Environmental impact assessment of a package type IFAS reactor during construction and operational phases: a life cycle approach

Nitin Kumar Singh, Rana Pratap Singh and Absar Ahmad Kazmi

ABSTRACT

In the present study, a life cycle assessment (LCA) approach was used to analyse the environmental impacts associated with the construction and operational phases of an integrated fixed-film activated sludge (IFAS) reactor treating municipal wastewater. This study was conducted within the boundaries of a research project that aimed to investigate the implementation related challenges of a package type IFAS reactor from an environmental perspective. Along with the LCA results of the construction phase, a comparison of the LCA results of seven operational phases is also presented in this study. The results showed that among all the inputs, the use of stainless steel in the construction phase caused the highest impact on environment, followed by electricity consumption in raw materials production. The impact of the construction phase on toxicity impact indicators was found to be significant compared to all operational phases. Among the seven operational phases of this study, the dissolved oxygen phase III, having a concentration of ~4.5 mg/L, showed the highest impact on abiotic depletion, acidification, global warming, ozone layer depletion, human toxicity, fresh water eco-toxicity, marine aquatic eco-toxicity, terrestrial eco-toxicity, and photochemical oxidation. However, better effluent quality in this phase reduced the eutrophication load on environment.

Key words | decentralized wastewater treatment, India, integrated fixed film activated sludge reactor, life cycle assessment, operational Scenario, SimaPro

Nitin Kumar Singh (corresponding author)
Rana Pratap Singh
Absar Ahmad Kazmi
Environmental Engineering Group, Department of Civil Engineering,
Indian Institute of Technology,
Roorkee 247667,
India
E-mail: *nitin261187@gmail.com*

INTRODUCTION

From an environmental perspective, decentralized wastewater treatment systems are reported to impose lower burdens on the environment compared to centralized systems by offering a lesser footprint, financial viability, less installation timeframe, options for treated water reuse as well as local communities development (Makropoulos & Butler 2010; Domènech 2011; Opher & Friedler 2016). To date, various decentralized treatment systems have been implemented across the world with wide ranges of configurations and technologies. However, to facilitate and to ensure environmental sustainability of the latest systems, further assessment is required to identify the approaches that will reduce the overall environmental impact of these systems (Larsen & Gujer 2013).

Life cycle assessment (LCA) is a valuable and scientific tool that compiles and evaluate the inputs, outputs, and potential environmental impacts of a product/system throughout its life cycle (cradle to grave; from raw material extraction, infrastructure construction, operation to final disposal or recycling) (ISO 2006; Li *et al.* 2013). In 1997, LCA was first applied for the wastewater treatment systems in the Netherlands (Roeleveld *et al.* 1997), as they had substantial environmental impacts during their life cycle due to high energy consumption, chemical usage, sludge generation, and gaseous emissions. Thenceforward until now, various scientists and engineers have applied it for the decentralized as well as centralized wastewater treatment systems using different LCA inventories, boundary conditions, functional units (FU), and impact assessment methods (Corominas *et al.* 2013). Some authors also reported that different variations of a decentralized treatment system are similar or better than a centralized one in terms of economic costs, greenhouse gases emissions, resources consumption, and human health and ecosystem impacts. Whereas, other studies

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utilized LCA to determine optimal designs of specific decentralized technologies. The results of these studies varied considerably due to the differences in the scope of the assessments and the technologies analysed, revealing that careful consideration is necessary when applying LCA to decentralized systems in order to draw useful conclusions for decision making (Hendrickson *et al.* 2015).

In the last two decades, integrated fixed-film activated sludge (IFAS) technology based systems were introduced for wastewater treatment. A detailed collection of these systems is given in our previous studies (Singh & Kazmi 2016). However, to ensure the suitability of these technologies at full scale level, a detailed and integrated assessment is required to investigate its development and operational impacts on human health and environment. To the best of our knowledge, to date no LCA has been performed for an IFAS technology based system, while these have been priorities for small communities by various researchers (Singh *et al.* 2015). Hence, the authors studied an IFAS technology based package treatment plant (in India) using an LCA approach. The results of this study may be used as a reference for similar future projects to determine their applicability in developing countries. The main goal of this study was to compare the environmental burdens associated with the construction and different operational phases of an IFAS reactor treating municipal wastewater under actual treatment conditions.

METHODOLOGY

SimaPro software (PRe Consultants 2013) comes with a large number of standard impact assessment methods. In this study, the CML 2 Baseline 2000 method was used for life cycle impact assessment using SimaPro Faculty 7.1 (Faculty version), which is based on the principles of best available practices. This problem-oriented method is an updated version of CML 1992 and developed by the Centre for Environmental Studies, University of Leiden, as part of the Dutch Guide to LCA. In the CML baseline version, only factors including fate are used and baseline indicators are mainly recommended for simplified studies (www.pre-sustainability.com, 2016). Weighting is also not available in this method (PRé Consultants 2004).

Goal and scope definition

The goal of this LCA study was to assess the environmental impacts of a decentralized wastewater treatment plant treating municipal wastewater. The following plant items/units are considered in this study: aeration tank incorporating fixed media and diffusers, settling tank, pumps with motors, pipelines and valves, coagulant storage tank, electric control panel, and blower. In the operational phases, small appliances such as monitoring instruments have not been considered in this study.

Experimental setup and operating conditions

All the experiments were conducted on a pilot-scale fixed media based IFAS reactor and operated in conventional activated sludge process mode (aeration tank followed by settling tank), located at the sewage pumping station in Rishikesh, Uttarakhand, India. The pilot plant was procured from HYDROK, UK. More details about the pilot plant are available in our previous studies (Singh *et al.* 2015, 2016, 2017; Singh & Kazmi 2016). The schematic of the experimental setup used in this study is illustrated in Figure 1.

