Environmental and economic assessment of proposed on-site wastewater management system in multi-storey residential building

Snehal V. Dewalkar and Sameer S. Shastri

ABSTRACT

In the present study, the concept of 'environmental floors' in the multi-storeyed building is proposed, where separate treatment of greywater by gravity-governed stabilization tank and blackwater by underground Malaprabha digester of the DOSIWAM (Decentralized On-Site Integrated WAste Management) system is carried out. The study evaluates the feasibility of the non-mechanised DOSIWAM system by comparing it with the mechanised activated sludge process (ASP) with the life cycle and cost assessment (LCA and LCCA) method. The LCA was carried out with the SimaPro software using the impact 2002+ method. Both systems served a multi-storeyed (G + 30) building with 890 population equivalent. The LCA results reveal that the non-mechanised DOSIWAM system has three to six times reduced environmental impacts than the ASP system in almost all impact categories. Although DOSIWAMS' weaker removal efficiency dominates in the results of aquatic eutrophication and acidification impact, the latter comparative economical assessment showed to be the most cost-effective alternative due to reduced land use cost, O&M cost, and benefits achieved with energy recovery in the form of biogas. The electricity and chemical consumption in the operation phase caused the highest environmental impact for the ASP system, whereas the production of clinker and steel are responsible for a detrimental impact in the construction phase of the DOSIWAM system.

Key words | activated sludge process, decentralised on-site integrated waste management, impact 2002 +, life cycle assessment, life cycle cost assessment

Snehal V. Dewalkar (corresponding author)
Department of Civil Engineering, Sinhgad College of Engineering, Vadgaon (Budruk),
Savitribai Phule Pune University,
Pune, Maharashtra 411048,
India
E-mail: *svdewalkar.sae@sinhgad.edu*

Sameer S. Shastri
Department of Civil Engineering, Sinhgad College of Engineering, Vadgaon (Budruk),
Savitribai Phule Pune University,
Pune, Maharashtra 411041,
India

HIGHLIGHTS

- An innovative approach of wastewater management.
- Concept of multi-storeyed building with environmental floors.
- Separate treatment of greywater and blackwater, where every drop of liquid and every grain of solid is treated hygienically.
- Land occupation and harmful environmental impacts can be well eliminated by decentralised on-site integrated waste management.
- Cost effective treatment with biogas recovery.

INTRODUCTION

Indian metro-cities have major downsides of inadequate infrastructural facilities and land unavailability for constructing a wastewater treatment plant (WWTP). Ever-increasing wastewater quantities give rise to major environmental and health problems. As against this, the treatment facilities provided are inadequate and nearly 50% of them have outdated infrastructure (CPCB 2016). A centralized approach for wastewater treatment is a costly affair, comes to 10 million Rs. per million litres daily (MLD) for infrastructure development and additional operation and maintenance (O&M) costs, which becomes challenging to the government day by day (CPCB 2016).

doi: 10.2166/wst.2020.548

Ever since the local government made treatment of sewage for housing society compulsory (built-up area ≥20,000 sq. meters), 30% of such existing sewage treatment plants were observed as non-functional, leading to continuous dumping of untreated wastewater to the river (MPCB 2016). This has not only adverse impacts on the environment but also downstream users are severely affected.

Many small communities of India are facing difficulties in constructing and maintaining conventional residential WWTPs because of land availability issues, limited financial resources, and plenty of problems associated with complex O&M. Thus, to tackle these problems and revolutionize waste management, systems for treating and recycling wastewater need to be on-site, cost-effective, and self-sustainable, delivering chemical-free treated effluent that would be entirely harmless to nature and residents. One such system is DOSIWAM (Decentralized On-Site Integrated WAste Management) (Mapuskar 1988). The fundamental concept of the DOSIWAM system is the profitable treatment, reuse and recycling of wastewater at the source of the generation itself.

The current study aims to propose the concept of the 'environmental floor' for the installation of the DOSIWAM system at intermittent levels of a multi-storeyed building. The term 'environmental floor' is designated for the refuge floor, where the treatment units are located, keeping the standard refuge area vacant and working on a gravity basis to fulfil the requirement for treated water used for various non-consumptive purposes like flushing, gardening, firefighting, floor washing, etc. The treatment units consist of the Malaprabha digester, the Intercepting tank, the Stabilization tank, and the Storage tank. Greywater treatment is carried out with treatment units positioned on environmental floors that receive wastewater from above located intermittent floors and pass treated water to below. Here, the system has a non-mechanised arrangement where no mechanical equipment is utilized that could cause additional weight and complications on the floors (Dewalkar & Shastri 2020).

Figure 1 shows the process flow of greywater collection from intermittent floors, treatment on the environmental floor, distribution of treated water for flushing purposes, and collection of blackwater at the underground Malaprabha digester. The refuge floors distribution is carried out as per the guidelines given by the Urban Development Department, Government of Maharashtra, India. If the height of a building is more than 39 meters, the first refuge floor should be after 39 meters and so on successively, at every 15-meters interval. The height and carpet area for current multi-storeys is 110

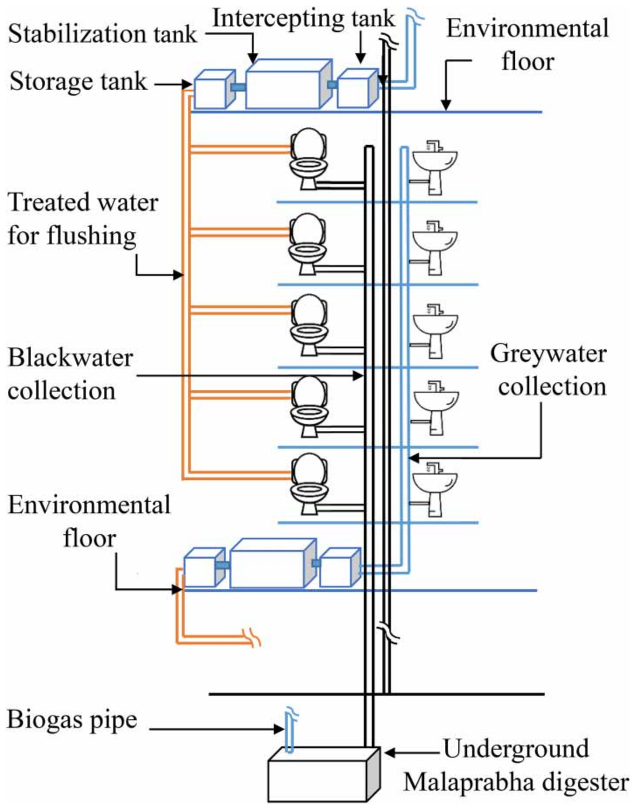

Figure 1 | Schematic representation of wastewater collection, treatment on environmental floors, and treated water distribution.

meters and 960 m^2 respectively. It is noteworthy that the area occupied by treatment units positioned at environmental floors (refuge floors) is comparatively minimum (7.8% of total carpet area) as its treatment capacity is governed by the volume of grey wastewater generated from intermittent floors, which ensure economy in cost.

