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Life Cycle Impact Assessment (LCIA), A Decision-Making Approach in Waste Water Treatment Plant: A Case Study

Anand Kushwah
School of Mechanical Engineering, Noida Institute of Engineering Technology, Gr. Noida U.P, India
anand.kushwah1989@gmail.com

Vikas Kumar, Sanjay Sundryal, Kamlesh Paswan, and Ajay Kumar
School of Mechanical Engineering, Noida Institute of Engineering Technology, Gr. Noida U.P, India

ABSTRACT

Environmental foot print of a waste water treatment plant is an important criterion to assess the performance of treatment unit. The novel waste water treatment technology was used to clean waste water up to a certain limit. Therefore, in whole process, beginning from electricity production to final disposal of water these treatment technologies can affect our environment. This environmental foot print can be determined by using CML 2000 guideline. In final performance of a waste water treatment plant environmental ill effects should also be incorporated instead of only using treatment efficiency, CML 2000 gives environmental performance. In this study four waste water treatment technologies namely Activated Sludge Process, up flow Anaerobic Sludge Blanket, Membrane Biofilm Bioreactor, Fluidized Aerobic Bed were taken. The environmental performance of all these novel technologies was assessed on the basis of eutrophication, global warming potential and removal efficiency, characterization factors are normalized by using CML 2000 guideline. The maximum and minimum results of Acidification was obtained as 0.2215 & 0.0569 in UASB and FAB respectively. The maximum and minimum results of Eutrophication was attained as 0.564 & 0.055 in MBBR and ASP respectively.

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Corresponding Author Contact:

anand.kushwah1989@gmail.com

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1. Introduction

There is a major requirement of society, process and every system that these should not harm our environment or if process is undergoing there should be minimum environmental ill effects. It is very essential to analyze every treatment unit with respect to their environmental performance and accordingly selected for best suited treatment technology. Mueller et al. developed a methodology which consists in generating the LCI from a parameterized LCI model.

Environmental footprint of treatment technology depends on treatment unit because every treatment plant has different input resources and different effluent characteristics. And main source of environment harm is energy consumption in operation and maintenance of treatment units. In this study 4 treatment technologies have been selected those are FAB (fluidized aerobic bed), UASB (Up flow anaerobic sludge blanket), ASP (Activated sludge process), and MBBR (Membrane biofilm bioreactor) are compared by using life cycle assessment approach (Chaudhary J. K 2020).

For Indian subcontinents there is no national data available on the basis of which LCA can be done, in the absence of that data it becomes much difficult to generate a material or emission inventory. the standard methodology is described in ISO 14040 series (ISO 1997) is employed for conducting the LCA. LCA depends on the collected data in various site visits of treatment plants during operation and maintenance phases (Wu, X., & Hu, F. 2020). Several studies have utilized Life Cycle Assessment (LCA) methodology to evaluate the environmental impacts of wastewater treatment plants. For example, The authors applied LCA to compare three different plant configurations: a traditional activated sludge plant with a sand filter, a similar plant with both a sand filter and nitrogen removal, and a plant incorporating Membrane Bioreactor (MBR) technology. The analysis revealed that the MBR configuration used less energy and produced lower emissions compared to the other two configurations that employed sand filters. Thus, determining the optimal flow pattern of the plant is crucial. Despite being known for its energy intensity, the MBR system ultimately consumes less energy than sand filters (Allami et al.2023.)

The authors employ Life Cycle Assessment (LCA) to evaluate the impacts of operating a wastewater treatment plant. They analyze three distinct scenarios: the first is a baseline scenario using conventional activated sludge technology, based on data from an existing plant in central Italy; the second scenario involves upgrading this baseline system with Membrane Bioreactor (MBR) technology; and the third scenario incorporates an anaerobic digester for biogas energy recovery, coupled with a photovoltaic system to meet the plant's energy needs (Viotii et al.2024.) The authors explore the cost-effectiveness of four sludge treatment scenarios for both centralized (C) and decentralized (D) wastewater treatment plants (WWTPs) using Life Cycle Cost Assessment (LCCA). They quantify the environmental impacts and costs with the Stepwise2006 tool. The study identifies the most environmentally and financially viable WWTP construction option for Bangkok, Thailand, for the period 2022–2031, based on LCCA and net present value (NPV) (Na Talang et al.2022). The authors Studied the major sources of environmental impacts in Tehran's wastewater treatment plant (WWTP) using the Life Cycle Assessment (LCA) method. Eco-Indicator 99 is employed for the Life Cycle Impact Assessment (LCIA), conducted with SimaPro 7.0 software. The findings indicate that substituting biogas for natural gas can substantially reduce the environmental impacts of Tehran's WWTP, including cutting the negative effects of fossil fuels by approximately threefold (Tabesh M et al. 2019).

