MAJOR PROJECT REPORT

ON

COMPARATIVE STUDY OF ENVIRONMENTAL ASSESSMENT OF WASTEWATER AND SLUDGE TREATMENT METHODS: A LIFE CYCLE APPROACH

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Submitted by

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CANDIDATE'S DECLARATION

I, Kulvendra Patel, Roll No. 2K19/ENE/05 of M.Tech (Environmental Engineering), hereby declare that the project Dissertation titled "Comparative Study of Environmental Assessment of Wastewater and Sludge Treatment Methods: A Life Cycle Approach" which is submitted by me to the Department of Environmental Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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I hereby certify that the Project Dissertation titled “Comparative Study of Environmental Assessment of Wastewater and Sludge Treatment Methods: A Life Cycle Approach” which is submitted by **Kulvendra Patel, Roll No. 2K19/ENE/05** (Department of Environmental Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work caried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

The Life cycle of Wastewater Treatment Plants (WWTPs) can adversely affect the environment in terms of climate change, ozone layer depletion, resource depletion and cause a toxicological effect on human health and the ecosystem. The Life cycle Assessment (LCA) approach is reported to be promising to resolve these issues. LCA is a tool for determining a product or a process's environmental effects and its associated by-products. In this study, LCA evaluates the critical sources of environmental impacts in WWTPs. The aim of study is to conduct comparative life cycle assessment of four wastewater treatment (WWT) methods: Activated Sludge Process, Constructed Wetlands, Sequential Batch Reactor, and Up-flow Anaerobic Sludge Blanket; including the sludge treatment methods: Anaerobic Digestion, Anaerobic Digestion with Pre-treatment, Lime Stabilization, and Lime Stabilization with Energy Recovery. Environmental impacts are analyzed using the IMPACT 2002+ approach and Simapro 9.1.1.1 software using the Ecoinvent v3.6 database. The study result shows that the Sequential Batch Reactor has highest impacts due to its high consumption of energy and global warming potential (GWP). Constructed Wetlands have negative GWP due to carbon sequestration. Anaerobic digestion with pre-treatment has the least impacts as compared to other sludge treatment methods. Electricity used for treatment, atmospheric emissions from the treatment methods are the primary contributors to WWT's environmental impacts. The findings of the study were categorized into three groups: midpoint indicators, endpoint or damage indicators, and single-score perspectives. The project's preliminary details will be discussed in the following chapters. This study shows that LCA is an effective environmental system tool that can enhance decision-making processes and create opportunities for achieving sustainable goals for wastewater and sludge treatment technologies.

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INTRODUCTION

1.1 Background of the study

Sustainability is a significant concern in many industries, especially regarding essential broad-spectrum resources like water (Beery & Repke, 2010). Wastewater treatment plants (WWTPs) are essential for achieving sustainable development goals (SDG) by reclaiming valuable resources like water and nutrients (Tabesh, et al., 2019). In many countries, wastewater generation is increasing as result of population growth and improved living standards. Wastewater treatment plants are built and operated with the goal of reducing wastewater pollution and minimizing emissions and harmful effects on the environment and human health (Wang, et al., 2012; Aenab & Singh, 2015). Despite continuing attempts to support the implementation of wastewater treatment systems worldwide, there is still no access to improved sanitation for about 2500 million people (WHO & UN-Water, 2014). The procurement of technologies for wastewater treatment is another problem facing municipal authorities. Only 20 percent of worldwide wastewater production obtains effective treatment in accordance with the Fourth World Water Development Report (UNESCO, 2012). Many developed nations have planned and implemented wastewater collection and treatment methods, which covers over 91% of their population as well as government infrastructure that generates wastewater, according to a report by (WHO & UNICEF, 2017) on Progress on drinking water, sanitation, and hygiene: 2017 update and SDG baselines. This is in line with the 2030 Agenda for Sustainable Development, which emphasizes the need for safe drinking water, effective and efficient WWT, and a clean environment.

It is important to assess environmental effect of various units that generate undesirable pollutants and release them into the environment and aquatic system. The LCA methodology is often used to assess products and services environmental impacts, taking into consideration a variety of energy and material inputs and outputs in the course of the life cycle, which allows quantification of the effects of the entire system study and not just the aspects of the facility environment (ISO, 2006a). The goal of this research is to compare the environmental footprints of municipal WWTPs using different technologies. This study aims to improve policymaking by including environmental impact estimates and WWTPs for decision-makers.

1.2 Wastewater Production and Treatment

In India, Municipal wastewater production in urban areas is about 61,754 MLD. Currently, there is only 22,963 MLD of capacity available for treating municipal wastewater. Due to a capacity deficit in WWTs, almost 62 percent of overall wastewater is drained directly into water bodies, leaving a significant gap in urban WWT (Kamble, et al., 2019). By 2050, it is expected that 132 billion liters of wastewater would be produced every day, expanding the gap even further (Bhardwaj, 2005). Thus, an overall analysis shows that in the coming years, there will be a double-edged challenge to cope with owing to increasing population and industrialization: reduced freshwater supply and increasing wastewater generation. In India, wastewater is currently utilized for irrigation, gardening, flushing, and industrial process water. According to CPHEEO estimates, over 70-80 percent of the total domestic water supplied is generated as wastewater. There are currently 1469 Sewage Treatment Plants (STPs) in India, out of which 1093 are operational, 102 are non-operational, and 274 are under construction. The compliance status of 900 STPs is available from 1093 operational STPs, and only

578 STPs with a combined capacity of 12,200 MLD are found to comply with the State Pollution Control Board's approved standards (CPCB, 2021).

The activated sludge process is the most often used technology in class 1 cities (populations of 100,000 or more) in India, accounting for 59.5 % of total installed capacity. It is followed by Up-flow Anaerobic Sludge Blanket technology, accounting for 26 % of total installed capacity. In addition, 28 % of the plants use the Waste Stabilization Ponds (Kaur, et al., 2012; Gupta, et al., 2018). Each technology generates sludge of differing consistency and quantities, necessitating a range of sludge management options. The wastewater treatment technologies must be evaluated in conjunction with appropriate sludge disposal methods. A WWT plant is considered efficient if it can harvest the potential energy contained in the organic matter and nutrients found in the wastewater. The plant's sludge treatment unit is where organic matters are processed for energy and nutrient recovery (Lazarova, et al., 2012). (Johansson, et al., 2008) has shown that it is important to minimize direct gas emissions and recover nutrients for the environmental outcome of sludge treatment. Best sludge management options for each technology are analyzed in this study, and system boundaries are defined as a result. Sludge treatment methods are included in the study along with the emissions generated during the operation and maintenance of sludge treatment plant. In several areas, wastewater treatment results in increased sludge production, and sludge removal approaches are becoming increasingly restricted (Renou, et al., 2008). Organic waste produced will be subject to more stringent landfill regulations, and incineration will face considerable social opposition in many countries. In comparison to the main wastewater treatment processes, sewage sludge disposal was perceived as a minor concern. However, in the last couple of years, owing to the strong growth in sludge production and the strengthening of its disposal regulations, it became one of the relevant pollution control systems (Suh & Rousseaux, 2002). Combining these unit processes is the solution to a variety of scientific and environmental concerns about wastewater and sludge treatment.

1.3 Impacts of wastewater on environment

Wastewater has a significant environmental impact and has adverse consequences, such as dissolved oxygen depletions, toxin discharges, bioaccumulation, significant water body changes, eutrophication, the transmission of waterborne diseases and destruction of aquatic species (Okereke, et al., 2016).

1.3.1 Bioaccumulation

The primary source of bioaccumulative deposits in wastewater is effluent discharge and household trash. Bioaccumulation is the process by which some compounds present in low concentrations in water, such as heavy metals, pesticides, and hazardous compounds, may be found in high concentrations in the tissues of plants and animals. This degrades the quality of freshwater bodies and releases harmful substances into receiving bodies of water (Akpor & Muchie, 2011).

1.3.2 Eutrophication

Nitrogen and phosphorus are the plants' growth nutrients and can produce unwanted weeds and algal blooms if they are higher than an optimal amount. This gives the water a faulty odor and taste, making it unsuitable for drinking (Owa, 2013). Eutrophication causes a deficiency of dissolved oxygen, killing fish and other aquatic organisms (Okereke, et al., 2016).

1.3.3 Decrement of Dissolved Oxygen

The dissolved oxygen is used as the substrate for the breakdown process during the degradation of organic and complicated chemical compounds by bacteria. This causes a dissolved oxygen deficit in the receiving freshwater bodies. The fish become significantly stressed at a dissolved oxygen level of 5 g/m^3, and at 2 g/m^3, the fish will die from a lack of oxygen unless they can migrate to more oxygenated waters.

1.4 Impacts of wastewater on human health

Wastewater includes heavy metals, persistent organic pollutants, dyes, pesticides, and nutrients. Each pollutant has a distinct effect and poses a severe health risk.

1.4.1 Heavy Metal Poisoning

The accumulation of heavy metals in lethal concentrations in the sensitive tissues of the human body is one of the most serious consequences of industrial effluent. (Naushad, et al., 2017). The degree of toxicity depends on the type of metal that has accumulated. Mercury, arsenic, cadmium, and lead are the most poisonous heavy metals, causing disease even in trace quantities.

1.4.2 Impacts of Microbes

Contaminated wastewater includes a variety of harmful microorganisms that come from animal and human feces. Bacteria, viruses, fungus, protozoa, and parasites are the most common disease-causing microorganisms found in wastewater. When this microbe-contaminated effluent is mixed with freshwater bodies, dangerous germs are transferred. Diseases are openly transferred through the water when this polluted effluent is consumed. Waterborne diseases such as giardiasis, cholera, typhoid fever, hepatitis A, salmonellosis, and cryptosporidiosis can all be transmitted by contaminated water (Akpor, 2011).

1.4.3 Effects of Dyes

The respiratory, gastrointestinal, and reproductive systems are all affected by azo dyes like Congo dye. It irritates the eye and promotes inflammation (Chawla, et al., 2017). Malachite green is a common dye that is a known carcinogen that causes cancer in critical organs (Pathania, et al., 2016). Humans' immune systems and reproductive systems are both suppressed by malachite green. It is very harmful to fish in trace quantities and, as a mutagen, damages the chromosomes (Srivastava, et al., 2004).

1.5 Life cycle assessment and wastewater systems

There is a requirement of a systematic process of evaluating and comparing wastewater treatment plants' environmental efficiency. LCA is a 'cradle-to-grave' approach that evaluates the operation's potential environmental impacts (Renou, et al., 2008). In the past, LCA has proven to be valuable method for calculating a wastewater treatment method's environmental footprint. Municipal wastewater and sludge include rich resources such as water, organic matter, energy, and nutrients (phosphorus and nitrogen) that may be recovered for various economic, social, and environmental uses (Mateo-Sagasta, et al., 2015). LCA has been used in various researches globally to discuss the environmental footprint and resource use of WWTPs.

(Corominas, et al., 2013) analyzed 45 papers but did not include specific sludge treatment research. Similarly, (Zang, et al., 2015) review contains 53 papers on various technologies but focuses on activated sludge plants. There are just a few research dealing with LCA and wastewater treatment in India so far (Kalbar, et al., 2014; Kamble, et al., 2017; Raghuvanshi, et al., 2017; Singh, et al., 2017) . The goal of (Kamble, et al., 2017) study was to analyse the Soil Biotechnology plant's sustainability from a technical, environmental, and economic perspective. (Singh, et al., 2017) calculated the environmental implications of an integrated fixed-film activated sludge reactor during its construction and seven operational phases. A number of LCA studies analysed practical application as case studies (e.g. (Tillman, et al., 1998; Pasqualino, et al., 2009; Singh, et al., 2016; Alyaseri & Zhou, 2017; Singh & Kazmi, 2018). These studies include water and wastewater treatment systems, water recycling facilities, and sludge treatment plants. In water politics throughout the world, a paradigm shift is necessary to prevent future damage to sensitive ecosystems and the aquatic environment and emphasize that wastewater is an essential resource to efficiently manage water security. In this situation, LCA may be used to analyse and compare the various approaches.

CHAPTER 2

LITERATURE REVIEW

Initially, LCA was primarily utilized for consumer and policy product comparisons. However, this technique has now become flexible and has thus been utilized in many scenarios in order to analyze various processes, including integrated applications in environmental analysis. The methods that improve environmental performance had been selected using LCA at the wastewater treatment facilities (WWTPs). Different process phases, combinations of the different treatment units, and variations of treatment scenarios were compared using life cycle assessment wastewater treatment studies. In this way, LCA now provides an alternative to quantify industrial processes through the identification of flows that contribute significantly to environmental impact. The environmental effects of various treatment facilities, including industrial and municipal facilities, have previously been evaluated by LCA in prior studies. This is particularly problematic since the system boundaries are difficult to delineate and because wastewater composition is not considered fully. The following describes a summary of the relevant research, especially to develop an idea of LCA application in the field of WWT.

2.1 Overview

Life Cycle Assessment has been used in various researches globally to discuss environmental footprint and resource use of WWTPs. It was (Tillman, et al., 1998) who first applied LCA to municipal planning in the context of wastewater systems for evaluating three alternatives- 1) existing wastewater system 2) use of local pre-treatment system and the use of sand bed filter. 3) separation of urine, faeces and grey water. The analysis found that the third alternative may be selected rather than the second alternative, and the first alternative was less favoured based on CO2 emissions. (Seghezzo, et al., 1998) researched and concluded that the anaerobic treatment process is more and more acknowledged by developing nations as the core technique of modern environmental protection and conservation technologies and represents a sustainable WWT system. (Lundin, et al., 2000) studied the influence of system boundaries and the scale on the LCA of wastewater systems. Using the results of life cycle inventory (LCI), the environmental impacts of conventional wastewater methods were compared with segregating systems. The municipal WWT system was constantly assessed with raw sewage as an influent, for over three years, in a research carried out by (Tandukar, et al., 2007), using a combination of an Up-Flow anaerobic sludge blanket (UASB) with a post-treatment Unit for Downflow Hanging Sponge (DHS). South Korean researchers (Chen, et al., 2007) performed the investigation to remediate pesticide wastewater with a high chemical oxygen demand (COD) value and low biodegradability. The Fenton-coagulation method was employed first to decrease COD and enhance biodegradability, and then biological treatment was used. While much effort has been made in LCA studies to integrate uncertainty analysis, there is still unusual practice (Lloyd & Ries, 2007). Many studies, including several comparative assessments of diverse wastewater sludge management and treatment processes (for example, (Lederer & Rechberger, 2010; Hong, et al., 2009; Pasqualino, et al., 2009; Akwo, 2008; Tarantini, et al., 2007;

Svanström, et al., 2005; Suh & Rousseaux, 2002), were not taken the consideration of the impact of uncertainty on the LCA results. Other authors (Hospido, et al., 2007) designed their analysis to evaluate the environmental impacts corresponding to four municipal wastewater treatment plants with primary and secondary treatment.

As a functional unit, the treatment of wastewater generated from a single person equivalent (p.e.) was formed. Systems borders were restricted to the operating stage as they were designed to primarily evaluate various technological choices at the plant level. The differences in configuration across the plants enabled them to compare and define the least harmful environment in WWT. (Hazrati & Shayegan, 2011) investigated activated sludge systems and discovered that most of Iran's Activated Sludge Plants are overloaded, resulting in low efficiency. (Ibrahim, et al., 2012) attempted to offer a comprehensive overview of biofilm technology as a wastewater treatment alternative. Several more studies have generally included municipal water and WWT plants, industrial WWT plants, and water-recycling facilities. According to (Nnaji, 2014) , the up-flow anaerobic sludge blanket (UASB) reactor has gained widespread adoption in the industrial WWT since its invention in the Netherlands.

LCA has been used in various researches globally to discuss the environmental footprint and resource use of WWTPs. Table 2.1 shows a short review of existing literature that addresses the categorical comparison of water and WWT systems using LCA.