A total of seven operational phases (one steady state, three intermittent aeration (IA), and three dissolved oxygen (DO) phases) were considered in this study. During different operational scenarios, parameters were changed and the same were used in LCA software as input parameters. Table 1 lists the operational scenarios of the IFAS reactor. Detailed descriptions and performances during these phases are described in our previous studies (Singh & Kazmi 2016; Singh *et al.* 2016, 2017). Alum powder was also used in order to achieve phosphorus precipitation and to enhance biomass settling in all operational phases except steady state operation.

System boundaries and FU

The selection of the system boundaries is a crucial step within the assessment of wastewater treatment facilities or technologies (Lopsik 2013). Therefore, the system boundaries of this study were established as shown in Figure 2. Only the construction and operational phases are taken into consideration in this LCA study, because they have the highest contribution to the total environmental impact of the life cycle (Mahgoub *et al.* 2010).

The demolition phase has been exempted in this study, as most of the waste is expected to be recycled. In the present study, the volumetric option was selected for FU and one cubic meter of treated wastewater was defined as the FU.

Inventory analysis

A life cycle inventory step is concerned with the data collection and calculation procedures necessary to complete the

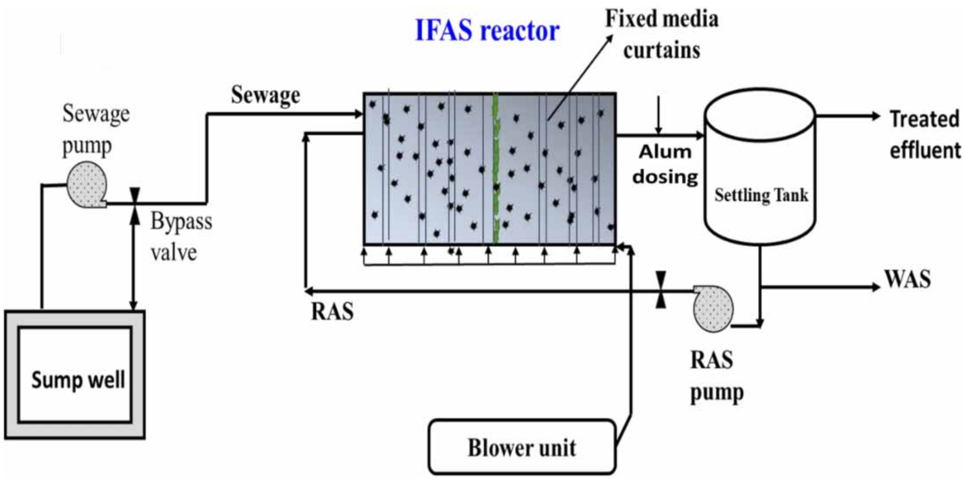

Figure 1 | Schematic of the pilot scale IFAS reactor used in this study (RAS, return activated sludge; WAS, waste activated sludge).

Table 1 | Summary of operational scenarios of IFAS reactor

Experimental phase		Description (reactor/blower condition)
Steady state[a]		DO ~3 mg/L
DO[b]	Phase – I	DO ~0.5 mg/L
	Phase – II	DO ~2.5 mg/L
	Phase – III	DO ~4.5 mg/L
IA[b]	Phase – I[c]	2.5 h on /0.5 h off
	Phase – II[c]	2 h on/1 h off
	Phase – III[c]	1.5 h on/1 h off

[a]Flow was set as 64.8 m^3/d.
[b]Flow was set as 50 m^3/d.
[c]Blower speed was set corresponding to 2.5 DO.

inventory (Lorenzo-Toja *et al.* 2016). Following the goal and scope definition, a construction inventory was prepared with respect to the materials required for plant fabrication, transport medium, processes used for raw material processing, type of electricity, surface treatment, and energy consumption. An operational inventory was prepared using the following data: inputs from nature and techno-sphere, electricity consumption in operation, air (biogenic) emissions, and emission to water and soil. The construction details have been obtained from the plant manufacturer (Hydrok, UK), whereas operational inventory data were compiled by ourselves, previous research and local municipalities. The following are the descriptions of each data collection step.

Materials for construction

Material quantities and specifications were estimated from original design documents provided by the manufacturer. In particular, the following materials were used for construction of the plant: stainless steel (aeration tank, settling tank, and inter-connecting pipelines etc.); mild steel (pump, blower, control panel etc.); polyurethane (diffuser membrane); polypropylene (biological media); and polyvinyl chloride (PVC) (plastic pipes). Total processed material was considered to be 25% more than the finished products. Table 2 lists the materials used in plant construction.

Transportation of raw materials

Transportation was considered only for shifting of construction materials to the site of installation. Three modes were chosen for this purpose: waterways, roads, and freight, seas, and transoceanic ship. Distance data were taken from internet sources (Google map) and travel documents. Transport for sludge disposal is not included in this study as the disposal site was very near to site of operation.

Processes used for the synthesis of raw materials

The major processes used in the manufacturing of plant materials were thermoforming with calendaring, blow moulding, and extrusion for steel, PVC and polypropylene, respectively.