The authors evaluates the environmental impacts of Ahvaz's wastewater treatment plant using Life Cycle Assessment (LCA) with SimaPro®9.0.0 software across two scenarios. The first scenario reflects the current operation of the plant, while the second explores the reuse of treated effluent in agriculture. This analysis aims to inform modifications to existing systems or the selection of the most effective treatment alternatives to minimize environmental impacts. According to the CML2001 method, human toxicity and global warming are the highest contributors to negative impacts, with values of 4.29×10^{13} and 3.67×10^{13}, respectively. The EcoIndicator99 method identified ecotoxicity and carcinogens as the primary contributors, with values of 5.2×10^{-13} and 2.82×10^{-13}, respectively, per cubic meter of treated effluent (Tayyeby F et al. 2023)

The objective of this study is to evaluate a wastewater treatment and reuse project in M.N.N.I.T, India, a developing country, by assessing the benefits and impacts of the treatment plant and wastewater reuse using the Life Cycle Assessment (LCA) method. This analysis will integrate both process-based and input-output LCA approaches within a single framework. The research aims to identify and address the current challenges and limitations of the project as comprehensively as possible.

2. Life Cycle Inventory

Life Cycle Assessment (LCA) is a standardized methodology for evaluating the environmental impacts associated with a product or process throughout its entire life cycle, as outlined in ISO 14040 and 14044. The concept of LCA originated in the late 1960s. Initially, in the 1970s, LCA focused solely on energy and raw materials. However, by the 1980s, the scope expanded to include emissions, water, air, and soil. From the 1990s onward, LCA was applied to wastewater treatment, having been recognized as suitable for related environmental evaluations. In 1994, the ISO began developing standards for LCA as part of its 14,000 series on environmental management, though the method was not yet fully detailed for all assessment fields. Since then, LCA has been extensively studied and applied across various disciplines, incorporating diverse boundary conditions, databases, impact assessment methods, and interpretations (Rashid S et al.2023).Several software programs have been developed to assist with LCA analysis, including both free and commercial options. Currently, various commercial LCA software tools are available, such as SimaPro, Gabi, Umberto, and open LCA. SimaPro, developed by Pre-Sustainability Consultants in the Netherlands, has been used for over 20 years in numerous studies and projects. It is a user-friendly tool designed to model and analyze complex products and systems, such as water and wastewater treatment, and can systematically calculate environmental impacts and identify environmental hotspots.

Before conducting life cycle assessment an inventory is prepared which is based on data collected during site visit of various WWTs. all influent and effluent characteristics of Waste Water is being clubbed. for emission inventory all emissions are calculated in one unit which is population equivalent. in this analysis it is assumed that all power generation is from coal based thermal power plant and this data is converted into population equivalent by using characterization factor by CML 2000. Finally, all data is being clubbed in a sheet which contains all input and output data of particular treatment plant (Poomagal.S et al.2021, Roy R et al. 2021). According to ISO 14040 [11], the LCA standards series follows these steps (see Figure 1):