Table 2.1 Studies on LCA of WWTPs

Reference	Country	Evaluated Technologies	Functional Unit	System Boundary	LCIA Method	Software
(Zhang & Wilson, 2000)	China	CT	1 GJ	C	Consumed Energy Demand	-
(Hospido, et al., 2004)	Spain	CT	Wastewater treated per day	C	CML 2002	Simapro 5.0
(Tangsubkul, et al., 2005)	Australia	CT; AT	delivery of 1 mL of recycled water to be used for irrigation of sensitive crops	A+WR	NA	Gabi 3.0 v2.0
(Pillay, 2006)	South Africa	CT; AT	1 m^3	D+WR	CML	Gabi 3.0
(Machado, et al., 2007)	Portugal	CDT	Population Equivalent (p.e.)	A	CML Baseline 2000	Simapro 7.0
(Foley, et al., 2010)	Australia	CT; AT	Wastewater flow rate of 2,200 m3/d at a strength of 4,000 mg COD/L, over 10 years of operation.	C	IMPACT 2002 + (v.2.03)	Simapro 7.0 v7.1.8
(Hong, et al., 2011)	China	NCT	1000 tonnes per day	C	CML	-
(Kalbar, et al., 2013)	India	CT; DEC	1 p.e. per year	C	CML 2 baseline 2000	MS Excel
(Meneses-Jácome, et al., 2014)	Colombia	NCT	1 m^3 Biogas	C	IMPACT 2002+	-
(Risch, et al., 2015)	Egypt	CT; DEC	1 p.e.	G	Recipe	Simapro 7.3
(García-Montoya, et al., 2016)	Mexico	CDT	1 p.e. per year	D	IMPACT 2002+	-
(Singh, et al., 2016)	India	CT	1 m^3	B	IPCC, Consumed Energy Demand	-
(de Oliveira Schwaickhardt, et al., 2017)	Brazil	AT	1 m^3 / 3h	A	Recipe	Simapro 7.3.3
(Kulak, et al., 2017)	India	CT; DEC	5.3 p.e.	E	Recipe;IPCC	Simapro
(Lu, et al., 2017)	China	CT	m^3	C	Eco-Indicator 99	Simapro 8
(Singh, et al., 2018)	India	CT	1 m^3	C+WR	CML	Gabi v6.0

CT: conventional technologies; NCT: non-conventional technologies; CDT: conventional technologies decentralized technologies; DEC: decentralized extensive systems; AT: advanced technologies.

A=WWT; B=WWT, sludge treatment and sludge transport; C=B+ sludge disposal; D=C+household wastewater collection and transport; E=D+production of fertilizer; WR=water effluent reuse.

2.2 Wastewater Treatment Methods

WWT involves eliminating contaminants from wastewater and turning it into an effluent that can be recycled. It has a low environmental effect or may be used for several purposes once it has been returned to the water cycle (known as water reclamation). WWT is the process of converting complex chemicals in wastewater into simpler ones that are stable and nuisance-free, either physicochemically or by employing microbes (biological treatment).

2.2.1 Activated Sludge Process

The activated sludge method is the most often utilized suspended growth technique for municipal WWT. In this method, aeration of organic matter containing water is carried out in an aeration basin, where the suspended and soluble organic matter were broken down by micro-organisms. Some organic matter is produced in new cells, the remainder being oxidized into carbon dioxide and water for energy generation. New cells generated during the reaction in activated sludge systems are removed by flocculent sludge from the water in settling tanks. A portion of this settled biomass is referred to as activated sludge and is returned to the aeration tank, while the remainder is referred to as waste or surplus sludge.

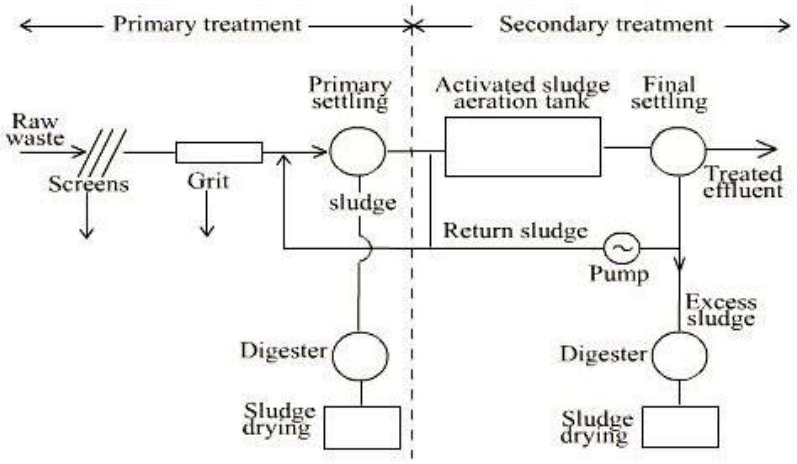

Figure 2.1 Flow Diagram of Activated Sludge Process

2.2.2 Sequential Batch Reactor

Sequential batch reactors (SBR) are industrial wastewater treatment tanks. Batch treatment of wastewater, such as sewage or wastewater from anaerobic digesters or mechanical biological treatment facilities, is performed using SBR reactors. To make wastewater acceptable for disposal into sewers or usage on land, oxygen is bubbled through it to minimize biochemical oxygen demand (BOD) and chemical oxygen demand (COD). To handle the constant intake of wastewater, the SBR system typically consists of a storage/equalization tank and a single SBR tank, or a minimum of two tanks. Traditional screening and grit removal are generally given with conventional active sludge treatment schemes as preparatory treatment. In SBR processes, primary sedimentation is typically not needed unless the influential suspended solids are excessive. Depending on the SBR installation, sewage settled downstream can also be treated.

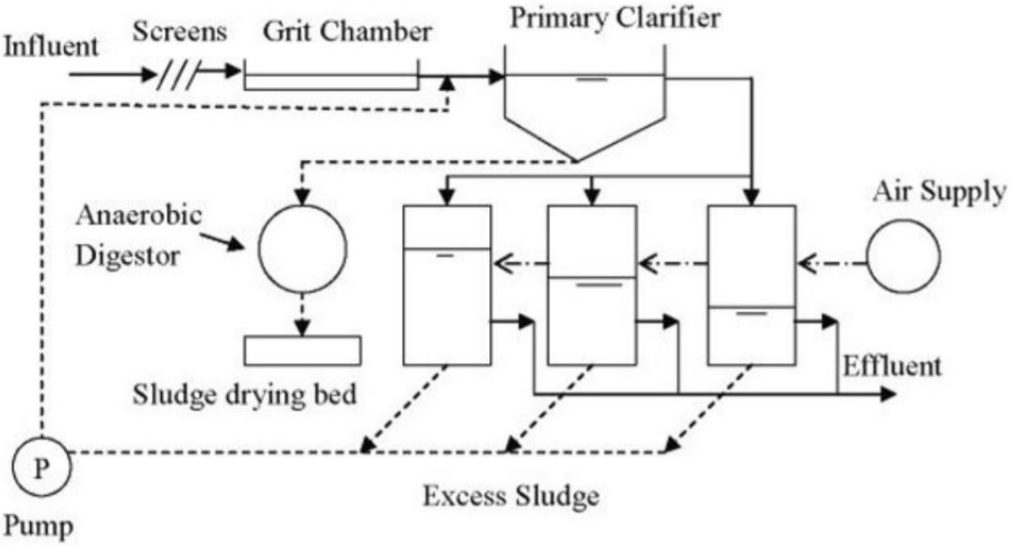

Figure 2.2 Flow Diagram of Sequential Batch Reactor

2.2.3 Constructed Wetlands

Constructed wetland (CWs) is WWT system that imitates and increases the efficacy of processes that aid water purification comparable to natural wetlands. It employs water, aquatic plants (i.e., reeds, duckweed), micro-organisms that naturally exist, and a filter bed (often sand, soil, and/or gravel). For secondary or tertiary wastewater treatment, CWs may be employed. There are many distinct designs, including vertical wetlands, which require less soil but more energy than horizontal wetlands for activities such as pumping or siphoning, but which can instead rely on terrain and gravity. The plants, microbes, and substrates, in general, serve as a filter and purifying system. First, water is slowed as it reaches the marsh, enabling sediments to settle. Plant roots and the substrate collect larger particles from the wastewater throughout the water flow process through the constructed wetland. Through natural breakdown and uptake by bacteria and plants, contaminants and nutrients contained in the wastewater are thereafter removed from the water. Water can be safely returned into surface waterways or utilized for various purposes after treatment in a constructed wetland.

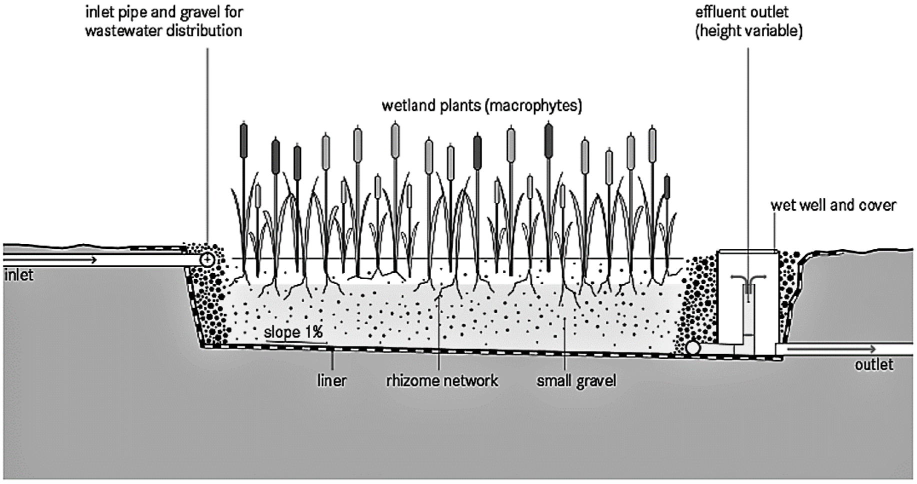

Figure 2.3 Flow Diagram of Constructed Wetlands

2.2.4 Up-flow Anaerobic Sludge Blanket

The anaerobic sludge blanket technology (UASB) is an anaerobic form of digester for WWT. The UASB reactor is a methane-producing digester that employs an anaerobic process, generates a granular sludge blanket, and is digested by an anaerobic microorganism. A Peristaltic pump transports the influent to UASB reactor from bottom. The influent rises and comes into contact with the biomass in the sludge bed, then continues to rise, and the rest of the substrates come into contact with the biomass again in the sludge blanket, which has a lower concentration of biomass than the sludge bed below. The sludge blanket consists of microbial granules (diameter 1 mm to 3 mm), i.e., small microbial agglomerations resist being washed off in the up-flow due to their weight. Organic chemicals are degraded by microorganisms in the sludge layer, and as a consequence, gases (CO2 and CH4) are emitted.

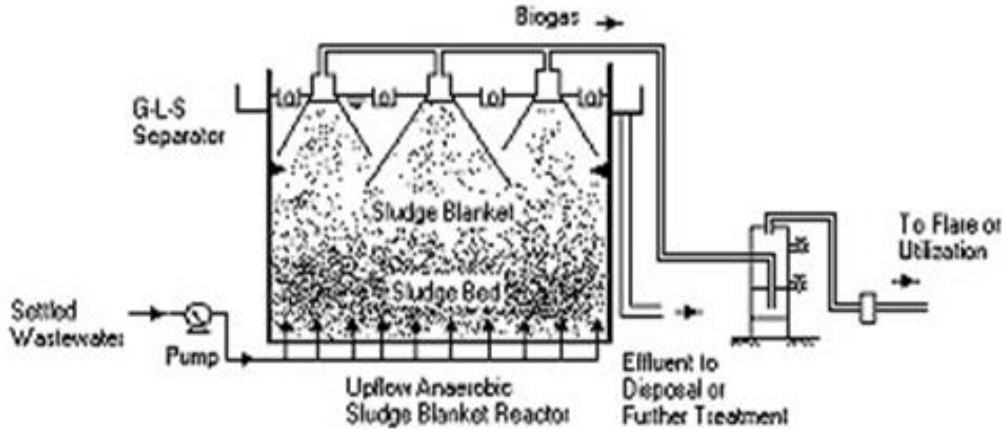

Figure 2.4 Flow Diagram of Up-flow Anaerobic Sludge Blanket

2.3 Sludge Treatment Methods

The residue collected in wastewater treatment plants is termed sludge (or biosolids). Waste sludge is the residual solid, semi-solid, or slurry material that is generated as a by-product of the treatment operations. This remaining material is usually categorized as primary or secondary sludge. Primary sludge is formed by the precipitation of chemicals, sedimentation, and other primary processes, whereas secondary sludge is the biomass activated by the biological processes. Sewage sludge treatment and disposal are essential for the design and operation of all WWT facilities. Two major objectives of sludge treatment prior to ultimate disposal are the volume reduction and stability of organic contents. Stabilized sludge has no unpleasant smell and may be handled without nuisance or health danger. A combination of thickening, digesting, and dewatering procedures may be involved in treating sludge.

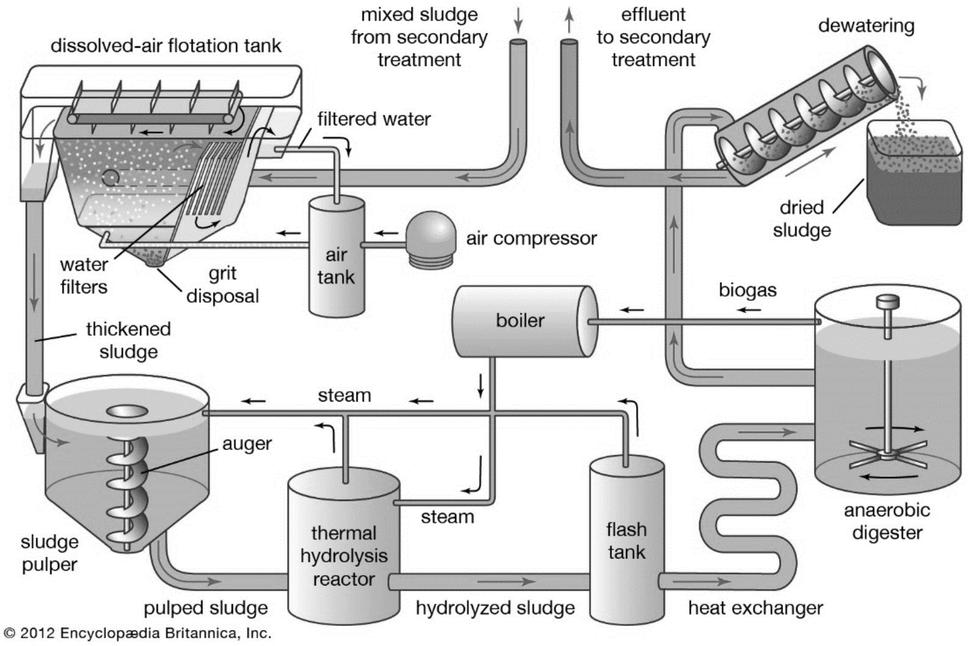

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Figure 2.5 Flow Diagram of Sludge Treatment Process **(source - Encyclopedia Britannica, Inc.)**

Thickening is generally the initial stage in sludge treatment because the slurry of solids suspended in water cannot be handled in practice. In a tank called a gravitational thickener, thickening is generally done. A thickener may decrease the total amount of sludge to less than half of what it was initially. Sludge Digestion is biological process that converts organic waste into stable compounds. Digestion reduces the total quantity of solids, removes pathogens, and simplifies dewatering or drying the sludge. Digested sludge is inoffensive, resembling rich potting soil in appearance and properties. Digested sewage sludge is usually dewatered prior to disposal. Dewatered sludge still contains a large amount of water, often up to 70 percent, but sludge no longer acts like a liquid and may be processed as a solid matter even when the moisture contents are there. The simplest dewatering technique is sludge-drying beds. The land is generally eventual destination of treated sludge. Sludge that has been dewatered can be buried underground in a sanitary landfill. It may also be used as a soil conditioner and fertilizer on agricultural land.