Extensive life cycle assessment (LCA) studies have been carried out worldwide addressing environmental impact assessment of mechanised and exclusively activated sludge treatment process (ASP) (Machado *et al.* 2007; Lopsik 2013; De Feo *et al.* 2016; Garfi *et al.* 2017; Laitinen *et al.* 2017), but LCA-driven studies for wastewater treatment in the Indian context, are very few (Kalbar *et al.* 2012a, 2012b, 2013, 2014; Kamble *et al.* 2017; Raghuvanshi *et al.* 2017; Singh & Kazmi 2017; Singh *et al.* 2018; Kamble *et al.* 2019) and to date, no detailed environmental and economical studies have been attempted for the DOSIWAM system. Ahmed *et al.* (2010) envisioned that 'research of LCA in wastewater extends mostly in developed countries with almost no contribution from developing countries'. Analysing LCA in the Indian context is a bit-challenging task, as availability of a national database is an issue (Kalbar *et al.* 2012a; Kamble *et al.* 2019). The software employed for LCA conduction is either generic or designed for one specific area. SimaPro and GaBi are the most widely used generic LCA software applied to analyse the wastewater treatment (WWT) system (Kulczycka *et al.* 2015). LCA and LCCA receive valuable importance for their decision-making ability towards environmental and economical sustainability (David & Messiha 1999).

The selection of treatment systems is a major concern in developing countries facing many problems due to insufficient data with respect to cost utilisation and performance evaluation, resulting in an inappropriate selection of treatment systems (Poch *et al.* 2004; Kalbar *et al.* 2012a). Such a situation is observed in India also, where wastewater treatment technologies are selected on the basis of past experience and existing cost and resources constraints (Singh & Kazmi 2017). Nowadays, residents are dealing with some major challenges with conventional residential WWT systems, such as:

1. Energy driven treatment with erratic supplies and unavailability of alternative sources to fulfil the requirements.
2. Power supply remains a major hindrance, interruption in treatment mechanism upsurges the risk of system failure.
3. Economical aspects of skilled manpower deployment for scientific handling and an annual burden to pay consent for O&M to municipal corporations create an extra burden on residents.
4. Improper allocation of the system in the premises leads to unbearable noise and vibration issues to ground floor residents.

Thus, people are in search of a simplified process-based, low-cost viable option. Hereby, the current study brings to light the importance and suitability of a virtually designed non-mechanised DOSIWAM system for a multi-storeyed building using an LCA and LCCA approach.

METHODS

Brief description of the compared systems

DOSIWAM

DOSIWAM is a sustainable, eco-friendly, hygienically safe sanitation process based on natural biodegradation, which converts waste into wealth. In this system, every grain of solid and every drop of liquid is treated hygienically by bio digestive process and natural aeration and end products are return to the soil through horticulture or agriculture in an ecologically sustainable manner.

Stabilization tank

The stabilization system works on the basis of settlement and degradation of the solids from the wastewater. A multi-sectional stabilization tank contains five main and sub-main compartments maintaining a length to breadth ratio of 1:3. Aerobic condition is provided to each compartment with sufficient freeboard and a one-day detention period to obtain proper contact time between air and wastewater. The intercepting tank where solids settle at the bottom diverts the water to the first compartment with controlled velocity within one-day detention time. It was observed that a small amount of solids get settled at the bottom of the first compartment and remain in the second compartment. Settled sludge is then digested gradually. A sludge valve can be used to remove the excess sludge, which may settle in the first two compartments and thus act as the settling zone. In the third, fourth, and subsequent compartments, some amount of dissolved solids is removed. Thus, horizontal and vertical zigzag flow patterns and gradual oxidation of pollutants using effective microorganisms in treatment units results in simpler and non-polluting effluent that can very well be used for non-consumptive purposes. The physiochemical characteristics of treated greywater are under acceptable limits of pollution parameters prescribed by the Central Pollution Control Board (CPCB) and free from obnoxious odour.

Malaprabha digester

The Malaprabha digester of the DOSIWAM system is an environmentally and economically sustainable solution for blackwater management. It consists of three main components: the digestion chamber (30 days HRT) followed by displacement (15 days HRT) and the outer chamber (15 days HRT). The high retention time of 45 days leads to pathogen-free faecal sludge. Waste entered inside the digester separates in three layers with heavier solids at the bottom, lighter solids at the top, and minimal solids in the middle layer, which are then promoted to move towards the second and third chambers during the process of anaerobic digestion. A scum breaker provided help to reduce the formation of the scum layer on the top surface, which could hamper the production of the biogas from the waste. The settled sludge can be removed from the first chamber, and later on can be used as fertilizer. Evolved scum can be removed from the provided gaskets. The design of the system is such that there is little to no human intervention required to work or maintain the system. The decomposition of organic matter to methane can be effectively carried out and fully trapped in the Malaprabha digester. Integrated and complementary treatment of human night soil serves dual purposes of managing human waste and recovering energy that can replace and reduce dependency on LPG (liquefied petroleum gas). Complete oxidation of bio-methane during the combustion of biogas (81.5 CO_2/MJ) is comparatively lower than LPG burning (139 CO_2/MJ) and is considered as neutral (Smith *et al.* 2000).

Activated sludge process (ASP)

In India, ASP is the most commonly used secondary sewage treatment system (Kamble *et al.* 2019). The treatment consists of an aeration tank, which acts as the biological reactor, with aerobic microorganisms used to produce a biological floc, and a final clarifier system, which separates solid and treated wastewater. Sludge acts as an adsorbent for organic and suspended solids and microorganisms carry out the oxidation of organic matter. Figure 2 shows a process-based flow diagram of both the studied systems.

Life cycle assessment (LCA)

LCA is an analytical tool that measures any product's or activity's environmental impacts from its raw material acquirement phase to its demolition phase (Tillman & Baumann 2004). The ISO 14040 series (ISO 2006a, 2006b) LCA standard elaborates all phases of life cycle assessment with the 'cradle-to-grave' and 'cradle-to-gate' approach. The methodology associated with LCA has four major components.

Goal and scope definition

The goal of the current study is to perform a comparative analysis of two different systems: DOSIWAM (non-mechanised) and ASP (mechanised) designed for the multi-storeyed building (G + 30) with 890 equivalent habitats, where the DOSIWAM system's greywater and blackwater treatment units positioned on the environmental floors and underground respectively and the ASP system provided at the premises of building under study. This comparative study assesses the critical source of environmental impacts associated with mechanised versus non-mechanised wastewater treatment and follows a 'cradle to gate' approach to carry out LCA.

Functional unit

In the present study, to measure the comparative performance of both the systems, the functional unit was chosen as 1 m^3 of treated wastewater, commonly used by many researchers (Godin *et al.* 2012; Kamble *et al.* 2019) over plant lifespan of 50 years.