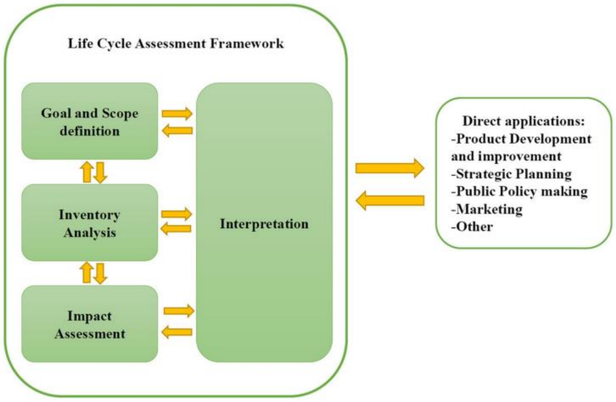

Figure 1 Different stages of Life cycle assesment

2.1 Goal and Scope Definition

In this study various waste water treatment plants are being compared on the basis of their environmental footprints. From past studies it is clear that in construction and demolition activities of WWTP does not affect much to the environment as compared to operation and maintenance phase. so, in this study all effects are computed only during operation and maintenance phase. All effects are computed between system boundaries of WWTPs which largely affect the causes of environmental ill effects, energy consumed in operation of plant and harmful gases emitted during this phase is also considered in this study. In terms of the boundaries set for LCA studies, the majority of papers have focused solely on the operational phase, with over 80% including the sludge treatment line (see Figure 2). Among the studies that examined both construction and operational phases, 21% evaluated activated sludge systems, while 17% considered constructed wetland systems.

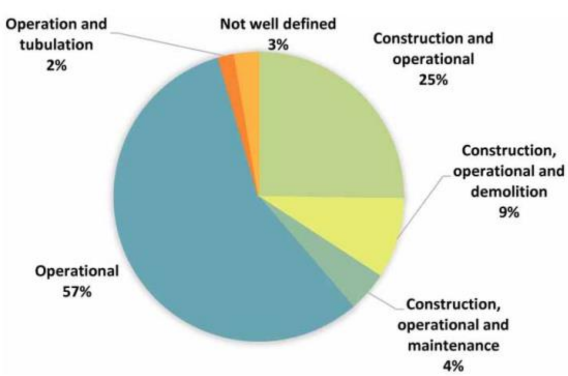

Figure 2 Descrption of boundries used during the experimentation

2.2 Inventory Analysis

This involves conducting mass and energy balances to measure all material and energy inputs, as well as the resulting wastes and emissions from the system. This process quantifies the environmental burdens associated with the system.

2.3 Impact Assessment

This step involves consolidating the environmental burdens identified during Inventory Analysis into a defined set of recognized environmental impact categories, such as global warming, ozone depletion, and acidification.

2.4 Interpretation

This step involves using the results to identify opportunities for minimizing the environmental impacts associated with the product or process.

3. CML 2000 Guideline

For any mathematical calculation all parameters should come in same ground all the emissions and input parameters should lie in one unit for this we are using characterization factor given by CML 2000. In 2001 some scientist of CML (Centre for Environment and Science of Leiden University) had designed a methodology to calculate environmental impact of various processes (Naderi Mahdei K et al. 2023).
In this methodology, characterization and normalization factors play a vital role and a life cycle inventory is prepared on the basis of input, output parameters and system boundary. All these selected WWTPs used electricity from coal-based power plants, therefore gases emitted due to consumption of coal is major cause of global warming effects in life cycle assessment of waste water treatment technologies (Zhan, J., & Xu, W 2020).These guidelines are designed to evaluate the environmental impacts associated with products and processes over their entire life cycle. Here are some key details:

Impact Categories: The CML 2000 technique categorizes environmental impacts into different areas such as global warming, ozone depletion, acidification, eutrophication, and human toxicity. These categories help in systematically assessing and comparing the environmental effects of various products or processes.

Characterization Factors: CML 2000 provides characterization factors for each impact category. These variables are used to quantify the potential effect of emissions and resource use. For example, the technique includes parameters for translating emissions of greenhouse gases into their global warming potential.

Normalization and Weighting: While CML 2000 focuses primarily on characterization, it provides options for normalization (to compare the results with a reference value) and weighting (to prioritize impacts based on their significance). These steps help in understanding the relative importance of different environmental impacts.

Documentation and Transparency: CML 2000 emphasizes the importance of thorough documentation and transparency in reporting results. This includes clearly outlining the technique, assumptions, and data sources used in the impact assessment.

4. Description of Study Area

Description of site area is discussed in Table 1. In current work, 04 sewage treatment plants of different treatment processes were selected on the basis of quality of treated water, energy and cost with Capacity 0.096, 29, 80, and 60 MLD. The MBBR treatment Plant with capacity 0.096 sited in Vivekananda Hostel M.N.N.I.T Teliyar Ganj (Presented in Figure 3), 2.5km away from prayagraj station Allahabad, with capital cost of 0.98 lakhs. The FAB technology with capacity 29 MLD situated in Bakshi dam Salori Allahabad, with capital cost of 19 crores 51 lakhs.

The ASP treatment plant with capacity 80 MLD situated in Naini Allahabad.