The sludge stabilization process is to break down the sludge's organic composites to lower its mass and produce a product that is less odorous and safer from point of view of public health. Aerobic and aerobic digestion, composting, lime stability, and heat treatment comprise the following processes to stabilize sludge (Czechowski & Marcinkowski, 2006). Lime is seen as a universal compound for stabling sewage sludges as it plays a crucial function in reducing and enhancing the agro-pathogenic content of sludge, the availability of heavy metals, and related environmental concerns (Wong & Selvam, 2006).

CHAPTER 3

METHODOLOGY

(LIFE CYCLE ASSESSMENT)

In order to meet the objective of sustainable development, comprehensive and rigorous tools are needed for decision-making to find the best options for sustainable development. Decisions must have a system perspective, take account of the life cycle and all the implications that the solution has on them. Life cycle assessment is a tool with above features. Life cycle studies range from comprehensive and quantitative evaluations that describe and occasionally evaluate environmental effects of energy consumption and raw materials, waste, and overall life cycles to quality assessments and to priority over the categories of life cycle impacts. Input information, an LCA modeling platform, and impact assessment methodologies are essential for developing an LCA. This chapter provides overview of methods and the ideas, concepts, and tools used in the study and contains description of the LCA tool and the use of Simapro software.

3.1 Introduction

Life cycle assessment had its origins in the US during the 1960s. Initially, focus was on energy

efficiency, consumption of raw materials and, to a lesser extent, waste disposal (Jensen, et al., 1998). Today LCA is defined as “a tool to assess the potential environmental impacts and resources used throughout a product’s life cycle, i.e. from raw material acquisition, via production and use stages, to waste management” (ISO, 2006b). The early studies relied on data from public sources and was known as ‘Resource and Environmental Profile Analysis’ (REPA) in the United States and ‘Ecobalance’ in Europe (Hunt, et al., 1992). LCA has therefore been formally defined by The Society of Environmental Toxicology and Chemistry (SETAC) as “a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements.” This definition is consistent with that put forward in the International Organization for Standardizations (ISO) environmental management standard on LCA (ISO, 1997). The ISO 14040 standard defines an LCA as a “compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its life cycle”. In this definition, it is clear that impact assessment is an integral part of LCA.

In terms of environmental product management, LCA may be beneficial in both the public and commercial sectors. This might include both an environmental comparison of existing products and the creation of new ones, including prototype comparisons. The essential feature of LCA is its 'holistic' aspect, which is both its principal strength and its main weakness. LCA does not offer the foundation for a full-fledged local risk assessment study that identifies which consequences may be expected due to a facility's operation in a given location. The LCA model is concerned with the physical features of industrial operations and other economic processes; it excludes market dynamics and indirect impacts on technological advancement.

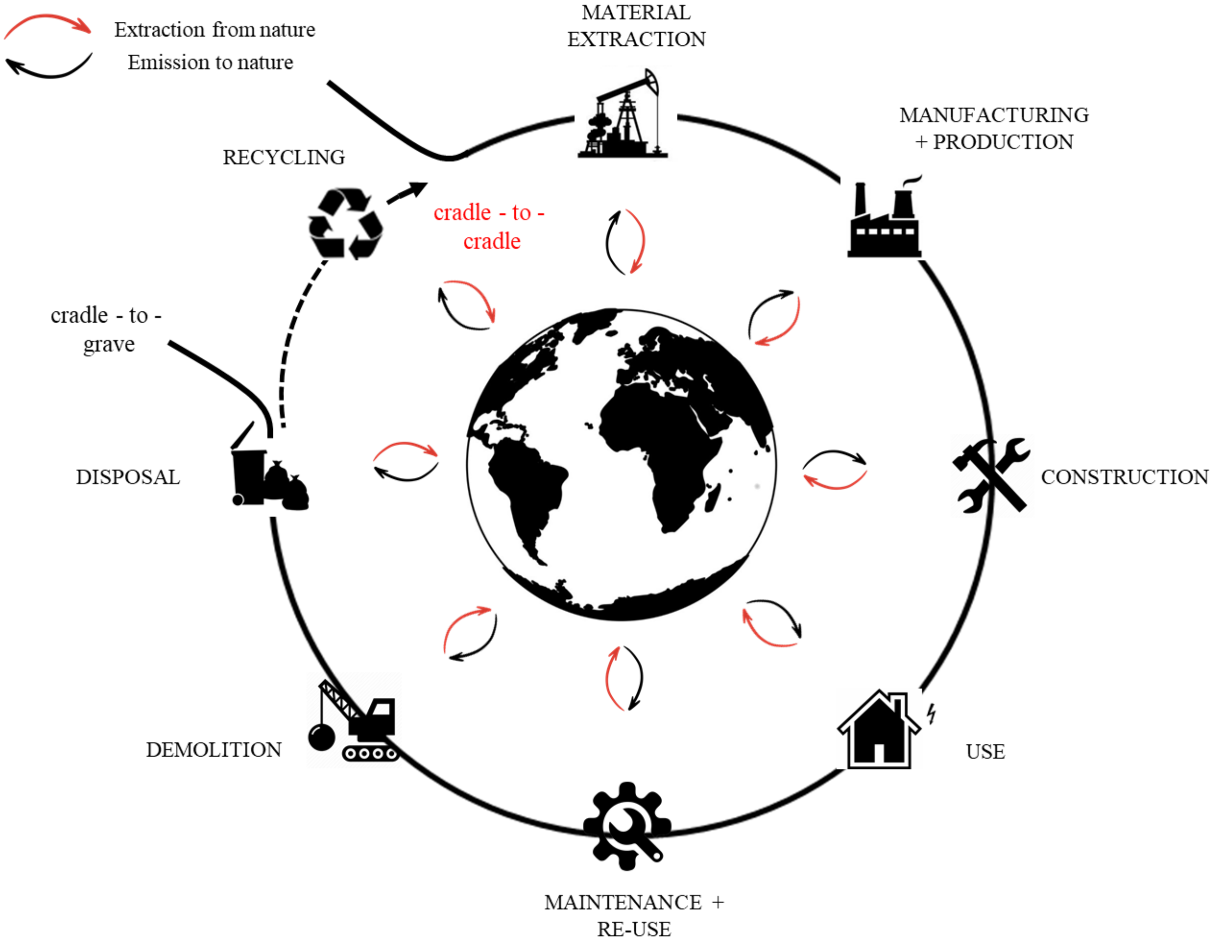


Figure 3.1 Life cycle tracking of emissions to and extractions from nature

3.2 Methodological Framework for LCA

The International Organization for Standardization (ISO) 14040 and 14044 characterize the LCA methodology: the first describes the principles and structure (ISO, 2006a), while the second outlines the requirements and criteria (ISO, 2006b) for conducting an LCA. Life cycle assessment comprises 4 stage models: -

a. Goal and Scope Definition
b. Inventory Analysis
c. Impact Assessment
d. Interpretation

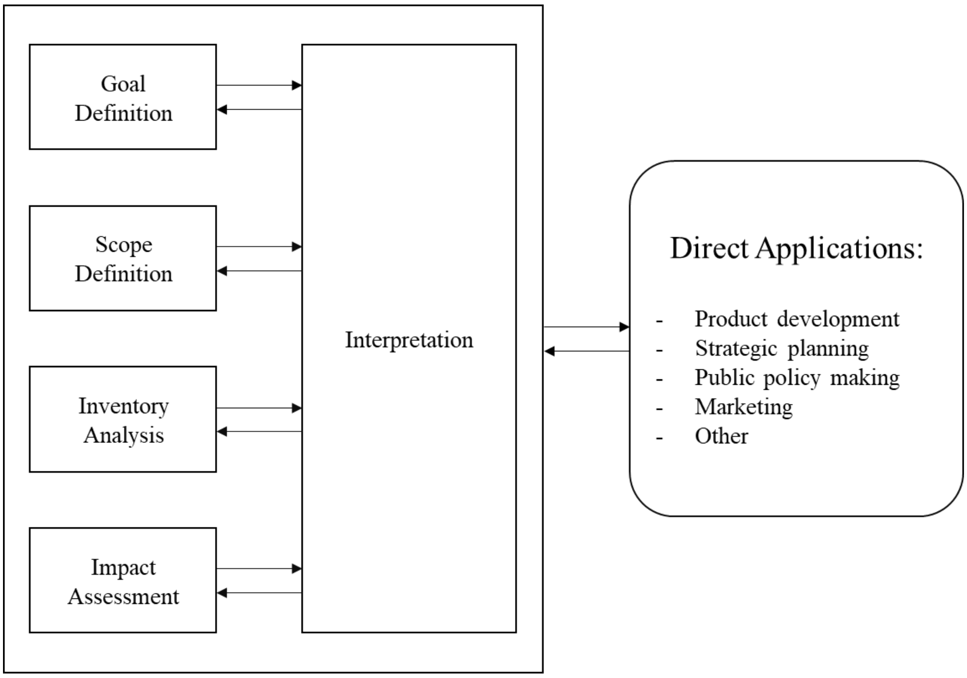


Figure 3.2 Framework of LCA (ISO, 2006a)

3.2.1 Goal and Scope Definition

As the initial component of any conventional life cycle assessment research, the ‘Definition of goal and scope' must be provided. Within the scope of the standard, the essential ideas of study are described here. While an iterative approach is clearly specified within standard (see Figure 3.2), every change in goal and scope must be recorded over course of LCA. ISO 14044 states “The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study”. The aim of study is specified and discussed in detail in the objective definition. This has an important impact on the LCA, since decisions taken in subsequent LCA stages must be compatible with the target specification. Six aspects are usually covered by the ISO Standard Definition:

a. results application
b. methodological choices limits
c. Decisive context and the reason for conducting the study
d. target audience
e. Comparative studies to be revealed to the public
f. commissioner of the study and other significant actors

The scope description specifies which product systems will be evaluated and how they will be evaluated. The scope description, together with the aim definition, provides a strong guidance for how the subsequent LCA phases should be done and how the LCA should be reported. A scope definition is made up of the nine scope elements listed below:

a. Deliverables
b. Assessment objective
c. Framework of LCI modelling and multifunctional process handling
d. System boundaries and criteria for completeness

e. LCI data Representativeness
f. Impact Assessment preparation
g. Specific criteria for system comparisons
h. The need for a critical review
i. Results reporting is planned.

The questions to be answered here will lay the basis of the rest of the study and define the purpose of the study, the expected product of the study, system boundaries, functional unit (FU) and assumptions (Roy, et al., 2009). A generalized input and output flow diagram is used to depict the system boundaries of a system. All operations that contribute to the life cycle of the product, process, or activity fall within the system boundaries (Roy, et al., 2009). It is useful to distinguish between foreground and background systems when determining system limitations. Foreground system defined as a set of processes that are immediately impacted by study and provide a functional unit stated in the aim and objectives description. The background system is that which supplies energy and materials to the foreground system (Azapagic, 1999). The system function is defined and represented in terms of the functional unit(s) and in the goal and scope definition. The goal of Functional Unit (FU) is to offer a reference unit against which inventory data may be normalized. The definition of FU is determined by the environmental impact category and the objectives of the research. The functional unit is often based on the mass of the product under study (Roy, et al., 2009).

3.2.2 Life Cycle Inventory

During LCI analysis phase of life cycle assessment, data is collected and flows within the product system(s) are modeled. This must conform to the goal description and, to the greatest degree feasible, satisfy the requirements determined from the scope definition. The LCI analysis is the phase that takes the most effort and resources from the LCA practitioner, and it is seldom practicable to gather the best quality of data for all LCI procedures due to the excessively high cost required. The following components must be quantified for LCI analysis: -

a. requirement of energy
b. demand for raw materials
c. atmospheric emissions
d. emissions to water
e. land emissions
f. solid waste
g. other environmental releases

Multifunctional processes, defined as activities fulfilling more than one role, are essential at this stage. A waste management procedure that deals with several wastes flow is an example of this scenario. Here the problem is to decide what share of the environmental load of the activity should be assigned to the product investigated (Ekvall & Finnveden, 2001). In cases like this, an allocation strategy, which describes partitioning of the input and output flows of the unit process to the different product or functions under study, is needed (ISO, 2006a).

3.2.3 Life Cycle Impact Assessment

ISO defines LCIA as “the phase of the process aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of that product.” This is the process that describes the impacts of the used resources and the emissions into the atmosphere, as shown in the LCI study. In terms of human health, resource availability, and natural environments, LCIA makes inventory analysis results better understood and more controllable. The aim of this stage is, within framework of goal and scope, to analyze and assess environmental consequences based on inventory analysis. In this context, the inventory results are assigned to several impact categories based on estimated environmental impacts.

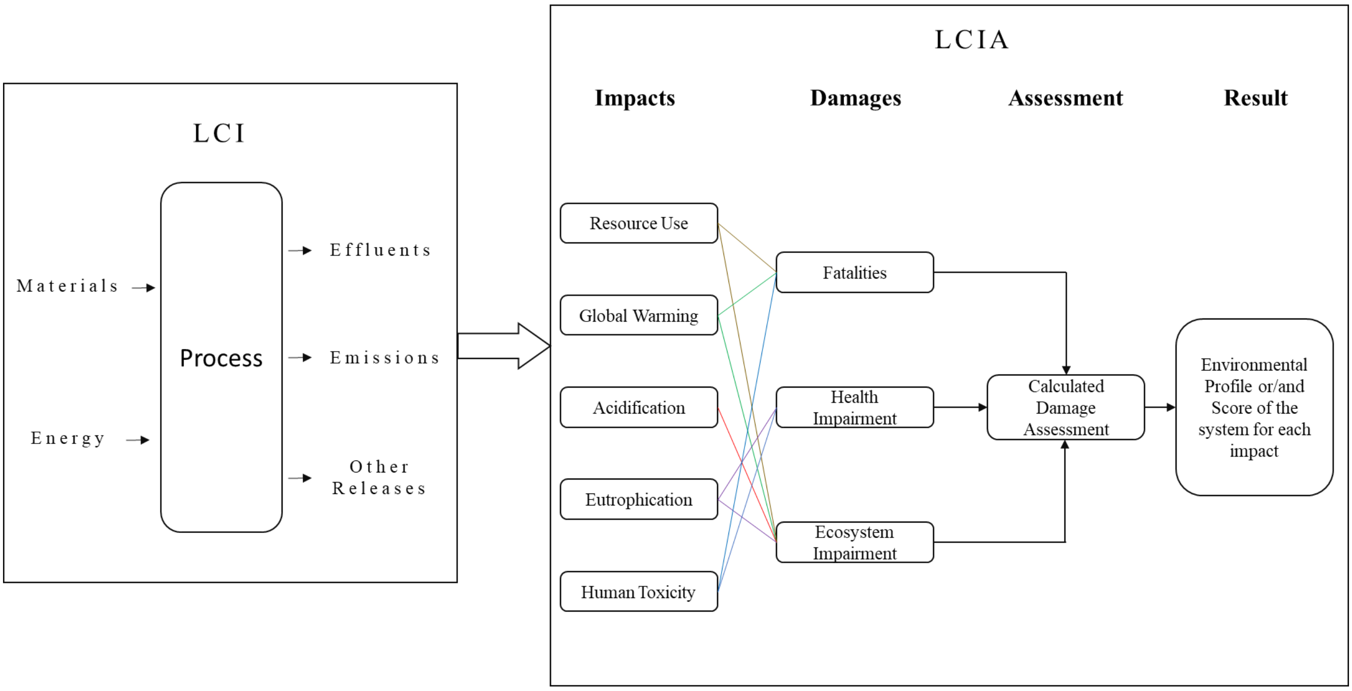


Figure 3.3 LCA Overview (Friedrich, 2001)

The selection process of the impact categories, category indicators and characterization models shall be both justified and consistent with the goal and scope of the LCA. Many LCA commercial tools in the market can help to carry out full LCAs of a big variety of systems and products; and within the packages are included different methodologies that have been developed for LCIA over the years: EDIP97, Eco-indicator 99, CML 2001 , IMPACT 2002+, Recipe etc. into which life-cycle inventory results may be assigned (Jacquemin, et al., 2012). Life cycle impacts can either be expressed with midpoint or end-point indicators. A midpoint method, according to the (Hauschild, et al., 2011), is "a characterization method that provides indicators for comparison of environmental interventions at a level of cause-effect chain between emissions/resource consumption and the endpoint level". An endpoint method, according to the same source, is “a characterization method/model that provides indicators at the level of Areas of Protection (natural environment's ecosystems, human health, resource availability) or at a level close to the Areas of Protection level” (e.g. climate change translated into its impact on human health represented as human years lost as a result of climate change.).