System boundary

The system boundary considered as per study objectives follows the 'cradle to gate' approach, where LCA evaluates impact from extraction, production, and processing of

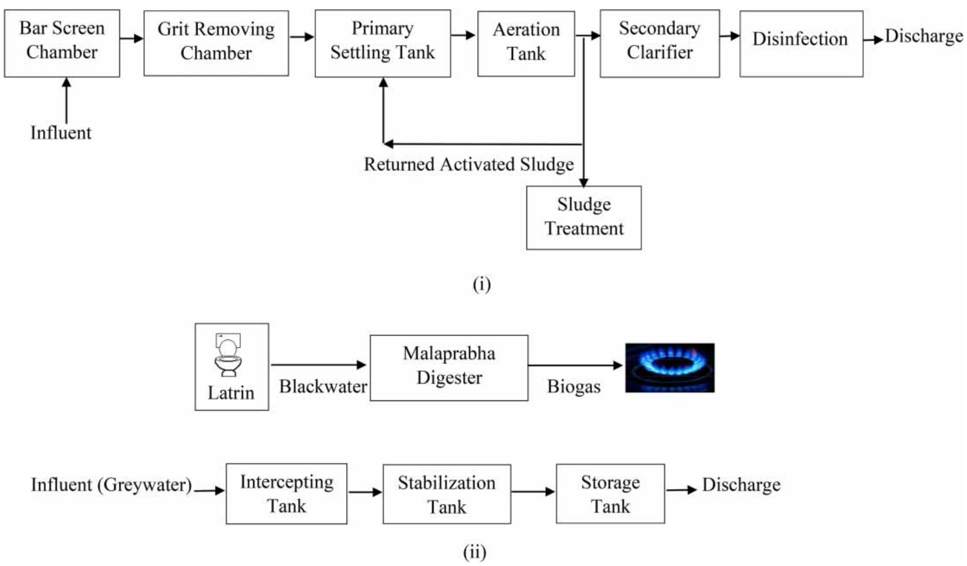

Figure 2 | Process-based flow diagram of analysed treatment systems (i) ASP (ii) DOSIWAM.

materials for infrastructure, operational equipment, and chemicals along with the energy required to carry out the operational process. In most of the studies, the end of life phase was excluded due to scarce information associated with dismantling and recycling of used materials. Furthermore, the demolition phase of the WWTP has a lower environmental impact than the construction and O&M phase (Lundin *et al.* 2000; Machado *et al.* 2007; Lopsik 2013). Moreover, the construction phase was also not considered in some studies, with an assumption that the impact of this phase is considerably lower than the O&M phase particularly for treatment plants with a long span of life. However, this considered assumption may not stand for some treatment technologies such as natural treatments like construction wetlands, an infiltration process where the construction phase has a significant impact and even to a greater extent than the O&M phase (Kobayashi *et al.* 2020). Thus, it is equally essential to consider the construction phase for environmental impact assessment (De Feo *et al.* 2016). In the current study, the emphasis was put on LCA of the construction and O&M phases and demolition phase, and sludge treatment was excluded; however, construction materials required for the sludge thickening bed of the ASP system were considered. In the case of the DOSIWAM system, the remaining floors above the topmost environmental floor were served by pumping treated water with a very low capacity pump, thus electricity consumption is taken into consideration. Further, during the phase of construction, transportation of construction materials, which were manufactured locally, contributes minor impact, and is thus excluded.

Inventory analysis

During the technical procedure of inventory analysis, LCA models for both treatment systems were constructed as per governed specifications in defined goal and scope. Inventory analysis enumerates raw materials, energy consumption, and environmental emissions to air, soil, and water throughout the life span of a treatment plant (Ahmed *et al.* 2010). In the case of the ASP treatment system, all foreground input data (i.e. infrastructural inputs, O&M resources, effluent characterization) required for life cycle inventory (LCI) were collected from documents of the existing plant situated at the premises of building under study. Infrastructural input data for a virtually designed DOSIWAM system were based on the detailed hydraulic design executed in the frame of a study and effluent characterization that was performed by collecting samples from a similar DOSIWAM system currently in operation and located in Pune, India. The O&M phase primarily required electricity, which was taken from the Indian energy mix database of Ecoinvent 3. Chemicals (sodium hypochlorite), input materials, building equipment for soil excavation, and transportation were taken from the global database of Ecoinvent 3. Guidelines given in the Intergovernmental Panel on Climate Change were used to estimate air emissions (Bartram *et al.* 2019). Anaerobic degradation of COD and nitrogen removal are the sources of biogenic CH_4 and N_2O emissions respectively. Besides, net CH_4 emission was obtained as a result of subtracting recovered methane from gross emission (Bartram *et al.* 2019). The mechanised treatment system's operational report suggests the replacement of electromechanical equipment; thus, substitution was considered every 12 years throughout the 50 year life span of the system. Input and output inventories per functional unit for both systems are presented in Table 1.

Life cycle impact assessment (LCIA)

LCA modeling and impact assessment of the studied systems were performed by SimaPro software with Ecoinvent 3 database (Pre-sustainability 2018). The method adopted was Impact 2002+. Impact assessment and damage assessment (midpoint and endpoint categories) were interpreted in the current study and all the critical sources of the impact associated with the input-output scenario are discussed below. The results are relevant only if the assumptions and limitations of the current study are taken into consideration. As discussed earlier, the study is limited to construction and operation phases. Sludge treatment, disposal, and heavy metal emissions were excluded due to a lack of data availability. Coal-based power generation (IN-Western grid medium voltage) was the only Indian database used in modeling and a global database was used for other background data due to a lack of appropriate Indian life cycle inventories. As per IPCC guidelines, CO_2 emission was excluded due to its biogenic nature, which results in no contribution to climate change (Coats *et al.* 2011).

RESULTS AND DISCUSSION

Global warming

The most significant impact category is global warming (GW). High energy consumption and chemical dosing during the O&M phase contribute the highest environmental burden for the ASP system (1.017 kg CO_2 eq.), whereas the DOSIWAM system has a significantly lower

Table 1 | Life cycle inventory results for DOSIWAM and ASP (expressed in terms of 1 m^3 of treated wastewater)