Electricity usage

During the construction phase, a combination of solar, wind and gas turbine energy (400v, 3 phase) is considered in this study as these are the major modes of energy in European countries. Whereas, hydro power (in India) was assumed to be the main source of electrical energy during the

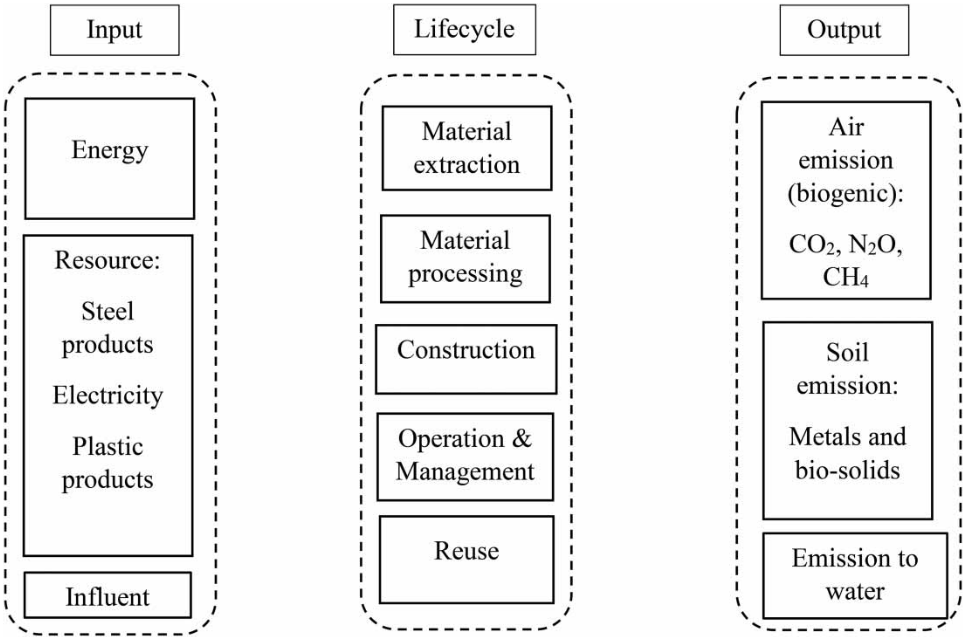

Figure 2 | Scope and system boundary of investigated life cycle.

Table 2 | List of materials along with the quantity used in different parts of plant

Items/materials[a]	SS	MS	PVC	PPL	Polyurethane	Total
Aeration tank	3,500	0	2	10	0	3,512
Settling tank	400	0	0	0	0	400
Blower	268	200	0	0	0	468
Control panel	50	0	0	0	0	50
RAS pump	2	23	0	0	0	25
Sewage pump	2	23	0	0	0	25
Alum dosing pump	0	7	0	0	0	7
Alum solution storage tank	0	0	5	0	0	5
Pipe line and accessories	100	0	500	0	0	600
Diffusers	50	0	0	0	5	55
Total quantity	4,372	253	507	10	5	

SS, stainless steel; MS, mild steel; PVC, polyvinyl chloride; PPL, polypropylene.
[a]All quantities are given in Kg.

operation of the IFAS reactor. During the operational phases, electricity was used to pump the wastewater, sludge streams, alum solution, and to run the blower for aeration. The electricity data during the reactor run were collected by noting down the theoretical rating of the pumps and their run hours, while blower power was calculated from the performance curve provided by the manufacturer as well as the computed working hours.

Surface treatment

The surface treatments such as polishing, coating or finishing in construction phase were also taken into account in this study.

Inputs from nature and techno-sphere

A total of four inputs were considered in this study during reactor operation, namely fresh water, air from the atmosphere (through a blower), electricity, and alum powder for biomass settling purposes.

Emission to air, soil and water

Effluent impact on the environment was accounted in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN), and total phosphorus (TP) content. The effect of sludge disposed of for landfill purposes was accounted for using mixed liquor volatile suspended solids (MLVSS) concentrations, TN, and TP content of wasted sludge using stoichiometric conversion ratio (Barker & Dold 1995). Data on heavy metal concentrations in wasted sludge were collected during the steady state phase only, and the same were used in all other operational scenarios. Emissions of biogenic air pollutants (CH_4, CO_2 and N_2O) were estimated using

Table 3 | Inputs and outputs for IFAS reactor in different operational phases

	Inputs				Outputs											
	From atmosphere		From techno-sphere		Emission to air (g)			Emission to soil (g)			Emission to water (g)					
Operational phase	Air (Kg)	Water (m^3)	Electricity (KW)	Alum (g)	CO_2	CH_4	N_2O	Metals	TN[a]	TP[a]	COD	BOD	SS	TN	TP	Metals
Steady state	32.66	A fixed amount of 0.01 m^3/m^3 of wastewater treated is considered for miscellaneous purposes	1.33	Nil	221	4.3	0.35	Cd: 0.0001 Fe: 0.7907 Cu: 0.0294 Mn: 0.0207 Zn: 0.0790 Pb: 0.0004 Ni: 0.0002 Co: 0.0003	2.8	1.2	50	25	35	15	2.20	Cd: 0.0059 Fe: 0.5990 Cu:0.0330 Mn: 0.0421 Zn: 0.1735 Pb: 0.043 Ni: 0.0010 Co: 0.0012
IA Phase – I	29.40		1.21	30	312	5.8	0.39		4.8	2.0	34	18	15	11	0.88	
IA Phase – II	23.52		1.13	30	317	5.8	0.38		3.7	1.5	30	14	16	12	1.25	
IA Phase – III	21.16		1.10	30	310	5.7	0.39		3.7	1.6	42	19	15	11	1.43	
DO Phase – I	28.22		1.19	25	280	4.5	0.07		2.6	1.1	85	46	59	43	0.77	
DO Phase – II	44.10		1.67	30	301	4.8	0.36		7.1	3.0	61	31	38	14	0.93	
DO Phase – III	63.50		2.01	48	331	5.3	0.36		0.5	0.2	25	9	15	14	0.59	

All values are based on 1 FU i.e. 1 m^3; Density of air considered, 1.225 Kg/m^3.
[a]Based on average waste sludge, MLVSS and stoichiometric content of sludge.

average consumption figures and emission factors found in the literature (Cakir & Stenstrom 2005; Foley et al. 2008, 2010a, 2010b). Non material emissions, social and economic issues are not taken into consideration in this study.