(Fava & Consoli, 1996) explained that the process of producing life cycle impact assessments is generally divided into three major steps. They are Classification, Characterization and Valuation.

3.2.3.1 Classification

Classification is used to classify inputs and output identified throughout the inventory process into categories of environmental effect, such as CH_4, CO_2 and CFCs, as global warming gases. As a required component, the classification according to ISO 14044 contains a difference between inventory results which can be allocated to only one category of impact and identification and assignment of findings related to more than one category of impact. Thus, inputs and outputs that are the subject of the inventory are usually classified into environmental impact categories such as -

a. Global warming
b. Stratospheric ozone depletion
c. Photochemical smog formation
d. Human carcinogenicity
e. Atmospheric acidification
f. Aquatic toxicity
g. Terrestrial toxicity
h. Habitat destruction
i. Depletion of non-renewable resources
j. Eutrophication
k.

3.2.3.2 Characterization

Characterization is the process of calculating outcomes of category indicators. The LCI findings are derived using the common factors mentioned in classification. ISO 14044 defines characterization as “the calculation of indicator results (characterization) involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category. This conversion uses characterization factors (CFs). The outcome of the calculation is a numerical indicator result.” The purpose of the characterization procedure is to combine all impacts in a specific category to achieve a single score in each previously specified category of impact. For this purpose, CFs are used. All the impact categories use characterization factors. The characterization factor according to ISO 14040 is “a factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator.” The total score for each impact category is obtained by multiplying the amount of each substance (classified in that category) by its characterization factor (expressed in relation to a reference substance) and by adding up all individual scores within an impact category.

3.2.3.3 Valuation

Valuation is the process of determining the proportional relevance of each environmental impact category so that a single index reflecting environmental performance may be generated. Thus, valuation entails weighting the findings of the characterization phase such that the most important environmental impact categories receive more attention than the least important impact categories. ISO 14044 states weighting as “the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results.”

3.2.4 Interpretation

In ISO 14040, interpretation is described as “Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together or, in the case of LCI studies, the findings of the inventory analysis only. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations.” Life Cycle Interpretation is the phase in which outcomes of the analysis, as well as all decisions and assumptions made throughout the analysis, are reviewed for soundness and robustness, and general conclusions are drawn. The purpose of this phase is to reduce a certain number of critical issues which may be utilized in decision-making in the qualitative and quantitative data acquired throughout the LCA study. However, this reduction is expected to ensure sufficient coverage and representation of the previous steps in an LCA. The interpretation phase interacts with other three stages of the life cycle assessment. If outcomes of preceding stages do not meet the aim and scope established at the start of the study, then improvements are required. According to the ISO 14043, three essential processes of interpretation are: identification of essential concerns based on inventory and LCIA phases, evaluation and findings, recommendations, and reporting.

3.3 LCA Methods

3.3.1 Eco-indicator 99

Eco-indicator 99 (EI99) is a top-down model that initially identifies three environmental damage endpoints: human health, ecosystem quality, and resources. The main advantage offered by the EI99 methodology is that a single environmental score can be estimated together with the scores for both the perspective-specified and perspective-averaged options within the egalitarian, hierarchical, and individualist perspectives (Pushkar, 2014).

3.3.2 CML

CML is a calculation method developed by the Institute of Environmental Science of the University of Leiden (Guinée, et al., 2002). CML includes CFs for several effect categories, as well as normalization data for all impact categories, with varying factors based on location and time. The CML is available in several variants. On the one hand, CML, baseline versions (CML 2000 baseline and CML-IA (baseline)), which develop the problem-oriented method to producing a list of midway impact categories, advised doing basic LCA studies. The collected list of impact categories may be classified into three groups: 1. Compulsory impact categories (category indicators used in most LCAs). 2. Additional types of impacts (operational indicators that exist but are not often included in LCA studies). 3. Other impact categories (no operational indicators available, making quantitative inclusion in LCA unfeasible.). For simpler research, these baseline techniques are advised. CML non-baseline techniques (CML 2001 (all impact categories) and CML-IA non-baseline), on the other hand are expanded versions of the baseline methods. These approaches include the baseline categories as well as alternate impact categories that are recommended for long-term LCA research.

3.3.3 Recipe

ReCiPe is a calculation method created by RIVM, CML, PRé Consultants and Radboud Universiteit Nijmegen (Goedkoop, et al., 2008). This approach was developed by combining two earlier methods, CML and Eco-indicator 99. This approach distinguishes two indicators: the 18 midpoint categories and the 3 endpoint/damage categories. This technique includes CFs for many substances, as well as normalization factors from Europe and throughout the world.

3.3.4 IMPACT 2002+

This technique provides a practical implementation of midpoint and/or endpoint approach, which connects all sorts of LCI data to multiple damage categories through various midpoint categories. There are fourteen midpoint categories in the IMPACT 2002+ methodology, and they are eventually connected to four endpoint categories to show an overall environmental impact of production system. The IMPACT 2002+ methodology allows normalizations to be performed at both midpoint and endpoint. At this time, about 1500 different LCI-results are covered in the IMPACT 2002+. The 1500 LCI-results are the data of their midpoint CFs, damage CFs, normalized midpoint CFs and normalized damage factors. They can be used directly when conducting different types of LCAs.

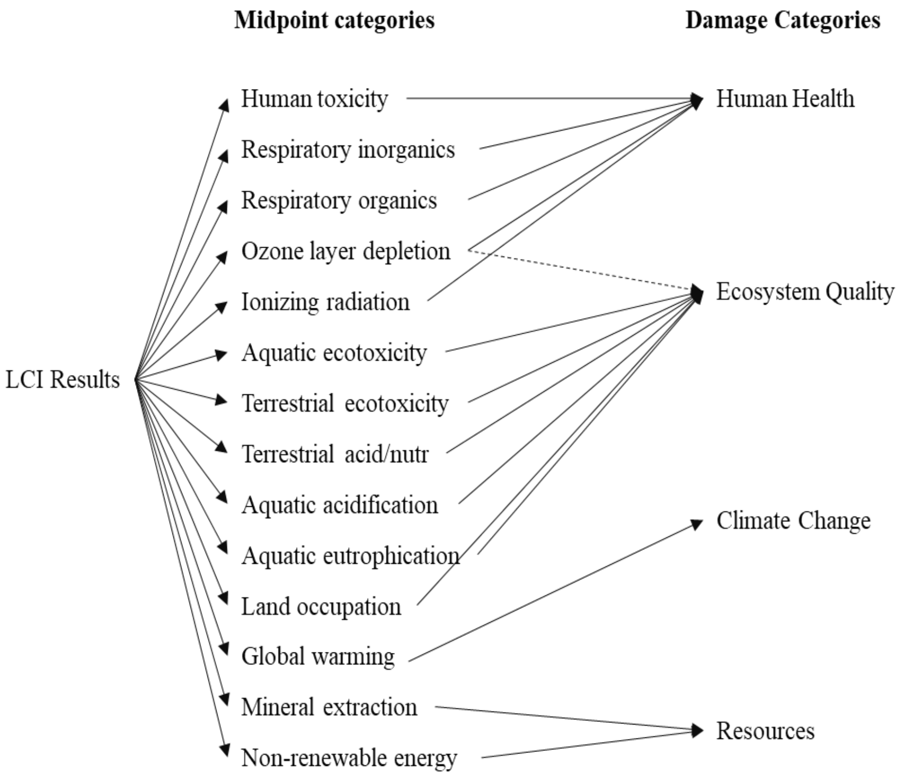


Figure 3.4 Overall scheme of the IMPACT 2002+, based on (Jolliet, et al., 2003)

3.4 Tools for the calculation of life cycle assessment studies

Several software tools are presently available to model the life cycle effects of any product or process, or service. Some of most well-known and commonly used LCA softwares are:

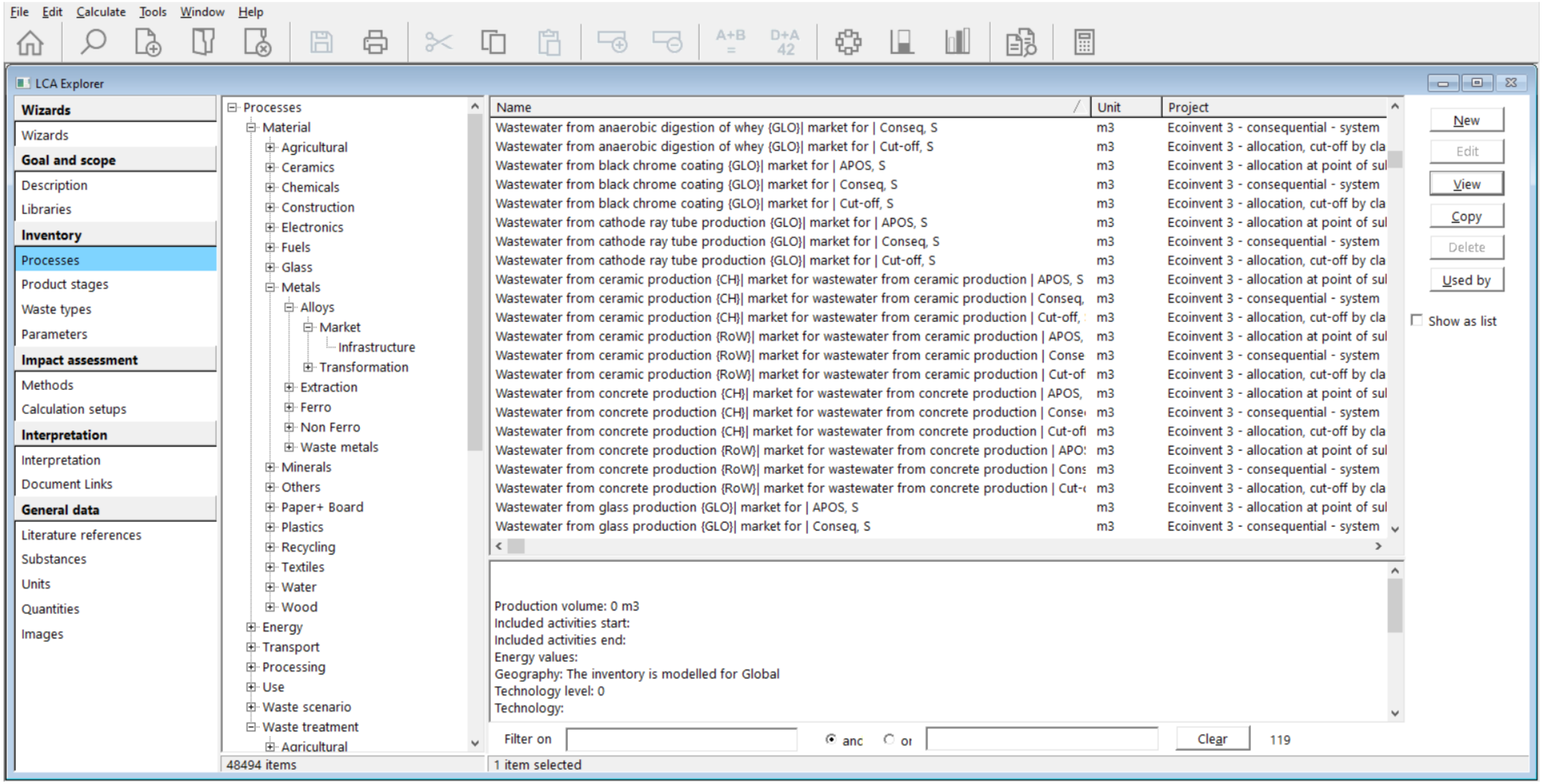
- Simapro
- Gabi
- OpenLCA
- Umberto
- TEAM
- Ecochain

3.4.1 Simapro

This is popular LCA tool for industrial purposes, and it is often regarded as one of the expert versions for practical LCA applications. Product life cycle and design choices may be made more efficiently using this tool. This tool was created considering scientific knowledge of nearly every product and material. The information provided in this tool is transparent to an extent and mostly avoids the black-box process (PRé, 2016) SimaPro organizes the LCA phases in line with the ISO14040 and ISO 14044 LCA standards.

SimaPro provides the following applications and features:

1. Because of the systematic and transparent methodology used in modeling, any complicated life cycle process may represented more simply in SimaPro.
2. The capacity to evaluate environmental impacts depending on categories during the life cycle of product.
3. It provides system for collecting, evaluating, and monitoring any product's data, as well as its sustainability performance.
4. Various hotspots exist across each supply chain, and depending on product and its life cycle, they may be critical. It is essential to identify them, which demands the use of professional modeling software such as SimaPro.
5. SimaPro will make the procedure easier to comprehend, enabling the identification of the hotspot.



Name	Unit	Project
Wastewater from anaerobic digestion of whey {GLO}| market for | Conseq, S	m3	Ecoinvent 3 - consequential - system
Wastewater from anaerobic digestion of whey {GLO}| market for | Cut-off, S	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from black chrome coating {GLO}| market for | APOS, S	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from black chrome coating {GLO}| market for | Conseq, S	m3	Ecoinvent 3 - consequential - system
Wastewater from black chrome coating {GLO}| market for | Cut-off, S	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from cathode ray tube production {GLO}| market for | APOS, S	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from cathode ray tube production {GLO}| market for | Conseq, S	m3	Ecoinvent 3 - consequential - system
Wastewater from cathode ray tube production {GLO}| market for | Cut-off, S	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from ceramic production {CH}| market for wastewater from ceramic production | APOS, S	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from ceramic production {CH}| market for wastewater from ceramic production | Conseq,	m3	Ecoinvent 3 - consequential - system
Wastewater from ceramic production {CH}| market for wastewater from ceramic production | Cut-off,	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from ceramic production {RoW}| market for wastewater from ceramic production | APOS,	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from ceramic production {RoW}| market for wastewater from ceramic production | Conse	m3	Ecoinvent 3 - consequential - system
Wastewater from ceramic production {RoW}| market for wastewater from ceramic production | Cut-of	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from concrete production {CH}| market for wastewater from concrete production | APOS,	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from concrete production {CH}| market for wastewater from concrete production | Conse	m3	Ecoinvent 3 - consequential - system
Wastewater from concrete production {CH}| market for wastewater from concrete production | Cut-ofi	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from concrete production {RoW}| market for wastewater from concrete production | APO:	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from concrete production {RoW}| market for wastewater from concrete production | Cons	m3	Ecoinvent 3 - consequential - system
Wastewater from concrete production {RoW}| market for wastewater from concrete production | Cut-	m3	Ecoinvent 3 - allocation, cut-off by cla
Wastewater from glass production {GLO}| market for | APOS, S	m3	Ecoinvent 3 - allocation at point of sul
Wastewater from glass production {GLO}| market for | Conseq, S	m3	Ecoinvent 3 - consequential - system

Production volume: 0 m3
Included activities start:
Included activities end:
Energy values:
Geography: The inventory is modelled for Global
Technology level: 0
Technology:

Figure 3.5 Explorer window in SimaPro showing all the LCA framework stages

CHAPTER 4

LIFE CYCLE ASSESSMENT OF WASTEWATER AND SLUDGE TREATMENT METHODS

One of the difficulties that emerging countries like India confront is WWT. It is critical to analyze the environmental impacts of WWTPs and design wastewater reuse technologies that have the least amount of negative impact on environment and human health. Traditional wastewater treatment techniques in India include the Activated Sludge Process, Up-flow Anaerobic Sludge Blanket Reactor, and other land-based treatment technologies. This chapter compares and contrasts the LCA of WWT techniques. Using the Simapro LCA tool and the Ecoinvent database v3.6, various emissions from the WWTP and their impact factors are evaluated. The goal of this study is to assist decision-making through the identification of significant factors that influence the consequences of life cycles and provides a credible environmental assessment of wastewater treatment technology.