Inventory Inputs	Unit	DOSIWAM system	ASP system	Ecoinvent process and data source
Inputs				
Earthwork	m^3	9.24E-04	5.77E-04	Excavation, hydraulic digger- (GLO) Excavation, skid-steer loader- (GLO)
Portland cement	Kg	2.65E-01	4.29E-02	Cement production, Portland- (RoW)
Reinforcing steel	Kg	2.82E-02	9.69E-03	Reinforcing steel production- (GLO)
Gravel	Kg	5.71E-01	1.73E-01	Gravel production, crushed –(RoW)
Sand	Kg	2.76E-01	1.11E-01	Sand quarry operation – (GLO)
PVC pipes	Kg	2.00E-03	2.92E-03	Polyvinylchloride production, suspension polymerised- (GLO)
GI pipes	Kg	4.04E-04	2.15E-04	Steel hot dip galvanized production- (GLO)
Cast iron	Kg	8.84E-06	1.27E-04	Cast iron production- (GLO)
Stainless steel	Kg	–	4.24E-05	Steel production, chromium steel 18/8- (GLO)
Mild steel	Kg	–	1.02E-04	Steel production unalloyed- (GLO)
Brass	Kg	–	5.46E-05	Brass production- (RoW)
EPDM	Kg	–	1.90E-05	Synthetic rubber production- (GLO)
Power cable (Al.)	Kg	–	2.13E-05	Aluminium production- (GLO)
Fiber-reinforced plastic	Kg	7.01E-04	–	glass fiber reinforced plastic production, polyester resin, hand lay-up– (GLO)
Paint	Kg	1.36E-04	1.10E-05	Acrylic varnish production, in 87.5% solution state-(RoW)
Sodium hypochlorite	Kg	–	2.82E-02	Sodium hypochlorite production, without water, in 15% solution state (RoW)
Electricity	Kwh	2.42E-03	6.02E-01	Electricity production, medium voltage-(IN-Western grid)
Outputs		Ecoinvent flow and laboratory method		
Emissions to water				
BOD_5	Kg	1.23E-01	6.00E-03	Biological oxygen demand, IS:3025 (PART 44): 1993 (RA 2014)
COD	Kg	3.21E-01	3.50E-02	Chemical oxygen demand, APHA-5220
T-N	Kg	1.38E-01	7.70E-03	Nitrogen, total, APHA-4500
T-P	Kg	2.31E-02	3.70E-03	Phosphorus, total, APHA-4500
T-Solids	Kg	1.42E-01	6.60E-02	Solids, total, APHA-2540
Emissions to air				
CH_4 (biogenic)	Kg	-3.78E-01	4.38E-05	Methane, biogenic, IPCC, guidelines
N_2O	Kg	3.35E-04	1.93E-05	Nitrous oxide, IPCC guidelines
Other output				
Biogas	Kg	7.06E-01	–	Estimated based on plant technology

Note: Values expressed for the DOSIWAM system represent emissions per functional unit (1 m^3 of treated wastewater) from the stabilization tank and the Malaprabha digester

contribution (−0.126 kg CO_2 eq.). Capturing biogas mitigates greenhouse gases (GHG) by preventing CH_4 emission, which is 25 times more detrimental than CO_2. The Malaprabha digester as a source of biogas energy reduces fossil CO_2 emission by substituting fossil fuel energy, which results in the reduction of the impact category by −0.451 kg CO_2 eq. Indian energy production is mainly coal-based thermal power (IN-Western grid medium voltage) accounting for 85.88% and chemical dosing 7.02% emissions during the operation phase of the ASP system. On the other hand, DOSIWAM tanks with RCC construction (cement 70.25% and reinforcing steel 28.54%) are responsible for the high share of GW impact in its construction phase.

Aquatic eutrophication

Aquatic eutrophication is closely associated with enrichment of recipients mainly due to phosphorous, nitrogen, and COD as organic matter, contributing to biomass formation. Aquatic eutrophication of the DOSIWAM system (0.0783 kg PO_4 P-lim.) dominates over the ASP system (0.0124 kg PO_4 P-lim.) due to effluent discharge of the human night-soil based Malaprabha digester with a high concentration of toxic ions (sodium, potassium, chloride, sulfur, ammonia, magnesium). In addition, the weaker efficiency of the Stabilization tank for phosphate removal (>42%) has a predominant effect on the water environment.

Aquatic and terrestrial eco-toxicity

Much like the impact of GW, the aquatic and terrestrial ecotoxicity impact is mainly due to heavy metal emissions from Indian coal-based electricity generation where landfill is dumped with coal mining spoils (Kalbar *et al.* 2013). It is noteworthy that ASP has substantial contribution towards electricity consumption, which leads to 80.2% impact and 12.7% impact is due to the upstream manufacturing process of sodium hypochlorite thus results in comparatively higher impact (95.762 kg TEG water and 22.67 kg TEG soil) than DOSIWAM (23.24 kg TEG water and 6.22 kg TEG soil) where heavy metal emissions during cement and steel production are the largest contributor.

Mineral extraction

Power cables with aluminium, use of copper for the electricity supply grid in the case of the ASP system (1.57E-02 MJ surplus), are foreground contributors to mineral extraction. This result is in line with a previous study (Lopsik 2013; Singh *et al.* 2019). While usage of iron, nickel, chromium, and manganese for the production of steel and various minerals used for cement production required for construction of DOSIWAM tanks (1.36E-02 MJ surplus) are responsible contributors to this impact indicator.

Carcinogens and non-carcinogens

Carcinogens (ASP: 7.33E-03 kg C_2H_3Cl eq. and DOSIWAM: 4.78E-03 kg C_2H_3Cl eq.) and non-carcinogens (ASP: 2.27E-02 kg C_2H_3Cl eq. and DOSIWAM: 5.88E-03 kg C_2H_3Cl eq.) impact of human toxicity potential is mostly due to the aromatic hydrocarbons and dioxin compounds emitted mainly from the production of PVC pipes, reinforcing steel, chemicals for disinfection and electricity generation.

Ozone layer depletion

Ozone layer depletion (OLD) impact recorded for the ASP system (5.31E-08 kg CFC-11 eq.) is almost five times higher than the DOSIWAM system (1.11E-08 kg CFC-11 eq.), this is due to the fact that the production of chemicals for disinfection is the principal contributor for OLD, accounting for 77.09% of the impact whereas DOSIWAM has a chemical-free treatment process.

Respiratory organics and inorganics

Respiratory organics impact is associated with sodium hypochlorite chemical, which has a major role in the treatment process for ASP, releasing non-methane volatile organic compounds that are responsible for 1.49 E-04 kg C_2H_4 eq. impact, whereas particulate pollution mainly during steel production for the DOSIWAM tanks results in 8.34E-05 kg C_2H_4 eq. impact. The combustion process of coal for electricity production, which releases harmful emissions like particulates, nitrogen oxides, sulfur dioxides, arsenic, barium, selenium, zinc, chromium, benzene, etc. primarily causes respiratory inorganic impact for ASP (2.06 E-03 kg PM2.5 eq.) and in the case of DOSIWAM (3.26E-04 kg PM2.5 eq.) emissions, mainly particulates, nitrogen oxides, sulfur dioxides during clinker production, have a most adverse effect on respiratory inorganics.

Aquatic and terrestrial acidification

Coal-based power generation is the largest source of sulfur dioxide leading to the formation of aquatic and terrestrial acidification. When emissions of acidifying pollutants are exposed to water they form sulfuric acid. Aquatic and terrestrial acidification for the ASP system was found to be 4.52E-03 kg SO_2 eq. and 1.66E-02 kg SO_2 eq. respectively. Whereas clinker incineration is mainly responsible for sulfur dioxide emissions in the case of the DOSIWAM system, which has 1.37E-03 kg SO_2 eq. and 7.89E-03 kg SO_2 eq. impacts respectively.