Impact assessment and results interpretation

Impact assessment is an important step in measuring the environmental impacts of various activities in LCA. According to the existing literature (Renou et al. 2008; Pasqualino et al. 2009, Mahgoub et al. 2010; Amores et al. 2013; Lemos et al. 2013), the following impact categories were selected for this purpose: Abiotic depletion (AD), Acidification (AF), Eutrophication (EU), Global warming potential (GWP), Ozone layer depletion (OLD), Human toxicity (HT), Fresh water aquatic eco-toxicity (FWAE), Marine aquatic eco-toxicity (MAE), Terrestrial eco-toxicity (TE), and Photochemical oxidation (PO). Detailed definitions of these terms are well documented in previous literature (Meneses et al. 2015; Lorenzo-Toja et al. 2016).

Interpretation of LCA results is the last and most important step in LCA, where recommendations and suggestions should be provided in such a way that the overall impact of the system on the environment can be minimized. In this section, the impacts of all operational phases are compared with each other as well as the construction phase of plant. Operational inventory data used for impact assessment are presented in Table 3.

RESULTS AND DISCUSSION

To assess the environmental impacts of the present IFAS system, the LCA includes all the inputs and the outputs related to each process where the inputs or the outputs can have direct environmental impacts such as resources depletion and/or indirect environmental impacts such as the impacts during the manufacturing of a certain type of material/chemical. Bearing these considerations in mind, qualitative LCA results of an IFAS reactor during its construction and operation phases is discussed in this section. The results presented in this study have enabled a qualitative comparison. Table 4 presents the quantitative information of LCA results extracted from the SimaPro software database and their explanation is provided in further sections.

Impact of construction phase

The LCA results of construction phase of IFAS reactor are presented in Figure 3. It can be seen from Figure 3 that

Table 4 | Quantitative LCA results of environmental impacts during construction and operational phases of IFAS reactor

Impact category	Unit	Construction phase	IA phase-I	IA phase-II	IA phase-III	Steady state	DO phase-I	DO phase-II	DO phase-III
AD	kg Sb eq	256.5319	0.0113	0.0106	0.0103	0.0124	0.0111	0.0156	0.0188
AF	kg SO2 eq	230.5102	0.0118	0.0111	0.0108	0.0130	0.0116	0.0163	0.0197
EU	kg PO4 eq	68.0806	0.0190	0.0183	0.0189	0.0221	0.0295	0.0261	0.0137
GWP	kg CO2 eq	37,106.4362	1.9247	1.8098	1.7688	2.0508	1.7760	2.5395	3.0253
OLD	kg CFC-11 eq	0.0034	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HT	kg 1,4-DB eq	354,314.1515	0.5284	0.4935	0.4805	0.5806	0.5197	0.7287	0.8767
FWAE	kg 1,4-DB eq	158,851.9659	0.5335	0.5043	0.4934	0.5771	0.5262	0.7016	0.8246
MAE	kg 1,4-DB eq	93,362,228.2752	973.4653	910.6867	887.1447	1,067.6333	957.7707	1,334.5434	1,601.2519
TE	kg 1,4-DB eq	586.9588	0.0059	0.0057	0.0056	0.0063	0.0059	0.0074	0.0082
PO	kg C_2H_4 eq	12.0499	0.0005	0.0004	0.0004	0.0005	0.0005	0.0006	0.0008

Values given in this table for construction and operational phases are presented for 20 years and 1 FU, respectively

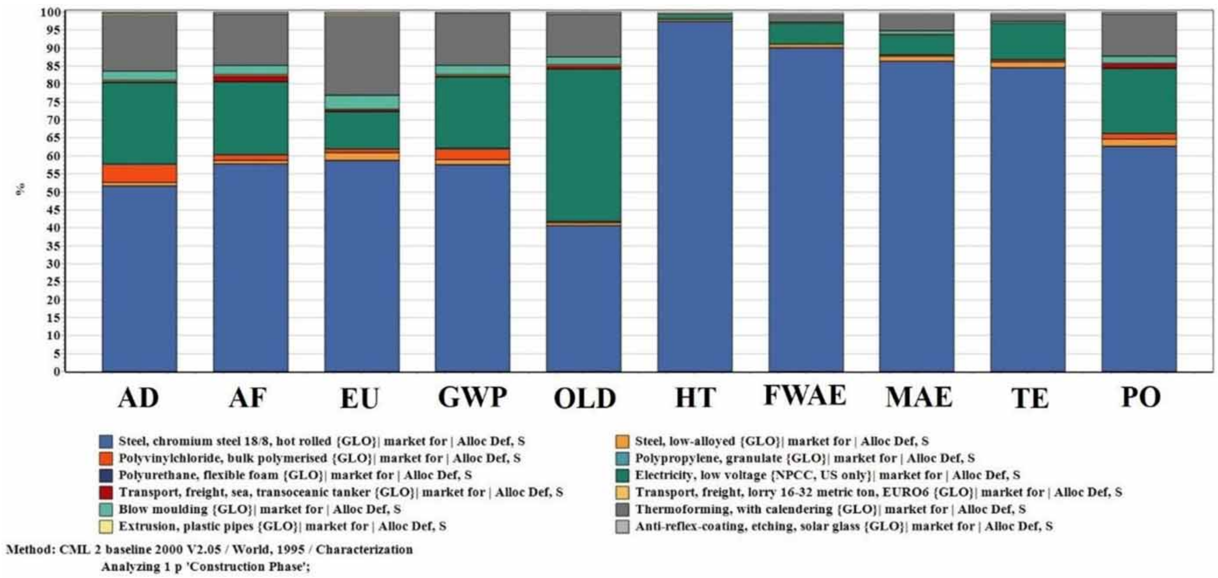

Figure 3 | Contribution (%) of different construction inputs of IFAS reactor on various impact categories.