Figure 3 Location of site for study

Case -1 ASP based treatment plant

The A.S.P (Activated Sludge Process) based treatment plant located at Naini, near Ganga pollution controlled board office Allahabad with capacity 80 MLD. This is a large scale plant, serving for population of 436503 having area of 43.67 hectare. This is a conventional treatment unit and the energy consumption of this plant is around 739145.08kwh per month. This unit mainly consist of 04 different 20MLD capacity units, and involve the recirculation and extended aeration system. It requires skilled personals to operate and take care of recycled waste water. The final effluent from this plant is disposed into ganga river, nutrient and technical efficiency of this plant is less as compared to other cases.

Case -2 FAB based treatment plant

F.A.B. (Fluidized Aerobic Bed) based treatment plant was located at 4km east from prayagraj station Bakshi dam Salori, Allahabad, having capacity of 29MLD. This is a large-scale plant having area of 19.67 Hectare and serving for population of 225956. The energy consumption of this plant is around 669417.513 kwh per month. In another other term, this is energy intensive plant therefore, Organic loading efficiency, nutrient removal and reliability is good. Hence, this plant overloaded many times, and its discharge up to 41 MLD. Since, works properly with only change in removal efficiency. The final effluent from this plant is disposed into Ganga River.

Case -3 UASB based treatment plant

U.A.S.B. (Up Flow Anaerobic Sludge Blanket Reactor) based plant was located at Rajapur, Allahabad having capacity of 60 MLD. It is also a large-scale plant, serving population of 348360, having area of 11.36 hectare. This treatment unit was conventional type and the energy consumption of this plant is around 474528.36 kwh per month, which is very less as compared to other cases. Therefore, this method is economical in term of initial capital cost, operation and maintenance of plant. The final effluent from this plant is disposed into ganga river. Nutrient and technical efficiency of this plant is less as compared to case 1 and 2 respectively.

Case -4 MBBR based treatment plant

M.B.B.R. (Moving Bed Biofilm Reactor) based plant was located at Swami Vivekananda boys' hostel M.N.N.I.T. Allahabad, having capacity of 96 kiloliters This plant is a small scale (having area 0.0186 Hectares) and employ the advanced treatment technology constructed for around 1000 students of hostel. Energy consumption of this plant is around 7206.36 kwh per month. The final effluent of this plant is passed through ultrafiltration unit, and plant is designed for biochemical oxygen demand of 5mg/L. The main advantage of this method that, the treated water is not disposed into river body rather it used vegetation and gardening.

Table 1 Site description

Name of Site	Technology	Capacity (MLD)	Area (Hectares)
Vivekananda Hostel, M.N.N.I.T, Allahabad	M.B.B.R	0.096	0.025
Salori, Allahabad	F.A.B.	29	6.6
Naini, Allahabad	A.S.P.	80	28.78
Rajapur, Allahabad	U.A.S.B.	60	16.0198

5. Inventory Sheets

In the context of Life Cycle Assessment (LCA), an inventory sheet, commonly referred to as a Life Cycle Inventory (LCI) sheet, plays a vital role in the systematic quantification of inputs and outputs throughout the life cycle of a product or process.

The required data of all different plants for evaluation are discussed in inventory sheets. Inventory sheets for all cases are discussed in Table 2, 3, 4, and 5 respectively.

Table 2 Input and output parameters of MBBR based treatment plant

PARAMETER	INFLUENT		EFFLUENT	
	Procured data	In functional unit (/p. e.-year)	Procured data	In functional unit
B.O.D. (mg/L)	85		22	
C.O.D. (mg/L)	122		40	1.6
T.S.S. (mg/L)	240		80	
TOTAL PHOSPHORUS (mg/L)	4.36		1.73, 0.82,0.93	0.0621
AMMONICAL NITROGEN (mg/L)	19.36		9.39,8.69,10.32	0.37
ENERGY (kwh)	7206.36	38.62		
GASES				
CO_2(kg)		45.687		
CO(g)		346.67		
NOx (g)		109.02		
SO_2(g)		330.58		

6. Life Cycle Impact Assessment (LCIA)

Environmental performance of waste water treatment plant is evaluate using an EMS (Environmental management system) tool, which is life cycle assessment. The performance is determined on the basis of following three impact categories, and value of parameters is taken from methodology section (Pena et al. 2022). Based on data collected three impact categories are being selected which depends on input and output parameters of various treatment units. The following are three categories on the basis of which impact assessment have been done (Muazu R. I et al. 2021).