Land occupation

Land occupation is mainly affected due to the usage of land for the construction of the treatment system (Lopsik 2013). The land occupation impact category is affected more in case of the ASP system (9.17E-03 m^2org.arable), which being an intense aeration process-based technology occupies a significant area for tanks (Risch *et al.* 2015). Whereas DOSIWAM's Stabilization tanks installed at environmental floors and the Malaprabha digester, positioned underground, showed an effective reduction of 79.4% in the land occupation category (1.89E-03 m^2org.arable).

Non-renewable energy

The ASP system was found to be the alternative for depleting non-renewable energy (13 MJ Primary), almost 6 times higher than DOSIWAM (2.02 MJ Primary), which is due to depletion of non-renewable resources; that is, hard coal utilization for electricity generation accounts for 82.4% impact in this category. DOSIWAM's non-mechanised treatment process and potential resource recovery lead to a beneficial effect on the total environmental impact index.

In addition, results from analysis reveal that impacts of categories like ozone layer depletion, respiratory organics and inorganics have a comparatively lower impact than other impact indicators. Figure 3(i) shows comparative midpoint characterisation between studied systems with impact 2002+ method and Figure 3(ii) shows normalization performed as per factors offered by global normalization LCIA methods, where the human health endpoint category showed the most significant impact for both the studied systems.

Individual scenario

More simplified and understandable results were found in individual scenarios, which determine the most influential phase of a treatment system that plays a substantial role in the results. Contribution towards impact categories in the case of the ASP system is a result of electricity usage (66.72%), chemical consumption (15.99%), overall construction materials (10.33%), and building equipment (<1%). The construction phase has the lowest share, with an average of 8.81% impact, where respiratory organics, carcinogen, and mineral extraction are influential categories. While the O&M phase influences almost all impact categories, being the highest share with an average of 91.18% of environmental impact loading.

The non-mechanised way of treating wastewater results not only in the reduction of impact but positive (beneficial) environmental impact due to the bio-digestive process of the Malaprabha digester, which helps in generating bioenergy. On the other hand, improperly maintained septic tanks are believed to be a substantial source of methane emission, accounting for around 12 Tg/yr (Bartram *et al.* 2019). Thus, the Malaprabha digester can conveniently replace a septic tank. The DOSIWAM system has dominating impact categories like eutrophication (98%), terrestrial acidification (77.07%), and aquatic acidification (66.5%), mainly due to effluent discharge quality with a significant concentration of phosphorous and nutrients. The construction phase stands out for almost all impact categories except eutrophication and outperforms with an average of 70.63% than the O&M phase accounting for an average of 22.22%. Figure 3(iii) shows the endpoint category normalisation for the individual scenario.

DOSIWAM is a simpler system that does not require any work to be done especially by any skilled labour, while unskilful maintenance of the ASP system could be the reason for dysfunctioning of the plant's service and other severe problems (Laitinen *et al.* 2017). Further, no specific chemicals are required to be added. The treated effluent is under acceptable limits of pollution parameters and can directly discharge into aquifers. Treatment is free from obnoxious odour and noise, therefore it can easily be installed on refuge floors of the multi-storeyed building. The obtained results for harmful impacts associated with electricity consumption for the ASP system and the construction phase of natural systems are in agreement with other studies (Lopsik 2013; Kobayashi *et al.* 2020).

Life cycle cost analysis (LCCA)

LCCA is an efficient and widely used decision-making tool, which assists in selecting economically feasible WWT solutions. Residential WWTPs are capital-intensive projects with considerable on-going O&M costs and a long span of life. The cost parameters (recurring and non-recurring) have brought financial pressure to residents, thus it is necessary to conduct LCCA for an effective decision-making process. The service life of both treatment systems was observed as 50 years, which was considered for LCCA with an assumption of a required construction period of one year for both treatment systems. The salvage value was considered as 10% of civil construction work. The current study attempts to foretell the economic solution by analysing data and identifying key