4.1 Introduction

In LCA, the comparable performance systems or products or procedures are selected by considering the impacts of their life cycle caused by alternatives. It may also used to identify most critical environmental impacts in the life phase and to establish baselines for potential research. The environmental effects are assessed by determining and quantifying the resources and products used and the atmosphere's emissions throughout the life cycle (Garfí, et al., 2017). ISO 14040 and ISO 14044 LCA guidelines characterize four distinct but theoretically iterated phases in the LCA –

(i) goal and scope, which involves a clear and consistent definition of the study;
(ii) perform a life cycle inventory (LCI), based on energy and mass quantification;
(iii) perform a LCIA utilizing the information collected at the LCI phase in conjunction with state-of-art impact assessment method;
(iv) interpretation of results and make some general conclusions and recommendations.

LCA may be used to analyze and evaluate the contributions of various activities or systems to global environmental impacts. The assumptions made in this study are: (i) The BOD inlet is assumed to be the average in India (200 mg/l) for all treatment plants (CPCB, 2009); (ii) and sludge transportation distance for all WWTPs is assumed to be 20 km; (iii) according to previously published literature (Tillman, et al., 1998; Machado, et al., 2007; Kalbar, et al., 2012), the construction phase of a WWTP in India accounts for around 1% of the entire life cycle impacts of the WWTP. As a result, the construction phase is excluded from this research and focuses on the operation phase of the WWTPs; (iv) LCAs need the usage of software such as SimaPro or openLCA. These software’s often incorporate a number of inventory databases. Since the databases were created mainly in the European context, they must typically be adapted when used in other regions as there are no national databases available in India to carry out the LCA, and the production of material and emission inventories has become difficult (Kalbar, et al., 2012). In this study, Simapro 9.1.1.1 software and Ecoinvent v3.6 database are used.

4.2 Materials and Methods

4.2.1 Goal and Scope

The study aims to compare the environmental impacts of the four WWT methods: (i) Activated Sludge Process (ASP), (ii) Constructed Wetland (CW), (iii) Sequential Batch Reactor (SBR), and (iv) Up-flow Anaerobic Sludge Blanket (UASB). The sludge from these wastewater treatments goes to considered sludge treatment methods (anaerobic digestion, anaerobic digestion with pre-treatment, lime stabilization, and lime stabilization with energy recovery), respectively. Figure-4.1 shows the boundary of considered system of analysis. The precise selection of system boundaries has significant impact on LCA. The system boundary starts when raw wastewater goes for primary treatment and terminates at the point of application of treated sludge. The system boundary includes first-order environmental impacts, including direct atmospheric pollution and effluent discharge. It also takes into account second-order effects such as electrical emissions and the material resources for the procedures of treatment. The Functional Unit (FU) specifies how the product's functions are quantified. A FU's primary purpose is to serve as a point of reference for relating inputs and outputs. This point of reference is required to ensure LCA outcomes are comparable; this is especially important when comparing various systems and ensuring that comparisons are performed on a common basis. Several analyses consider population equivalent (p.e.) as FU, but they calculate it in very different ways. One p.e.

represents 50g of BOD_5 load per day in India (Arceivala & Asolekar, 2007). Other functional units used in research are m^3 (Kamble, et al., 2017; Singh, et al., 2018); kg of sludge (dry basis) (Suh & Rousseaux, 2002; Hospido, et al., 2005; Cartes, et al., 2018). According to (Zang, et al., 2015), WWT related LCA should use more than one FU to define the system under study and avoid ambiguities in the conclusions. Two separate FU have been used in this study since the LCA covers both wastewater and sludge treatment. For WWT, FU is 1 m^3 of treated wastewater, and for sludge treatment, FU is 1kg of sludge (dry basis) is considered.

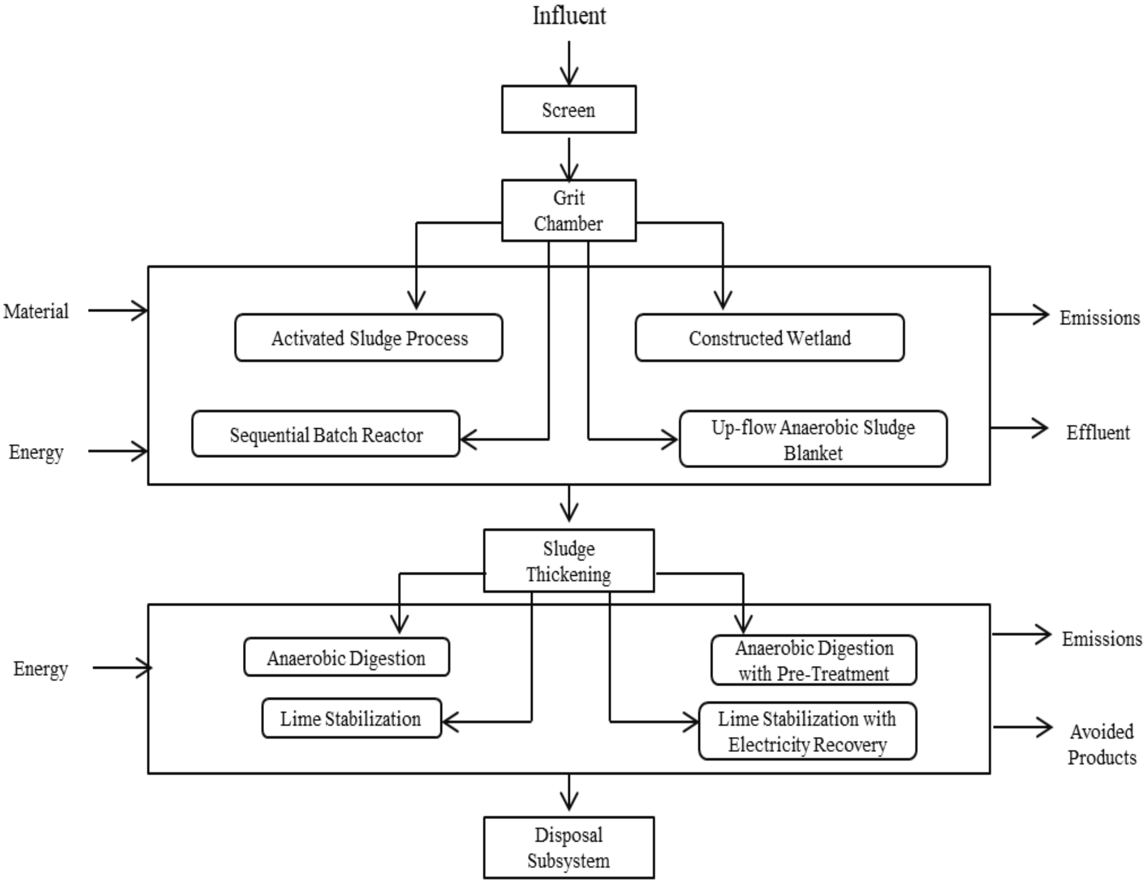


Figure 4. 1 System Boundary of the WWT Process

4.2.2 Life Cycle Inventory

This is the LCA stage, which involves gathering system inputs and outputs for end of life phase of process. System inputs are raw materials and energy, and the system outputs are materials such as compost, pollutants to air, water, and soil. Data of input/output, including raw materials, products, and emissions, are collected and recorded for each system boundary phase. The life cycle inventory (LCI) is critical since it directly influences the impact assessment phase and is important for the interpretation of results and conclusions. The inventory used in this study was compiled using the Ecoinvent v3.6 database and previously published research (Tangsubkul, et al., 2005; Cartes, et al., 2018). Since there is no central database on all types of inventories in India, creating a life cycle inventory of all units is challenging. More information on each WWTP and its inventories can be found in the subsections below.

4.2.2.1 Activated Sludge Process

ASP is most commonly used WWT system. Although there are several different designs, all ASPs have three main components: an aeration tank (coarse bubble aeration) where microorganisms metabolize suspended and soluble organic matter; a settling tank for the separation of activated sludge (AS) and effluent; and returned AS equipment to move settled AS from the sedimentation tank to aeration tank. All of these elements are included in the study's scope. Material and emission inventory of this analysis is generated for a 50 MLD sewage treatment plant based on (Kalbar, et al., 2013). Waste-activated-sludge from the main treatment process is further treated using an anaerobic digestion (AD) process. Sludge from WWT is thickened prior to AD to reduce its volume. The ASP flow diagram is shown in Figure -4.2(a). In terms of solids recovery, a 90 percent efficiency was assumed (Hobson, 2003). The biogas produced is used to generate electricity. A loss of 5 percent of total biogas generated, with 50 percent directly emitted and the other 50 percent released and emitted during storage, was taken into account (Cakir & Stenstrom, 2005). It was assumed that dewatering would take place in a centrifuge using polyacrylamide, and the sludge would then be transported 20 km to the application site in a 21-metric-ton lorry. Table-1 shows the inventory data of ASP.

4.2.2.2 Constructed Wetland

CWs are integrated structures designed with natural processes, including wetland plants and microbial assemblies, assisting with wastewater management (Vymazal, 2010). According to (Arceivala & Asolekar, 2007), the CWs are designed for a BOD5 of 200 mg/l. When evaluating the environmental effect of CWs, it is important to account that when CO_2 is sequestered in biomass, CW will serve as a carbon sink. CWs, but on the other hand, release significant quantities of greenhouse gases (de Klein & van der Werf, 2014) especially CH4 and N2O. In the study, Phragmites karka (P. karka) is assumed to be used to treat sewage. The CW pollution inventory is shown in Table-1. After the primary treatment, wastewater enters the horizontal flow wetland, causing solids to settle. After being treated in CW, sludge is thickened, then chemically stabilized with lime, dewatered, and transported to landfill site to dispose. A 21-metric-ton lorry was assumed to have been used to transport the sludge over a 20-km distance. The Figure – 4.2 (b) depicts the phase flow diagram of CWs.

Table 4.1 Inventory Data of WWTPs (Tangsubkul, et al., 2005; Kalbar, et al., 2012; Cartes, et al., 2018)

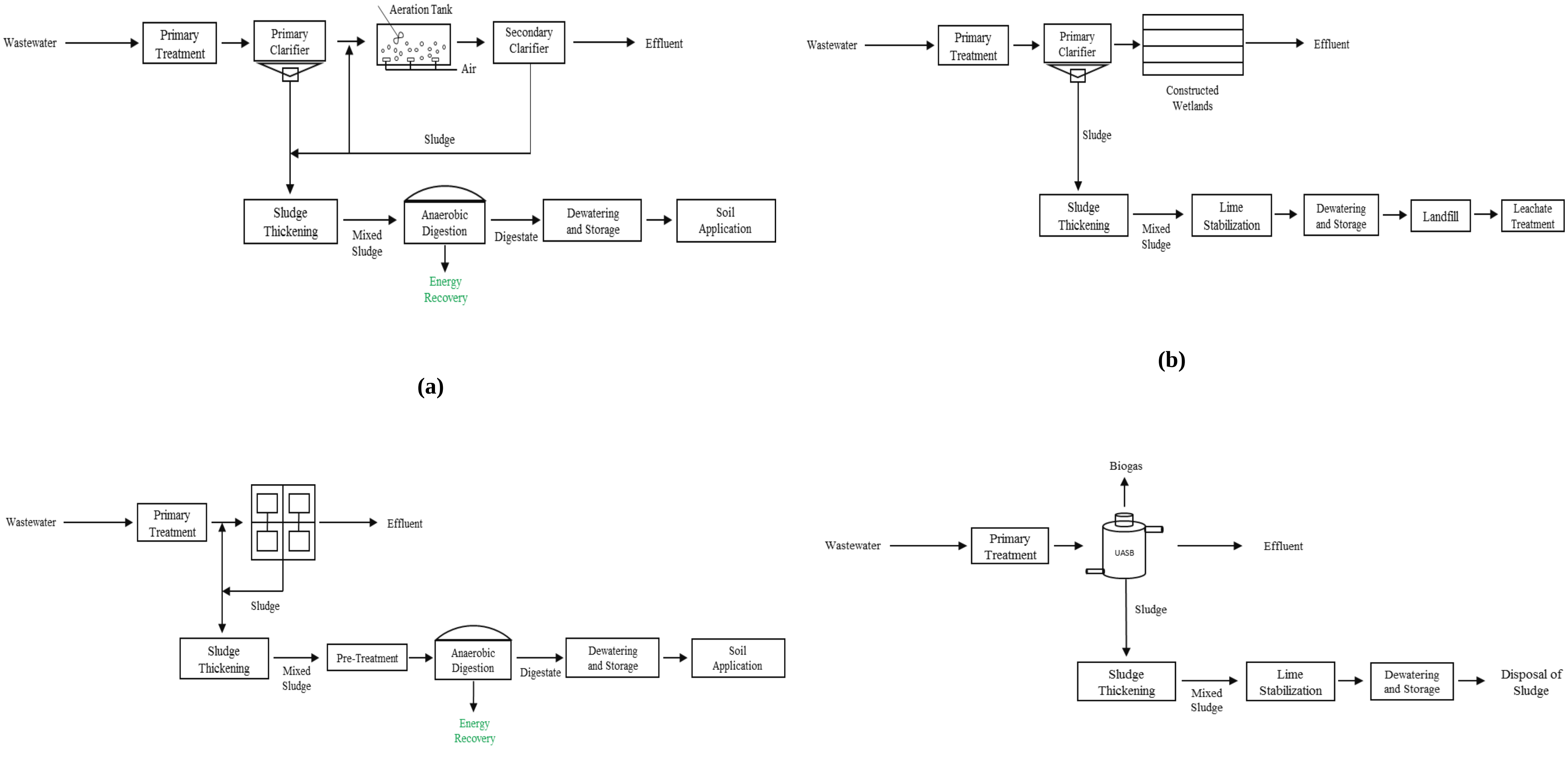
Parameters	Unit	ASP	CW	SBR	UASB
Wastewater Treatment*					
Input from Technosphere					
Electricity	kWh	0.173	0.0219	0.309	0.0329
Emissions to Air					
Carbon Dioxide	kg	0.197	-0.0438	0.351	0.0822
Sulfur dioxide	g	1.62	0.219	2.87	0.438
Nitrogen oxides	g	0.701	0.11	1.24	0.241
Carbon monoxide	g	0.932	0.219	1.6	0.625
Mercury	mg	0.0252	0.00329	0.0438	0.00471
Particulates	g	0.416	0.0515	0.723	0.0964
Emissions to Water					
COD	kg	0.070	0.0548	0.05	0.0986
Nitrogen, total	kg	0.0329	0.0219	0.0145	0.0986
Phosphorus, total	kg	0.006	0.005	0.000997	0.00767
Heavy metals	g	2.29	1.96	0.964	2.49
Emission to Soil					
Nitrogen, total	g	1.81	0.997	2.82	3.5
Phosphorus, total	g	0.449	0.252	0.707	0.877
Output to Technosphere					
Sludge	kg	0.05	0.02	0.01	0.02
Sludge Treatment**					
Input from Technosphere					
Electricity	kWh	0.166	0.0975	0.235	0.0975
Heat	kWh	0.64	-	0.65	-
Truck	tkm	0.074	0.06	0.1	0.06
Polyacrylamide	kg	0.0091	0.0091	0.0091	0.0091
Lime	kg	-	0.165	-	0.165
Avoided Products					
Ammonium sulfate, as N	kg	0.012	-	0.011	-
Phosphate fertiliser, as P2O5	kg	0.0016	-	0.0014	-
Electricity	kWh	0.7	-	0.84	0.0649
Heat	kWh	0.75	-	0.895	-
Emissions to Air					
Methane, biogenic	kg	0.0089	0.024	0.0106	0.024
Carbon dioxide, biogenic	kg	0.6	0.308	0.712	0.308
Nitrogen oxides	kg	8E-5	-	0.0001	-
Dinitrogen monoxide	kg	0.00017	-	0.00016	-
Hydrogen sulfide	kg	1E-5	-	1E-5	-
Ammonia	kg	0.0007	0.014	0.00085	0.014
Emissions to Water					
Phosphate	kg	0.0272	0.029	0.028	0.029
Nitrate	kg	0.3	0.262	0.264	0.262
Ammonium, ion	kg	0.058	0.06	0.058	0.06
Nitrogen dioxide	kg	0.0034	0.0036	0.0034	0.0036

4.2.2.3 Sequential Batch Reactor

SBR is a modification of ASP. Wastewater is applied to a single batch reactor in this method and then processed and discharged to eliminate undesirable components. Equalizing, aerating, and clarification will all be done with a single batch reactor. They are generally used for WWT with low or intermittent-flow conditions (Gupta, et al., 2012). The process diagram of SBR shown in Figure – 4.2 (c). The inventory data is generated for 33 MLD capacity SBR plant (Gupta & Singh, 2012) based on the design procedure given in (Metcalf & Eddy, 2003). The sludge from SBR is assumed to be subjected to anaerobic digestion before applying to the land. The inventory data of SBR is given in Table – 4.1.