1. Acidification
2. Eutrophication
3. Global warming

7. Result and Discussion

In the final step, results interpretation involved using software for statistical analysis of the data. The outcomes from the experiments were then presented through graphs and tables. Additionally, the potential environmental impacts of wastewater treatment (WWT) at the M.N.N.I.T WWTP unit were assessed, and recommendations were provided to address and improve environmental sensitivity based on the study's outcomes.

7.1 Acidification

Acidification is mainly due to SO_2 and NOx. Emission which is emitted due to coal combustion from coal based thermal power plants, since there is very high energy consumption in FAB based treatment plant. Therefore, the emission of gases due to coal-based power plant will be more, and the nutrient removal is also low because of overloading. Thereby the ammonia nitrogen emission is also high as compared to other plants. Hence acidification due to FAB based plant is high as compared to other treatment process. Weightage of acidification due to WWTP treatment technologies is discussed in Table 6. Figure 4 shows the acidification potential of treatment technologies. The maximum and minimum results of Acidification was obtained as 0.2215 & 0.0569 in UASB and FAB respectively.

Table 3 Input and output parameters of FAB based treatment plan

PARAMETER	INPUT		OUTPUT	
	Value	In functional Unit (/p. e.-year)	Value	In functional Unit
Emission into water B.O.D. (mg/L)	129 (Procured)		27	
C.O.D. (mg/L)	217 (Procured)		43	2.205
T.S.S. (mg/L)	362 (Procured)		44	
TOTAL PHOSPHORUS (mg/L)	7.39 (Experimental)		3.85,3.02,4.57	0.197
AMMONICAL NITROGEN(mg/L)	21.28 (Experimental)		14.11,11.32,10.81	0.723
ENERGY (kwh) Emission into air	669417.513	38.92		
GASES				
CO_2(kg)		46.042		
CO(g)		348.76		
NO_X (g)		109.87		
SO_2 (g)		333.155		

Table 4 Input and output parameters of UASB based treatment plant

PARAMETER	INPUT		OUTPUT	
	Values	In functional Unit (/p. e.-year)	Value	In functional Unit
Emission to water B.O.D.(mg/L)	158(procured)		27	
C.O.D.(mg/L)	414(procured)		48	2.963
T.S.S.(mg/L)	307 (procured)		55	
TOTAL PHOSPHORUS(mg/L)	9.46 (experimental)		7.42,.31,6.96	0.226
AMMONICAL NITROGEN(mg/L)	28.21 (experimental)		24.36,31.32,26.43	0.807
ENERGY(kwh) emission to air	474528.36	20.32		
GASES				
CO_2 (kg)		24.03		
CO(g)		182.087		
NO_X (g)		57.363		
SO_2 (g)		173.93		

Table 5 Input and output parameters of ASP based treatment plant

PARAMETER	INPUT		OUTPUT	
	Values	In functional Unit (/p. e.-year)	Value	In functional Unit
Emission to water B.O.D.(mg/L)	110 (procured)		28	

PARAMETER	INPUT		OUTPUT	
	Values	In functional Unit (/p. e.-year)	Value	In functional Unit
C.O.D.(mg/L)	330(procured)		48	3.210
T.S.S.(mg/L)	350 (procured)		45	
TOTAL PHOSPHORUS(mg/L)	8.42 (experimental)		5.64, 6.87,5.39	0.459
AMMONICAL NITROGEN(mg/L)	26.87 (experimental)		19.83,20.87,18.39	1.396
ENERGY(kwh) emission to air	739145.08	20.32		
GASES				
CO_2 (kg)		24.03		
CO(g)		182.087		
NO_X(g)		57.363		
SO_2 (g)		173.93		

Table 6 Weightage of acidification due to WWTP treatment technologies

PARAMETER (Kg/p. e.-year)	ACIDIFICATION (kg SO_2eq.)			
	MBBR	FAB	ASP	UASB
Ammonia Nitrogen	0.37×1.88=0.69	1.359	0.679	1.517
NO_X	0.109×0.7=0.0763	0.0769	0.040	0.0308
SO_2	0.330×1	0.333	0.173	0.139
TOTAL	1.0963	1.7683	0.892	1.68