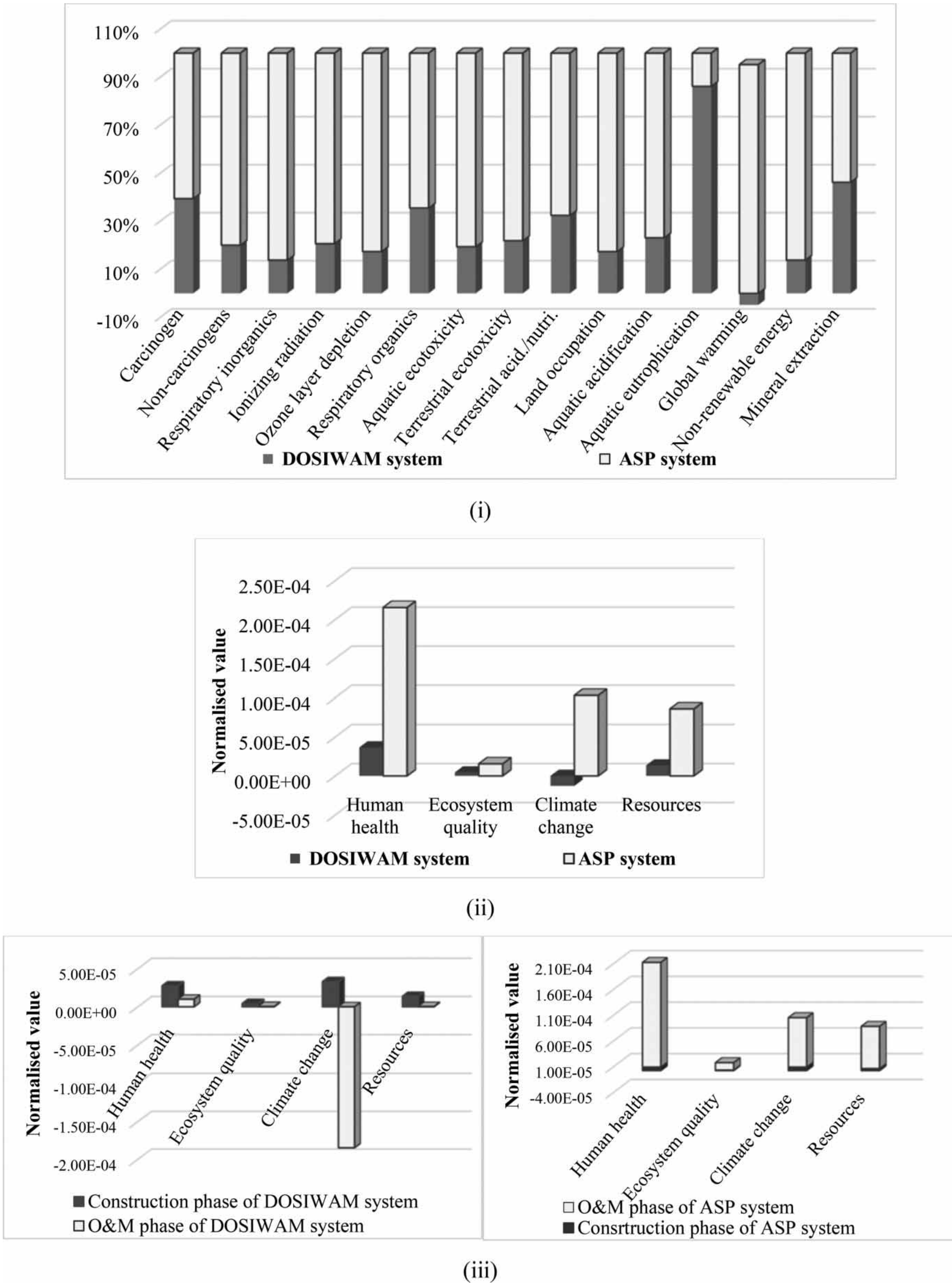

Figure 3 | (i) Comparative midpoint characterisation between DOSIWAM and ASP with Impact 2002+ method; (ii) endpoint category normalisation between DOSIWAM and ASP with Impact 2002+ method; (iii) endpoint category normalisation for the individual scenario with Impact 2002+ method.

parameters, which are responsible for cost escalation. LCCA for both the studied systems is summarised in Table 2.

Initial capital expenditure (CAPEX)

The selection of the WWT system is primarily based on various components of CAPEX. It includes initial capital costs associated with land use, material consumption, construction and installation, initial electromechanical setup, plumbing, and pipe fittings. ASP, being a land-intense treatment technology, its land-use cost significantly influences CAPEX compared to DOSIWAM, where treatment units are positioned on environmental floors; however, the cost of building floor space utilized for installation of these treatment units was considered. Civil construction and installation, and labour requirements were estimated as per the Central Government Guidelines (CPWD)-District Schedule of Rate. Plumbing and pipelines, comprising the collection and distribution setup, were governed by sources of wastewater and consecutive height of floors.

Operation and maintenance expenditure (OPEX)

The OPEX phase of the WWT system is typically dominated by the costs associated with electricity consumption, repair and replacement of electromechanical equipment, wages of workers, and chemicals (disinfectant) along with some miscellaneous costs such as the treatment plant's infrastructure maintenance and routine inspections. The replacement schedule of electromechanical equipment was considered as 12 years. Simplification was made by assuming a replacement cost equal to the price of the initial cost. Energy and chemical consumption together attribute 90% of OPEX cost for the mechanised ASP system; also, skilled workers for operational efficiency are an essential requirement that influences OPEX. The natural gravity-governed DOSIWAM system, with no chemical and energy input, has minimal to very low effect on OPEX.

LCCA methodology

Change in time value money considerably affects future cost, thus for a fair evaluation of both treatment alternatives, the current study adopted the present worth (PW) method as per Bureau of Indian Standards IS 13174 (1991) and IS 13174 (1994) Parts 1 and 2. The cost parameters of respective treatment systems were calculated with a common base date of January 2019. A comparative assessment study usually follows the real discount rate, where fluctuations with respect to both inflation rate and interest rate are taken into consideration (Equation (2)) (Fuller & Petersen 1996).

$$\mathrm{NPW} = \mathrm{CAPEX} + (\mathrm{OPEX} * \mathrm{upwf}) \quad (1)$$

Table 2 | Life cycle cost analysis for DOSIWAM and ASP

		DOSIWAM system (million Rs.)		ASP system (million Rs.)	
Cost breakdown	**Discounting factor (a)**	**Base date cost (b)**	**Present cost (a) x (b)**	**Base date cost (b′)**	**Present cost (a) x (b′)**
CAPEX	0.966	20.535	19.837	12.279	11.862
OPEX					
Electricity cost, maintenance cost, chemical cost, manpower cost (recurring annually)	23.456	0.123	2.885	0.606	14.214
Replacement cost at the end of					
12th year	0.661	0.005	0.003	0.700	0.463
24th year	0.437	0.005	0.002	0.700	0.306
36th year	0.289	0.005	0.001	0.700	0.202
48th year	0.191	0.005	0.001	0.700	0.134
Expected residual cost at the end of 50 yr.	0.179	2.004	−1.350	1.100	−0.814
Total life cycle cost			21.380		26.366
Total benefit (recurring annually)	23.456	2.168	50.828	1.778	41.704

Note: CAPEX = Initial capital expenditure; OPEX = Operation and maintenance expenditure; DOSIWAM = Decentralized on-site integrated waste management; ASP = Activated sludge process.

where uniform present worth factor $(\text{upwf}) = \frac{(1+d)^n - 1}{d(1+d)^n}$ for a series of a uniform cash amount and Present worth factor $(\text{pwf}) = \frac{1}{(1+d)^n}$ for single-year cost evaluation, at the discount rate (d) for period (n).

$$\text{Discount rate } d = (1 + \text{interest rate})/(1 + \text{inflation rate}) - 1 \quad (2)$$

Benefits gained in the form of treated water by reducing withdrawal of freshwater were reported as similar for both treatment systems. Biogas production from the Malaprabha digester is 24.92 m^3/day for 890 p.e. (222 families) and it is estimated that the household burner uses biogas at 200–450 L/h. Thus, each family can be made completely self-reliant for 30-minutes biogas daily usage as fuel for cooking. The initial investment cost of the DOSIWAM system was higher owing to numerous treatment units on the environmental floors compared to the ASP system, which particularly incurs specialised material, set up for electromechanical equipment and skilled labour. The benefit-cost ratio (BCR) was evaluated by summarising the relation between the operational benefits achieved and the cost invested. The measure of BCR for both treatment systems is greater than 1; this implies both options are economically viable over the life span of 50 years. However, between both systems, BCR for the DOSIWAM system (2.37) is comparatively greater than the ASP system (1.58), making it a more cost-effective option. Similarly, the period required to recover investment cost pertaining to its base date is payback measured in terms of years. It was observed that the DOSIWAM system required a comparatively shorter period of service; that is, 13 years to recover its initial investments compared to the ASP system with a payback period of 22 years. The economic effectiveness with regard to the performance of both studied systems was analysed by evaluating their adjusted internal rate of return (AIRR) on project investment. The minimum acceptable rate of return (MARR) for both systems is their discount rate under consideration. AIRR is generally observed as the most accurate and consistent method for evaluating the rate of return on the project's investment and it can be calculated by Equation (3) (Fuller & Petersen 1996).

$$\text{AIRR} = \left[(1+d)\,(\text{BCR})^{1/n} - 1\right] \quad (3)$$

where d is the reinvestment rate (discount rate) and n is the total life span of studied systems.

AIRR of the DOSIWAM system with 5.30% and the ASP system with 4.45% is greater than MARR (3.5%), thus both the alternatives are economical; however, while ranking the options, DOSIWAM holds a higher rank than ASP.

