Life Cycle Assessment Approach for Sustainability of Biological Wastewater Treatment Methods

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CERTIFICATE

This is to certify that the research work embodied in this dissertation entitled "**Life Cycle Assessment Approach For Sustainability of Biological Wastewater Treatment Methods"** has been carried out in the Department of Environmental Engineering, Delhi Technological University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma to any university or institute.

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ABSTRACT

This study shows the comparative analysis of four different wastewater treatment methodologies, amongst which one is a conventional method, which is Activated Sludge Process and other three are advanced and ecofriendly methodologies to perform wastewater treatment. The analysis is carried out on OpenLCA 2.0.0 with the database ecoinvent 3.9.1. The output parameters are generated in the form of impact assessment results and consists of damage categories to indicate the impact on environment. The model followed by the OpenLCA is IMPACT 2002+ approach. Soil Biotechnology results in least environmental impacts on most of the impact assessment and all the damage categories. The life cycle which initiates from extraction of raw materials, construction of treatment plants, operational phase and then disposing the waste generated from each method produces different types of environmental impacts which are essential to be assessed. There are many methods available to perform this analysis, however, this study uses life cycle assessment approach. LCA has been done to evaluate the environmental impacts in different phases of ECW, SBT, ASP and MBR methods of treating wastewater. More than 90% of the chemical oxygen demand (COD) and biochemical oxygen demand (BOD) may be removed with this approach. Additionally, this technology has good proficiency in removing nutrients like nitrate, nitrite, ammonia, total nitrogen, and phosphates. SBT, on the other hand, has low yearly operation and maintenance costs that are lower than traditional or advanced technologies and equivalent to land-based systems. It is found that SBT among all the methods is producing fewest environmental impact with respect to all impact categories except for that of aquatic eutrophication, in which SBT has the highest impact.

KEY WORDS: LCA, Wastewater Treatment Plants (WWTPs), LCIA, CML.

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CHAPTER 1

INTRODUCTION

1.1 Background

Water is an essential substance among other renewable resources that cannot be replenished. Water plays an important role in food production, economic development and sustaining life itself. Purification of water is a difficult task and it is costly to transport (Kumar 2003: Mehta 2012). Wastewater refers to the water that has got an adverse influence in its quality due to Anthropogenic activities. There are numerous sources of wastewater, including penetration into the soil, surface runoff or storm water, industrial, chemical, or agricultural processes. In India, combined sewage systems or sanitary sewers are often used to transport and treat municipal wastewater. An effluent pipe is subsequently used to transport the treated wastewater to the receiving water body. On-site wastewater systems are used to treat wastewater produced in locations without access to a centralized sewage system. These on-site systems often include an on-site treatment unit such as a septic tank, drain field, etc. Like the management of human excreta, solid waste, and storm water (drainage), the management of wastewater is crucial and frequently corresponds to the word sanitation. Industrial wastewater is any wastewater that is generated by a manufacturing facility, processing facility, institutional setting, commercial establishment, or due to agricultural operations that discharge wastewater other than domestic or sanitary wastewater. Wastewater output is rising as a result of population expansion and general improvements in people's living conditions in different nations throughout the world.

Generally, Wastewater treatment plants are developed to minimize the negative effects on the environment and human health (Wang et al. 2012). This has made advancements in WWT approaches and the accompanying water reclamation of a vital and important role to safeguard both human health and the natural/aquatic environment, which is done by reusing water in a manner that lowers total water demand. There are various environmental impacts produced by the wastewater treatment facility during its life cycle due to various reasons such as consumption of energy at various subunits, usage of chemicals, emissions of gas, generation of sludge which needs further treatment. However, the amount of each impact category depends on the wastewater method being adopted. A lot of technologies have been developed with reference to the existing conventional technologies for WWT (such as MBR, SBT, etc.). These advancements are being made in order to obtain economic efficiency and to reduce the life cycle environmental impacts (Corominas et al. 2013a, 2013b). The LCA methodology is adopted in order to access the environmental impacts of any product or service. LCA is able to provide by analyzing a variety of materials, chemicals and energy inputs and outputs during the complete life cycle of a product (ISO, 2006a). This research work aims to assess the environmental impacts due to various WWT methods followed at the treatment plant, a comparison between the conventional method used and the advanced methods which are being used as well as are in the pilot phase in India will be made and hence to propose the best-suited method causing minimum damage to the climate.(Patel & Singh, 2022a) The environmental impacts will be assessed in terms of various parameters such as CO_2 emissions, Eutrophication, Carcinogenic released, Aquatic toxicity produced, etc.

To perform such an analysis, the input database is required of the particular treatment plant which is following these methods. The input parameters required include the electricity consumption by various units of the particular method being used. The output will be in the form of the emission of different gases into the atmosphere such as CO_2, SO_2, NO_X, etc., in addition to this the pollutants remain in the effluent such as heavy metals, after treatment by a particular method (Mohr et al., 2009). The output received with respect to the climate/environmental impacts will be produced by the software, which will use the input data and using a particular method, will perform the life cycle analysis (LCA) (Vlasopoulos et al., 2006).

1.2 Wastewater Production and Treatment

India is the second most populous nation in the world, with 1.38 billion people living there. 35% (483 million) of the overall population is concentrated in metropolitan regions, while 65% (900 million) reside in rural areas. For the year 2020–2021, the Central Pollution Control Board (CPCB) has anticipated that the wastewater generation in rural areas would be around 39,604 million Liters per day (MLD), while it will be 72,368 MLD in urban areas. Due to the accompanying water demands for flushing and sewage drainage, it is estimated that urban wastewater is about twice as large as rural wastewater, and the availability of additional water for sanitation has raised living standards in metropolitan centers (Theodosiou et al., 2014). Due to increased urbanization, there is therefore greater population expansion and migration to cities in search of better living conditions, and as a result, there is an urgent need to manage wastewater. The water demand-supply gap may be significantly reduced in order to achieve water security in the future thanks to an increasing number of practical but unconventional water sources, such as wastewater (Jones et al., 2020). Although wastewater is becoming more widely recognized as a dependable and affordable supply of fresh water, particularly for agricultural purposes, it is still mostly "untapped" and "undervalued" (WWAP, 2017), notably in India. In addition, treated wastewater flows can serve as a significant source of freshwater flows to support river flows, particularly in times of drought (Luthy et al., 2015). As many as 53 cities in India have a population more than a million, according to the Census of 2011. By 2030, there will be 607 million people living in urban areas, and by 2050, it is predicted that 877 million people, or 50% of the total population, would live in urban areas. Urban planners are under tremendous pressure as a result of this steady population growth, particularly when it comes to providing utilities like clean, inexpensive water. According to predictions, India would need 1,447 km3 of water by 2050, of which 74% will be used for agriculture. The remaining water will be used for drinking water (7%), industry (4%), energy (9%), and other purposes (6%), Amerasinghe et al. (2013). The installed capacity for treating sewage is 31,841 MLD, however the actual capacity is only 26,869 MLD, which is substantially less than the load produced. Only 28% (20,236 MLD) of the entire amount of urban sewage generated was actually processed into wastewater. This suggests that 72% of the wastewater is still not cleaned before being dumped into a river, lake, or groundwater. There have been some proposed infrastructure improvements, including an additional 4,827 MLD sewage treatment capacity. There is a gap of 35,700 MLD (or 49%) between the wastewater generated and the capacity available for treatment even if this is added to the currently established capacity (CPCB 2021b). The projected wastewater generation from Class I cities and Class II towns (as per the 2001 Census) is 29,129 MLD, and it is anticipated to increase to 33,212 MLD at this time assuming 30% decadal rise in urban population (Fig. 1).

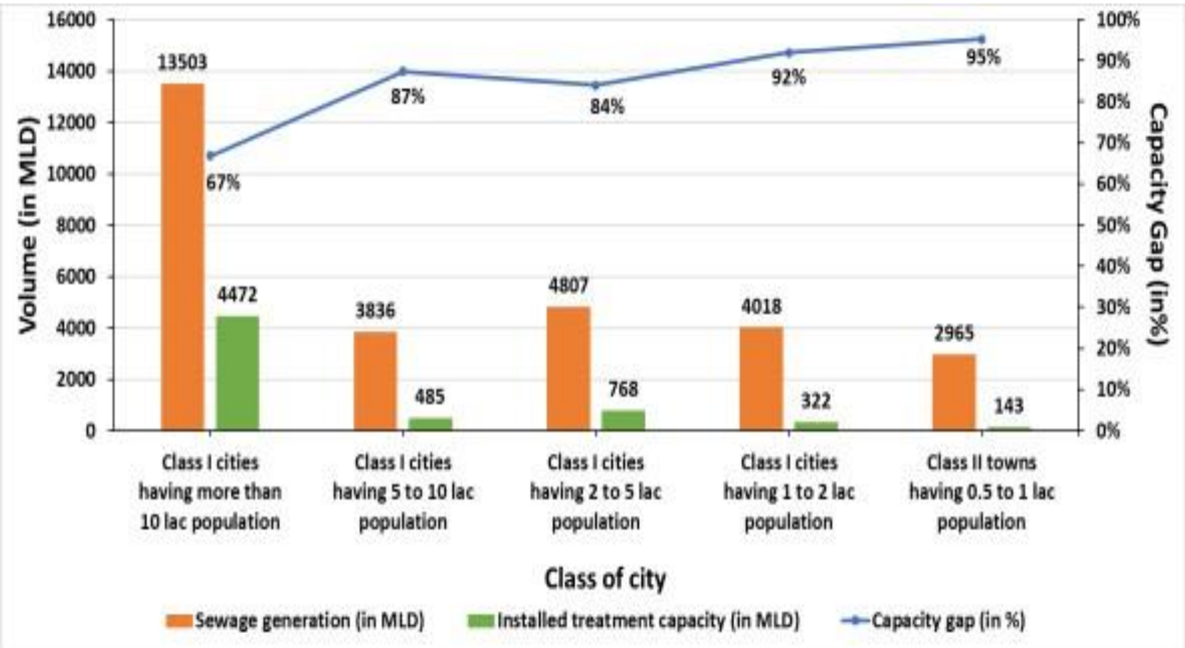


Figure 1.1 Production of Wastewater and their treatment capacity for different class of city in India (CPCB, 2022)

The existing sewage treatment capacity is just 6,190 MLD in contrast to this. The difference between sewage generation and existing sewage capacity is still 79% (22,939 MLD). An additional 1742.6 MLD wastewater treatment capacity is being planned or built. Even with this added to the current capacity, there is still a shortfall in sewage treatment capacity of 21,196 MLD, or 73% (CPCB, 2021c). The majority of the untreated effluent ends up in the adjacent lakes, rivers, and subterranean aquifers where it contaminates and degrades the water quality. Using biochemical oxygen demand (BOD) as a measure of pollution, the CPCB has designated 351 areas on 323 rivers for raw water quality monitoring. According to the monitoring statistics (Table 1), 13% of Indian River spans are seriously contaminated, while 17% of Priority 2 and 3 portions are moderately polluted. In addition to having high BOD and COD levels, many areas have significant concentrations of heavy metals, arsenic, fluorides, and dangerous compounds, particularly in groundwater (CPCB 2018).

Table 1.1: Priority-wise number of polluted Indian river stretches

Priority Category	Health Status	BOD Value (mg/L)	Number of stretches
1	Severely polluted	BOD >30 mg/L	45
2	Moderately polluted	BOD between 20-30 mg/L	16
3	Moderately polluted	BOD between 10-20 mg/L	43
4	Mildly polluted	BOD between 6-10 mg/L	72
5	Clean	BOD between 3-6 mg/L	175
Total			**351**
Data Source: CPCB. (2018)			

In addition to surface water contamination, groundwater contamination is also occurring at a rapid rate. Studies on groundwater contamination are carried out with respect to their sources and related health risks were estimated for North West Delhi region (Sarma &Singh, 2023). Also there are variations in the quality of groundwater with the variations in seasons along a year. Studies have been conducted for the assessment of seasonal variation of groundwater quality in metropolitan areas of Afghanistan. Variation of water quality parameters with respect to space as well as temporal variation were developed to analyze groundwater quality and seasonal variation (Noori & Singh, 2022).

1.3 Urban Wastewater as a growing global challenge

According to Moteo-Sagasta et al. (2015), data on the present amounts of wastewater that are produced, collected, treated, and reused at various sizes is dispersed, seldom observed and documented, or absent in many countries. In an era when the globe is starting to achieve the Sustainable Development Goals (SDGs) set by the United Nations, such significant information is crucial for sustainable development connected to water and energy. SDG 6.3, which focuses on wastewater in particular, seeks to reduce the amount of untreated wastewater globally while increasing recycling and safe reuse. The SDG 6.3 target is interconnected with many other SDGs and targets, which can aid in achieving their goals and targets and vice versa (Fig. 2). These include the SDG 6.a goal to increase international cooperation and capacity-building support for activities and programmes related to water and sanitation in developing countries, the SDG 6.b goal to increase access to clean energy research and technology, and the SDG 6.c goal to encourage investment in energy infrastructure and clean energy technology. Understanding wastewater production and the accompanying reuse strategies is crucial.

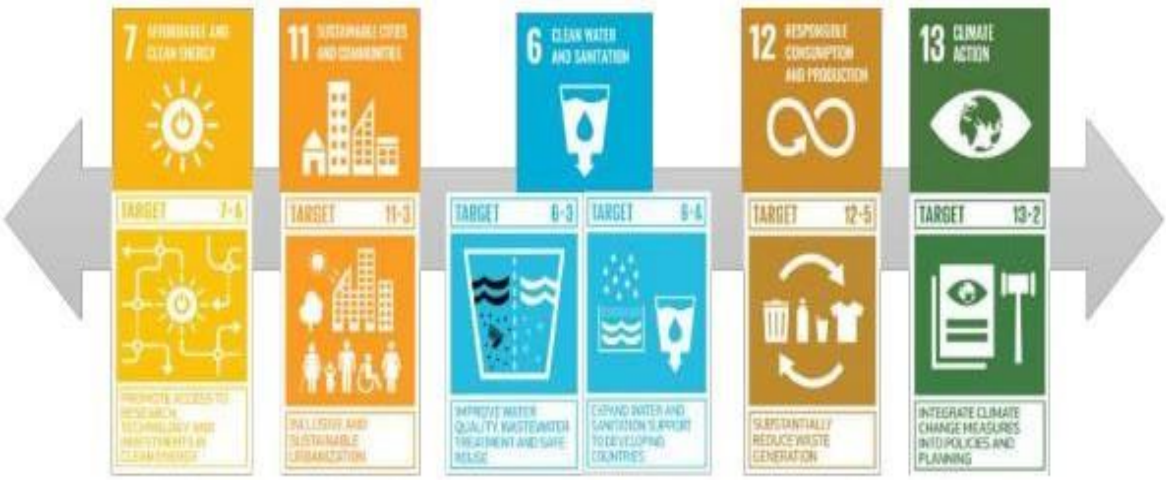


Fig 1.2: Interlinkage of SDGs with wastewater treatment and its treatment (Adopted from UN SDGs)

Recently, few global studies have been carried out to estimate the wastewater volumes and make predictions for the future. For example, Qadir et al. (2020) evaluated that 380 Billion m^3 of wastewater is generated across the world. In urban areas, increasing solid waste is a growing challenge and requires an emphasis on its source reduction and sustainable methods to carry out its treatment. Industrial pollutants received from various effluent treatment plants during their disposal to the streams causes a reduction in the quality of stream water. Iron and Steel industries are essential for driving the nation’s economic growth and governments of various countries entails large investments in several steel sectors. Studies have been carried out for ascertaining the treatment technologies for sustainable wastewater management, particularly from the Iron and Steel industry (Garg & Singh, 2022).

1.4 Requirement to perform Life Cycle Assessment in Wastewater Systems

Building a wastewater treatment plant is a difficult process that incorporates many different materials, including concrete, wood, steel, and polymers, as well as intricate operational design and equipment. The procedure needs:

(i) Electricity requirement for aeration or pumping

(ii) Chemicals for coagulation, waste treatment, and

(iii) Transportation of various components of plant as well as waste

Due of consumption of energy, usage of chemicals, formation of sludge, discharge of effluents, and emissions of gases over its life time (which starts from construction, its operation, and destruction), WWTPs have a very significant negative effects on the surrounding environment. Electricity consumption for the treatment of wastewater used in various equipment is considered to be the primary contributor to environmental impacts. The results and analysis have been conducted on different wastewater treatment methods using LCA analysis and the best suited method is determined. (Patel & Singh, 2022)

The conservation of the environment, especially water resources, has gained more attention in recent years in the worldwide civilization. In this regard, a huge number of WWTPs are built and run to avoid environmental contamination by eliminating various toxins from wastewater and so restoring the water's acceptable quality, making it suitable for disposal at a specific disposal site.

The drawback with this is that some wastewater contaminants, such as greenhouse gases (GHGs), might be transmitted to the air and soil as a result of wastewater treatment, which could have a harmful impact on human health and the environment in other foams. The United Nations Sustainable Development Goals address climate change, eutrophication, and acidification of water bodies as the most pressing environmental impacts. Other environmental effects from plant operation include eutrophication from the release of nutrients into water bodies, ecosystem damage from the release of heavy metals, and climate change from the emission of GHGs. Therefore, it becomes very important to conduct the environmental impacts of particular methods used in the treatment of wastewater for which various techniques can be used. Currently, a variety of evaluation methodologies, including the life cycle assessment (LCA) method, economic and energy analysis, environmental impact assessment (EIA) method, and net environmental benefit analysis (NEBA), may be used to analyze the impact of wastewater treatment systems. Environmental effects are evaluated in LCA from the extraction of raw materials through the final disposition of the resources, or from cradle to grave. Due to its significant potential for contributing to global warming and the degradation of ecosystem quality when compared to other approaches, studies employing LCA have revealed that landfills with composting have a very high environmental effect (Patel & Singh, 2022b).

1.5 Impacts of Wastewater on the Environment

Wastewater released from various sources has significant impacts on the environment depending on what is the site selected for disposing off the wastewater and associated sludge. With respect to determining the sustainability associated with the methods of treatment, there are many different categories into which impacts on the environment due to wastewater treatment or any general method are defined which are land use, global warming, ozone layer depletion, toxicological impacts, eutrophication, non-renewable energy, carcinogens, non-carcinogens produced (Risch et al., 2014). In addition to this, damage assessment categories are also defined as human health, resources, ecosystem quality and climate change. However, international consensus has not been reached for the treatment of all impact categories.

1.5.1 Resources

Resources are all-natural matter available at and below the surface of earth. These include biotic and abiotic resources.

Abiotic Resources

It covers three subcategories:

- Depositions, which include fossils, aquifers, sediments, soil, etc.
- Collection, which includes surface and ground water sources.
- Resources for natural movements, such as air, water, sunlight, ocean currents, etc.