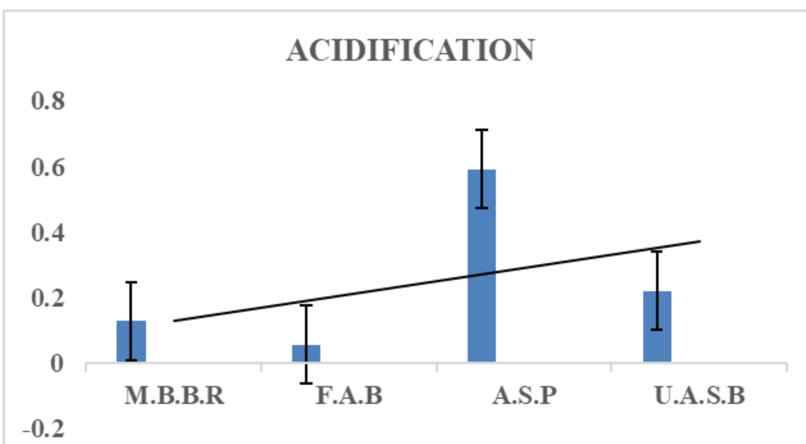

Figure 4 Acidification potential of treatment technologies

7.2 Eutrophication

Eutrophication is mainly due to phosphate, ammonia nitrogen, and C.O.D. The nutrient removal of MBBR and FAB based treatment plant is more as compared to conventional treatment plants ASP and UASB respectively. Hence, the final weightage of UASB base treatment plant is more. Weightage of several technologies and representation is illustrating in Table 7 and Figure 5. The maximum and minimum results of Eutrophication was obtained as 0.564 & 0.055 in MBBR and ASP respectively.

Table 7 Weightage of eutrophication due to WWTP treatment technologies

PARAMETER (Kg/p. e.-year)	EUTROPHICATION (kg PO_4 eq.)			
	MBBR	FAB	ASP	UASB
Phosphate	0.0621	0.197	0.459	0.453
Ammonia Nitrogen	0.37×0.35=0.1259	0.253	0.488	0.518
C.O.D.	1.6×0.022=0.0352	0.04851	0.0706	0.1303
TOTAL	0.2268	0.4985	1.0176	1.1013

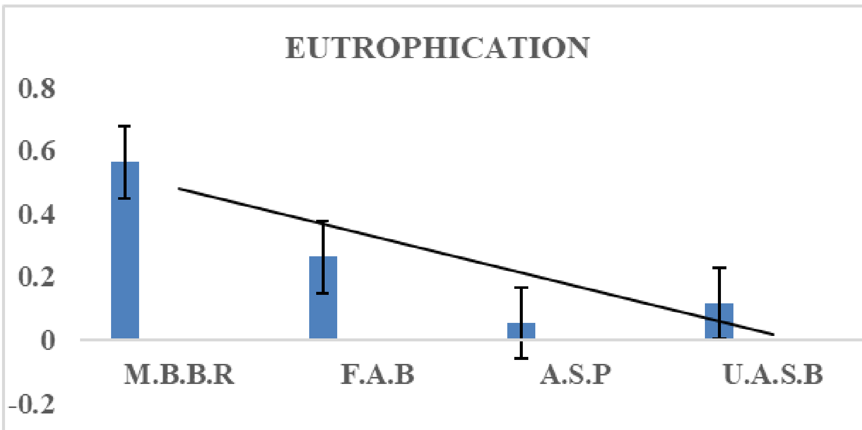

Figure 5 Weightage of alternatives W.R.T acidification

7.3 *Global warming*

Global warming is due to CO_2, CH_4 and NO_2. Energy consumption for the operation of waste water treatment plants is the largest contributing parameter for CO2 emissions. Global warming weight age due to FAB base treatment plant is more, as it is energy intensive process so emission of gases will be more (energy is provided by coal-based power plant), here methane is also emitted by UASB based plant but the NO_2. Global warming due to WWTP Treatment Technologies is display in Table 8 and Figure 6. The maximum and minimum results of global warming was achieved as 0.564 & 0.055 in UASB and FAB respectively.