Uncertainty analysis

Uncertainty is associated with many input parameters, which have significant impacts on the final decision; this is because some parametric assumptions need to be made in the future. The discount rate is the most vital source of uncertainty, thus is varied from 1% to 15%. Figure 4 shows the impact of various real discount rates on net capital cost. Higher discount rate favours ASP, which would have lower NPW and vice versa, this is due to high OPEX, whereas DOSIWAM was found to be less sensitive towards real discount rate. The most prominent elements of LCCA with a major impact on sensitivity were cost associated with electricity requirement (40% of O&M) and capital investments. CAPEX, OPEX, and residual cost were then increased arbitrarily by 5, 10, and 15%, and results were formulated with a sensitivity slope; that is, the ratio of the percentage change in output for the given percentage change in input, shown in Figure 5 (Rawal & Duggal 2016). The ASP system's high sensitivity towards OPEX showed relative impacts on LCCA, whereas DOSIWAM was found to be CAPEX sensitive. The purpose of system comparison will suffice with single lifespan consideration, nonetheless, by varying the life span of both alternatives, the DOSIWAM system was observed to be more affordable for a long span of life due to its negligible cost disruption towards O&M compared to the ASP system. Also, it has been noted that WWT systems with large variations in operating costs are more sensitive towards variation in the value of lifespan (National Institute of Urban Affairs 2019).

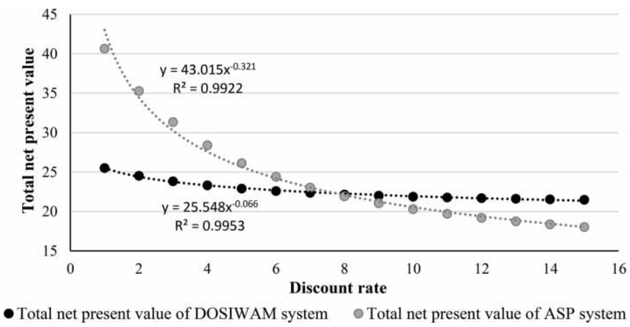

Figure 4 | Sensitivity analysis by varying discount rates.

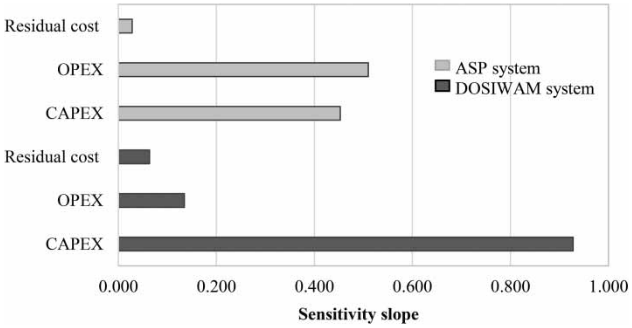

Figure 5 | Sensitivity slope versus cost parameters.

CONCLUSIONS

In the present day context of Indian metro-cities, major downsides of the substantial drop in groundwater level and population growth result in an earnest need for water recovery. Most of the centralised WWTP across India are on the verge of cost upgrade and untenable maintenance. Thus, source-separated decentralised treatment systems are the most convenient alternative to centralised systems as their applications to residential would substantially abridge the impact on freshwater depletion. Presently, both the studied systems have different direct impacts and performance characteristics. In accordance with assumed conditions, the current mechanised conventional WWT system, although it is superior in treatment and removal efficiency; however, the high O&M cost, land occupation, and harmful environmental emissions should not be ignored. Moreover, environmental impacts generated were observed to be about three to six times higher than the DOSIWAM system, mainly due to energy and chemical consumptions. These impacts can be well eliminated by accommodating the DOSIWAM system and even further monetary benefits come from replacing LPG for cooking, a considerable reduction in land expanse, and plumbing network. These environmental and economic considerations direct the sustainability of the studied DOSIWAM system as the best suitable alternative, which can replace conventional mechanised WWT systems.

This study encourages a new outlook in the direction of providing a sustainable on-site gravity governed DOSIWAM system, which would serve as an environmentally friendly and economically affordable solution. In view of current research, a proposal can be made to the respective local planning authority to incentivize the effort undertaken for the benefit of residents as well as the government. Such sustainable activities may incentivize in terms of extra FSI or concession in taxes. The Malaprabha digester for the generation of renewable energy could be well coordinated with the 'Clean India Mission'. Furthermore, awareness has to be raised for the use of efficient and naturally working systems among stakeholders and beneficiaries.

In the current study, only the environmental and economic aspects were evaluated. However, if sustainability is aimed for decision making on WWT system selection, the social aspect, which is a third important pillar of sustainability, should also be taken into consideration (e.g. social acceptance of night soil-based biogas plant, treatment units positioned at intermittent floors, etc.). Further, as a future scope, instead of allocating treatment units at environmental floors, an environmental shaft may be provided in the building wherein the whole shaft is composed of stories and can treat wastewater from individual floors.

ACKNOWLEDGEMENT

We express our sincere thanks to Sinhgad Technical Education Society and Savitribai Phule Pune University, Maharashtra, India for providing help, support, and opportunity.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Ahmed, M. T., Barceló, D. & Petrovic, M. 2010 Life cycle analysis in wastewater: a sustainability perspective. In: *Waste Water Treatment and Reuse in the Mediterranean Region*. Springer Verlag, Berlin, Germany, pp. 125–154.

Bartram, D., Short, M. D., Ebie, Y., Farkaš, J., Gueguen, C., Peters, G. M., Zanzottera, N. M., Karthik, M. & Masuda, S. 2019 Wastewater treatment and discharge. In *Waste 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Geneva, Switzerland*.

Coats, E. R., Watkins, D. L. & Kranenburg, D. 2011 A comparative environmental life-cycle analysis for removing phosphorus from wastewater: biological versus physical/chemical processes. *Water Environment Research* **83** (8), 750–760.