among the all construction inputs, the most significant contribution on all impact categories (AD, ~52%; AF, ~57%; EU, ~58%; GWP, ~56%; OLD, 40%; HT, ~97%; FWAE, ~90%; MAE, ~86; TE, ~84%, and PO, ~63%) is caused by the use of stainless steel for plant construction. This can be attributed to the energy and processes involved in the production of stainless steel. The environmental impacts associated with the PO may be due to the emission of sulphur dioxide and sulphur monoxide during steel manufacturing. These results suggest that an alternate material or civil construction for this plant may be a better option for its sustainability. Following the stainless steel usage, electrical energy consumption was found to be the second major contributor, which affected all the impact categories significantly. Other materials, inputs, and transport media showed relatively low impact of the construction phase on the environment.

Impact of various operational phases

The LCA of the operational phases was performed by considering the FU as 1 m^3 of treated wastewater, to draw attention towards the importance of operational strategies. The inputs in each operational phase are considered as the amount of water and air required, energy consumption, and/or chemical usage. The outputs are water-borne, airborne, and solid waste emissions. The impact of three DO phases of operation on the environment is shown in Figure 4. Concerning the impact indicator results, it is clear from the figure that environmental damage in all impact categories from this operational phase was found to be directly proportional to the amount of DO in the reactor. This can be attributed to the increased demand of air as well as electricity usage with respect to DO.

These results suggest that energy saving solutions should be implemented to reduce the impacts caused by the use of electricity in this phase. Similar results have been reported in previous studies (Foley *et al.* 2010b). The only impact category that did not follow this trend was EU, where the impact is due to the nutrient contaminants remaining in the water despite treatment. This could be decreased by enhancing the nutrient removal efficiency, for instance, by adding a primary anoxic unit before the hybrid aerobic unit. It is important to mention here that in the DO phase III, treatment performance was recorded quite satisfactory, as per the local discharge standards. In particular, an increase of ~22% in all impact categories was observed with respect to DO increase from phase I to phase II as well as from phase II to phase III. Hellström *et al.* (2000) defined EU as one of the priority criteria for considering a treatment system to be environmentally sustainable. DO phase III contributed to the lowest impact on the environment in terms of EU potential. These results suggest that maintaining a high bulk DO ~4.5 mg/L in the reactor will affect the environment significantly; however, from a treatment potential point of view, the requisite quality effluent can be achieved at this DO level.

Considering the IA phases, a slightly decreasing trend was observed in all impact categories except the EU, with the increased aeration off time of the blower. It clearly indicates that electricity consumption is playing the main role in this operational phase. With respect to EU potential, all IA phases were almost same, as the difference in concentrations of nutrient parameters was recorded as insignificant. This can be attributed to the balanced nitrification and denitrification activities in each IA phase of reactor. As shown in Figure 5, with respect to each other, a decrease in impacts of ~5% was observed in all impact categories by reducing the blower run time during operation.

A comparative account of the LCA results of all operational phases is also shown in Figure 6. The results clearly indicated that among all the operational phases, DO phase III was the least favourable from an environmental impact point of view. Duan *et al.* (2011) also reported that a high DO phase contributed mainly to all impact categories, due to high consumption of electricity. However, the EU potential of this phase was low compared to other phases. On the other side, DO phase I contributed most to the EU of water bodies, as the concentration of nutrient parameters (N & P forms) in this phase was highest compared to other operational phases.

It is important to mention here that although the DO levels were almost same in steady state and DO phase II