4.2.2.4 Up-flow Anaerobic Sludge Blanket

The UASB reactor is the widely used anaerobic treatment system for wastewater. UASB is a suspended growth reactor that promotes granulation to sustain a high microbial biomass concentration (Khanal, et al., 2017). Table 1 shows the emission inventory. A75 MLD capacity sewage treatment plant based on (Kalbar, et al., 2013) is used to generate LCI. UASB sludge is assumed to be treated with lime stabilization before being disposed of, having an energy recovery facility. The UASB phase flow diagram is shown in Figure – 4.2 (d).



(a)

(b)

(c)

(d)

Figure 4.2 Flow Diagram of (a) Activated Sludge Process (b) Constructed Wetlands (c) Sequential Batch Reactor (d) Up-flow Anaerobic Sludge Blanket

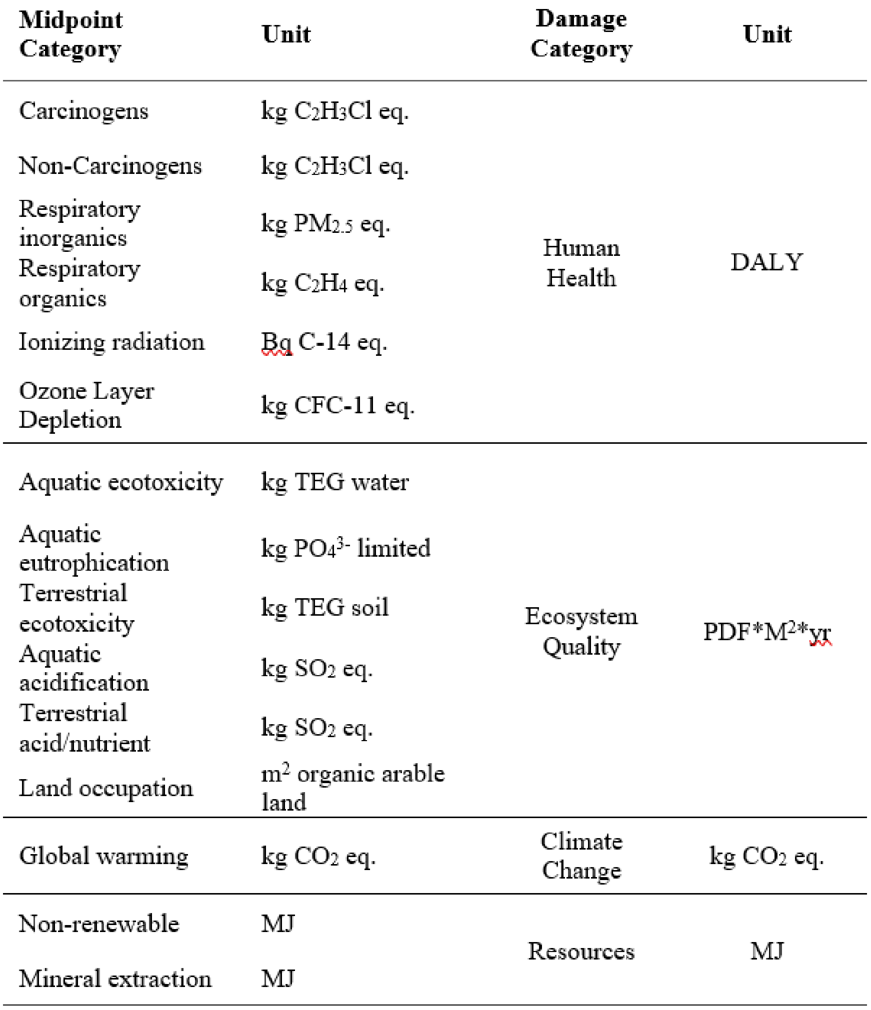
4.2.3 Life Cycle Impact Assessment

An LCIA aims identify and quantify potential consequences of product, operation, or service on environment. LCIA comprises several steps: choosing the appropriate impact categories, assigning the elementary flows, characterization, normalization, grouping, and weighting (Nieuwlaar, 2013). LCIA methods take two different approaches: midpoint and endpoint. The midpoint method embraces the categories in the middle of the cause-effect chain without computing final damages, such as human health or environmental damages. Global warming, Acidification, ionizing radiation, and eutrophication are some examples of these midpoint categories. The endpoint method takes it a step further by converting midpoint effects into more specific human and ecosystem damage categories.

LCIA methods attempt to link each LCI to the respective environmental impacts. The LCI results are categorized according to ISO 14044 into impact categories with an indicator. There are many approaches for calculating environmental effects. The most often used LCIA approaches are CML, IMPACT 2002+, Eco-indicator 99, and Eco-points 97. Damage assessment and weighting are not supported by the CML method. Eco-point 97 can calculate impacts in single score; however, it does so by using 30 separate impact categories and does not reflect ultimate damages to human health or resources. The IMPACT 2002+ approach was used in this analysis. This method consists of four other methods: IMPACT 2002, Eco-indicator 99, CML (Guinée, et al., 2002) and Intergovernmental Panel on Climate Change (IPCC). The method consistently combines midpoint and endpoint categories. This method includes 15 midpoint level categories grouped into four damage impact scores or damage categories: Human Health, Ecosystem Quality, Climate Change, and Resources. Table

– 4.2 shows the midpoint and damage categories of IMPACT 2002+ (Jolliet, et al., 2003). The following impact categories are chosen based on studied processes and emissions: Global Warming, Toxicity, Eutrophication, Acidification, Respiratory Effects, and Fossil Depletion. Midpoint characterization factors are based on equivalency rules, which means that midpoint characterization scores are calculated in kg-equivalents of a substance relative to a reference substance. This study does not consider model uncertainty or uncertainty from the LCIA methods.

Table 4.2 Impact categories of IMPACT 2002+



Midpoint Category	Unit	Damage Category	Unit
Carcinogens	kg C_2H_3Cl eq.	Human Health	DALY
Non-Carcinogens	kg C_2H_3Cl eq.		
Respiratory inorganics	kg $PM_{2.5}$ eq.		
Respiratory organics	kg C_2H_4 eq.		
Ionizing radiation	Bq C-14 eq.		
Ozone Layer Depletion	kg CFC-11 eq.		
Aquatic ecotoxicity	kg TEG water	Ecosystem Quality	PDF*M^2*yr
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		
Global warming	kg CO_2 eq.	Climate Change	kg CO_2 eq.
Non-renewable	MJ	Resources	MJ
Mineral extraction	MJ		

4.3 Results and Discussions

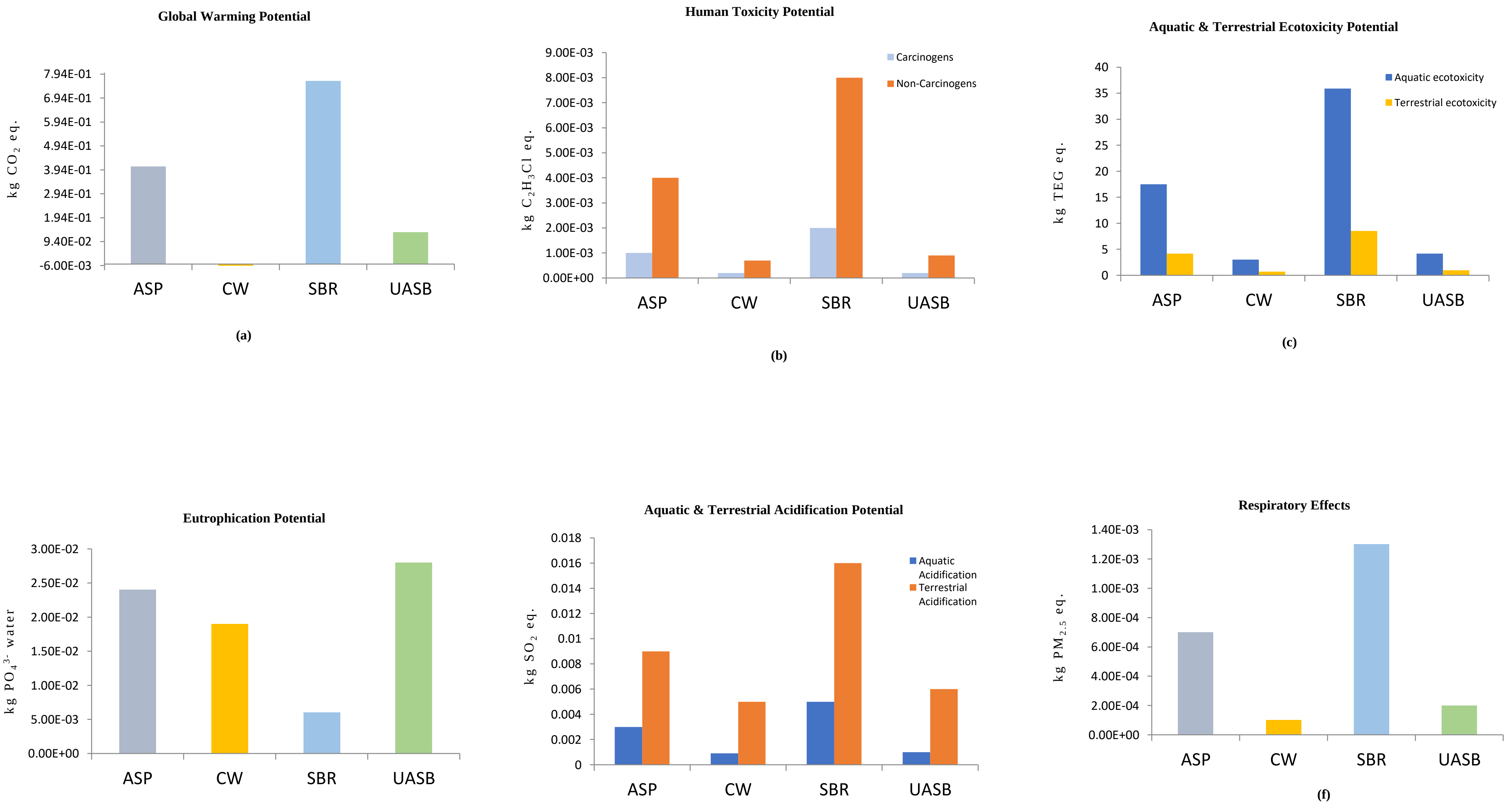
A comparative LCA of wastewater treatment methods was performed in this study. The overall energy consumption of the plants through their life cycle has been found to be SBR > ASP > UASB > CW, which is consistent with previous studies conducted in India (0 - 1 kWh/m3) (Singh & Kazmi, 2018; Kamble, et al., 2019). The wastewater treatment LCA was carried out using SimaPro, in which inventories of WWT were entered and evaluated. In this evaluation, the inventories were analyzed using the IMPACT 2002+ approach. The inventory data were derived from previously published publications and the ecoinvent database. The analysis shows that electrical consumption contributes the most to global impact categories such as global warming, abiotic depletion, and acidification. The WWTP does not have a direct influence on the surrounding environment. Its environmental effect is attributed to the production of electricity (Ioannou-Ttofa, et al., 2016). This is due to the extraction and combustion of fossil fuels, which emit pollutants and CO_2 into the atmosphere. The data obtained from the analysis of impact categories are as follows: -

4.3.1 Global Warming Potential (GWP)

Figure – 4.3 (a) shows that CWs have negative CO_2 emissions (-6.63E-03 kg CO_2 eq.) due to sequestration of CO_2 during the treatment. The important contributor to CO_2 emissions is electricity usage. Due to its high electricity consumption, the SBR process has the highest impact on climate change (0.766217 kg CO_2 equivalent.) compared to other treatment processes. The higher energy requirements of SBRs compared to ASP is because SBRs are often built for both organic and nutrient removal, which takes more oxygen and hence more energy (Kalbar, et al., 2012). However, the sludge treatment method used for SBR has the least impact due to pre-treatment and energy recovery from AD process. The negative global warming potential of CWs suggests that natural treatment systems can help to reduce global warming. The midpoint values of each method are available in Appendix A. The results of this analysis are in line with the findings of (Kamble, et al., 2019).

4.3.2 Toxicity Potentials

Toxicity potential depends mainly on the heavy metals released in the air, water, and soil environment. Human Toxicity (HT) is due to carcinogenic and non-carcinogenic impacts. HT calculates cumulative toxicological risk and probable consequences of releasing a certain amount of a chemical into the environment. As shown in Figure – 4.3 (b), SBR has the highest HT potential due to non-carcinogens 8.58E-03 kg C2H3Cl eq. (mainly due to emission of Arsenic 7.13E-03 kg C2H3Cl eq. from the electrical process) followed by ASP 4.15E-03 kg C2H3Cl eq. The CFs of aquatic ecotoxicity are given for emissions into the air, water, and soil and quantify the ecotoxicity effects on (surface) freshwater. Ecotoxicity is measured in kg of Triethylene glycol (TEG) / kg and is calculated by dividing the damage CF of the substance under consideration by the damage CF of the reference substance (Triethylene glycol) (Jolliet, et al., 2003). Terrestrial ecotoxicity is calculated similarly. SBR has the highest Aquatic and terrestrial ecotoxicity, 35.9 kg TEG water and 8.54 kg TEG soil, respectively, shown in Figure – 4.3 (c). However, the sludge treatment process AD with pre-treatment has negative toxicity potential due to avoided products (fertilizers as ammonium sulfate and diammonium phosphate) and energy generation.