CPCB 2016 *CPCB Bulletin*. Central Pollution Control Board, Ministry of Environment and Forests, Govt. of India, Delhi, India. Available at: http://cpcb.nic.in/

David, A. & Messiha, H. M. 1999 Life cycle cost analysis (LCCA) in municipal organizations. *Journal of Infrastructure Systems* **5** (1), 1–10.
De Feo, G., Ferrara, C. & Iuliano, G. 2016 Comparative life cycle assessment (LCA) of two on-site small-scale activated sludge total oxidation systems in plastic and vibrated reinforced concrete. *Sustainability* **8** (3), 212.
Dewalkar, S. V. & Shastri, S. S. 2020 Provision of staged on-site wastewater treatment units at environmental floors of multi-storeyed building with hydraulic and structural feasibility. *International Journal of Recent Technology and Engineering* **8** (5), 4488–4493.
Fuller, S. K. & Petersen, S. R. 1996 *Life- Cycle Costing Manual for the Federal Energy Management Program*. National Institute of Standards & Technology. NIST Handbook 135, Washington, U.S.
Garfi, M., Flores, L. & Ferrer, I. 2017 Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high rate algal ponds. *Journal of Cleaner Production* **161** (1), 211–219.
Godin, D., Bouchard, C. & Vanrolleghem, P. A. 2012 Net environmental benefit: introducing a new LCA approach on wastewater treatment systems. *Water Science and Technology* **65** (9), 1624–1631.
IS 13174 1991 *Indian Standard Life Cycle Costing Part 1 Terminology*. Bureau of India Standards, New Delhi, India.
IS 13174 1994 *Indian Standard Life Cycle Costing Part 2 Methodology*. Bureau of India Standards, New Delhi, India.
ISO-International Organization for Standardization 2006a *Environmental Management. Life Cycle Assessment. Principle and Framework. ISO14040:2006*. International Organization for Standardisation (ISO), Geneva, Switzerland.
ISO-International Organization for Standardization 2006b *Environmental Management. Life Cycle Assessment. Requirements and Guidelines. ISO 14044:2006*. International Organization for Standardisation (ISO), Geneva, Switzerland.
Kalbar, P. P., Karmakar, S. & Asolekar, S. R. 2012a Technology assessment for wastewater treatment using multiple-attribute decision-making. *Technology in Society* **34** (4), 295–302.
Kalbar, P. P., Karmakar, S. & Asolekar, S. R. 2012b Estimation of environmental footprint of municipal wastewater treatment in India: life cycle approach. In: *Proceedings of International Conference on Environmental Science and Technology*, Vol. 30. IACSIT Press, Singapore, pp. 30–34.
Kalbar, P. P., Karmakar, S. & Asolekar, S. R. 2013 Assessment of wastewater treatment technologies: life cycle approach. *Water and Environment Journal* **27** (2), 261–268.
Kalbar, P. P., Karmakar, S. & Asolekar, S. R. 2014 Life cycle-based environmental assessment of municipal wastewater treatment plant in India. *International Journal of Environment and Waste Management* **14** (1), 84–98.
Kamble, S. J., Chakravarthy, Y., Singh, A., Chubilleau, C., Starkl, M. & Bawa, I. 2017 A soil biotechnology system for wastewater treatment: technical, hygiene, environmental LCA and economic aspects. *Environmental Science and Pollution Research* **24** (15), 13315–13334.
Kamble, S., Singh, A., Kazmi, A. & Starkl, M. 2019 Environmental and economic performance evaluation of municipal wastewater treatment plants in India: a life cycle approach. *Water Science and Technology* **79** (6), 1102–1112.
Kobayashi, Y., Ashbolt, N. J., Davies, E. G. R. & Liu, Y. 2020 Life cycle assessment of decentralized greywater treatment systems with reuse at different scales in cold regions. *Environment International* **134**, 105215.
Kulczycka, J., Lelek, L., Lewandowska, A. & Zarebska, J. 2015 Life cycle assessment of municipal solid waste management – comparison of results using different LCA models. *Polish Journal of Environmental Studies* **24** (1), 125–140.
Laitinen, J., Moliis, K. & Surakka, M. 2017 Resource efficient wastewater treatment in a developing area-climate change impacts and economic feasibility. *Ecological Engineering* **103**, 217–225.
Lopsik, K. 2013 Life cycle assessment of small-scale constructed wetland and extended aeration activated sludge wastewater treatment system. *International Journal of Environmental Science and Technology* **10**, 1295–1308.
Lundin, M., Bengtsson, M. & Molander, S. 2000 Life-cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads. *Environment Science Technology* **34** (1), 180–186.
Machado, A. P., Urbano, L., Brito, A. G., Janknecht, P., Salas, J. J. & Nogueira, R. 2007 Life cycle assessment of wastewater treatment options for small and decentralized communities. *Water Science and Technology* **56** (3), 15–22.
Mapuskar, S. V. 1988 Malaprabha biogas plant: new design for recovery of biogas from latrine. *Jyostna Arogya Prabodhan*, Pune, India, pp. 1-40.
MPCB 2016 *MPCB Bulletin*. Maharashtra Pollution Control Board, Environment Department, Govt. of Maharashtra, India. Available at: https://www.mpcb.gov.in/
National Institute of Urban Affairs 2019 Cost Analysis of Faecal Sludge Treatment Plants in India. National Institute of Urban Affairs, New Delhi, India.
Poch, M., Comas, J., Rodríguez-Roda, I., Sànchez-Marrè, M. & Cortés, U. 2004 Designing and building real environmental decision support systems. *Environ. Model. Software* **19** (9), 857–873.
PRe-Consultants. 2018 *Database Manual SimaPro*. General Introduction, The Netherlands. Available at: http://www.pre-sustainability.com/download/DatabaseManualMethods.pdf.
Raghuvanshi, S., Bhakar, V., Sowmya, C. & Sangwan, K. S. 2017 Wastewater treatment plant life cycle assessment: treatment process to reuse of water. *Procedia CIRP* **61**, 761–766.
Rawal, N. & Duggal, S. K. 2016 Life cycle costing assessment-based approach for selection of wastewater treatment units. *Natl. Acad. Sci. Lett.* **39** (2), 103–107.
Risch, E., Gutierrez, O., Roux, P., Boutin, C. & Corominas, L. 2015 Life cycle assessment of urban wastewater systems: quantifying the relative contribution of sewer systems. *Water Research* **77**, 35–48.

Singh, N. K. & Kazmi, A. A. 2017 Performance and cost analysis of decentralized wastewater treatment plants in Northern India: case study. *Journal of Water Resources Planning and Management* **144** (3), 05017024.

Singh, A., Kamble, S. J., Sawant, M., Chakravarthy, Y., Kazmi, A., Aymerich, E., Starkl, M., Ghangrekar, M. & Philip, L. 2018 Technical, hygiene, economic, and life cycle assessment of full-scale moving bed biofilm reactors for wastewater treatment in India. *Environmental Science and Pollution Research* **25** (3), 2552–2569.

Singh, A., Sawant, M., Kamble, S. J., Herlekar, M., Starkl, M., Aymerich, E. & Kazmi, A. 2019 Performance evaluation of a decentralized wastewater treatment system in India. *Environmental Science and Pollution Research* **26**, 21172–21188.

Smith, K. R., Uma, R., Kishore, V. V. N., Lata, K., Joshi, V., Zhang, J., Rasmussen, R. A. & Khalil, M. A. K. 2000 *Greenhouse Gases From Small-Scale Combustion Devices in Developing Countries Phase IIa: Household Stoves in India, 98*. US Environmental Protection Agency, Research Triangle Park, NC.

Tillman, A. M. & Baumann, H. 2004 *The Hitch Hiker's Guide to LCA,1:7 ed.*, Vol. 1. Holmsbergs, Sweden, p. 543.

First received 28 August 2020; accepted in revised form 30 October 2020. Available online 12 November 2020