Biotic Resources

They consist of subcategory defined below:

- Collection, which includes fauna (in the aquatic system) and flora (plants)

Both non-sustainable and sustainable methods can be used to extract biotic resources. Take the harvesting of trees as an illustration. Due to the high qualities of hardwood, which are utilized in building, in some regions, especially those where hardwood is cultivated, the cut down of wood resource is quicker than to replenish them. This causes resources to exhaust and leads to rise in survival competition in between the species available locally. In comparison to this, there are areas in which softwood is present, so the rate of harvest is slower than growth of the trees.

1.5.2 Global Warming

The phenomenon of an increase in the temperature of the lower atmosphere of the earth's surface is known as global warming or the greenhouse gas effect.. It takes place due to the trapped heat radiation coming from the sun by a number of gases which have the ability not to allow the radiations to go out after reflection from the earth surface. Since the heat energy is getting trapped so it leads to the melting of ice caps, elevated sea water levels. The greenhouse effect is caused by a number of gases. The effect of each gas is converted into kg CO_2-eq by multiplying each gas value with their respective Global Warming Potential values and adding all to get the final value.

According to IPCC report, the main greenhouse gases (GHGs) of concern are as following:

1. Carbon Dioxide (CO_2)
2. Industrial gases like CFCs, PFCs, HFCs, SF_6
3. Ozone (O_3)
4. Water Vapour (H_2O)
5. Methane (CH_4)
6. Nitrous Oxide (N_2O)

Except water vapour, the levels of all other GHGs is found to be increasing directly due to the human activities. This level is determined by finding the source and sink of these gases. Sources are those processes which tends to generate the GHGs and sinks are those which tends to destroy or remove them. Human affects the GHG levels by generating new sources or by interfering with the existing sinks and not allow them to capture or remove GHGs.

The Global Warming Potential (GWP) values over a period of 100 years are mentioned in the following tabular form:

Table 1.2: Global Warming Potential of various gases with their lifetime

Gas	Lifetime (years)	GWP (over a 100 year period)
Energy Origin (CO_2)		1
Non-energy origin (CO_2)		1
Methane (CH_4)	12	21
Nitrous Oxide (N_2O)	114	310
Hydrofluoro carbon (HFCs)	1.3-270	140-11,700
Perfluorocarbon (PFCs)	800-50,000	6,500-9,200
Sulphur hexafluoride (SF_6)	3200	23,900

1.5.3 Ozone Layer Depletion

As the stratospheric ozone layer decreases, it causes increase in the incoming ultraviolet radiations to the earth surface and directly puts an adverse impact on human health Humans are affected by increasing rates of skin cancer, cataracts, and immune system decline. Planktons in the South Pole region have been affected, as a result of the South Pole's extensive ozone layer degradation, along with other natural animals.

The stratospheric ozone layer is present at altitudes between 10 and 40 km, with its peak concentration occurring between 15 and 25 km. The ozone layer is produced by the chemical reaction of O_2 with the nascent oxygen atoms available resulting in the formation of O_3 molecules. Anthropogenic halogenated substances like CFCs, HCFCs, halogens, and others speed up this ozone degradation. With respect to different halogenated compounds their respective ozone depletion potential (ODP) are defined by World Meteorological Organization

(WMO). These ODPs are represented as CFC-11 equivalents by the following equation:

$$ODP_i = \frac{modelled\ stratospheric\ ozone\ depletion\ due\ to\ compound\ i}{modelled\ stratospheric\ ozone\ depletion\ due\ to\ same\ qualtity\ of\ CFC-11}$$

The ozone depletion potential, or ODP, of a substance is measured in comparison to the same quantity of trichlorofluoromethane (CFC-11). In order to calculate ozone depletion potential, the ozone depletion potential of CFC-11 is considered to be 1.0. The more harm a substance can do to the ozone layer, the greater its ozone depletion potential value. A naturally occurring greenhouse gas with a zero-ozone depletion potential is carbon dioxide.

The Table for CFCs, HCFCs, and halogens includes ODPs. By condensing the ODPs as follows, it is possible to estimate the probable ozone depletion caused by a particular process:

Stratospheric ozone depletion potential (kg CFC-11 equivalents) = $S_i\ ODP_i\ m_i$

Where, m_i = proportion by % mass of component i

ODP_i = ODP of chemical i

Table 1.3: Ozone depletion potential of various substances

Ozone depletion potentials (OPD) given in kg CFC-11 equivalents/kg gas (Solomon & Wuebbles, 1995; Pyle et al., 1991; Solomon & Albritton, 1992).

Substance	Formula	Life time, years	Total ODP	5 years	10 years	15 years	20 years	30 years	40 years	100 years	500 years
CFC-11	$CFCl_3$	50±5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CFC-12	CF_2Cl_2	102	0.82	-	-	-	-	-	-	-	-
CFC-113 C	$CF_2ClCFCl_2$	85	0.90	0.55	0.56	0.58	0.59	0.62	0.64	0.78	1.09
FC-114	CF_2ClCF_2Cl	300	0.85	-	-	-	-	-	-	-	-
CFC-115	CF_2ClCF_3	1,700	0.40	-	-	-	-	-	-	-	-
Tetrachloromethane	CCl_4	42	1.20	1.26	1.25	1.24	1.23	1.22	1.20	1.14	1.08
HCFC-22	CHF_2Cl	13.3	0.04	0.19	0.17	0.15	0.14	0.12	0.10	0.07	0.05
HCFC-123	CF_3CHCl_2	1.4	0.014	0.51	0.19	0.11	0.08	0.06	0.04	0.03	0.02
HCFC-124	CF_3CHFCl	5.9	0.03	0.17	0.12	0.10	0.08	0.06	0.05	0.03	0.02
HCFC-141b	$CFCl_2CH_3$	9.4	0.10	0.54	0.45	0.38	0.33	0.26	0.22	0.13	0.11
HCFC-142b	CF_2ClCH_3	19.5	0.05	0.17	0.16	0.15	0.14	0.13	0.12	0.08	0.07
HCFC-225ca	$C_3F_5HCl_2$	2.5	0.02	0.42	0.21	0.14	0.10	0.07	0.05	0.03	0.02
HCFC-225cb	$C_3F_5HCl_2$	6.6	0.02	0.21	0.17	0.14	0.11	0.09	0.07	0.04	0.03
1,1,1-Trichlorethan	CH_3CCl_3	5.4±0.4	0.12	1.03	0.75	0.57	0.45	0.32	0.26	0.15	0.12
Halon 1301	CF_3Br	65	12	10.3	10.4	10.5	10.5	10.7	10.8	11.5	12.5
Halon 1211	CF_2ClBr	20	5.1	11.3	10.5	9.7	9.0	8.0	7.1	4.9	4.1
Halon 1202	CF_2Br_2		−1.25	12.8	12.2	11.6	11.0	10.1	9.4	7.0	5.9
Halon 2402	CF_2BrCF_2Br	25	−7	-	-	-	-	-	-	-	-
HBFC 1201	CF_2HBr		−1.4	-	-	-	-	-	-	-	-
HBFC 2401	CF_3CHFBr		−0.25	-	-	-	-	-	-	-	-
HBFC 2311	$CF_3CHClBr$		−0.14	-	-	-	-	-	-	-	-
Methylbromid	CH_3Br	1.3	0.64	15.3	5.4	3.1	2.3	1.5	1.2	0.69	0.57

1.6 Objective of Study

The main objective of this research selected four different method of wastewater treatment, out of which one is a conventional method and the other three are advanced/latest technologies made to enhance environmental sustainability. The four methods which I have considered in my study are as following:

1) Activated Sludge Process (ASP)
2) Soil Biotechnology (SBT)
3) Bio electrochemical Constructed Wetlands (ECW)
4) Membrane Bioreactor Technology (MBR)

A comparative analysis is carried out in order to determine the best suited technology with respect to Urban Indian context. The LCA results shows the characterization of various environmental effects such as Eutrophication, Global Warming, Acidification, Carcinogenic, Non Carcinogenic produced. In addition to this, the results demonstrate damage to environment such as climate change, human health, etc. Hence, by comparing the four methods, best suited method for the environment can be assessed.

CHAPTER 2

LITERATURE REVIEW

In order to perform environmental impact analysis to establish sustainability different methods are available, life cycle assessment is one of such tool. LCA is different from that of conducting an environmental impact assessment. EIA is conducted in order to assess the damage to the environment due to works carried out for some specific duration of time, i.e. how much impact some particular work will pose on particular environment related parameter such as on air, degradation of land, water quality etc. In place of this LCA carries out the assessment for the complete life cycle of a system and not for some specific duration. The various literatures which were taken into use while carrying out this study have been mentioned below. The works considered for conducting the study includes thorough knowledge of LCA process, software which can be used to perform this analysis, the methodology which various software follows in order to calculate the impact categories, defining the various damage categories if the analysis is performed using different software.(Campos et al., 2016) Among various literatures being used in the study, below mentioned those which are directly related to the wastewater treatment methods which this study uses.

Two modest, decentralised wastewater treatment systems linked to artificial wetlands have undergone research to determine their efficacy (ecoefficiency). A life cycle analysis was carried out using data from two actual pilot constructions (Piao et al., 2016). The functioning stage of the aerated wetland had the greatest potential to negatively impact the environment across all impact categories, according to the analysis. In comparison to the system without aeration, the system with aeration had a life cycle cost per cubic meter of treated sewage that was 1.8 times cheaper. By making investments in energy efficiency and the decarbonization of the power it consumes, S2's life cycle performance is slightly improved. Potential consequences might be reduced if fibreglass is used instead of stone during the S1 building phase. However, compared to brick, fibreglass construction is more expensive. The LCC results show that S2 is the least expensive choice even after accounting for land and power costs. Finally, when both systems are taken into account, S2 (an aerated system) has a higher nutrient removal efficiency than S1 does (Juliana Dalia Resende et al., 2019).

The environmental impact and economic performance of conventionally constructed wetland (CW) and environmentally conscious wetland (ECW) were evaluated as part of an inquiry into the life cycle assessment approach. Additionally, the economic study, which used an inventory and parametric approach to examine the ECW's economic viability, was finished. The ECW produced considerable environmental effects on the AD, but overall, those effects were 49.2% less severe than those of the conventional CW, according to his findings. Both conventional CW and ECW had a large influence on the MAE, contributing 87.5% and 83.5% of the total impacts, respectively (Hao et al., 2019). The use of the electrode module, particularly the power supply, increased the environmental effects because plastics and metals were widely used. The overall GWP, however, is lower than the conventional CW. However, the overall GWP of the ECW was 69.1% lower than the conventional CW. According to further economic study, the ECW may remove the same amount of nitrogen overall as the regular CW while using 65.0% less area. The ECW's construction and operating costs were consequently 61.8% less expensive than those of the traditional CW. When the ability of ECW to remove TN was sufficiently greater than that of traditional CW, the cost of ECW was always lower than that of conventional CW, showing that ECW was both environmentally and economically viable (Castillo et al., 2016).

Compared the life cycle assessments of high-rate anaerobic-aerobic digestion, trickling filters, and activated sludge. In order to transform municipal wastewater into an effluent that satisfies USEPA standards, it has been identified what is required in terms of operations. The lower energy requirements of the TF and HRAAD are mostly to blame (Nizam et al., 2021). Both TF and HRAAD had the lowest impacts when the entire system (liquid stream treatment and sludge dewatering) and the IMPACT 2002 model were used. TF outperformed HRAAD using the TRACI 2 model in seven out of nine categories (Awasthi et al., 2021). The HRAAD system, which produces the least sludge overall, had the lowest effects in all impact categories according to the LCA, which used IMPACT 2002 and TRACI 2. The reduced production of sludge is thus a key benefit of the proposed HRAAD technology Leonardo Postacchini et al. (2016). Emissions from treated wastewater, emissions from the generation of energy used to run the WWTPs, and emissions from dangerous heavy metals have been recognised as the main contributors to the overall environmental impact. Soil biotechnology (SBT) had the least negative environmental effects of all the considered WWTPs, with the exception of eutrophication potential. However, because the Aerated Lagoons (AL) system used so much electricity and chemicals, the results were the poorest (Englande et al., 2015). The findings of the examination of this advantage show a decrease in the toxicity potential when the rate of treated effluent reuse is increased (S. Kamble et al., 2019). Overall, it was found that MBR technology was an environmentally friendly way to treat sewage from cities, with construction having less of an impact than operation. Numerous possible scenarios and potential improvement areas, including the diversification of the electrical mix and the material of the membrane units, were investigated in order to minimize the overall cost as much as is practical. The MBR pilot unit's overall sustainability has been shown to be significantly impacted by the energy mix, with as much as ninety-five percent of the total greenhouse gas emissions being decreased (Ioannou-Ttofa et al., 2016). Wastewater Treatment System Modelling. One strategy for dealing with the water crisis is the indirect potable reuse (IPR) of wastewater. This study used an innovative membrane bioreactor-membrane distillation (MBR-MD) technology in contrast to an existing IPR facility (the "Baseline") to evaluate the impacts of treatment on the environment (Glover et al., 2022). The development of membrane bioreactor (MBR) technology in the modern period has been greatly influenced by advances in water treatment technology. The old activated sludge process's huge area requirements, poor efficiency, and high cost have created the space required for the MBR system to function. Immersed and side-stream MBR can be used in place of tertiary filtering and the standard activated sludge (CAS) procedure. Therefore, MBR is a viable technique for long-term water treatment (Tanzim Ur Rahman et al., 2023)**.**

In order to remediate pharmaceutical wastewater, this extract compares the life cycle assessments (LCA) of homogeneous and heterogeneous Fenton procedures. The study intends to assess the treatment technologies' effectiveness at degrading and detoxifying patients as well as the effects they have on the environment (Campos-Guzmán et al., 2019). Advanced oxidation processes (AOPs), such as Fenton processes, are well known for being resource-intensive in terms of chemicals, energy, and the production of residual fluxes that could have an adverse effect on the environment. Utilising the LCA technique, it is possible to quantify resource consumption, emissions, and their impacts on human health as they relate to the environmental changes brought on by the AOP treatment (Cashman et al., 2018). The ReCiPe version 1.06 and ICCP 2007 methodologies are used by the authors to calculate the probable environmental impacts using the Gabi 6.0 software. With a 77% reduction in water footprint, the heterogeneous Fenton process is a more environmentally friendly option when compared to the homogeneous Fenton method. The extract emphasizes how crucial it is to take into account not only the effectiveness of pollutant degradation, but also the impacts of wastewater treatment technology on the environment and human health (García-Montoya et al., 2016). While LCA has been frequently used in urban wastewater treatment facilities, it has been less widely used in AOPs, especially at the lab size. The authors come to the conclusion that for sophisticated wastewater treatment procedures that heavily rely on freshwater resources, the Water Footprint functions as a supplemental parameter to LCA. Overall, the study reveals that the heterogeneous Fenton method, which offers higher environmental performance and a smaller water footprint than the homogeneous process, is a more sustainable choice for treating pharmaceutical wastewater (Rodríguez et al., 2016). Chemical auxiliaries including NaCl, Na2CO3, and CH3COONa that are frequently present in textile wastewaters have an impact on the process's economic and environmental aspects. These auxiliary substances lengthen treatment times and increase H2SO4 and NaOH requirements during conditioning processes. According to an IPCC-2013 method-based life cycle assessment (LCA), dyeing auxiliaries greatly raise carbon dioxide equivalent (CO2-Eqv) emissions (Hauck et al., 2016). With electricity use making over 60% of the Fenton process' carbon footprint, it is recognised as a major environmental problem. Auxiliaries also increase the relative impact across a range of environmental factors. Furthermore, because more energy is consumed and more reagents are needed when using chemical auxiliaries, treatment costs significantly rise as a result. Due to its technological simplicity and relatively low economic and environmental costs, the Fenton process is thought to be a desirable choice for the treatment of textile effluents in emerging nations notwithstanding these difficulties. The type of contaminants is found to have less of an impact on fenton and photo-fenton processes, which offer potential for large-scale applications. In contrast to Fenton procedures, photo-Fenton methods are more expensive and have more complicated technical requirements. For treatment systems to be implemented on an industrial scale, technical, financial, and environmental evaluations are essential. According to studies, Fenton methods with simplified reactors and optimised reagent dosing can lower the cost of treating complex effluents. In the extract's conclusion, it is mentioned that Fenton reactions are constrained by high NaCl concentrations and organic acids produced by the decomposition of aromatic molecules. Reaction rates, mineralization effectiveness, and pollution removal are all impacted by these parameters. The effluents are complicated by the inclusion of dyeing auxiliaries in dye baths, necessitating a detailed comprehension of their influence on reagent use, environmental performance, and cost in large-scale operations (Grisales et al., 2018). The evaluation of two SBT facilities in the Mumbai area is the main focus, taking into account technical, environmental, and financial factors. These plants are compared in the study to three other SBT plants listed in previous studies. SBT is particularly effective at treating wastewater, with COD and BOD removal rates exceeding 90%. Using the method successfully eliminates nutrients like nitrate, nitrite, ammoniacal nitrogen, TKN, total nitrogen, and phosphates. SBT is also discovered to have low yearly operation and maintenance expenses, cheaper than traditional or advanced technologies and equivalent to land-based systems. Life cycle assessment (LCA) is used to assess the environmental effects of SBT plant construction and operation. The main causes of the total impact are determined to be sludge disposal, COD discharges, P-PO43- discharges, and N-NH4+ discharges. It is discovered that the building phase has a substantially bigger influence than the operation period. According to the analysis, plant I is one of the plants with the lowest sanitation efficiency. SBT, which is based on a bio-conversion process, is recognised for its advantages over traditional wastewater treatment methods because it uses the least amount of energy, requires less maintenance, and doesn't produce odorous bio-sludge. Background information on the significance of water resources, the difficulties brought on by urbanisation and population increase, and the requirement for efficient wastewater treatment are provided in the introduction section. It claims that only 4% of the world's water resources are used by India, yet has 16% of the global population. The extract also briefly discusses various land-based wastewater treatment system types, emphasising their affordability and potential results. These systems' environmental effects, contaminant removal, and performance evaluation are briefly covered. With a complete investigation of one plant, including physicochemical and microbiological characteristics, economic factors, social aspects, and life cycle evaluation, the study's stated goal is to do a technical, environmental, and economic assessment of SBT plants. According to the study's findings, the SBT plant under consideration has the ability to treat wastewater sustainably and is comparable to ecological approaches that have already been investigated. The extract gives a general review of SBT as an environmentally acceptable method of treating and recycling wastewater, emphasizing its efficiency, advantages from an economic standpoint, and environmental considerations (S. J. Kamble et al., 2017).SBRs have the largest global warming potential (GWP), highest energy consumption, and best effluent quality in terms of nutrients and organics. Conversely, because of the carbon storage by the macrophytes, artificial wetlands have low energy use and a negative global warming potential. The technology comparison implies that LCA data, together with other sustainability indicators, can function as indicators in a multi-criteria decision-making framework. Urban local governments in India face a big issue when choosing the best wastewater treatment technologies. This study will help decision-makers by assessing the environmental footprints of WWTPs. The study relies on field data gathered during visits to genuine local WWTPs because there are no national databases for LCA in the Indian environment. The study offers insights into the environmental performance of various wastewater treatment technologies by examining the operation and maintenance phases of the four WWTPs, assisting in the logical comparison and selection of technologies for wastewater treatment in India.

