, for ADP (fossil), AL is found to have the highest AP and ADP as compared with other technologies.

EP

The EP of a WWTP is mostly associated with the emissions to water, mainly due to the phosphorus (P), nitrogen (N) and to a lower extent, degradable organics in wastewater effluent. This is not surprising since WWTPs' discharge acting as source point is one of the main contributors to aquatic eutrophication worldwide, and the eutrophication impact would have been worse in the absence of WWT (Renou *et al.* 2008).

The MBR (0.0000291 kg $PO_4{}^{3-}$Eq) has the lowest EP value as compared to other technologies, which matches with values (for nutrient removing systems) reported by Gallego *et al.* (2008). ASP has the highest EP (0.000816 kg $PO_4{}^{3-}$Eq) because there is negligible removal of nutrients in the ASP system. Thus, the EP impact can be decreased immediately by implementing more sophisticated technology to enhance the nutrient removal efficiency (however, generally with an increase of other environmental impacts).

ODP

This category mainly refers to the emission of gases that reduce the ozone layer (principally CFC-11, CFC-12 and Halon 1301) and these emissions are found to be minimal in this study.

POCP

The values obtained for POCP in the current study are far smaller from consideration.

Toxicity potentials (FAETP, HTP, MAETP and TETP)

Ecotoxicity potential is mostly dependent on the heavy metals released in the air, water and soil environment, for which in the considered WWTPs there is no special provision for heavy metal removal. However, some removal takes place through the physicochemical and biological processes. Further, the disposal of sludge containing heavy metals contributed substantially to the ecotoxicity impact categories.

FAETP

Concerning to FAETP, the emissions of metals that take place during electricity production dominate the impact for all the secondary reactors. Far from the item energy use, the discharge of treated water is the second element, mainly to the release of Zn, Ni and Cu to the aquatic environment.

HTP

It is mainly because of the release of heavy metals in water, air and the soil environment. In this study, SBT has the lowest HTP (0.020238 Kg DCB-Equiv).

MAETP

The current study revealed that MAETP contributes most to the overall impacts, the result is in agreement with the results of earlier studies (Kalbar *et al.* 2012b, 2013a, 2014; Kamble *et al.* 2017). The characterization factors in this category (for chemical consumption, sludge production, energy consumption, etc.) are generally higher than those of other impact categories. AL presented the highest environmental impact in MAETP since this treatment scheme had the highest electricity consumption.

TETP

It is dominated by the presence of heavy metals in the sludge being Zn, Pb, and Cu as the main contributors. This contribution is directly dependent on the quantity of sludge produced. AL system is found to have the highest TETP (0.0141 kg 1,4-DCB-Eq). The TETP for MBR (0.0001) is almost negligible mainly because, very much less sludge is generated during the WWT process. The reason for this is the MBR's ability to operate at much longer sludge retention times (Sadr *et al.* 2016).

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 Kamble *et al.* (2017).

Evaluation of benefit from reuse of the treated effluent

Properly treated wastewater can be reused for various purposes to provide ecological benefits, reduce the demand for potable water and augment water supplies (Mo & Zhang 2013). The cost of treating 1 KLD (kilolitre per day) of sewage costs about *INR* (Indian Rupees) 18 to 20, while the cost of treated water lies between *INR* 40–60, thereby posing a profitable option (Singh *et al.* 2015).

In the current study, treated effluent was used to replace tap (fresh) water, and the benefits are gained from water saving. In conclusion, is it understood that the total life-cycle benefit from reuse of the tertiary treated effluent is much higher than the life cycle energy consumption for the tertiary treatment. This indicates that the implementation of the tertiary WWT facility is beneficial. The results of SBT and MBR with and without reuse of effluent are shown in Figures 2 and 3, respectively.

The main environmental concerns obtained through the LCA are linked to increased toxicity impacts from the chosen end use of wastewater and related recovery products. The results obtained clearly indicate that there is a drop in the toxicity potential when the rate of effluent reuse is increased.