Table 8 Global warming due to WWTP treatment technologies

PARAMETER (Kg/p. e.-year)	GLOBAL WARMING (Kg CO_2 eq.)			
	MBBR	FAB	ASP	UASB
CO_2	45.687	46.042	24.03	18.79+0.197 = 18.987
NO_X	0.109×298=32.48	32.74	17.09	13.36
CH_4				0.367×25=9.175
TOTAL	78.17	78.782	46.124	41.522

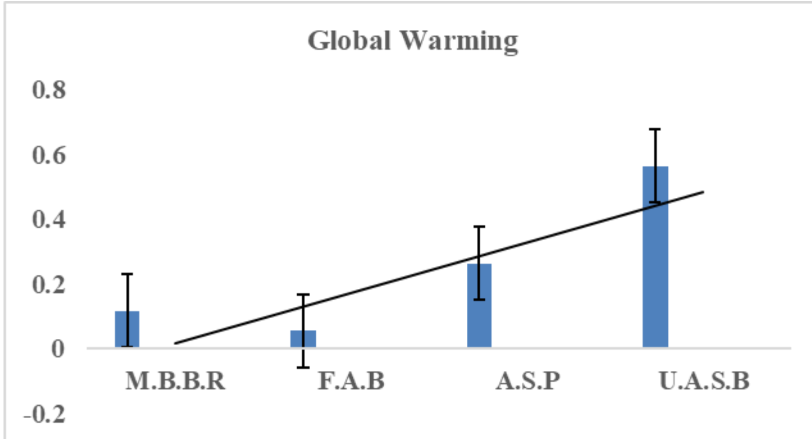

Figure 6 Relative weightage of alternatives with respect to global warming

From the results of impact assessment, it is clear that a treatment technology cannot perform very well. In all scenarios and by judgment of only environmental impact we cannot make decision which treatment technology is best suited. There are several more criteria such as administration criteria, local public interest, treatment efficiency etc. Since, there should be incorporation of these factors in characterization factor so that result may come closer to real aspects. Design and requirement of treatment technology also depends on regional factor so the characterization should change with respect to region also.

8. Conclusion

To the best knowledge of author, it is the first LCIA for the treatment plants of Allahabad city. Since, there is no previous data available to compare these results. Following are the observations which are being carried out by the calculating environmental impact values using characterization factor and normalizing the values.

- Four most commonly treatment technologies are being selected based on their biological treatment efficiency. All treatment plants were electrically driven and the electricity is being produced by coal based thermal power plants. The final effluent UASB, ASP and FAB plants is disposed in Ganga River while effluent of MBBR based treatment plant is used inside for the gardening purpose.
- Comparing wastewater treatment technologies is vital for effectively managing water resources and tackling current environmental challenges. By using Life Cycle Assessment (LCA), the environmental impacts of each technology can be precisely evaluated, facilitating informed and sustainability-driven decisions.
- Almost 80% of water supplied to domestic use becomes waste water after use. Water being very important for almost every living being, so the treatment technologies should be such that effluent water should not affect purity of rivers.
- FAB based treatment technology is highest energy consuming treatment technology. Hence, global warming potential of FAB Based treatment plant is more as compared to three treatment technologies.
- Selection of treatment technology in India is mainly based on economic and treatment efficiency criteria whereas all other criteria should also be incorporated which may not give immediate advantage but will surely give advantaged in future terms in respect of environmental pollution and safety of river system.
- To avoid long term wastage of electricity and to safeguard our environment LCIA of treatment technologies should be done by incorporating all effecting factors.
- The maximum and minimum results of global warming was achieved as 0.564 & 0.055 in UASB and FAB respectively.
- The maximum and minimum results of Acidification was obtained as 0.2215 & 0.0569 in UASB and FAB respectively.
- The maximum and minimum results of Eutrophication was attained as 0.564 & 0.055 in MBBR and ASP respectively.

9 Future Research Opportunities

Future trends in the Life Cycle Assessment (LCA) of wastewater treatment plants (WWTPs) show a growing interest in incorporating Data Envelopment Analysis (DEA) approach, which can be categorized into two main areas: first one energy and second one is environmental aspects. Several studies have already combined these approaches.

Another noteworthy development is the integration of various LCIA methodologies to improve the result accuracy and reliability. Although not yet prevalent in the reviewed literature, combining big data with LCA presents a promising avenue for future research.

Additional research opportunities in the LCA of WWTPs include focusing on the optimization of WWTP operations and applying LCA to resource recovery systems. There is also potential for integrating LCA with other methodologies, such as life cycle cost assessment and social LCA, to create comprehensive life cycle sustainability assessments. Furthermore, establishing regulations that promote the application of LCA in WWTPs globally could advance environmental analysis and sustainability in this field.

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