(a)

(b)

(c)

(d)

(e)

(f)

Figure 4.3 Comparison of Environmental impacts of various Wastewater Treatment methods. ASP -Activated Sludge Process; CW-Constructed Wetlands; SBR- Sequential Batch Reactor; UASB-Up-flow Anaerobic Sludge Blanket

4.3.3 Eutrophication Potential (EP)

Eutrophication in WWTP is mainly due to the release of phosphorus, nitrogen, and ammonia and, to some extent, degradable organics in wastewater effluent. Figure – 4.3 (d) shows that UASB system had the highest EP (2.89E-02 kg PO43-Eq) because there is negligible nutrient removal in the UASB system followed by ASP because of its nutrient removal capacity of 40-50%. SBR has the lowest eutrophication potential (6.67E-03 kg PO43-Eq) because of its intrinsic nutrient removal capacity of 70-80%. This result is in line with the findings of (Gallego, et al., 2008).

4.3.4 Acidification Potential (AP)

Acidification is caused due to the release of NOx and SOx associated with energy production. SBR is found to have highest Aquatic and Terrestrial AP, 5.56E-03 kg SO_2 equivalent. and 1.63E-02 kg SO_2 equivalent., respectively, followed by ASP as shown in Figure – 4.3 (e). The impact is majorly due to the emission of Nitrogen oxide (0.012 kg SO_2 eq. for Terrestrial AP) and Sulfur dioxide (3.87E-03 kg SO_2 eq. for Aquatic AP).

4.3.5 Respiratory Effects

This category refers to impacts that are caused by inorganic substances. The CFs are given for air emissions only. SBR has the highest respiratory effects (1.37E-03 kg PM2.5 eq.) due to the release of particulates from the electrical process, followed by

ASP (7.17E-04 kg PM2.5 eq.). Figure – 4.3 (f) shows the comparison of respiratory effects caused by WWT methods.

4.3.6 Fossil Depletion

Coal consumption has major contribution to Fossil depletion. The study shows that due to the high energy consumption of the SBR process, it has the highest fossil depletion potential (5.35 MJ), followed by ASP (2.72 MJ) shown in Figure – 4.4, which matches with the study by (Kalbar, et al., 2013).

Figure 4.4 Comparison of Fossil depletion potential of WWT method

4.3.7 Damage Categories

Endpoint indicators are considered to represent changes in stresses at point in a cause-effect chain where overall outcome might significantly impact society's perception of it. In IMPACT 2002+ method, the midpoint impacts grouped into 4 endpoint categories: Human Health represented in DALY ("Disability Adjusted Life Years") i.e. years lost to early mortality and reduced quality of life due to illness; Ecosystem determined by PDF*m^2*yr (“potentially disappeared fraction of species over a certain area in m^2 over a certain year”) (Jolliet, et al., 2003); Climate Change similar as global warming and estimated in kg CO_2 eq.; and Resources expressed in MJ. Table -3 shows the damage category values of considered WWT methods.

Table 4.3 Damage category values of WWT methods

Damage Category	Unit	ASP	CW	SBR	UASB
Human Health	DALY	5.17E-07	1.04E-07	9.93E-07	1.54E-07
Ecosystem quality	PDF*m^2*yr	0.10044724	0.021339154	0.20404619	0.028493449
Climate change	kg CO_2 eq.	0.40866499	-0.006634808	0.7662169	0.13313895
Resources	MJ	2.7172232	0.45711043	5.3530308	0.62724869

4.3.8 Normalization

Normalization is a technique for analysing each impact's contribution to total damage by adding normalization variables to impact groups to make analysis simpler. Comparing various groups on the same graph with the same units makes it simple to analyze the data. As per IMPACT 2002+ impact guide, "Normalization is accomplished by dividing the impact by the appropriate normalization variables." Figure – 4.5

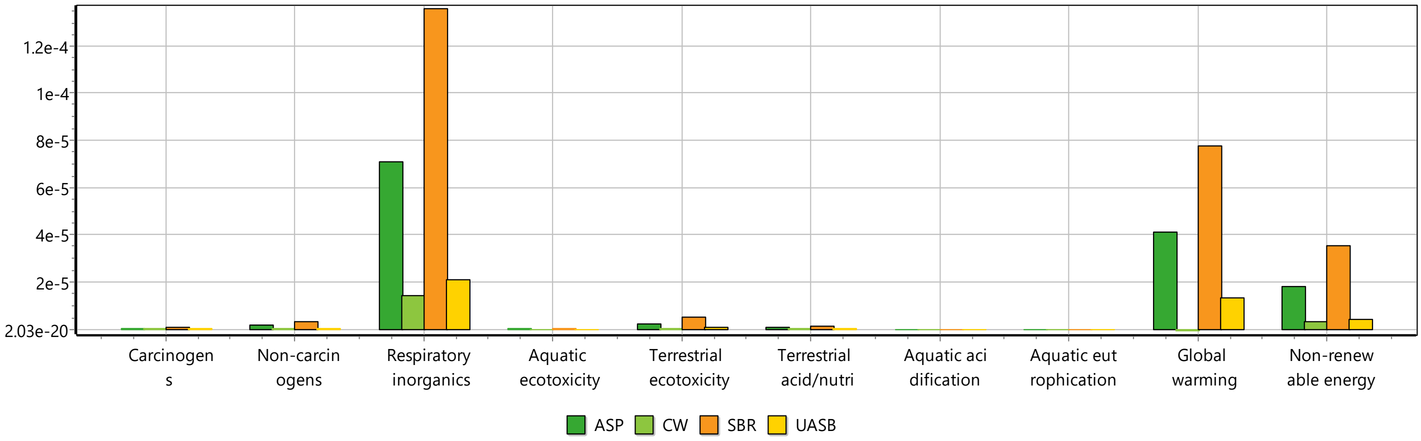


Figure 4.5 Normalized values of midpoint impact categories of WWT methods

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The ISO 14040 defines this chapter as the second phase of interpretation. The studied information is brought together in the conclusion part, and the significant aspects of the research are presented. The chapter connects the analysis and theory employed to reality, attempting to make this study relevant not just in academic circles but also in the actual world.

The LCA approach used in this study adheres to the ISO 14040 set of standards, which specify four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Because it is designed to apply the approach mentioned above in the impact assessment phase, the Simapro 9.1.1.1 software tool played an essential role in performing this study and somewhat pre-empted the methodological choices.

In order to conduct the LCA on WWT and assess environmental effect of the wastewater plant, this project fulfilled its objectives by using the IMPACT 2002+ procedure. The existing technical facility for treating sewage, industrial and municipal waste is a wastewater treatment plant to reach a minimum permissible waste quality. Therefore, it is essential to ensure that the WWT facility has no substantial environmental impact, which might cause significant problems. The importance of LCA in Indian WWTPs is highlighted in this analysis. These techniques are capable of addressing environmental challenges and maximizing waste economic and technical aspects. The result implies that SBR has the most potential for global warming and resource degradation because of high electricity consumption. Due to the less capacity to remove nutrients, UASB has the highest aquatic eutrophication potential. CWs, in comparison to all other systems, have the fewest environmental impacts and have been shown to help mitigate global warming due to their carbon sequestering potential. These studies suggest that any given technology will work well in one specific category of impact and poorly in another, making it hard to compare depending on the impact categories. The CWs, accompanied by UASB, are the required wastewater management strategies in accordance with system boundary of the study, with which environmental effects of wastewater treatment can be reduced. The analysis also shows that the sludge treatment method, anaerobic digestion with a pre-treatment facility, has least impact on the environment, followed by anaerobic digestion (without pre-treatment) and Lime stabilization with an energy recovery facility. The impact of pre-treatment on digestive efficiency was related to its impact on energy recovery, transport demands, and loading of nutrients, emphasizing the need for a life cycle assessment. Precise information on environmental or human health threats cannot be provided directly by LCAs for wastewater systems. However, LCA input and output data can be used in additional methods, such as risk evaluation. Local and regional priorities are inconsistent with present LCIA approaches, necessitating modifications to the characterization factors to account for regional variances. A full-scale environmental and economic review of technologies should also be carried out using the long-term collected information in relation to potential study requirements. The comprehensive framework developed in the study will aid in the formulation of suitable decision-making approach to choose right technology for WWT.

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APPENDIX – A

Table A.1 Single Score of all WWT methods

Substance	Compartment	Unit	ASP	CW	SBR	UASB
Particulates, < 2.5 um	Air	µPt	32.47298	5.366339	66.75533	7.491968
Carbon dioxide, fossil	Air	µPt	20.45657	3.4208	40.85977	4.720124
Carbon dioxide	Air	µPt	19.92329	-4.4274	35.41918	8.30137
Sulfur dioxide	Air	µPt	16.37397	2.337981	30.05272	4.288194
Nitrogen oxides	Air	µPt	15.45262	2.528033	28.33289	4.621997
Coal, hard	Raw	µPt	15.05565	2.467229	31.15051	3.460069
Particulates	Air	µPt	6.458959	0.798871	11.21819	1.495759
Occupation, urban, green areas	Raw	µPt	4.009116	0.675789	8.30482	0.940507
Aluminium	Air	µPt	2.066503	0.348041	4.284333	0.484619
Arsenic	Water	µPt	1.486952	0.246914	3.088171	0.345382
Remaining substances		µPt	5.614047	4.830667	8.007189	5.169185

Table A.2 Normalization values of all WWT methods

Impact category	**ASP**	**CW**	**SBR**	**UASB**
Carcinogens	4.52E-07	7.76E-08	8.27E-07	1.04E-07
Non-carcinogens	1.64E-06	2.81E-07	3.39E-06	3.89E-07
Respiratory inorganics	7.08E-05	1.43E-05	0.000136	2.12E-05
Ionizing radiation	1.48E-08	2.64E-09	2.92E-08	3.57E-09
Ozone layer depletion	4.36E-10	8.86E-11	5.83E-10	1.06E-10
Respiratory organics	9.71E-09	2.06E-09	1.47E-08	2.50E-09
Aquatic ecotoxicity	6.41E-08	1.11E-08	1.32E-07	1.53E-08
Terrestrial ecotoxicity	2.41E-06	4.18E-07	4.93E-06	5.75E-07
Terrestrial acid/nutri	7.10E-07	4.25E-07	1.24E-06	5.12E-07
Land occupation	4.15E-06	7.04E-07	8.59E-06	9.78E-07
Global warming	4.13E-05	-6.70E-07	7.74E-05	1.34E-05
Non-renewable energy	1.79E-05	3.01E-06	3.52E-05	4.13E-06
Mineral extraction	2.38E-09	9.63E-10	6.86E-09	1.19E-09

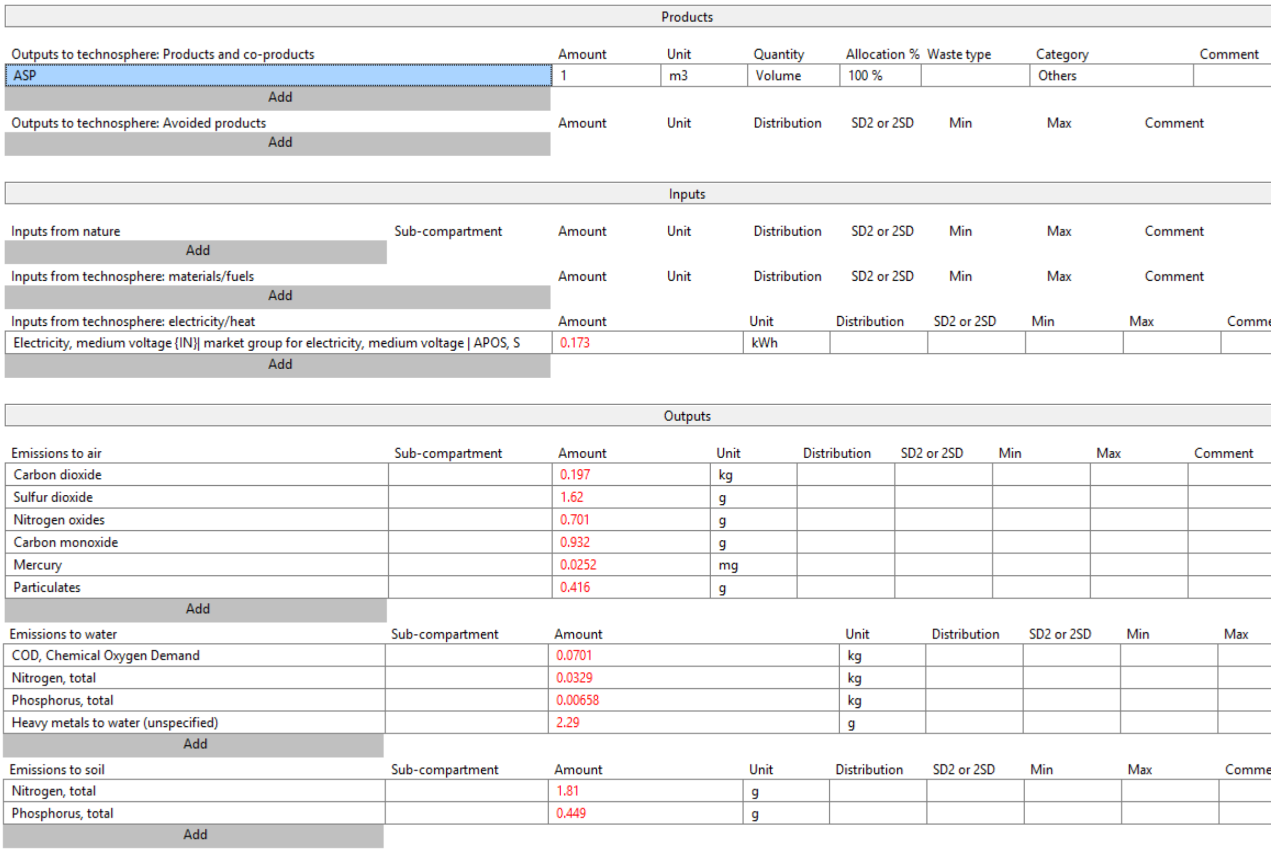
Table A.3 Comparison of Damage categories values with different impact methods

Damage Category

	Recipe 2016			Eco-Indicator 99		
	Human Health (DALY)	**Ecosystem (species.yr)**	**Resources (USD 2013)**	**Human Health (DALY)**	**Ecosystem Quality (PDF*m^2*yr)**	**Resources (MJ surplus)**
ASP	1.15E-06	7.18E-09	0.00658	4.07E-07	0.0665	0.00036
CW	1.65E-07	4.16E-09	0.00121	6.43E-08	0.0154	0.00014
SBR	2.16E-06	5.32E-09	0.01122	7.86E-07	0.1347	0.00104
UASB	3.70E-07	6.18E-09	0.00156	1.19E-07	0.0204	0.00018

APPENDIX – B

B.1 Activated Sludge Process inventory in Simapro



Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
ASP	1	m3	Volume	100 %		Others	

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comme
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.173	kWh					