The analysis, which focuses on the geographic applicability of LCA in both developed and developing countries, is based on 35 studies that were published between 2006 and 2022. The analysis points out a dearth of studies that carry out LCA of WWTPs while taking specific local conditions into account, particularly in developing nations. It recommends examining site-specific inventory data in developing nations, assessing the environmental sustainability of various upgrading techniques for WWTPs, and assessing the impact of seasonality on the environmental impact of wastewater treatment. The report emphasises how crucial it is to evaluate both the financial and environmental costs of developing WWTPs sustainably. To make recommendations for future legislation and direct the water business in making ecologically responsible decisions, thorough environmental impact evaluations are required. It emphasises the environmental effects connected with the development, maintenance, and dismantling of WWTPs, including gas emissions, sludge production, chemical use, energy consumption, and effluent outflow. The extract also examines cutting-edge techniques for using LCA in WWTPs. To determine factors including total dissolved solids, pH, electrical conductivity, hardness, chloride, bicarbonate, and different ion concentrations, a total of 35 groundwater samples were thoroughly analysed. These parameters were measured by the study using spectrophotometers and portable devices. ArcGIS was used to predict the spatial distribution of the measured parameters and the Water Quality Index (WQI). Recent investigations, however, have revealed a decrease in groundwater levels and a drop in its quality. The ability of groundwater to be used for domestic and commercial reasons can be impacted by groundwater pollution, which can result from both natural and manmade sources. The WQI and other techniques for assessing water quality are essential for protecting human health and managing water resources sustainably. The development of a spatially distribution model of water quality parameters using GIS technology is another focus of the project. This model helps to comprehend the general quality of groundwater, detect potential issues for consumers of groundwater, and support groundwater management programmes. The study offers insights into the hydrogeochemical mechanism of groundwater and evaluates its acceptability for drinking by examining the physicochemical properties and ion concentrations. The research advances our knowledge of the Kabul Basin's water quality, empowering local government officials to manage groundwater sustainably. A combined total of 152 samples of water were gathered from various sites over a 3767 km2 area. 18 parameters, including pH, EC, TDS, TA, TH, major anions, and cations, were measured in the samples. The analysis resulted in a drinking water quality index that showed 2.6% of the samples to be outstanding, 57.9% to be good, 32.9% to be poor, 4% to be very poor, and 2.6% to be unsuitable. According to the study, the order of the ions' abundance in the groundwater is as follows: Na+ is the most numerous cation, followed by Ca2+, Mg2+, and K+, while HCO3 is the most prevalent anion, followed by Cl, CO32, and SO42. To illustrate the spatial variability of these values, interpolation maps were employed. Additionally, the ion exchange mechanism was seen there. Halite, fluorite, and sylvite were discovered to be undersaturated in the groundwater, whereas calcite, dolomite, and aragonite were found to be oversaturated. Principal component analysis

(PCA) revealed that both geogenic and human influences on groundwater mineralization were present, accounting for 75.4% of the total variation. The study's findings indicate that, with the exception of a few locations, most of the study area's groundwater is appropriate for drinking. It highlights the significance of comprehending the state of the groundwater's quality in order to stop additional contamination and interpolation maps were used to depict the spatial variability of these parameters. In order to evaluate and manage the quality of groundwater, it is important to apply techniques like GIS mapping, water quality indexing, multivariate statistical analysis, and saturation index computations. This thorough investigation advances our understanding of the district of Ludhiana's groundwater quality and can help us make decisions and develop policies related to the management of water resources. The Mann-Kendall statistical test was used to identify seasonal and annual fluctuations in groundwater depth, and cluster analysis was used to classify long-term patterns in groundwater levels. Groundwater drought was assessed using the Standardized Groundwater Level Index (SGI). According to the data, 82% of the observation wells had significant water level drops, pointing to a severe and enduring drought from 2014 to 2020. The study also examined how the land use and land cover (LULC) had changed in the region, identifying a rise in populated regions and a decline in barren land. Groundwater overuse and LULC changes were blamed for the fall in groundwater levels, annual precipitation is decreasing. For the city's water supply to be sustainable, the researchers emphasised the necessity for long-term groundwater management strategies. The study emphasised the significance of groundwater resources, particularly in arid and semiarid areas, for a variety of uses, including agriculture, industry, and the supply of drinking water. It listed several causes that contribute to groundwater depletion, including overexploitation, urbanisation, increased agricultural productivity, population growth, and industrial development. Furthermore, it was discovered that recurrent droughts and climate change hinder groundwater recharge and worsen water scarcity. An efficient technique for groundwater conservation practises, trend evaluation of groundwater levels offers insights into long-term changes in groundwater storage. The study emphasised the value of treating groundwater drought, which are hydrological droughts that have an impact on groundwater supplies. Previous research have revealed a steady fall in groundwater levels in Kabul city, which heavily relies on groundwater. The study's goals included grouping observation wells according to variability scenarios, using trend analysis to analyse and identify changes in groundwater levels, looking into LULC changes to better understand groundwater recharge mechanisms, and using the SGI to gauge the effects of climatic changes on the water table and groundwater drought. Overall, this study highlights the necessity for sustainable water resource management strategies by shedding light on Kabul City's diminishing groundwater levels and the corresponding difficulties. The sustainability and quality of Kabul's principal water supply, groundwater, are essential for the city's water use. The study involves a thorough analysis of pertinent papers and literature to determine their applicability and reliability. The results show that groundwater levels have significantly decreased, with an average annual loss of 1.7 metres between 2008 and 2016. Due to falling groundwater levels, about 33% of supply wells are inoperable. The vast majority of inhabitants are served by private water supply companies. The report includes suggestions for sustainable development and strives to provide a thorough grasp of the existing state of groundwater in Kabul. In order to improve groundwater and alternative water resource management in the area, it is helpful to evaluate the literature and reports that have already been published. The natural infiltration of groundwater has been hampered by population development and uncontrolled urban expansion, which has resulted in pollution from a variety of sources, including wastewater, drainage, and agricultural operations. Overall, the paper underlines the value of Kabul's groundwater resources, outlines the difficulties associated with diminishing levels and water quality, and offers recommendations for further research and sustainable management initiatives. Several physicochemical factors, such as pH, conductivity, hardness, alkalinity, and the presence of ions including chloride, nitrate, fluoride, and others were examined in groundwater samples from the study region. According to the hydrochemical facies investigation, magnesium was the main cation and bicarbonate was the dominating anion in the aquifer. Only 20% of the samples passed the criteria for acceptable drinking water, according to the water quality index values, while 54% were too salinized to be used for irrigation. However, the geographic distribution of the fluoride contamination suggested that a broader population was impacted by the pollution. The report emphasises the requirement for ongoing groundwater monitoring and the adoption of corrective actions to raise the region's water quality and public health. It also emphasises the importance of evaluating the quality of groundwater on a worldwide scale. Nitrate and fluoride are two toxins that have been found in groundwater, and their negative impacts on human health, particularly for newborns and children, have been well-documented. The North-West region of Delhi, where considerable changes in land use have occurred as a result of urbanization, is the focus of the study. The research aims to comprehend the effects of growing urbanization on groundwater quality and human health by analyzing the hydrogeochemistry of groundwater and pinpointing the pathways of contamination brought on by urbanization. The environmental issues that India's iron and steel companies face, particularly when it comes to wastewater treatment. The Indian government has made investments in industries related to steel in an effort to grow the economy and meet its goals. On the other hand, severe environmental contamination and heavy water use have historically been associated with the iron and steel sectors. The effectiveness of various wastewater treatment methods is examined, as well as the effluent quality and wastewater management practices. The research of more cutting-edge treatments like membrane separation and membrane bioreactors is prompted by the fact that conventional procedures alone are frequently insufficient for the total reclamation and remediation of effluents (Garfí et al., 2017). A possible strategy for obtaining a high rate is the integrated system combining chemical treatment and membrane separation. Reusing wastewater and managing it well, together with intensifying processes, are essential for assuring commercial viability and environmental friendliness. The relationship between India's GDP and steel production shows how important the iron and steel industry is to the country's economic development (Atilgan & Azapagic, 2015). Steel is a recyclable material with numerous uses across numerous industries. However, the manufacture of steel is a water-intensive process since it needs a lot of water. Numerous pollutants present an environmental risk to receiving water bodies in the effluents from mines and mineral beneficiation facilities. It is necessary to adopt technologies that reduce water usage or encourage wastewater reuse and recycling after treatment since the excessive water use in the steelmaking process strains freshwater resources (Corominas et al., 2013). Technologies for treating wastewater are divided into primary, secondary, and tertiary stages with the goal of removing suspended solids, oil and grease, heavy metals, and inorganic and organic contaminants. Advanced oxidation techniques such UV photolysis, hydrogen peroxide oxidation, and ozone treatment are used after these steps (Bernhard et al., 2006). Although they necessitate several steps, prolonged treatment timeframes, and constrained shock load-bearing capacities, biological techniques like activated sludge processes are also used in India. The extract illustrates membrane treatment's potential as a substitute for conventional techniques, while issues like membrane fouling and falling efficiency need to be addressed. This research especially focuses on the steel industry, giving a critical assessment of production technology, effluent generation, present practices, and future directions (Coats et al., 2011). Previous studies have primarily concentrated on wastewater treatment in other industries. Five frequently employed data-driven models for forecasting diminishing groundwater levels in Delhi, India's National Capital Territory, are evaluated for their accuracy. This study offers insights for policymakers to prioritize groundwater management activities and is useful for choosing an acceptable model for areas with little data available. The paper also covers the popularity of numerical modelling methods for predicting water resource availability as well as the benefits of univariate forecasting in regions with little data (N. K. Singh et al., 2017). Changes in the region's geological formation, hydraulic conductivity, and recharge volume were among the causes of the water quality changes. The study showed that quality indices increased during the rainy season, especially in wells along river channels or agricultural areas. The findings offer insightful information on the Kabul basin's groundwater quality (EMMERSON et al., 1995). These findings can be used by local authorities to create sustainable water resource management plans. The study emphasizes the significance of long-term monitoring for determining temporal fluctuations and determining trends in groundwater quality. Anthropogenic causes, such as sewage contamination, were identified as important contributors to groundwater pollution in the area given Kabul's rapid population increase and the absence of coordinated infrastructure for wastewater management (Gallego et al., 2008). The goal of the study is to identify any major seasonal variations in groundwater quality measures and compare them to requirements for drinking water quality. Understanding the spatial range of qualitative indicators is aided by spatial examination using ArcGIS. The study aids in attempts to manage groundwater sustainably by analyzing seasonal variations and evaluating changes in quality (R. P. Singh et al., 2020). The ozone layer, which is formed by ozone and is mostly present in the stratosphere, shields us from the Sun's harmful UV rays. However, it was found in the 1970s that man-made compounds, such as chlorofluorocarbons (CFCs) employed in a variety of applications, might deplete the ozone layer. Researchers looking into this environmental problem discovered that the manufacturing and usage of ozone-depleting compounds was leading to an increase in the amount of these substances in the atmosphere (Cartes et al., 2018). The chemical processes involved in ozone breakdown were characterized by laboratory studies and air measurements, which allowed the creation of computer models to forecast the degree of ozone depletion. Significant ozone loss was seen in observations, especially over Antarctica, or the "ozone hole." Other places also saw ozone layer thinning (Ternes et al., 2004). It was made clear by the combined efforts of experts from around the world that additional ozone depletion would happen if ozone-depleting substances kept accumulating. In response, as a global effort to solve the problem, the international community created the United Nations Montreal Protocol in 1987 (Sahar et al., 2011). Compliance with the Protocol has slowed the global buildup of ozone-depleting gases and decreased the risk of further depletion, along with the development of ozone-friendly alternatives for restricted substances. The excerpt illustrates the accomplishments made possible by the research, comprehension, choices, and actions of scientists, technologists, economists, lawyers, and policymakers. The Scientific Assessment of Ozone Depletion: 2002 offers 20 questions and answers regarding the intricate science of ozone depletion to promote ongoing discussion (Vlasopoulos et al., 2006). These inquiries address issues such atmospheric ozone, ozone-depleting substances, polar and global ozone depletion mechanisms, and the ozone layer's future. The solutions are supported by international scientific study and collaboration (Fahey, 2002). The development of blends by combining several single component refrigerants has been prompted by the demand for refrigeration and air conditioning with a variety of applications. Blends fall within the zeotropic or azeotropic categories. Zeotropic mixtures have a range of boiling and condensing temperatures at a specific pressure, or "temperature glide." The relative ability of ozone-depleting substances (ODS) to deplete stratospheric ozone is compared using the ODP values (Risch et al., 2014). The worldwide loss of ozone caused by a particular substance is compared to the global loss of ozone caused by CFC-11 (trichlorofluoromethane), which is given an ODP value of 1. For typical HCFCs and CFCs, the extract yields ODP values (Mohr et al., 2009). The mass-weighted average of the ODPs of a blend's constituent components is used to calculate the ODP of the mixture. By summing the ODPs of each component in proportion to its mass, one can calculate the ODP of a blend. The ODP is calculated by averaging the data after multiplying each component's proportion by its individual ODP (Theodosiou et al., 2014). A table containing examples of blend compositions, their corresponding ODPs, and ASHRAE designations is also included in the extract. In its whole, the extract describes the idea of refrigerant blends, how to calculate ODP for blends, and offers examples to clarify the procedure (Jensen et al., 1997). It emphasizes the need for both rigorous scientific methods and simple, easy-to-understand approaches that align with life cycle thinking. The choice of method should be based on specific goals, scope, target audience, and publication strategy. A key requirement for all life cycle assessments is to provide reliable and solid results that can serve as a foundation for subsequent decision-making (Mandal et al., 2014). Over the past decade, several projects focused on LCA and life cycle thinking have received financial support. The outcomes of these projects will be published as a mini-series called Environmental News by the Danish EPA, starting in 2000 and continuing in the coming years. These publications will complement the results of the 1996 EDIP-project (Sivakumar Babu et al., 2014). The tools, experience, advice, and guidance derived from these projects collectively form a strong platform for various applications of life cycle assessments. However, due to broad and complete nature of life cycle assessment, it is almost not possible that a single book can cover all situations and applications. Nevertheless, the Danish EPA hopes that the LCA publications will provide a valuable resource for companies, institutions, authorities, and others interested in adopting the life cycle approach (Stranddorf et al., 2005). Various methods for assessing toxicity impacts are being used or developed, but no single method has gained universal acceptance (Nogueira et al., 2009). The University of Tennessee (UT) presents a detailed approach to chemical toxicity impacts in their LCIA methodology, addressing human and ecological toxicity, which is often overlooked in other methods (McDonald et al., 2014). The ISO 14042 standard considers the first two steps mandatory, while valuation is optional.

The classification phase involves identifying impact categories and assigning inventory inputs and outputs to those categories (Hospido et al., 2012). The UT methodology includes impact categories such as natural resource impacts, impacts on abiotic ecosystem, impacts on human health and ecotoxicity impacts. The disposition of outputs determines the applicable impact categories for calculation (Sikosana et al., 2019). Quantitative estimation of life-cycle impact category indicators is performed in the characterization step. Overall, the extract provides an overview of the evolving nature of LCIA methods, highlights the UT methodology's approach to chemical toxicity impacts, and outlines the classification and characterization phases of LCIA. Computers play a significant role in LCA, aiding data analysis and transforming it into valuable information and knowledge (Rodriguez-Garcia et al., 2011). However, the misuse or mismanagement of computer-based LCA software can be detrimental. While full LCA studies can be time-consuming and expensive, simplified forms tailored to specific products or purposes are commonly used (Pasqualino et al., 2011). LCA supports environmentally sound choices and can lead to product improvements, process optimization, and new approaches to meeting environmental targets. LCA is not mandatory but is being encouraged by customer companies and some countries through environmental accounting and reporting requirements (Yildirim & Topkaya, 2012). Green procurement and ecolabelling are emerging trends associated with LCA, where product policies and procurement systems are leveraged to drive eco-efficiency. Stakeholder views and external perception of LCA's usefulness are critical, and a growing number of information sources, scientific papers, reports, and websites dedicated to LCA are available for further exploration (Morera et al., 2016).

2.1 Wastewater Treatment Methods

The water which is free from any external treatment given to it is called raw water. From various sources of water, it is carried to residential, commercial, industrial areas. After its usage, the water produced is called wastewater. This wastewater carries lots of contaminant constituents in it, the concentration of which depends upon the source which generates this wastewater. When this wastewater is disposed of into streams then it deteroit the neighboring water quality levels. In addition to this, it also brings down the water quality level at the downstream of the stream from where the water was needed to be carried and treated as a source of water. So environmental degradation as well as degradation of a source of water both takes place simultaneously. These problems can be tackled by recycling of water but for recycling of wastewater the efficiency of treatment is to be increased. Conventional wastewater treatment methods are not sufficient for the recycling purpose. In this study, we will look at the

WWT methods which are at par with the conventional methods and will compare different methods as to which one is the best amongst all with respect to the environmental sustainability.

2.1.1 Activated Sludge Process (ASP)

The activated sludge process, a type of biological wastewater treatment method, uses a biological floc made up of bacteria and protozoa to treat sewage or industrial wastewaters. Utilising air (or oxygen) and microorganisms, it biologically oxidises organic pollutants to produce waste sludge (or floc) that contains the oxidized material. (R. P. Singh et al., 2020). The activated sludge procedure for removing carbonaceous pollution starts with the aeration tank. In this instance, waste water is pumped with air (or oxygen). The biological flocs (the sludge blanket) are then allowed to settle in a settling tank, where they are separated from the clean, treated water. (Cañote et al., 2021). The remaining waste sludge is removed, treated further, and eventually disposed of, with some of it going back into the aeration tank. Sludge thickening, which frequently affects the effluent quality in the end and makes activated sludge challenging to settle, can occur. (Castro & SÉBASTIEN CARON, 2006). Professional management is important to treat sludge thickening and maintain the facility to prevent a recurrence. It might also be necessary to staff a facility full-time to enable quick response.