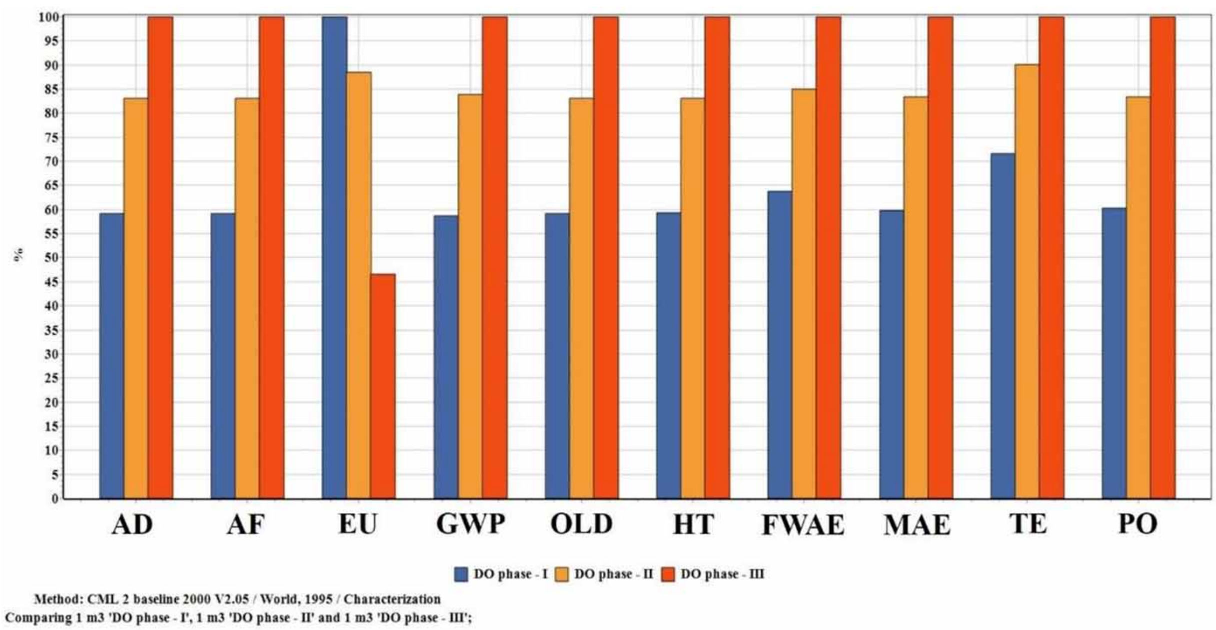

Figure 4 | Comparative qualitative account (%) of impact of DO phases on various impact categories.

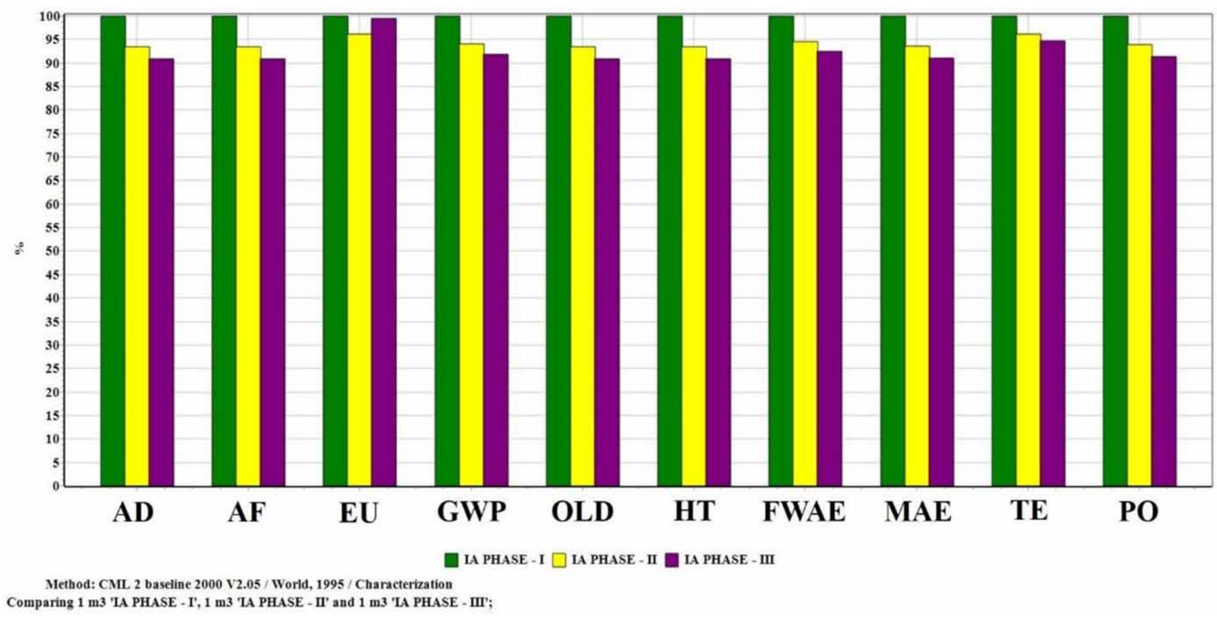

Figure 5 | Comparative qualitative account (%) of impact of IA phases on various impact categories.

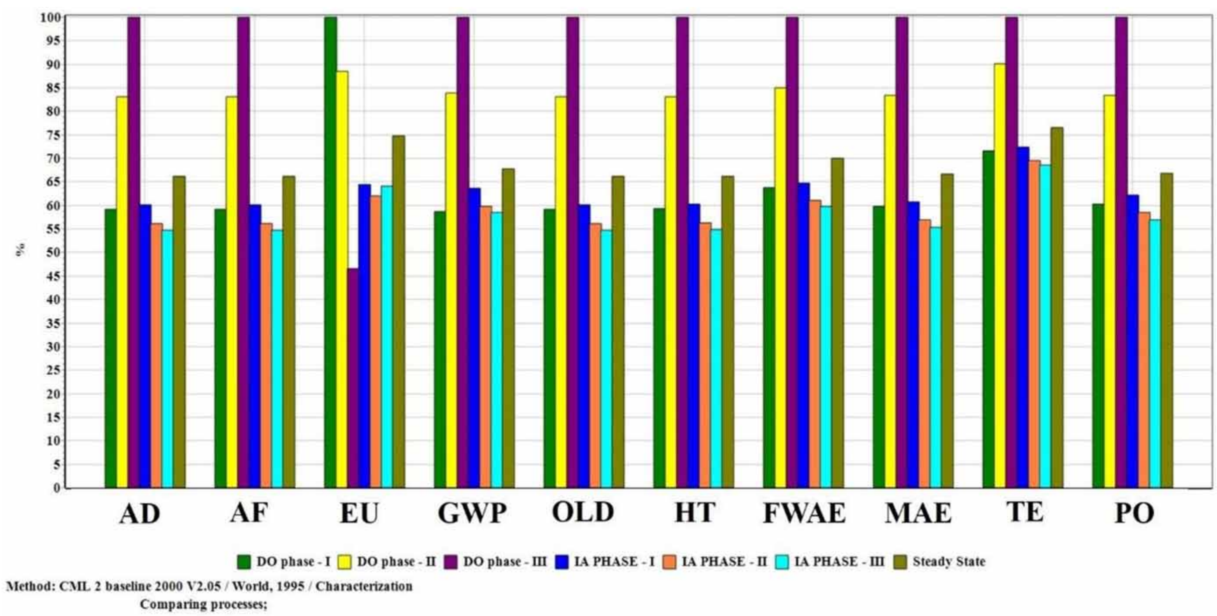

Figure 6 | Comparative account (%) of LCA results of all operational phases of IFAS reactor.

but the observed difference in impact was due to the difference in treatment capacity under experimental conditions. Furthermore, these results also suggest that increasing the hydraulic loading decreases the treatment capacity but consequently decreases the environmental impacts on the surroundings.