Life cycle costing – LCC

In this study, capital cost and O&M costs have been considered. Capital cost includes civil, mechanical, electrical and any other related items during the construction of the plant. The capital cost also includes land cost estimated as per the Rs. 0.02 lakh per m^2. O&M costs incurred usually account for labour requirement, energy, chemicals, repair

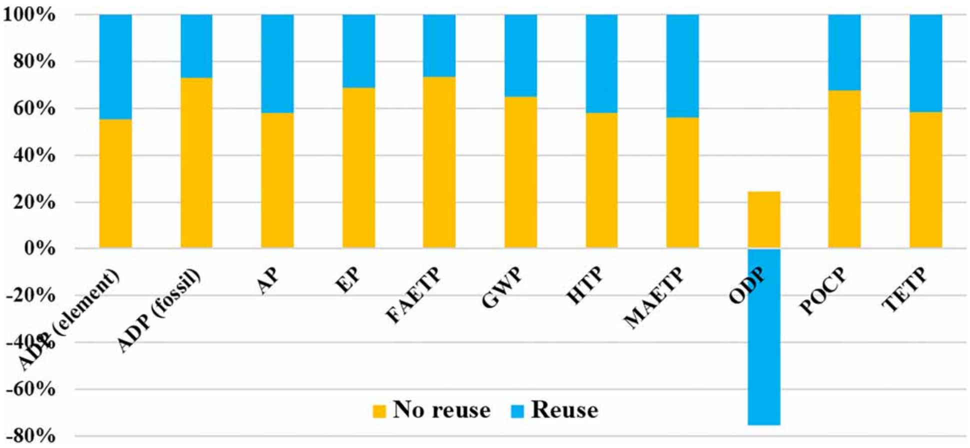

Figure 2 | LCIA results of SBT with No reuse and Reuse (50%) scenarios.

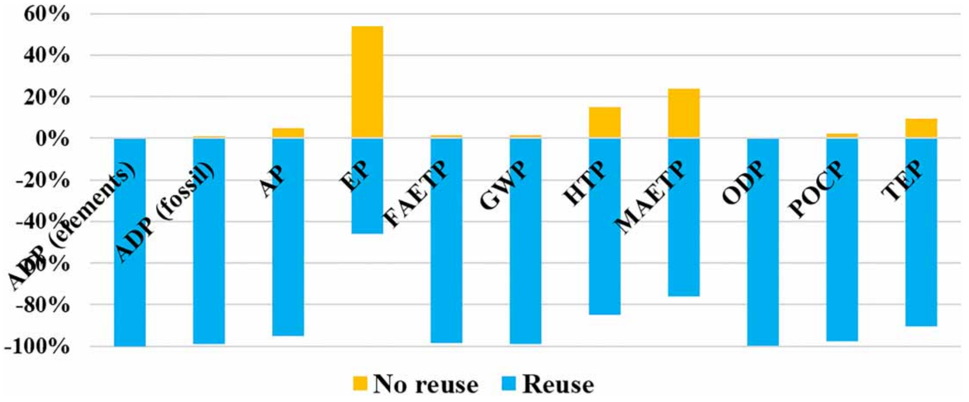

Figure 3 | LCIA results of MBR with No reuse and Reuse (100%) scenarios.

and replacement of electro-mechanical materials. LCC was calculated using the IS 13174 (1991) and IS 13174 (1994) Parts 1 and 2 methodologies of Bureau of Indian Standards. The current study employed the present worth (PW) method for LCC.

PW

The uniform present worth factor (UPWF) is used to estimate the present worth of O&M cost spent every year. The following equation is used to estimate the total present worth of the WWTPs:

$$\mathrm{PW} = \mathrm{Capital\,Cost} + (\mathrm{O\&M\,Cost} * \mathrm{UPWF})$$

$$\mathrm{UPWF} = (1+\mathrm{i})^{\mathrm{T}} - 1/\mathrm{i}(1+\mathrm{i})^{\mathrm{T}}$$

$$\mathrm{UPWF} = 0.0833$$

where i is the interest rate, and T is the economic life of the asset. For this study, economic life is defined as 50 years and the interest rate is taken as 12%. The costs data for the six WWTPs under study and the results of LCC are presented in Table 3.