2.1.2 Membrane Bio Reactor (MBR)

Membrane bio reactor is an advanced wastewater treatment method in which membrane is used to separate out the solid biomass and microbes on the one side and allow the clean water to pass through it to the other side (Rahman et al., 2023). It is an advancement of Activated Sludge process in which secondary units are to settle down the biomass present in the wastewater which takes a lot of time and efficiency is on lesser side as biomass with smaller specific gravity may remain in suspended form and could not be separated out (Postacchini et al., 2016). Since, the membrane allows only the water to go out, due to this biomass accumulated has higher density and hence more aeration is required in the aeration tank as compared to the ASP, due to which the electricity consumption rises causing more damage to the environment (Glover et al., 2022). Also since the membrane is used to separate all kind of contamination, the pores of this membrane get clogged with time and hence causes odor problems, which is a big drawback in case of MBR. The requirement of area and machinery is reduced as secondary settling tank and clarifier is not required in MBR. The overall quality of effluent received from MBR is much better than that received from an ASP(Postacchini et al., 2016).

Membrane used in reactor

A membrane is a substance that allows the flow of some selective substances through it while retaining some material on the other side of the membrane.

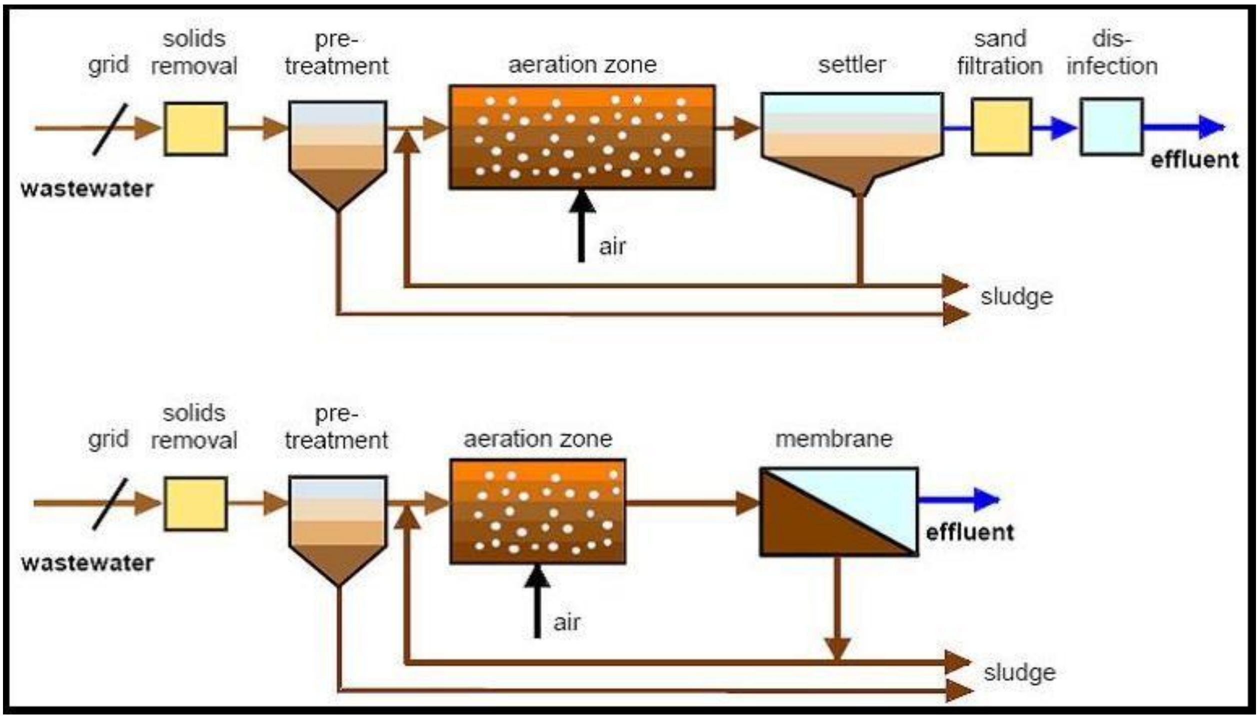


Figure 2.1. A typical diagram showing the stages at which ASP (top) is different from MBR (bottom)

In case of purification of water, the main aim is to allow the flow of clean water and retaining the undesirable particles and microorganisms on the other side. Membrane bio reactors are of following types based on the configuration:

- Internal (submerged) modules
- External (side stream) modules

Fouling in MBRs

By way of physical and chemical interactions, particles (such as colloidal particles and solute macromolecules) are deposited onto the membrane surface or pores during fouling. As a result, the membrane's pores become smaller and blocked. This is a crucial factor to take into account while constructing MBRs.

2.1.3 Bio Electrochemical Constructed Wetland

These are engineered wastewater treatment system which are designed to replicate the natural phenomena used by wetlands to treat the wastewater. Major treatments which constructed wetland can provide are as following:

- Adsorption
- Filtration
- Hydrolysis
- Biodegradation
- Bioaccumulation
- Phytoremediation
- Photo-remediation

Studies have been conducted in order to determine the environmental sustainability of conventional constructed wetlands (CW) an bioelctrochemical constructed wetlands (ECW) using life cycle assessment approach, which shows that both CW and ECW have significant impacts on aquatic environment, especially on the marine aquatic ecotoxicity (Resende et al., 2019).

2.1.4 Soil Biotechnology

In the research work reviewed six locations were considered, of which soil biotechnology wqs installed and studied. The on-site data of two plant locations was available. Soil biotechnology is a green methodology in which natural treatment of wastewater is given, the water after treatment can be used for the purpose of agriculture and other purposes. Wastewater received is made to pass through a number of different layers, which contains gravels, microorganisms and aggregate in an order of increasing particle size. This acts as a filter media and the microbes carries out decomposition of organic matter. A gradient at the surface is provided so that water percolated can be received in the tank ahead.

CHAPTER 3

METHODOLOGY

3.1 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) refers to evaluate some characteristics of a system over all of its life cycle, frequently the environmental concerns. It consists of various tools and techniques which are useful to carry out environmental management in the long term and hence aids to provide data and information needed to achieve sustainable development. The historical discovery and further enhancement of LCA is discussed later on. Sustainable development has gained importance on national and international agendas. It is necessary to provide checks on the amount of natural resources being used, in minimizing the waste generated and to improve the efficiency of a particular amount of energy being used by bringing advancements in conventional technologies.

In the past, a manufacturer would no longer be concerned about their product once they had handed it off to a distributor or customer. But in the modern era, where Sustainability is an essential requirement with respect to product manufacturing, and various SDGs have been defined to safeguard against adverse environmental impacts. As a result, the producer's obligation does not stop at the factory gate. Governments are also starting to enact "take back" regulations, which mandate that producers return their trash and reprocess at least some of the waste they generated. Many different resources renewable or non-renewable land, plants, minerals, water, animal are needed to be added in the LCA study. Depending on country or region from where the study belongs the process of production of same energy changes, as in some part of the world as in India most of the electrical energy production is by Thermal power plants which requires coal (fossil fuel) for its production, similarly there are countries which use renewable energy sources such as tidal, wind, nuclear. So this represents that to produce the similar amount of energy the environmental impacts can be drastically different as the renewable sources produces very less environmental degradation compared to the renewable sources for the same amount of energy production.

Further computer software helps in the calculation of damage assessment by using the inputs given to the software in the form of electricity consumption for that process, the emissions of various gases to the air, emissions to water, emissions to the soil such as heavy metal. The database i.e. how to calculate the damage assessment, characterization of various major pollutant released based on the region in which the study is being carried out is already predefined in the software, which makes the calculations and time consumption lower. LCA is not mandatory but an option for the companies. The database available for conducting an LCA is not available easily with respect to Indian context, also no governmental organizations had made available on online portal for easy access.

In the late 1960s and early 1970s, the first studies that were conducted using life cycle elements of goods and materials were carried out, with an emphasis on calculating energy use, raw material consumption, and waste disposal. Coca Cola Company financed the research work in 1969 to ascertain the amount of resources used and environmental discharges related to beverage containers. Ian Boustead performed a research in the UK in 1972 to ascertain the amount of energy consumed in the manufacture of several kinds of beverage containers, including those made of glass, plastic, steel, and aluminum. Later, Boustead refined this methodology so that it could be used with other materials as well, and he released "Handbook of Industrial Energy Analysis" in 1979. LCA is still regarded as a new tool on the market even if there has been progress over the last three decades. But LCA has acquired industrial and commercial relevance with the advent of the SDGs and the need to identify which technology fits the most sustainably to carry out a set of activities. There are several software solutions available right now that have a variety of databases built into them that can be utilised both locally and globally. Ecochain Mobius, Ecochain Helix, GaBi, OneclickLCA, and Simapro are among of the programmes in this list. The methods used in a general LCA procedure is described in this chapter. Additionally, the technique utilised specifically for my research project, the software employed, the database utilised, and the life cycle inventory taken from several research articles are all explained in depth. Depending on the specific approach used in the same programmed, the outputs created consist of several categories that indicate the consequences on different environmental factors.

Basically, as per ISO to perform the life cycle assessment, there are some basic steps that are required to be followed which are mentioned in different codes. By identifying and quantitatively evaluating the energy and materials consumed, as well as the waste that is emitted throughout this process, life cycle assessment (LCA) is a technique to analyze the environmental consequences on the production and use of a product. This evaluation covers every stage of the product's or activity's life cycle, such as the gathering of raw materials, processing of those materials, production, distribution, usage and re-use, maintenance, recycling, and final disposal. It also covers the transportation needed for each individual subprocess. The research system's effects on ecological systems, human health, and resource depletion are addressed through LCA. However, socioeconomic implications are not included.

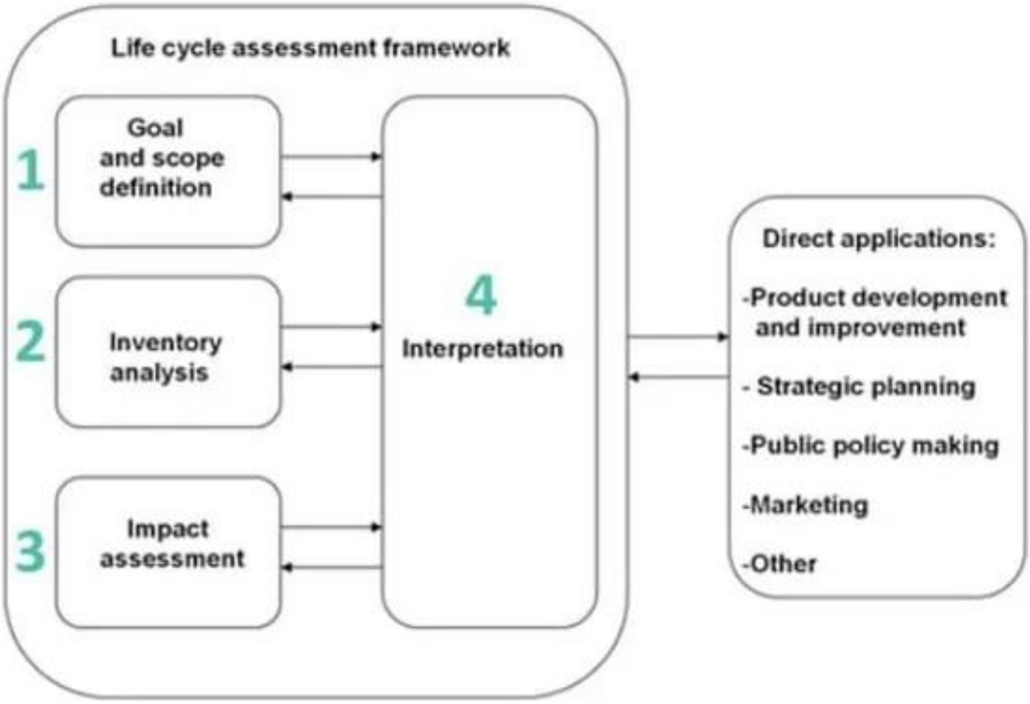


Fig. 3.1: Life cycle assessment framework: phases (ISO, 1997a)

3.2 Goal and Scope definition

The initial stage of LCA involves defining the objective and scope of the work that will be done. As part of the life cycle assessment, the aim, the zone up to which work is to be considered (i.e., cradle to grave approach), the functional unit employed, the limits of the system being evaluated (i.e., cradle to gate, cradle to grave), etc. are all defined. The objective of this study is to conduct a comparative analysis of biological wastewater treatment technologies in order to evaluate the environmental implications they are posing and, as a result, to determine the most effective treatment method that is practical and long-lasting. Four alternative approaches are taken into consideration in this study, three of which are cutting-edge technologies and one of which is a traditional approach called the Activated Sludge Process. Among these latest methods there is a method which provide very high quality treated water but its energy consumption is high during operation due to which it poses higher environmental impacts. The rest two methods viz. Soil Biotechnology and Bio Electrochemical Constructed Wetland are majorly eco-friendly methods and requires very less machinery and anthropogenic work but the efficiency of treated water received is of order lesser than the membrane bioreactor.

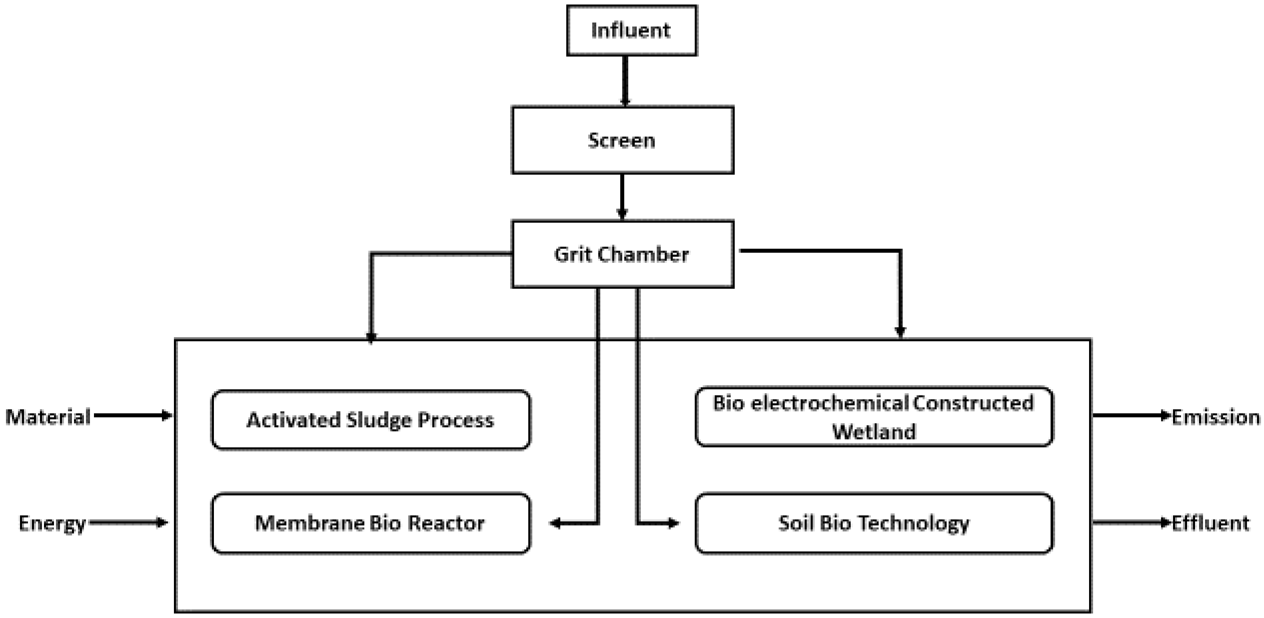


Fig. 3.2 System boundary of wastewater process

These methods perform the function of biological treatment of wastewater, however, all four process differs in some or the other way. The functional unit considered is m3 i.e. volume. Environmental impacts considered during the construction phase of each treatment techniques are very less as compared to the impacts due to the whole treatment process. Hence, the environmental impacts during the construction phase are ignored. If we are doing the analysis for a particular method then each of the object involved in it, during construction, during operation phase, objects required for maintenance works, the LCA of all objects is needed to be considered in addition to the LCA of the original method. Due to this, it becomes a time consuming and a lethargic process to handle. Here, software packages are brought into help, which consists of in-built database of the various in between materials used other than the original process. For example, if LCA of a particular wastewater treatment method is carried out, then construction materials would be required so resources/ raw material are used, these material must be brought by transportation from some location, so here also emissions during transportation will cause environmental impact. In addition to this, the truck itself is manufactured using some raw material, so it itself will be requiring an LCA, so these all LCA of the materials or objects in between used other than the original thing for which LCA is being is performed with lesser efforts using software which have in-built LCA database.

3.2.1 Functional Unit

Defining the functional unit of the system for which LCA is being performed is very essential and a careful step. While carrying out the study if comparison between two or more systems is required then a common base is needed or a normalized base is required for assessing the comparison among different methods. Depending on the functional unit, data is collected in the inventory and a life cycle inventory is made. The main purpose of functional unit is that the inputs and outputs are clearly defined and normalized with respect to this unit. Now the impact assessment results produced will be represent the results per unit of that functional unit. In this study, functional unit considered is m3. It means that the inventory which contains the input of electricity consumption, emissions to air, emissions to water, emissions to soil, transportation fuel/energy consumption will give the output by performing an LCA, that output means that 1 m3 of wastewater treated using a particular method, will create this much amount of certain environmental impact. The same goes for all the damage categories. These environmental impacts being different will have different output units, the different damage assessment will have different output units, but the functional unit with respect to which the outputs are produced will be same which is m3.

3.3 Inventory Analysis

Inventory analysis is the second step in a life cycle. It includes the collection of data to be used in assessing the material consumption, energy consumption, emission profiles with respect to air, water and soil for all phases of life cycle.