Role of construction and operational phases of IFAS reactor on environment

A further comparison was also made between all operational and construction phase of the present IFAS reactor. It is important to mention here that all the comparisons are

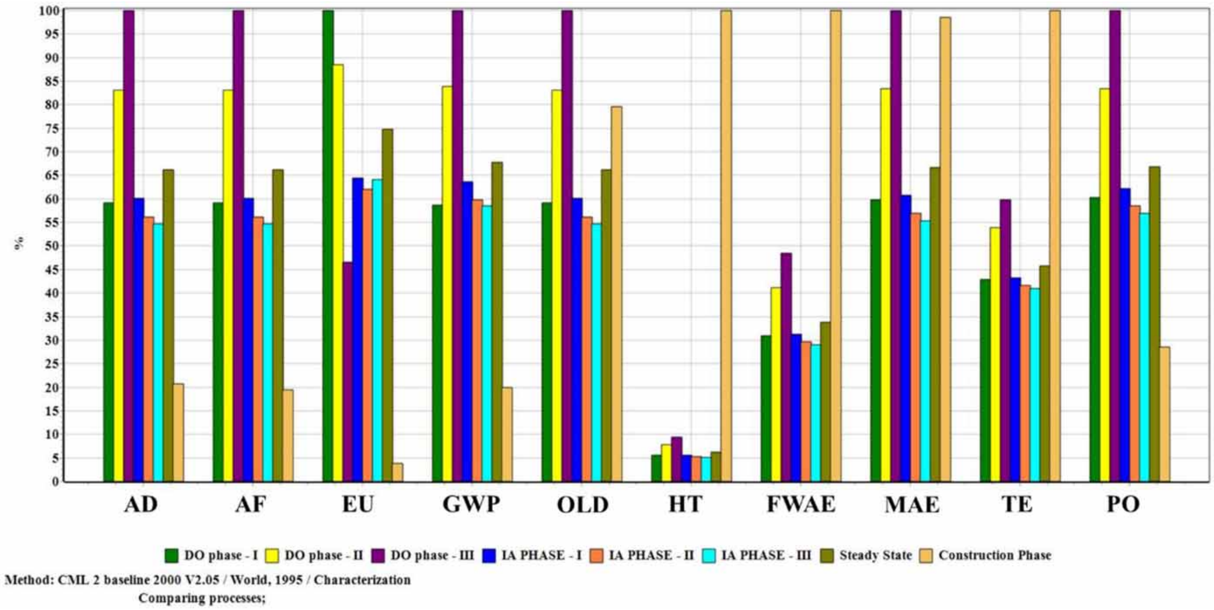

Figure 7 | Role of construction and operational scenarios of IFAS reactor on various impact categories.

made on the basis of 1 FU. As shown in Figure 7, the impact of the construction phase on the AD, AF, EU, GWP and PO impact categories was observed to be much lower than all the operational phases of the IFAS reactor. Whereas, considering all the toxicity impact categories (i.e. HT, FWAE, MAE, and TE), the effect of the construction phase was significantly higher than the operational phases. With respect to the OLD impact category, impact due to the construction phases was found to be quite comparable with the impacts caused by all the operational phases of the IFAS reactor. The results clearly show that there is a need for modification in the construction phase of this reactor as it impacts the environment significantly, especially with respect to the toxicity impact categories, to ensure its sustainability and implementation in the field.

CONCLUSIONS

The present study highlighted the impacts of the construction phase and different operational scenarios of an IFAS reactor on the environment using a life cycle approach. The following conclusions were drawn from this LCA study:

- LCA results of the construction phase of the present IFAS reactor revealed that among all the construction inputs/items, use of stainless steel was observed to be the major contributor among the all inventory items, followed by electricity consumption. It was also identified that in order to reduce the burden of the construction phase of the IFAS reactor on environment, it is necessary to opt for an alternate to stainless steel. The paradigm shift based on civil infrastructure was found to be the better scenario to ensure the environmental sustainability of this system.
- From the comparison between the LCA results of the variable DO phases, it can be inferred that although the high DO levels improve the treatment performance, on account of it the impact on the environment also increases due to higher electricity consumption. One possible conclusion from this LCA study would be that there is a need for further improvement in the energy efficiency of the IFAS systems.
- LCA results of IA phases revealed that decreasing the blower run time will reduce the burden on the environment of all impact categories except the EU. A balance of nitrification and denitrification activities was found to be effective at all IA phases. Comparative LCA results of the construction and operational phases revealed that the construction phase significantly affected the environment, particularly with respect to toxicity indicators.

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REFERENCES

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A. & Castells, F. 2013 Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *Journal of Cleaner Production* **43**, 84–92.

Barker, P. S. & Dold, P. L. 1995 COD and nitrogen mass balances in activated sludge systems. *Water Research* **29**, 633–643.