The PW of SBT was estimated to be Rs. 40 million/MLD which is the highest compared to other technologies. This high cost is due to the very large land requirement and high-density polyethylene liner cost. MBR has the second highest (Rs. 24.7 million/MLD) which is mainly contributed by civil, electro-mechanical costs and membrane cost.

Although high capital and O&M costs have been pointed out as a major drawback for MBRs' widespread implementation, in this case, such costs are counteracted again by the environmental damage avoided, due to the total absence of solids in MBR permeates and their high treatment quality (Castillo *et al.* 2016). MBR technology is found to be comparable or sometimes better than upgraded MBBR and SBR plants to produce effluent of excellent quality, as the water quality produced by other WWTPs is insufficient (Singh & Kazmi 2017). MBBR is economical,

Table 3 | Costs data and results of LCC (all values are expressed per MLD basis)

Parameter	Unit	SBR	MBBR	MBR	ASP	SBT	AL
Capital cost	million Rs.	6	5.8	24	4	30	5
Land requirement	m^2	550	500	353	1,400	5,010	1,123
Costs of land (Rs. 0.02 Lakh/m^2)	million Rs.	1.1	1.0	0.7	2.8	10.0	2.2
Total capital cost	million Rs.	7.1	6.8	24.7	6.8	40	7.2
Total O&M costs per year	million Rs.	0.72	1.0	1.9	0.83	0.1	0.37
Economic life	years	50	50	50	50	50	50
Interest rate	%	12	12	12	12	12	12
PW	million Rs.	7.2	6.9	24.8	6.9	40	7.2

but the removal of TSS and BOD5 is unsatisfactory and produces a medium quality effluent.

In fact, if the legislation of discharge standards are tightened further, such as conventional and other technologies are not able to meet the demand, then MBR is the only viable option. According to Starkl *et al.* (2018), trade-offs between pollutant removal and costs were not possible, as lacking fulfilment was extreme; either legal requirements were violated or costs were excessive.

The main findings from the LCA and LCC study are as follows:

- Energy is very often a great source of an impact as the Indian electricity mix is mainly carbon-based. In this study, energy consumption is a central contributor to the environmental profile of the studied plants, in that it contributes to different impact categories in varying degrees.
- The potentials of the impact categories dominated by energy consumption are heavily influenced by electrical grid-mix. Plants operating in countries with high levels of fossil fuels in the electrical grid-mix may exhibit a higher GWP than a plant with similar energy consumption rates operating in a country with a greener electrical grid-mix.
- The organic loading rate had the largest influence on energy consumption rates because it is directly related to the oxygen demand and, subsequently, the required aeration power.
- In comparison to conventional technologies, natural technologies such as SBT has been proposed as a better alternative with lower environmental impacts and reduced pollutant loads as these technologies are highly efficient for heavy metal removal and have low energy demand; nevertheless, implementation of these technologies requires large areas of land.
- LCA and LCC are determined as being the most appropriate environmental assessment and economic tools, respectively, for system evaluation.
- The results of this study can be used to design and simulate new technologies compared with the existing ones. This work intends to provide the decision support to the decision makers through identification of the important components that influence the life cycle impacts as well as through providing a reasonable estimation of the environmental impact of the WWTPs.

CONCLUSIONS

A comprehensive LCA and LCC have documented in this study can help decision makers to take sustainable decisions taking into account both environmental and economic aspects of WWTPs. The results obtained from the LCA study provide insightful information about the potential environmental impacts triggered by every aspect of the operation of the treatment processes. Whilst there are some uncertainties in the data quality, different operating performance parameters, system boundaries, background inventories and different LCIA methodologies may significantly vary the results of an LCA. This study reflects the need for the development of exhaustive and relevant Indian life cycle inventories to add to the Indian database.

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