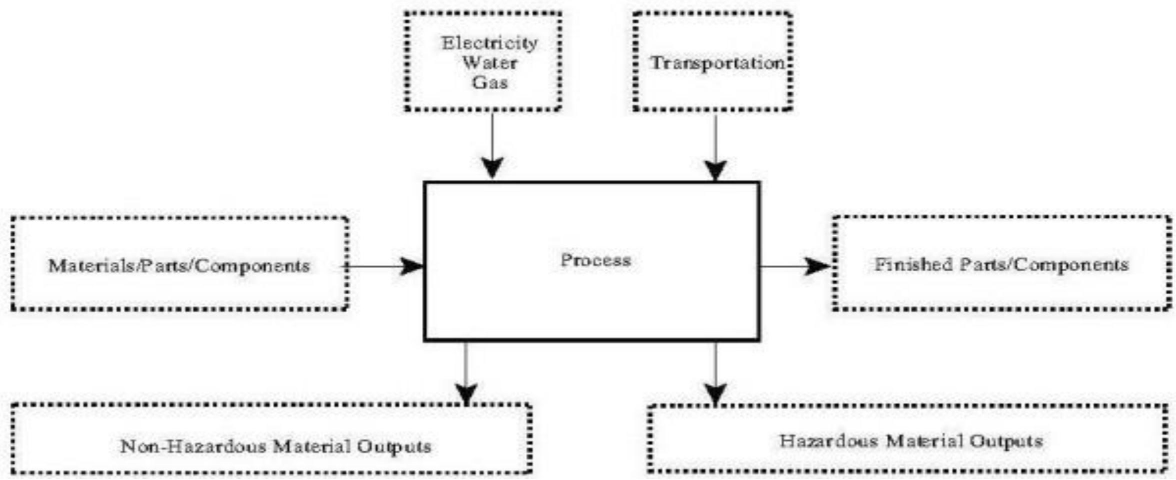


Fig. 3.3 Input and Output of LCIA

It also includes the transportation emissions during each step of the whole life cycle. In many countries this data is available on the government website but in India LCA data is not or very less available in such a manner. This data can be gathered by going through the previous studies conducted by different researcher of that area, can be issued from companies which formulate such data, from more general data sources such as trade organization, public surveys, etc. Data collection is the most intensive part in the LCA study. Table 4.1 shows an example of a flow sheet consisting of life cycle inventory, it shows the various categories of input and output data required to form an inventory. The input data includes various type of fuels used to generate energy for that particular process. It also includes the raw materials which are to be extracted forming a part of natural resources. The output consists of the emissions to various resources which causes the deterioration of the environment. The emissions to air leads to increased levels of harmful gases such as CO_2, SO_2, nitrogen oxides, hydrogen sulfide, hydrocarbons, etc. The emissions to water includes contamination in the form of COD, BOD, pH, dissolved solids concentration, etc. It also includes the sludge/waste generation which is to be carried to the disposal, now this process again requires transportation usage.

In addition to the data collection, inventory also includes the calculation procedures to be followed. Since the amount of data is huge and is of different categories such as inventory input-output data, impact assessment results, damage assessment results, thus, it is required to assemble this data in different spreadsheet. Data is to be recognized into graphical outputs so that it becomes easy to understand and perform the comparative analysis. In addition to these data analysis, outputs are produced through huge LCA analysis of each sub material being used in the main wastewater methods. So use of software becomes an important tool for conducting the LCA. Each software consists of large number of methods to provide impact assessment, the results and outputs associated with each method are different. In this study, the software tool used is OpenLCA 2.0.0 with database ecoinvent 3.9.1. Moreover, in OpenLCA there are further different methods available to carry out the analysis.

Amongst these methods the study is carried out using IMPACT 2002+ approach. This method performs analysis and provides output in the form of fifteen impact categories, moreover, includes four damage assessment categories which are human health, climate change, etc., further discussion will be carried out in later sections.

Table 3.1. Inventory Data of WWTPs

Parameters	Unit	ASP	MBR	SBT	ECW
Wastewater Treatment					
Input from Technosphere					
Electricity	kWh	0.189	0.46982	0.036	7.58E-2
Emissions to Air					
Carbon Dioxide	g	283	701	54.7	-
Sulfur Dioxide	g	1.66	4.11	0.318	-
Nitrogen oxides	g	1.23	2.91	0.225	0.003
Carbon monoxide	g	0.138	0.341	2.81E-2	-
Methane	g	-	-	7.42E-2	0.015
Heavy metals	g	1.93E-3	4.79E-3	3.7E-4	-
Emissions to Water					
COD	g	9.9E-2	0.245	21.3	-
Nitrogen, total	g	2.58E-7	6.38E-7	7.33	-
Phosphorus, total	g	7.29E-7	1.29E-6	2.65E-10	-
Heavy metals	g	0.189	0.469	0.18	-
Emissions to Soil					
Heavy metals	g	1.2E-3	2.96E-3	2.29E-4	-
Output to Technosphere					
Sludge	kg	0.051	0.004	0.00113	-
Input from Technosphere					
Truck	km	50	50	50	-

3.4 Impact Assessment

The life cycle inventory list, which includes various materials and energy consumption amounts relevant to the researched product, is analysed and converted into comprehensible effect indicators in this stage. These indicators show how seriously each effect category contributes to the environmental load. According to ISO standard 14042, these indications are evaluated after a number of processes, some of which are required and others of which are optional. Category definition, classification, and characterisation are required processes, but valuation/normalization is an optional phase. Impact assessment is the third phase in the life cycle assessment. The draught ISO standard CD 14042.1 is used to illustrate these problems (ISO, 1997c). Utilising the input and output characteristics for the specified system in the inventory database, the impact assessment refers to the quantitative and/or qualitative process of characterising and calculating the impacts on the environment.

3.4.1 Category Definition

Defining the various effect categories that will be taken into account in the LCA research is the first step in the life cycle impact assessment process. The definition of the category is dependent on the kinds of data gathered throughout the inventory used in life cycle stage and extent to which environmental consequences must be evaluated. Additionally, the definition of the effect category changes as the scope of the life cycle evaluation, such as whether it is a cradle to grave or cradle to gate system, changes. A number of things are to be kept in mind while defining each category. It should be covering all possible environmental problems which can be produced when the treatment of wastewater from different methods is being carried out. It should be having practical importance I.e. the magnitude of values coming out should be significant order so that it should get a place in the category list. However, it also depends on the software model which we are choosing to produce output, as it contains predefined impact category outputs. In this study, IMPACT 2002+ software methodology of OpenLCA software is being used.

3.4.2 Classification

Classification is qualitative step which is based on scientific analysis of different environmental processes. During classification each input output is required to be assigned to a particular impact category, which represents that a particular output of impact category is associated with some particular data inventory as input, so if these input data are present in the LCI then, a set of outputs for impact category will be required to be generated. Till now, a common conclusion cannot be reached so as to ascertain single default list of impact categories. Therefore, depending on a particular system to be analyzed using LCA the category list can be chosen based on previous study results. This selection is handled by the software database by the use of which life cycle assessment is being performed. Different software models provide different impact categories and classification. As a result, in order to conduct analysis using the acquired inventory data, it becomes vital to recognize and comprehend the many models that are contained in the LCA programmed. The impact categories are established and chosen to explain the effects of emissions and resource consumption at the time of creation, utilization, and discarding of the product or technology under consideration.

These three primary regions of shielding are lead up by a number of impact indicators (midpoint and endpoint indicators) that reflect the influence on the environment. Later, we'll talk about each methodology's properties-

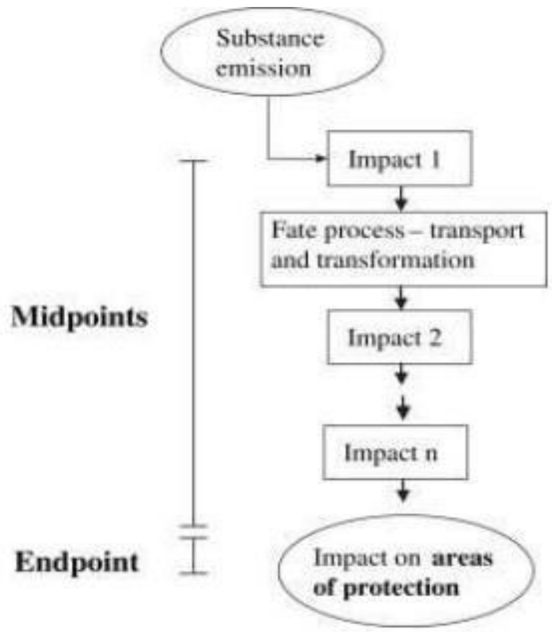


Fig. 3.4 Midpoint and Endpoint categorization difference

3.4.3 Characterization

After selecting and defining the impact categories, the environmental burden of each input and output within the system is assigned to them. These impact categories are then transformed to indicators that show the relevant possible environmental impact. To achieve this, multiply the categorization findings from the inventory by the characterization factor for each drug inside each effect category.

For instance, global warming potential (GWP) is frequently used to aggregate the relative contribution of various gases to climate change in terms of carbon dioxide equivalents. A GWP500 of 100, for instance, means that 1 kilogram of that chemical has the same overall impact on the climate that 100 kg of carbon dioxide would have over the course of 500 years. Utilizing quantitative methods of scientific study for a specific environmental process, the characterization factors are computed.

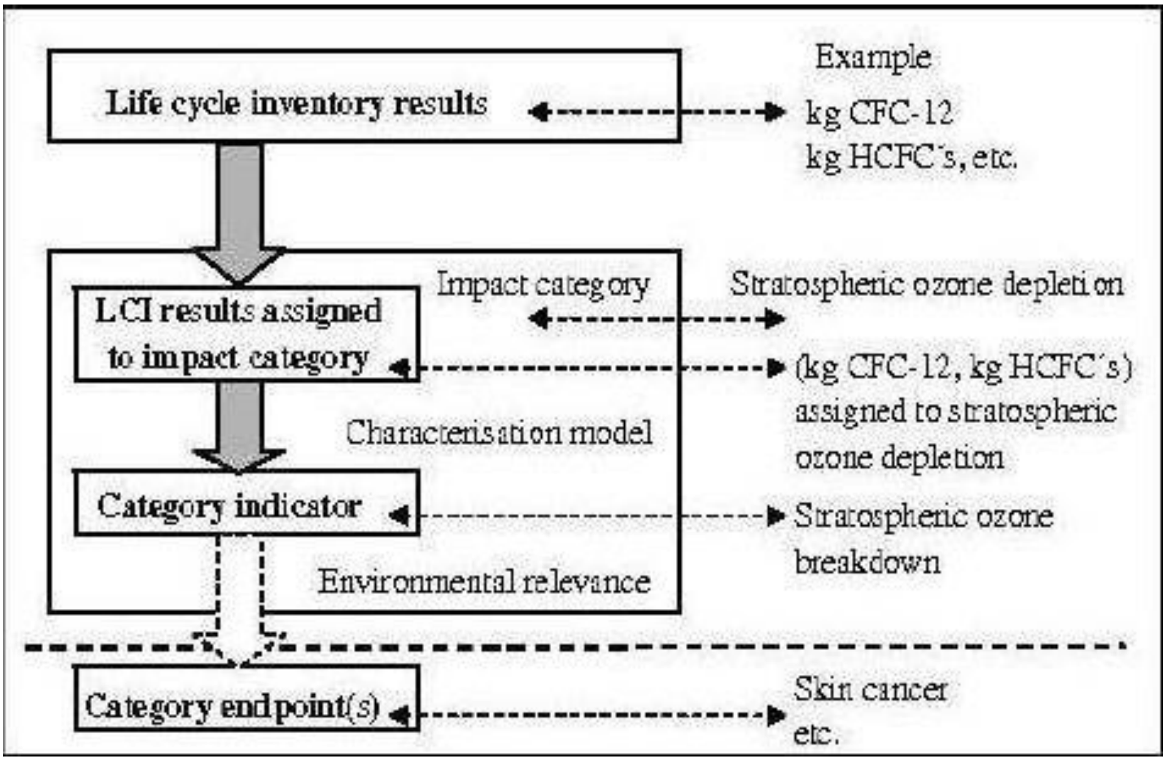


Fig 3.5. Midpoint and endpoint assessment approaches

The LCIA step is considered to be the most crucial phase in an LCA study. The enormous amount of data that was reported in the results of the inventory analysis must be dealt with in this stage. Utilizing sophisticated environmental modelling, these inventory findings are converted into effect indicators. Methodologies to amplify and optimize the LCIA were developed to address these challenges.

3.5 Combine midpoint and endpoint approach

3.5.1 IMPACT 2002+

This approach, which was created by the Federal Institute of Technology and Federal Polytechnic School of Lausanne, France, combines midway and endpoint focused methodologies. This methodology's initial iteration was referred to as impact 2002. Regarding the comparative assessment of several impact categories, nevertheless, changes were made. The following midpoint categories are included in this methodology: human toxicity, respiratory effect, ionizing radiations, ozone depletion, formation of photochemical oxidants, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication and acidification, land occupation, global warming, non-renewable energy, and mineral extraction. Four endpoint harm categories—human health, environmental quality, climate change, and resources—are connected to these intermediate categories. The characterization criteria used in this technique were modified from Impact 2002, Eco indicator 99, and CML.

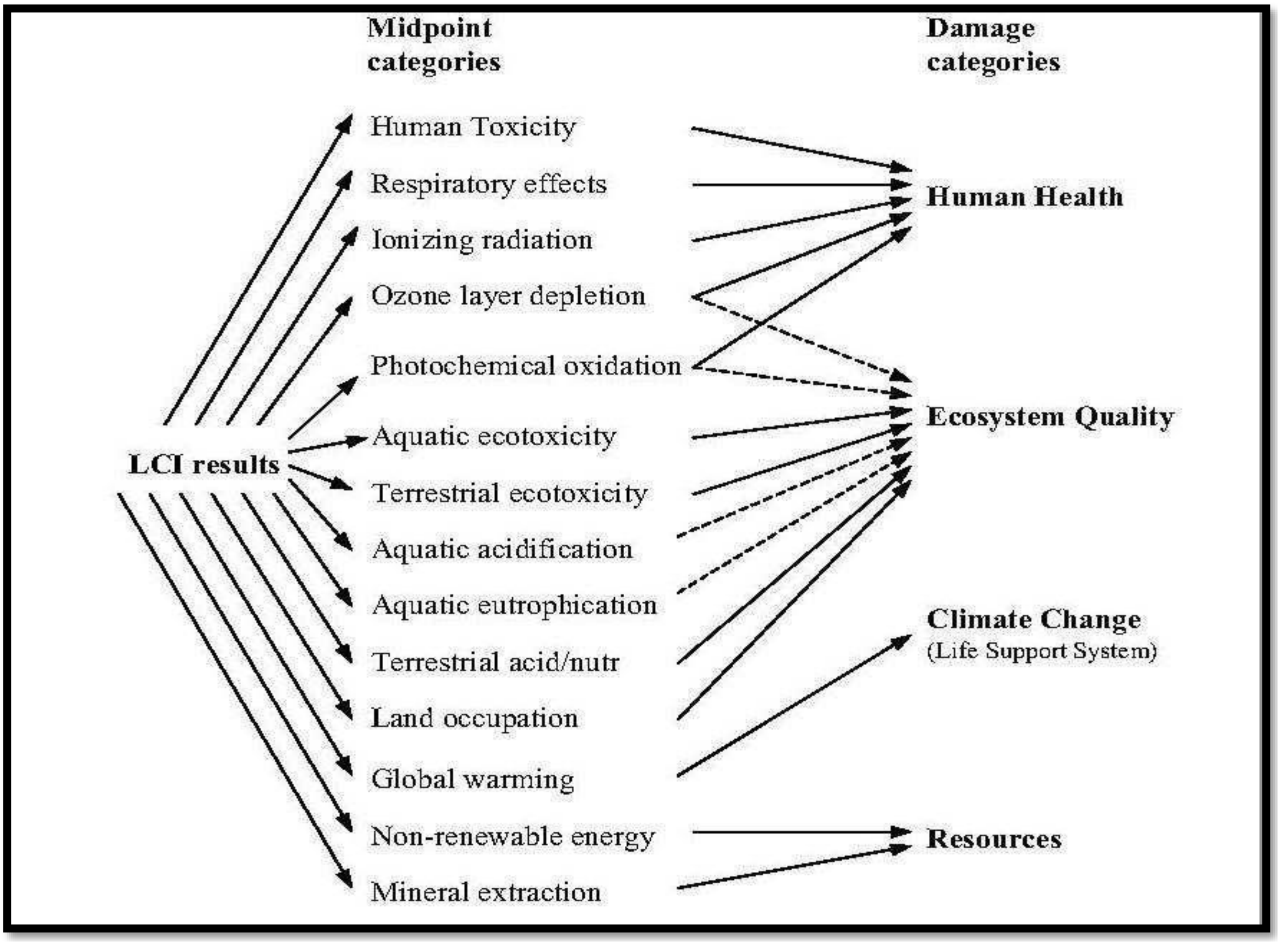


Fig 3.6 Methodology of IMPACT 2002+ approach

Table 3.2. Impact categories of IMPACT 2002+

Midpoint Category	Unit	Damage Category	Unit
Carcinogens	kg C_2H_3Cl eq.		
Non-Carcinogens	kg C_2H_3Cl eq.		
Respiratory Inorganics	kg $PM_{2.5}$ eq.		
Respiratory Organics	kg C_2H_4 eq.	Human Health	DALY
Ionizing Radiation	Bq C-14 eq.		
Ozone Layer Depletion	kg CFC-11 eq.		
Aquatic Ecotoxicity	kg TEG water		
Aquatic Eutrophication	kg PO_4^{3-} limited		
Terrestrial Ecotoxicity	kg TEG soil		
Aquatic Acidification	kg SO_2 eq.		
Terrestrial acid/nutrient	kg SO_2 eq.		
Land Occupation	m^2 organic arable land	Ecosystem Quality	PDF*M^2*yr
Global Warming	kg CO_2 eq.	Climate Change	kg CO_2 eq.
Non-renewable	MJ	Resources	MJ
Mineral Extraction	MJ		

CHAPTER 4

RESULTS AND DISCUSSIONS

A comparative life cycle assessment was performed in which four different methods were considered. The results which have been been assessed are represented with the help of data analysis tools. The result analysis is done for life cycle inventory, impact categories and damage assessment. Further, these results are validated by considering the current scenario in India.

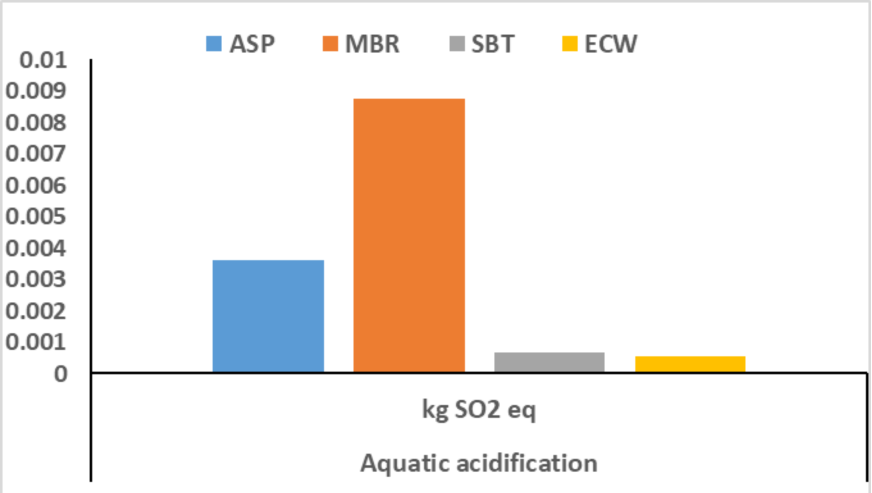
4.1 Life Cycle Inventory

The electricity consumption during operation phase is found to be least for ECW followed by SBT, ASP and MBR. Thus, the electricity consumption is maximum in case of MBR. The emissions to air are produced by MBR in maximum amount followed by ASP, SBT and ECW. The wastewater treatment methodology was conducted using OpenLCA 2.0.0, in which inventory data was inserted and results were evaluated. The inventory data is analyzed using IMPACT 2002+ approach. The life cycle inventory data were derived from research papers published particularly for the Indian scenario. In addition to this, the data required for the LCA of materials through which different parts of a system are made is performed by the ecoinvent 3.9.1 database.