Cakir, F. Y. & Stenstrom, M. K. 2005 Greenhouse gas production: a comparison between aerobic and anaerobic wastewater treatment technology. *Water Research* **39**, 4197–4203.

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S. & Shaw, A. 2013 Life cycle assessment applied to wastewater treatment: state of the art. *Water Research* **47**, 5480–5492.

Domènech, L. 2011 Rethinking water management: from centralised to decentralised water supply and sanitation models. *Documents d'anàlisi geogràfica* **57**, 293–310.

Duan, N., Liu, X. D., Dai, J., Lin, C., Xia, X. H., Gao, R. Y., Wang, Y., Chen, S. Q., Yang, J. & Qi, J. 2011 Evaluating the environmental impacts of an urban wetland park based on emergy accounting and life cycle assessment: a case study in Beijing. *Ecological Modelling* **222**, 351–359.

Foley, J., Lant, P. & Donlon, P. 2008 Fugitive greenhouse gas emissions from wastewater systems. *Water* **35**, 62–72.

Foley, J., De Haas, D., Hartley, K. & Lant, P. 2010a Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Research* **44**, 1654–1666.

Foley, J., De Haas, D., Yuan, Z. & Lant, P. 2010b Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. *Water Research* **44**, 831–844.

Hellström, D., Jeppsson, U. & Kärrman, E. 2000 A framework for systems analysis of sustainable urban water management. *Environmental Impact Assessment Review* **20**, 311–321.

Hendrickson, T. P., Nguyen, M. T., Sukardi, M., Miot, A., Horvath, A. & Nelson, K. L. 2015 Life-cycle energy use and greenhouse gas emissions of a building-scale wastewater treatment and non-potable reuse system. *Environmental Science & Technology* **49**, 10303–10311.

ISO, ISO 14040 2006 *Environmental Management – Life Cycle Assessment – Principles and Framework*. International Organisation for Standardization, Geneva, Switzerland.

Larsen, T. A. & Gujer, W. 2013 Implementation of source separation and decentralization in cities. In: *Source Separation and Decentralization for Wastewater Management*. IWA Publishing, London, UK, pp. 135–150.

Lemos, D., Dias, A. C., Gabarrell, X. & Arroja, L. 2013 Environmental assessment of an urban water system. *Journal of Cleaner Production* **54**, 157–165.

Li, Y., Luo, X., Huang, X., Wang, D. & Zhang, W. 2013 Life cycle assessment of a municipal wastewater treatment plant: a case study in Suzhou, China. *Journal of Cleaner Production* **57**, 221–227.

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.

Lorenzo-Toja, Y., Alfonsín, C., Amores, M. J., Aldea, X., Marin, D., Moreira, M. T. & Feijoo, G. 2016 Beyond the conventional life cycle inventory in wastewater treatment plants. *Science of the Total Environment* **553**, 71–82.

Mahgoub, M. E. S. M., van der Steen, N. P., Abu-Zeid, K. & Vairavamoorthy, K. 2010 Towards sustainability in urban water: a life cycle analysis of the urban water system of Alexandria City, Egypt. *Journal of Cleaner Production* **18**, 1100–1106.

Makropoulos, C. K. & Butler, D. 2010 Distributed water infrastructure for sustainable communities. *Water Resources Management* **24**, 2795–2816.

Meneses, M., Concepción, H., Vrecko, D. & Vilanova, R. 2015 Life cycle assessment as an environmental evaluation tool for control strategies in wastewater treatment plants. *Journal of Cleaner Production* **107**, 653–661.

Opher, T. & Friedler, E. 2016 Comparative LCA of decentralized wastewater treatment alternatives for non-potable urban reuse. *Journal of Environmental Management* **182**, 464–476.

Pasqualino, J. C., Meneses, M., Abella, M. & Castells, F. 2009 LCA as a decision support tool for the environmental improvement of the operation of a municipal wastewater treatment plant. *Environmental Science & Technology* **43**, 3300–3307.

PRé Consultants 2004 Available at: https://www.pre-sustainability.com/.

PRé Consultants 2013 Database Manual SimaPro. General Introduction, The Netherlands. Available at: http://www.pre-sustainability.com/download/ DatabaseManualMethods.pdf.

Renou, S., Thomas, J. S., Aoustin, E. & Pons, M. N. 2008 Influence of impact assessment methods in wastewater treatment LCA. *Journal of Cleaner Production* **16**, 1098–1105.

Roeleveld, P. J., Klapwijk, A., Eggels, P. G., Rulkens, W. H. & Van Starkenburg, W. 1997 Sustainability of municipal wastewater treatment. *Water Science and Technology* **35**, 221–228.

Singh, N. K., Bhatia, A. & Kazmi, A. A. 2017 Effect of intermittent aeration strategies on treatment performance and microbial community of an IFAS reactor treating municipal wastewater. *Environmental Technology* pp. 1–11 (online).

Singh, N. K. & Kazmi, A. A. 2016 Environmental performance and microbial investigation of a single stage aerobic integrated fixed-film activated sludge (IFAS) reactor treating municipal wastewater. *Journal of Environmental Chemical Engineering* **4**, 2225–2237.

Singh, N. K., Kazmi, A. A. & Starkl, M. 2015 Environmental performance of an integrated fixed-film activated sludge

(IFAS) reactor treating actual domestic wastewater during start-up phase. *Water Science and Technology* **72**, 1840–1850.
Singh, N. K., Kazmi, A. A. & Starkl, M. 2016 Treatment performance and microbial diversity under dissolved oxygen stress conditions: Insights from a single stage IFAS reactor treating municipal wastewater. *Journal of the Taiwan Institute of Chemical Engineers* **65**, 197–203.

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