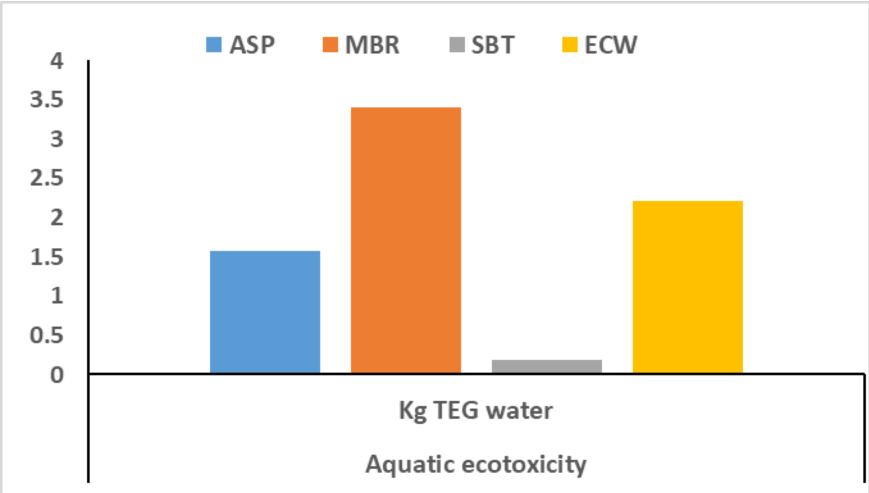
4.2 Impact Categories

4.2.1 Aquatic acidification and ecotoxicity

As shown in figure 4.1 and 4.2, MBR is causing the maximum environmental impact (0.0087 kg SO2 eq.) among all other processes on the aquatic acidification. The analysis performed, shows that this huge impact is due to the higher consumption of electricity with respect to other processes. The higher electricity consumption by MBR as compared to ASP is since the aeration tank in MBR requires more supply of oxygen as the biomass accumulation is more in due to presence of membrane.



(a)



(b)

Fig. 4.1 (a) Aquatic acidification (kg SO_2 eq.); (b) Aquatic ecotoxicity (kg TEG water)

4.2.2 Aquatic Eutrophication

SBT is causing the highest impact on acidic eutrophication as shown in the comparative analysis in the figure 4.2. This is the only impact category in which SBT shows an increased environmental impact with respect to other methods.

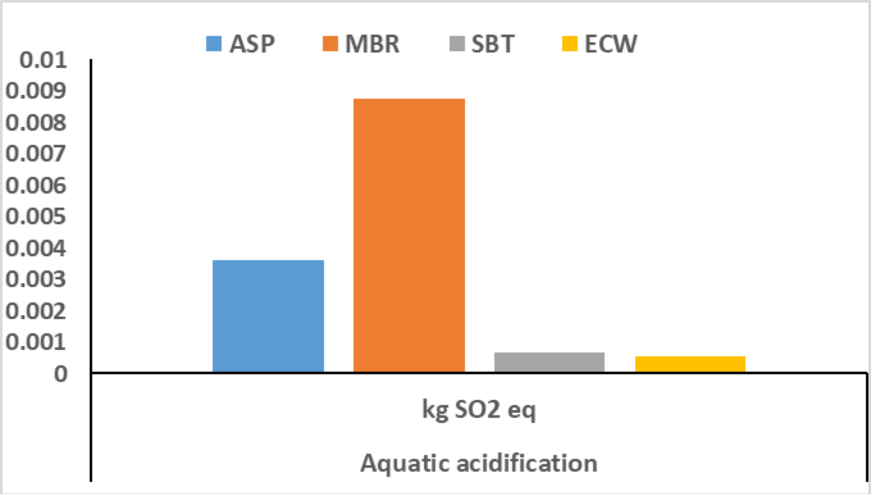


Fig. 4.2 Aquatic Eutrophication (kg PO_4 P-lim)

4.2.3 Mineral Extraction

Bio electrochemical Constructed wetland has the highest environmental impact with respect to mineral extraction of the order of 0.00537 MJ Surplus. This is the impact category in which it ECW exceeded all other methodologies. This is due to a number of construction materials such as gravel, sand being used in this methodology, out of other materials steel is causing the maximum impact on the environment.

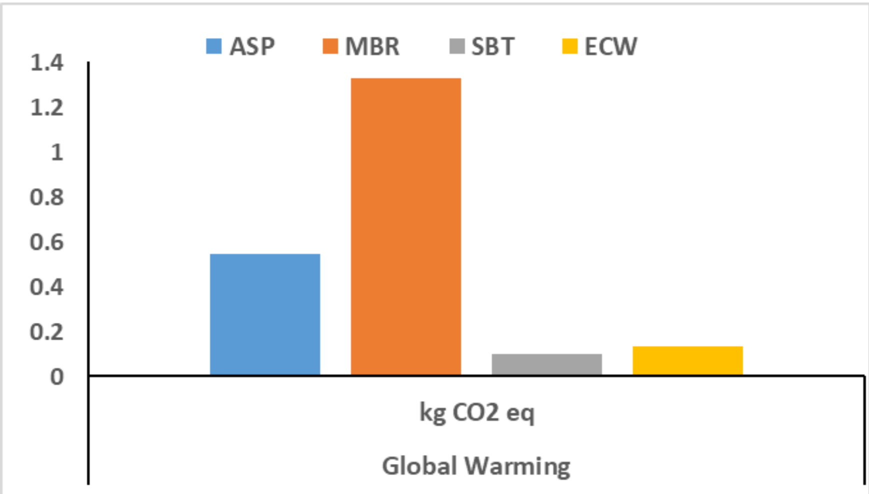


Fig. 4.3 Global Warming (kg CO_2 eq.)

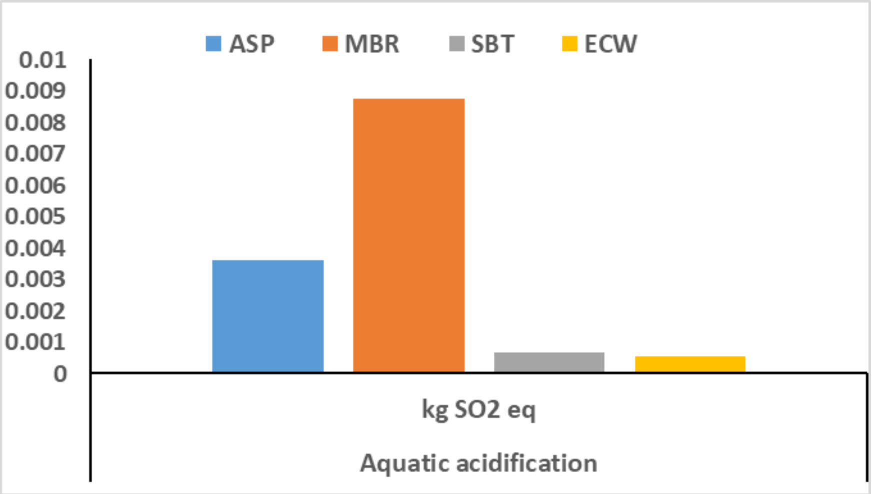


Fig. 4.4 Mineral Extraction (MJ)

4.2.4 Global Warming

Global warming is calculated in terms of the total kg CO_2 equivalents of gas produced or released into the environment. To calculate this global warming potential values are used with different gases which are released into the air. Each greenhouse gas has a different value of global warming potential. This impact also depends upon the lifetime of gases for which they can sustain in the atmosphere. The result shows that maximum amount of global warming is produced due to MBR method (1.33 kg CO_2 eq.), while SBT produces the least impact with a magnitude of 0.0996 kg CO_2 eq. ECW produces 0.131 kg CO_2 eq., followed by ASP with value 0544 kg CO_2 eq.

4.2.5 Ozone Layer Depletion

Ozone layer depletion refers to the depletion in the stratospheric ozone layer allowing more UV radiations to enter into the earth's atmosphere. This causes direct impact on the environment as well as adverse impact on human health, as it leads to increase in skin cancer, cataract, etc. In order to determine the value or magnitude of ozone layer depletion, different substances which are responsible for causing the ozone layer depletion, their mass fraction is to be multiplied with the ozone depletion potential values of the respective substances and then added up to get the final value. Approximately, no effect is posed by the SBT method, however, MBR causes the maximum amount of effect amongst all with a magnitude of 2.84E-8 kg CFC-11 eq., ASP with a value 1.64E-8 kg CFC-11 eq.and ECW 6.47E-10 kg CFC-11 eq.

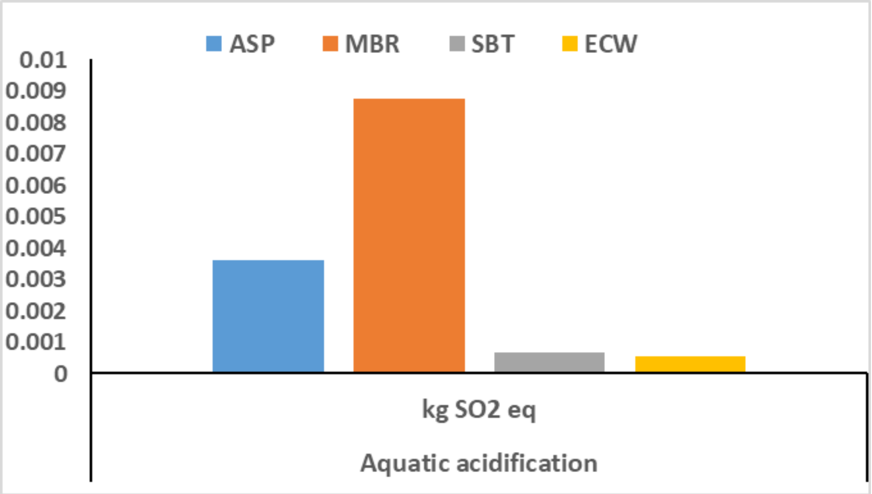
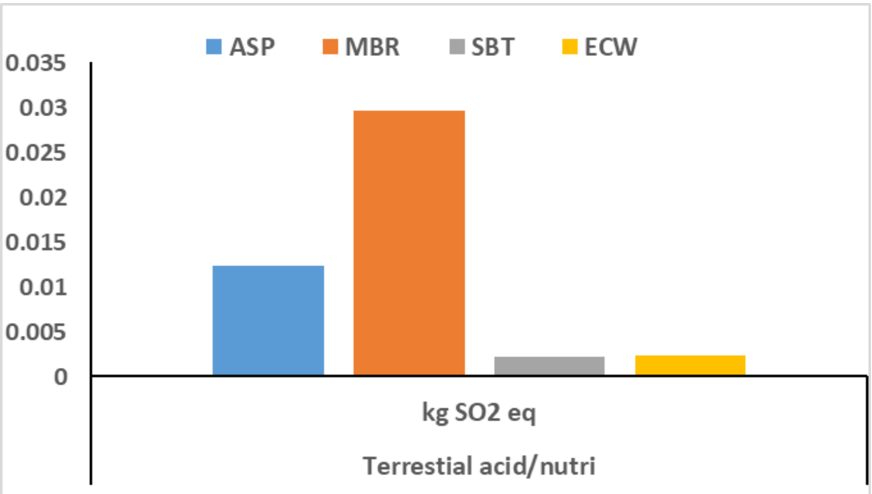


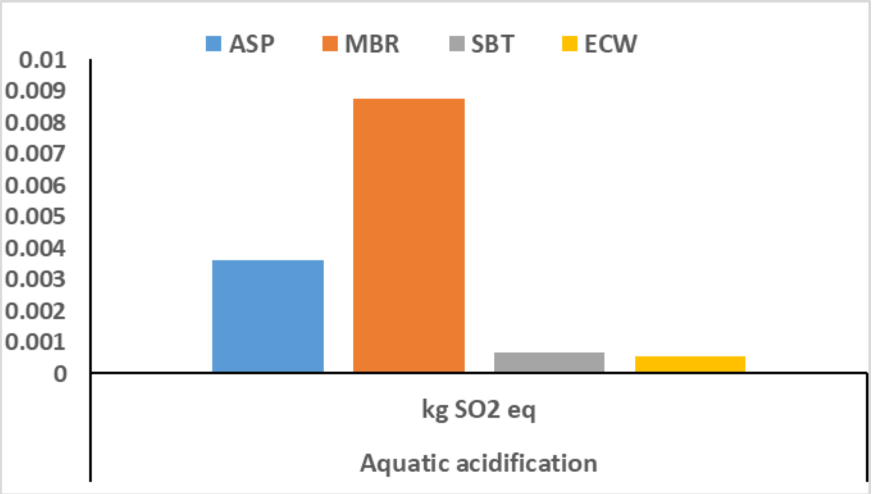
Fig. 4.5 Ozone Layer Depletion

4.2.6 Terrestrial acid/nutrient and ecosystem

Terrestrial ecosystem refers to the all the biotic and abiotic species which is surviving on land. This includes forests, grasslands, etc., in the impact category presented in this, the environmental impact on terrestrial ecosystem is measured in terms of kilograms of triethylene glycol produced in the soil. MBR and ECW produces comparable amount of impact to the terrestrial ecosystem with the respective values as 2.16 kg TEG soil and 1.92 kg of TEG soil. However, result shows that SBT produces least amount of impact with 0.122 kg TEG soil and ASP produces 1 kg TEG soil.



(a)



(b)

Fig. 4.6 (a)Terrestrial acid/nutrient; (b) Terrestrial Ecosystem

4.2.7 Carcinogens and Non-carcinogens

Carcinogens and non-carcinogens are measured in terms in terms of kilograms of C_2H_3Cl equivalents. These represents the production of cancer causing substances and non-cancerous organic matter produced as a result of some process leading to environmental impact. In both these categories maximum effect is produced by the MBR method. However, there is a distinction that the carcinogens produced by ECW (0.00103) are higher than that of ASP (0.000785), whereas, the non-carcinogens produced by ASP (0.00479) is higher in magnitude as compared to ECW (0.00249).

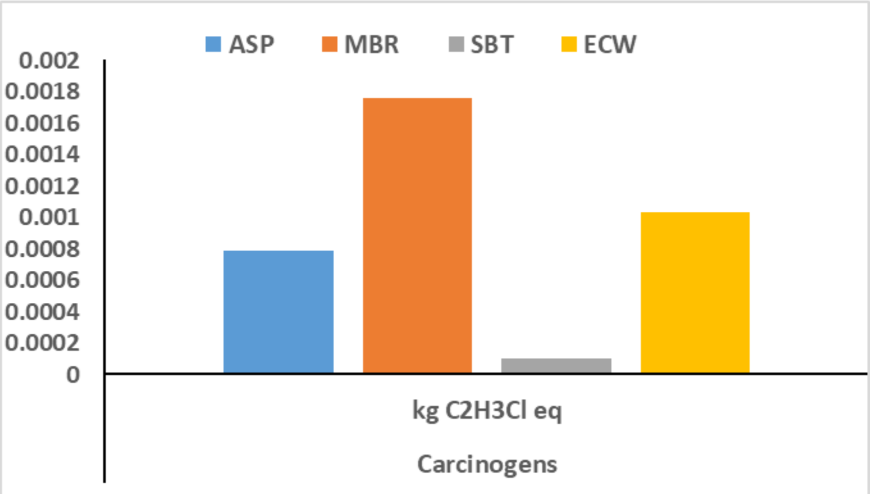


Fig. 4.7 (a) Carcinogens

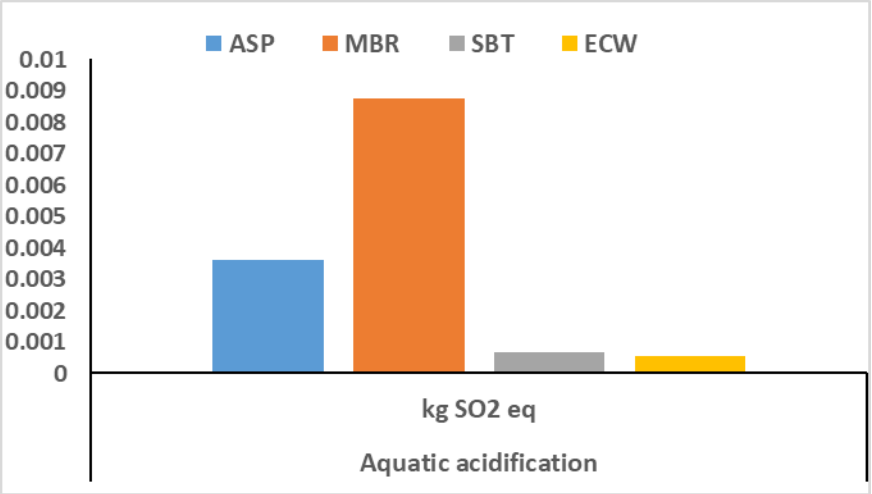


Fig. 4.7 (b) Non Carcinogens

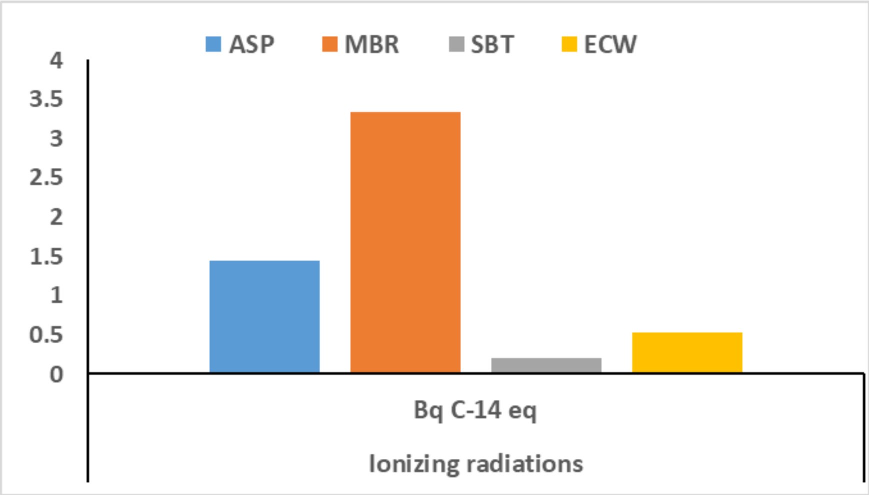


Fig. 4.8 Ionization radiation

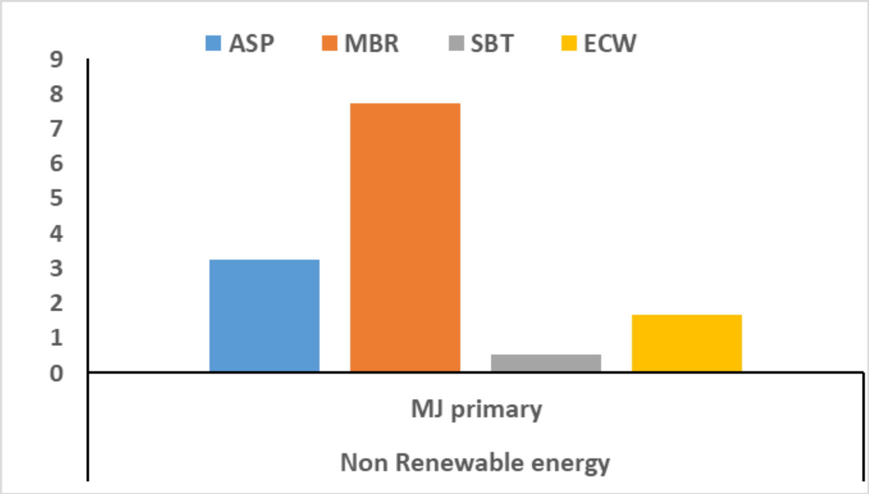


Fig. 4.9 Non-renewable energy (MJ)

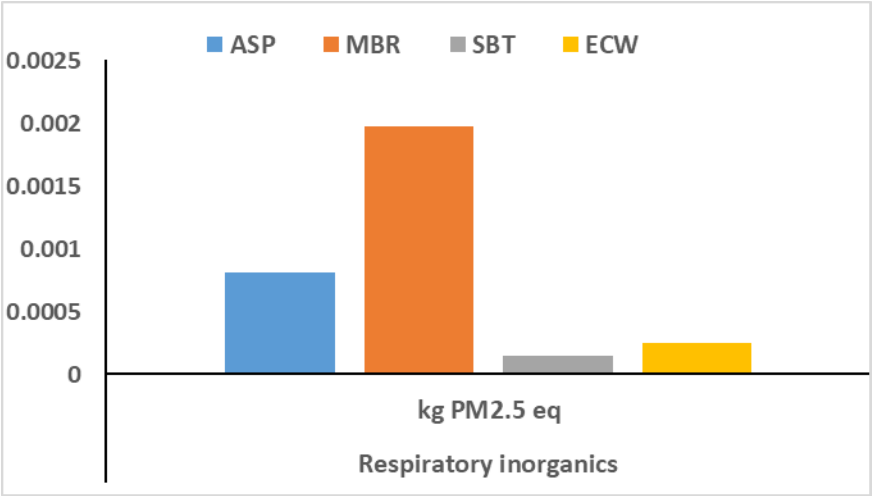


Fig. 4.10 (a) Respiratory Inorganics (kg $PM_{2.5}$ eq.)

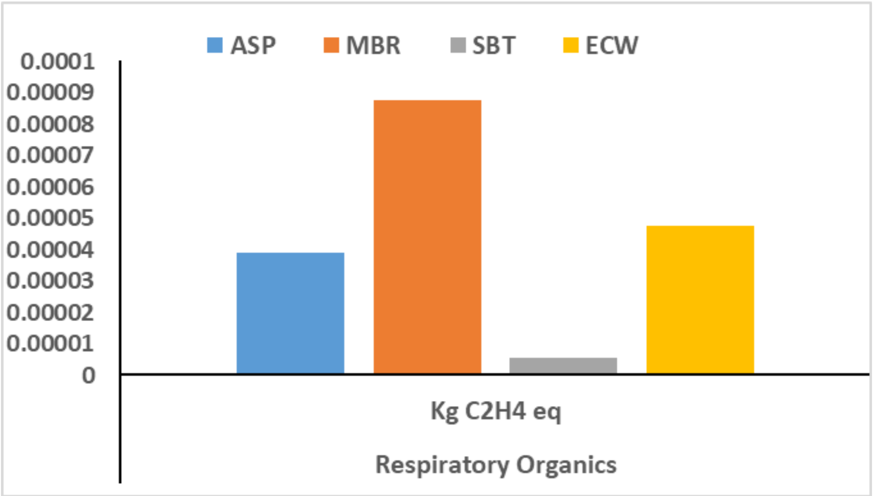


Fig. 4.10 (b) Respiratory Organics (kg C_2H_4 eq.)

Table 4.1: Impact category results

S. No.	Impact Category	Unit	ASP	MBR	SBT	ECW
1	Non Renewable energy	MJ primary	3.24	7.73	0.539	1.66
2	Aquatic ecotoxicity	kg TEG water	1.58	3.4	0.181	2.21
3	Ionizing radiations	Bq C-14 eq	1.45	3.34	0.21	0.535
4	Terrestial Ecosystem	kg TEG soil	1	2.16	0.122	1.92
5	Global Warming	kg CO_2 eq	0.544	1.33	0.0996	0.131
6	Terrestial acid/nutri	kg SO_2 eq	0.0124	0.0296	0.00221	0.00233
7	Land Occupation	m2org.arable	0.00347	0.00819	0.000564	0.00272
8	Aquatic acidification	kg SO_2 eq	0.00361	0.00874	0.000655	0.000552
9	Mineral Extraction	MJ surplus	0.00222	0.00436	0.000143	0.00537
10	Respiratory inorganics	kg $PM_{2.5}$ eq	0.000815	0.00197	0.000145	0.00025
11	Carcinogens	kg C_2H_3Cl eq	0.000785	0.00176	0.000105	0.00103
12	Non-carcinogens	kg C_2H_3Cl eq	0.00479	0.0111	0.000718	0.00249
13	Aquatic Eutrophication	kg PO4 P-lim	8.56E-05	0.000208	0.000483	3.44E-05
14	Respiratory Organics	kg C_2H_4 eq	3.89E-05	8.74E-05	5.35E-06	4.74E-05

15	Ozone Layer Depletion	kg CFC-11 eq	1.64E-08	2.84E-08	9.58E-11	6.47E-10

4.3 Damage Assessment and Results

Damage category refers to the endpoint indicators which represent the cause effect chain i.e. what and how much these impact categories overall cause the effect on the human health and living being at large. In this manner, the damage category and hence LCA can change the perspective of a particular method to be adopted or shall not be adopted. In the IMPACT 2002+ methodology used, the midpoint categories have been classified further and aggregated into four major categories.

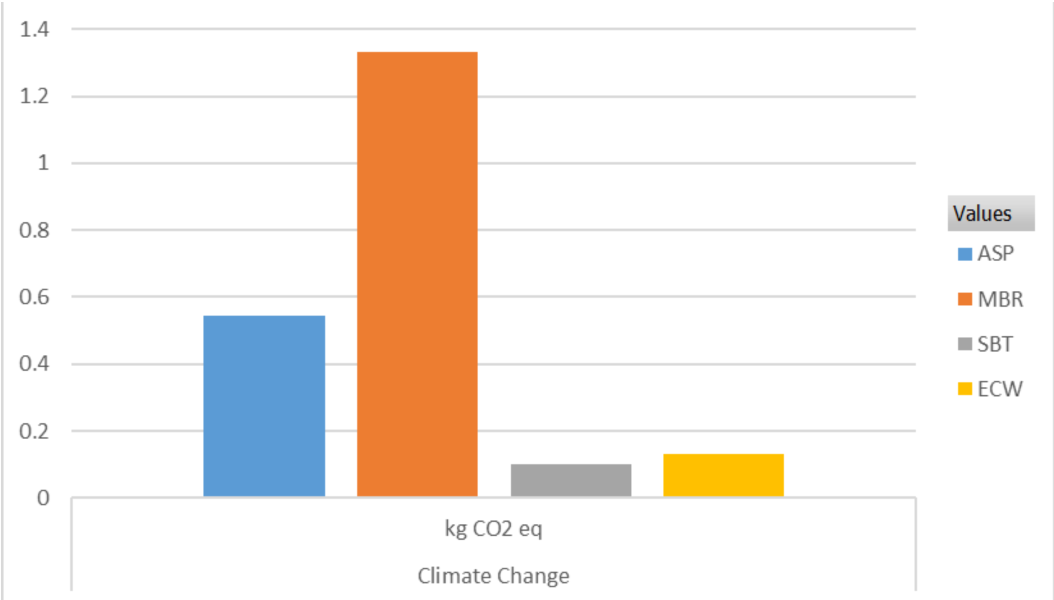


Fig. 4.11 Climate Change (kg CO_2 eq.)

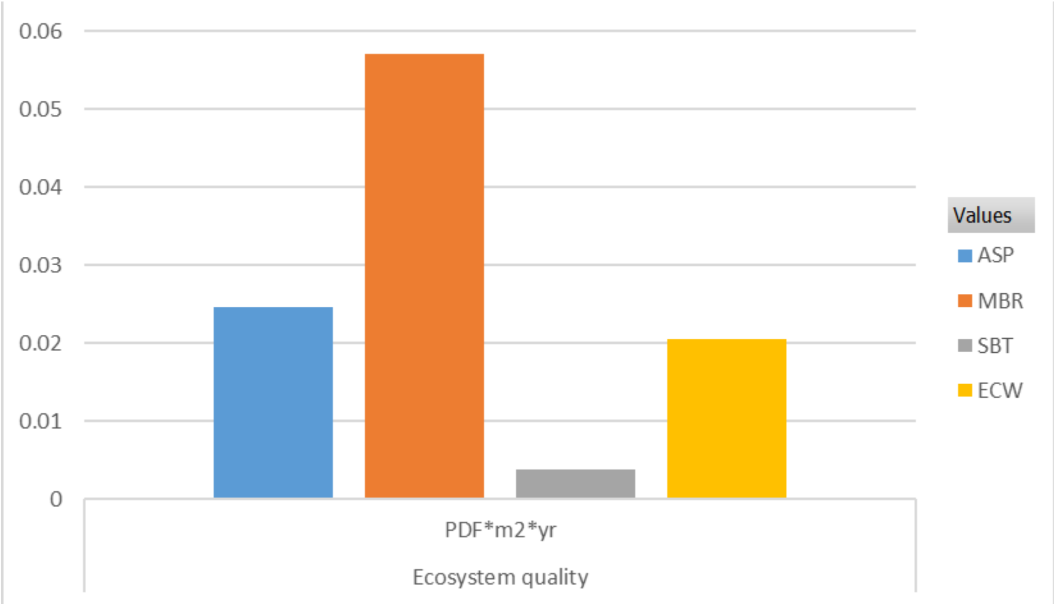


Fig. 4.12 Ecosystem quality (PDF*m²*yr)

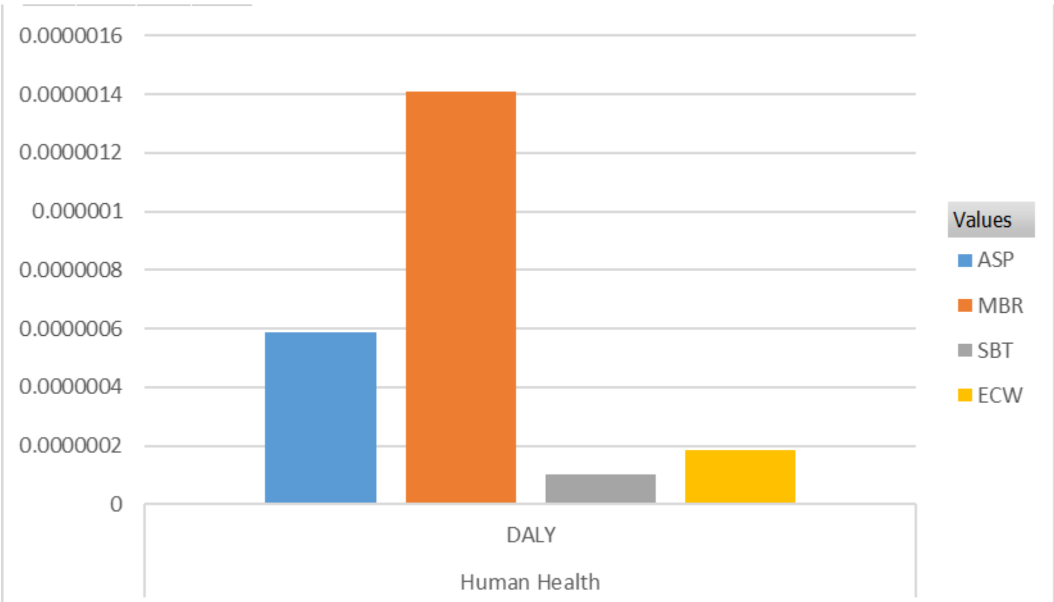


Fig. 4.13 Human health (DALY)

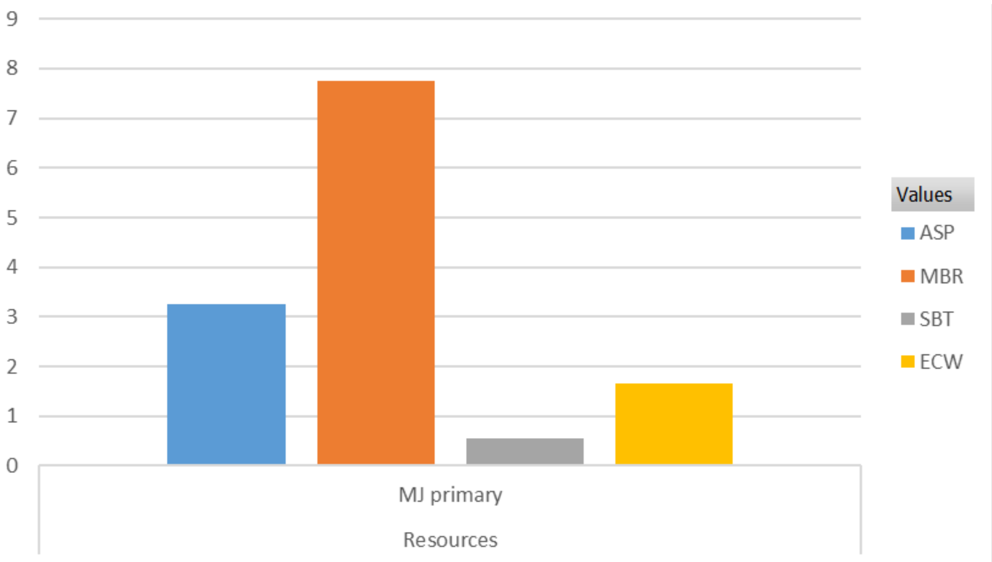


Fig. 4.14 Resources (MJ)

Human health is represented as DALY (Disability Adjusted Life Years) which represents the years lost to early mortality and reduction in quality of life due to illness; Ecosystem quality is determined in terms of potentially disappeared fraction of species over a certain area in m^2 over a certain year (PDF*m^2*yr); Climate change is represented in terms of kg CO_2 eq. released, which consists of all gases represented in terms of their respective CO_2 equivalents and resources are represented as MJ. The comparative analysis among the different methods of wastewater treatment with respect to damage category is shown in above figures.

Table: 4.2 Damage Category results

S. No.	Damage Category	Unit	ASP	MBR	SBT	CW
1	Human Health	DALY	5.86E-07	1.41E-06	1.04E-07	1.85E-07
2	Ecosystem quality	PDF*m^2*yr	0.0247	0.057	0.00389	0.0206
3	Climate Change	kg CO_2 eq	0.544	1.33	0.0996	0.131
4	Resources	MJ primary	3.25	7.74	0.539	1.66

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Life cycle assessment is a useful methodology which can be adopted to assess the environmental aspects with respect to comparison between the wastewater treatment methods. This study shows that SBT causes the least impact in most of the impact categories as defined under combined midpoint and endpoint methodology of IMPACT 2002+ used for the analysis. The damage assessment results depict that there is minimal effect being caused by the SBT on all the damage categories and out of the four methods MBR is causing the maximum amount of environmental impact.

The LCA approach used to perform the analysis adheres to the ISO 14040 standards, which states that the work should be conducted in four phases viz. defining goal and scope of the study, impact analysis, assessment and further interpretation. The IMPACT 2002+ method was used in this project to carry out the LCA on WWT and evaluate the environmental impact of the wastewater facility. A wastewater treatment plant is the current technical facility for treating sewage, industrial waste, and municipal waste to achieve a minimum allowable waste quality. Therefore, it is crucial to verify that the WWT plant has no significant environmental impact, as this could result in serious issues. This analysis emphasizes the value of LCA in Indian WWTPs. These methods can maximize waste economic and technical elements while solving environmental concerns. A full-scale study in which considerable amount of time, involving sophisticated and advanced wastewater treatment methodologies should be conducted using life cycle approach, in order to determine which method is best suited with respect to sustainability, and to assess the suitability depending on meteorological conditions of that region. Given that the majority of India's electricity comes from carbon sources, energy is frequently a significant source of effect. Energy use is a major factor in this study's analysis of the environmental profile of the plants under review because it affects several impact categories to variable degrees. Electrical grid-mix has a significant impact on the potentials of the impact categories where energy consumption is the dominant factor. When compared to a plant with equal energy consumption rates running in a country with a greener electrical grid-mix, those plants operating in countries with high quantities of fossil fuels in the electrical grid-mix may have higher GWPs. Because it is directly related to the oxygen demand and thus the needed aeration power, the organic loading rate had the biggest impact on energy consumption rates. Natural technologies, such as SBT, have been suggested as superior alternatives to conventional technologies because they have fewer negative environmental effects and pollutant loads, are highly effective at removing heavy metals, and require little energy. However, the implementation of these technologies necessitates a sizable amount of land. In comparison to current technologies, the study's findings can be utilized to create and simulate new ones.

Through the identification of significant factors that affect the life cycle impacts as well as the provision of a credible estimate of the environmental impact of WWTPs, this work aims to help decision-making for decision-makers. This study has shown that a thorough LCA can assist decision-makers in making sustainable decisions by taking into account the environmental and economic elements of WWTPs. The outcomes of the LCA analysis offer important details regarding the potential environmental effects brought on by each element of how the treatment processes function. Although there are certain concerns regarding the quality of the data, differing operating performance factors, system boundaries, background inventories, and various LCIA approaches may significantly alter the outcomes of an LCA. This study highlights the requirement for the creation of thorough and pertinent Indian life cycle inventories to supplement the Indian database. The study's findings suggest that a thorough LCA can assist decision-makers in making sustainable choices that take into account the economic and environmental implications of WWTPs. The LCA study's findings offer illuminating details regarding the potential environmental effects brought on by each element of how the treatment processes function. Although there are certain concerns regarding the quality of the data, variable operating performance factors, system boundaries, background inventories, and different LCIA approaches may greatly alter the outcomes of an LCA. This study highlights the requirement for thorough and pertinent Indian life cycle inventories to be created in order to expand the Indian database.

Since this is the first LCA of a WWTP conducted in India, to the best of the authors' knowledge, it is unable to specifically compare the results with those from other places. Utilizing a life cycle approach, the four most widely used wastewater treatment systems are assessed. The primary factors in the total environmental effects of WWTPs are determined to be emissions related to the electricity needed to operate the WWTPs, emissions to water from treated effluent, and heavy metal emissions from waste sludge applied to land. In order to manage trash in a sustainable way, emerging nations like India must choose the right wastewater treatment technologies. In India, the selection of technology is mostly influenced by a small number of factors, including cost and adherence to established regulatory norms. When determining the best technology to use in a particular situation, many other important factors are not taken into account, including geography, socioeconomic status, and the environmental receptor (air, soil, stream, river, lake, etc.). Such choices unintentionally result in long-term waste of resources like energy and chemicals as well as inefficient use of scarce financial resources. It is essential to include indicators from LCA and life cycle costing as well as sustainability indicators based on regional and local priorities when creating a complete framework for technology assessment. The thorough framework created during the procedure will assist in creating an appropriate decision-making approach to choose the best wastewater treatment.

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ANNEXURE 1

Impact 2002+ approach output of ASP

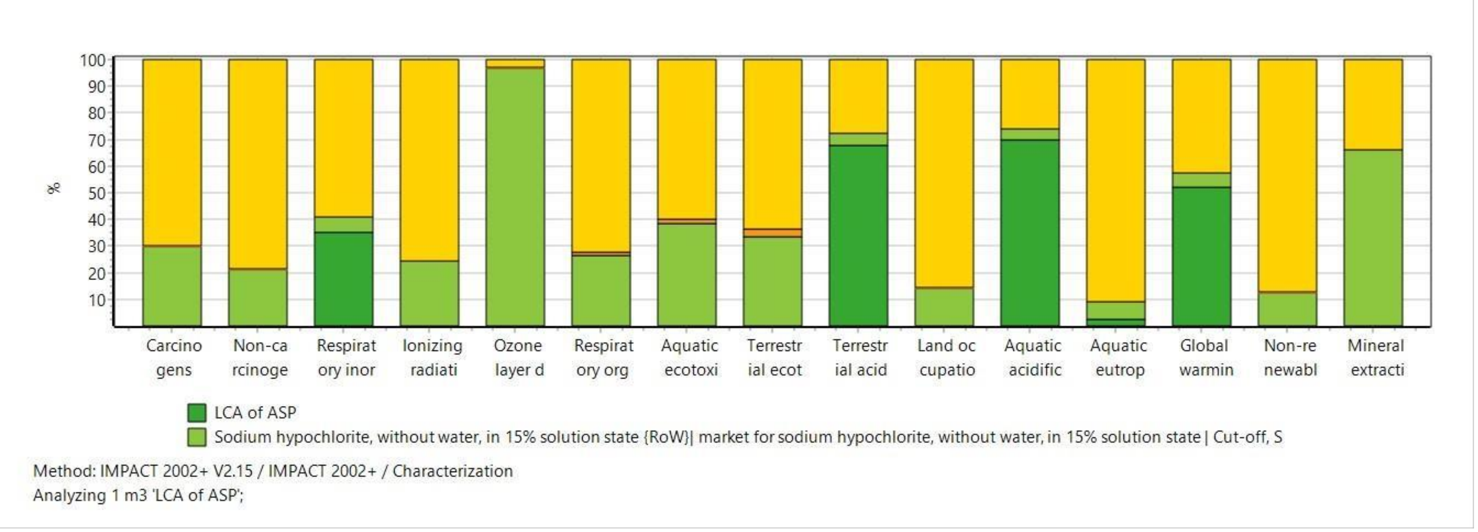

Fig. A.1 Impact category for ASP

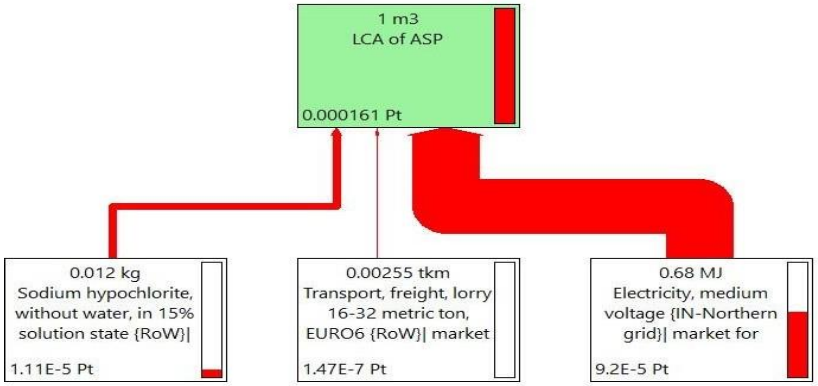

Fig. A.2 Sankey diagram for ASP

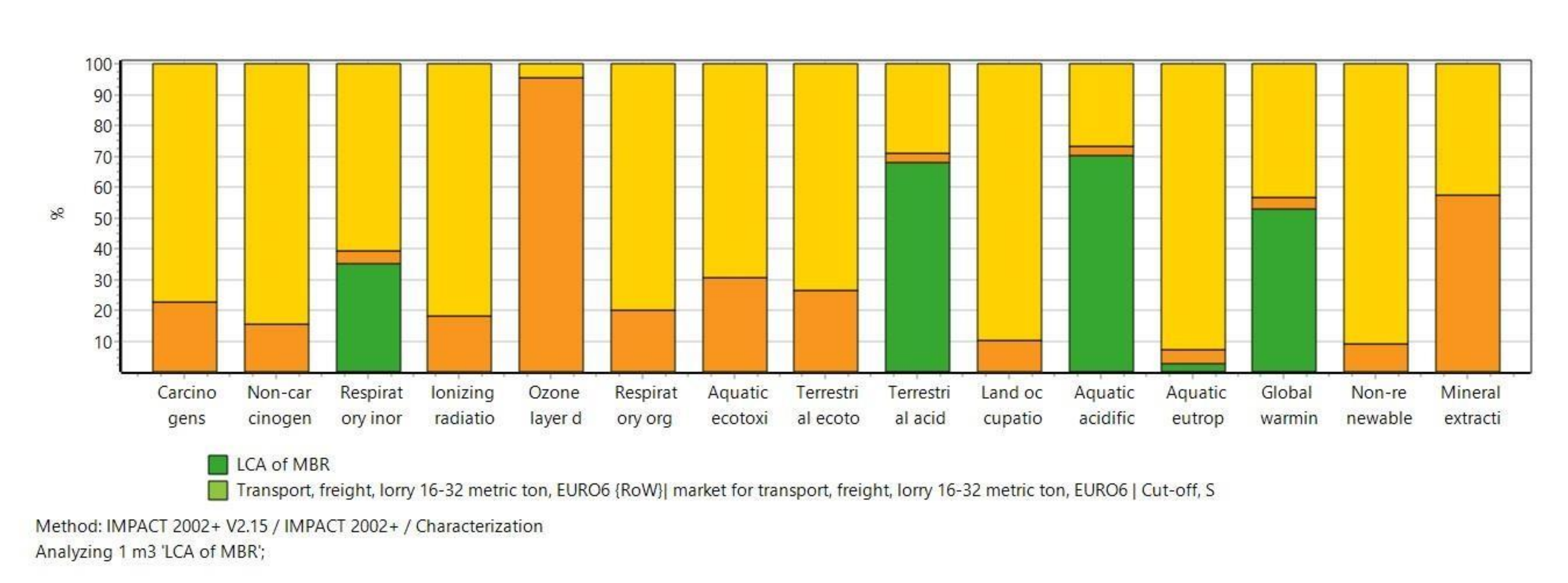

Fig. A.3 Impact category for MBR

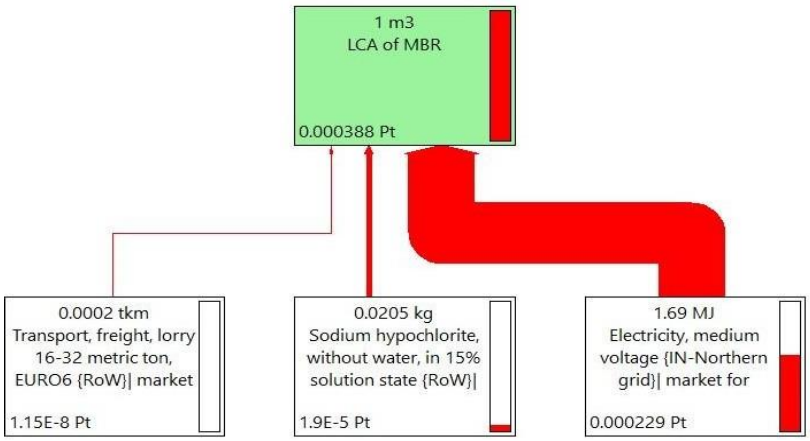

Fig. A.4 : Sankey diagram of MBR process

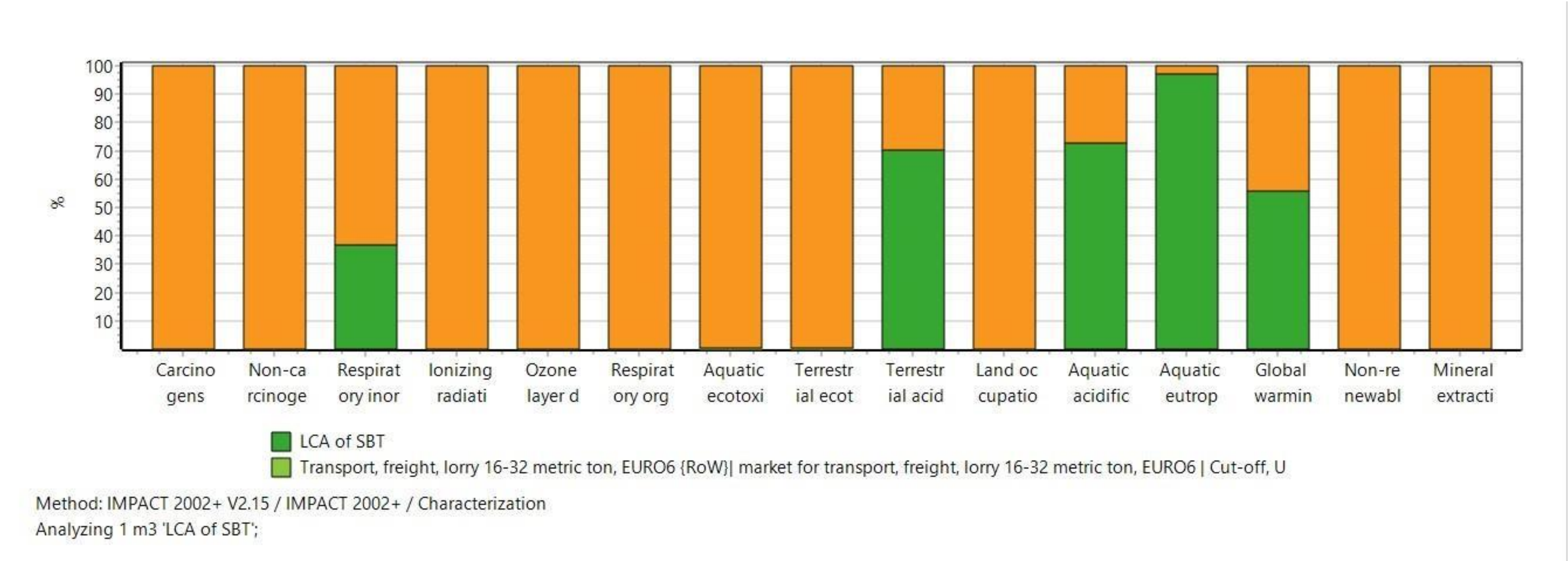

Fig. A.5 Impact category for SBT

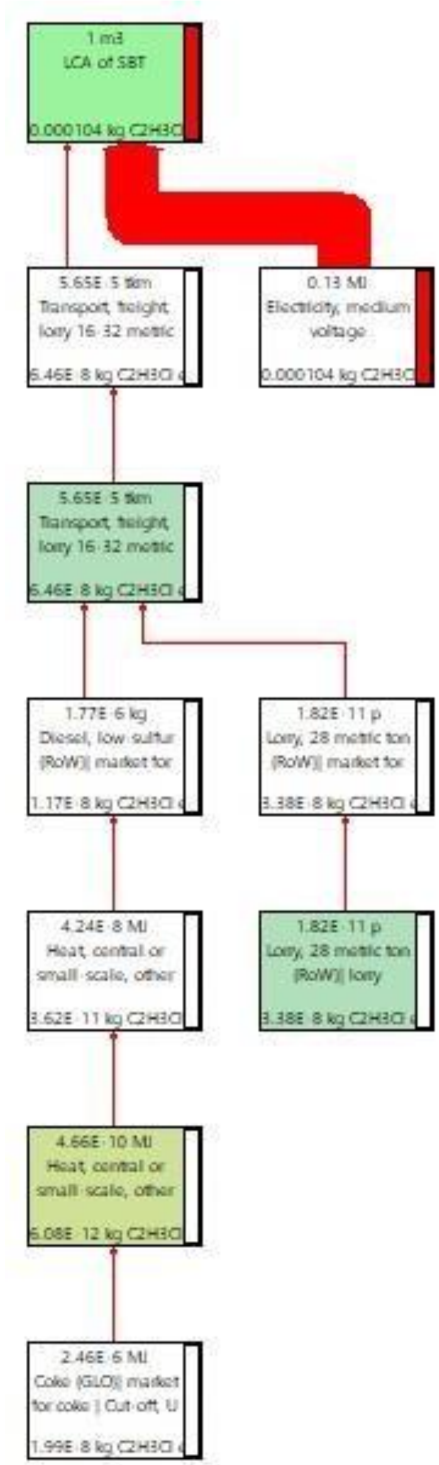

Fig. A.6 Sankey diagram for SBT

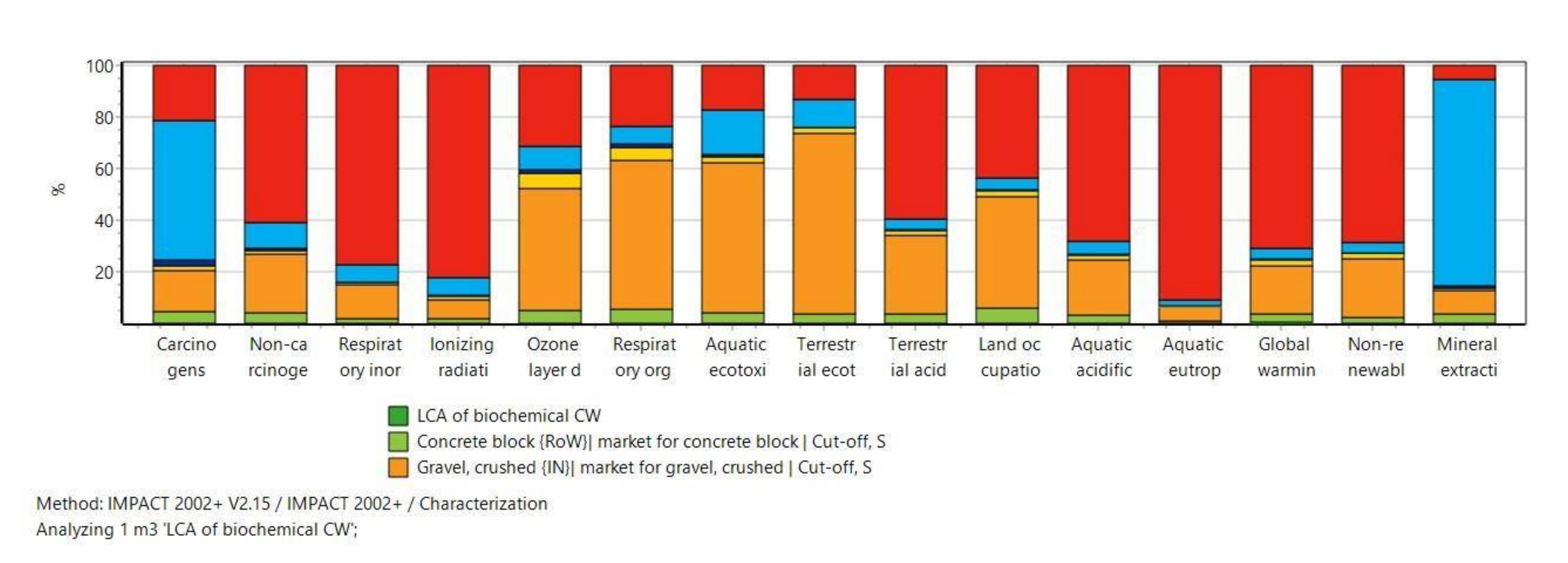

Fig. A.7 Impact category for ECW

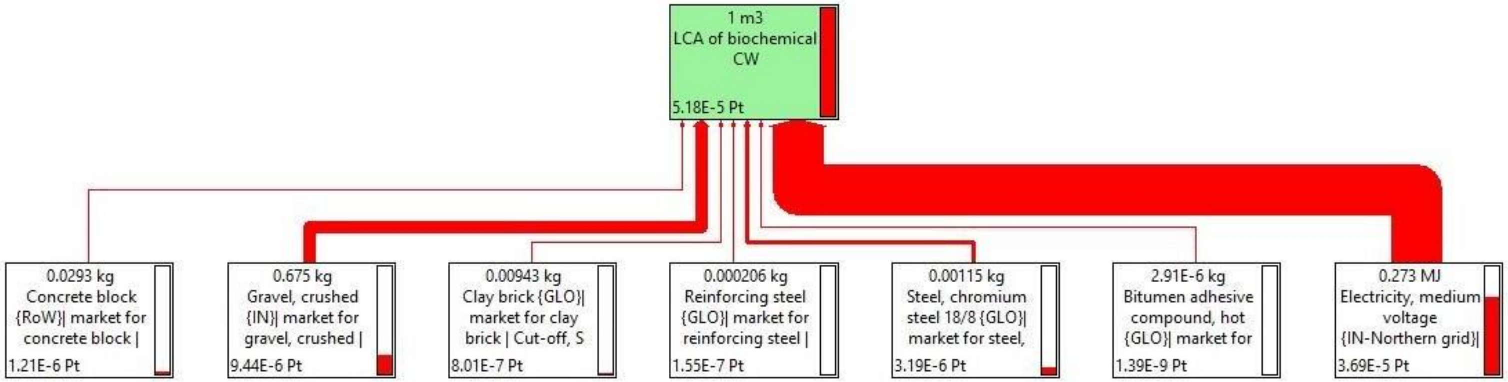

Fig. A.8: Sankey diagram for ECW