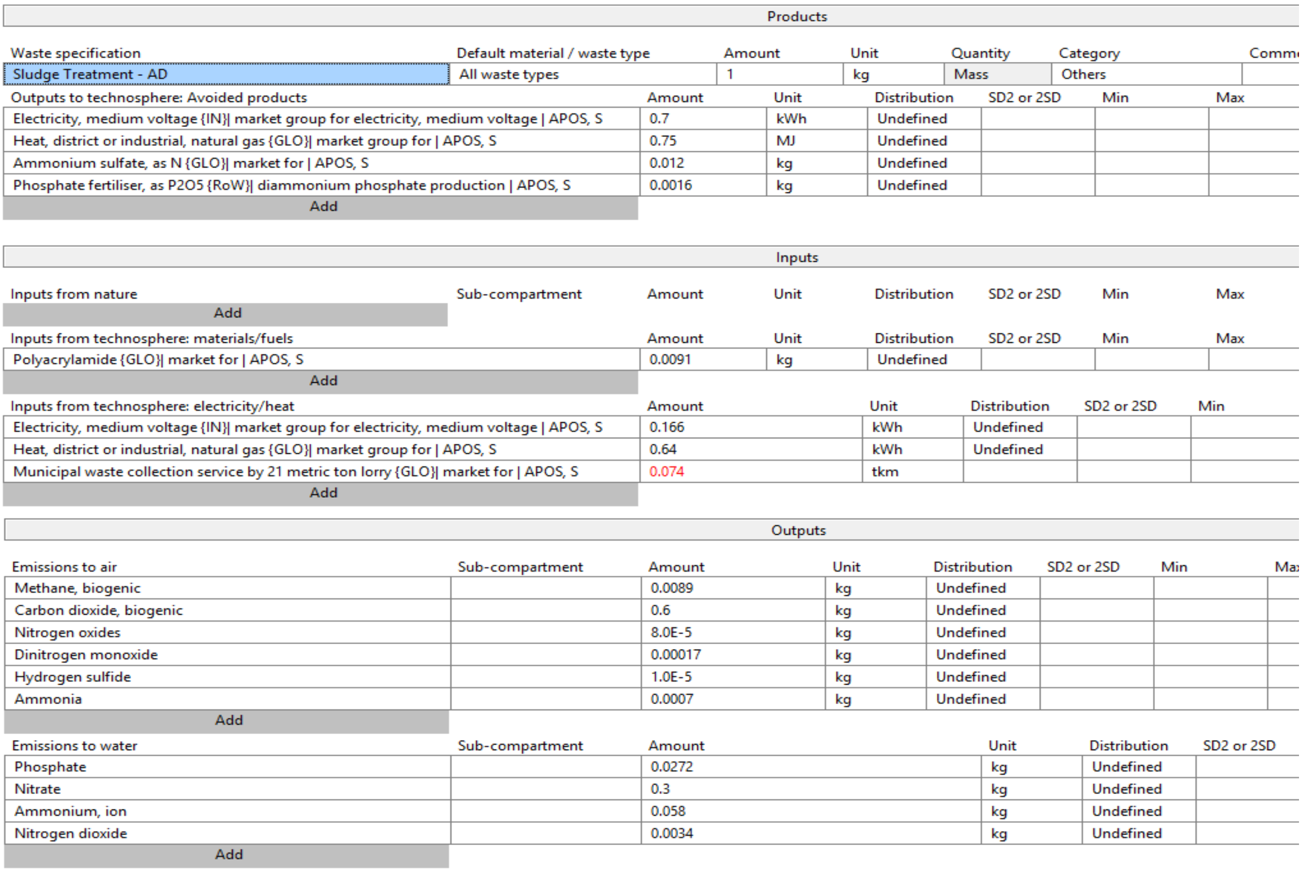
Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Carbon dioxide		0.197	kg					
Sulfur dioxide		1.62	g					
Nitrogen oxides		0.701	g					
Carbon monoxide		0.932	g					
Mercury		0.0252	mg					
Particulates		0.416	g					

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max
COD, Chemical Oxygen Demand		0.0701	kg				
Nitrogen, total		0.0329	kg				
Phosphorus, total		0.00658	kg				
Heavy metals to water (unspecified)		2.29	g				

Emissions to soil	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comme
Nitrogen, total		1.81	g					
Phosphorus, total		0.449	g					

Figure B.1 Input of inventories in ASP



Products

Waste specification	Default material / waste type	Amount	Unit	Quantity	Category	Comm
Sludge Treatment - AD	All waste types	1	kg	Mass	Others	

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.7	kWh	Undefined			
Heat, district or industrial, natural gas {GLO}| market group for | APOS, S	0.75	MJ	Undefined			
Ammonium sulfate, as N {GLO}| market for | APOS, S	0.012	kg	Undefined			
Phosphate fertiliser, as P2O5 {RoW}| diammonium phosphate production | APOS, S	0.0016	kg	Undefined			

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max
Polyacrylamide {GLO}| market for | APOS, S	0.0091	kg	Undefined			

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.166	kWh	Undefined		
Heat, district or industrial, natural gas {GLO}| market group for | APOS, S	0.64	kWh	Undefined		
Municipal waste collection service by 21 metric ton lorry {GLO}| market for | APOS, S	0.074	tkm			

Add

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Ma
Methane, biogenic		0.0089	kg	Undefined			
Carbon dioxide, biogenic		0.6	kg	Undefined			
Nitrogen oxides		8.0E-5	kg	Undefined			
Dinitrogen monoxide		0.00017	kg	Undefined			
Hydrogen sulfide		1.0E-5	kg	Undefined			
Ammonia		0.0007	kg	Undefined			

Add

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Phosphate		0.0272	kg	Undefined	
Nitrate		0.3	kg	Undefined	
Ammonium, ion		0.058	kg	Undefined	
Nitrogen dioxide		0.0034	kg	Undefined	

Add

Figure B.2 Input of inventories in Anaerobic Digestion

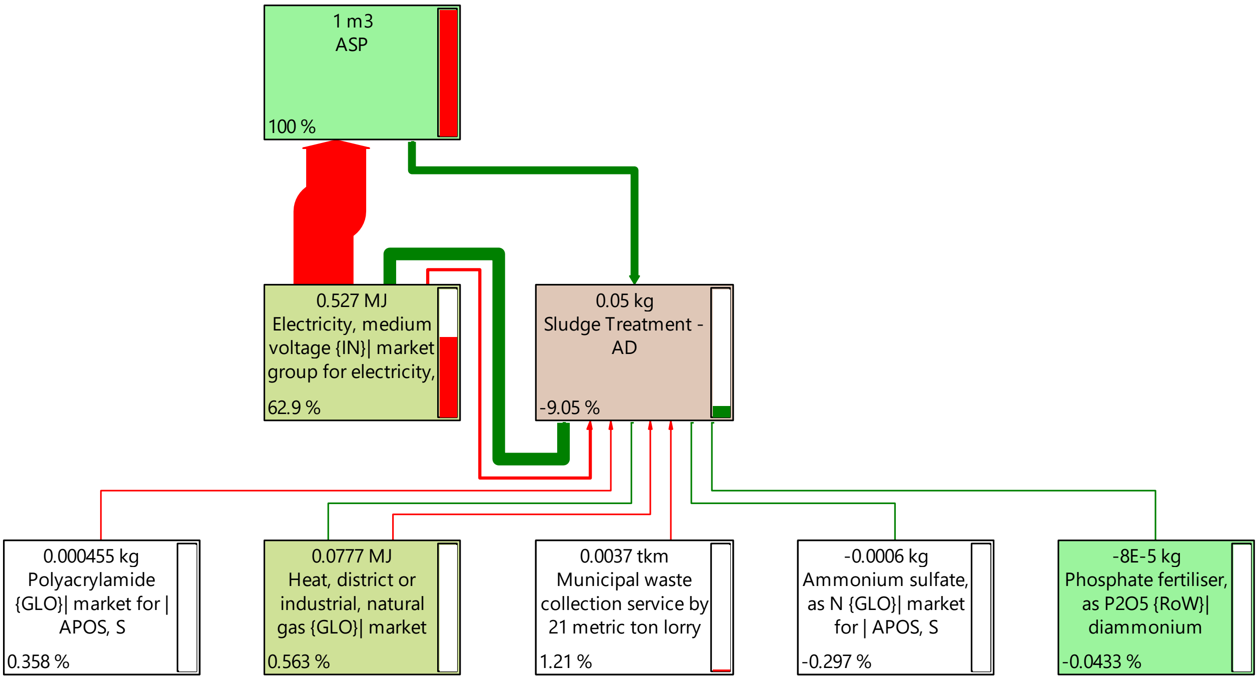
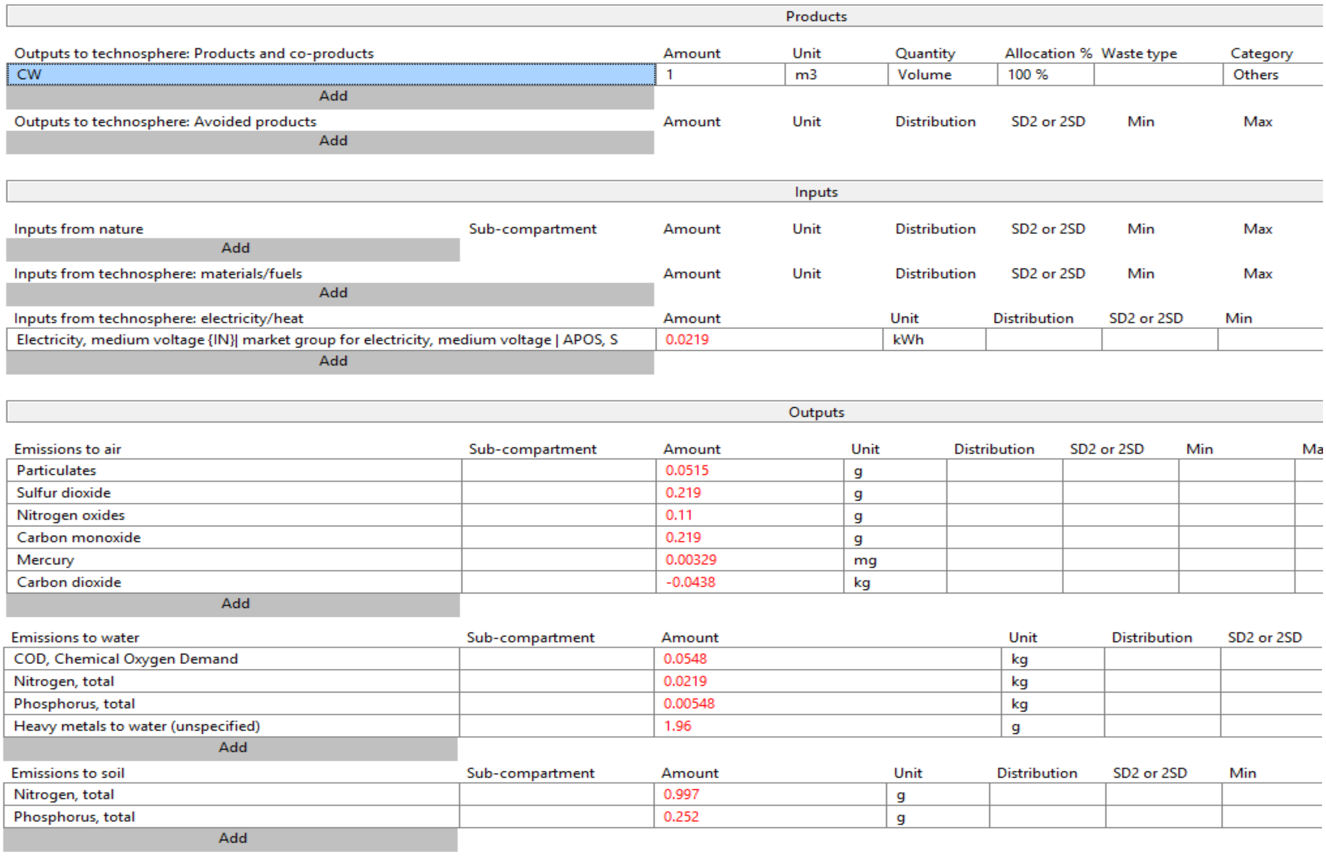


Figure B.3 Sankey diagram of ASP process

B.2 Constructed Wetlands inventory in Simapro



Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Waste type	Category
CW	1	m3	Volume	100 %		Others

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.0219	kWh			

Add

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Ma
Particulates		0.0515	g				
Sulfur dioxide		0.219	g				
Nitrogen oxides		0.11	g				
Carbon monoxide		0.219	g				
Mercury		0.00329	mg				
Carbon dioxide		-0.0438	kg				

Add

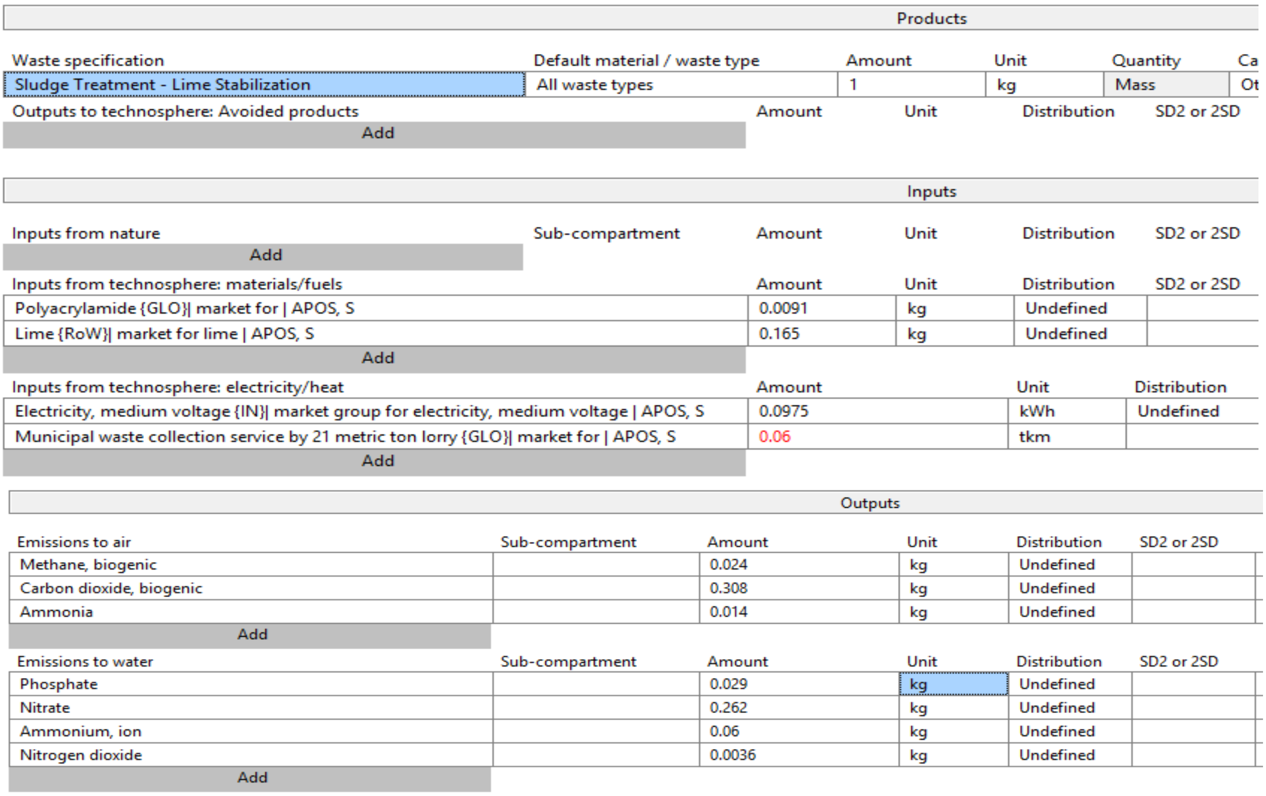
Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
COD, Chemical Oxygen Demand		0.0548	kg		
Nitrogen, total		0.0219	kg		
Phosphorus, total		0.00548	kg		
Heavy metals to water (unspecified)		1.96	g		

Add

Emissions to soil	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min
Nitrogen, total		0.997	g			
Phosphorus, total		0.252	g			

Add

Figure B.4 Input of inventories in CW



Products

Waste specification	Default material / waste type	Amount	Unit	Quantity	Ca
Sludge Treatment - Lime Stabilization	All waste types	1	kg	Mass	Ot

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD
Add				

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Add					

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD
Polyacrylamide {GLO}| market for | APOS, S	0.0091	kg	Undefined	
Lime {RoW}| market for lime | APOS, S	0.165	kg	Undefined	
Add				

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.0975	kWh	Undefined
Municipal waste collection service by 21 metric ton lorry {GLO}| market for | APOS, S	0.06	tkm	
Add			

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Methane, biogenic		0.024	kg	Undefined	
Carbon dioxide, biogenic		0.308	kg	Undefined	
Ammonia		0.014	kg	Undefined	
Add					

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Phosphate		0.029	kg	Undefined	
Nitrate		0.262	kg	Undefined	
Ammonium, ion		0.06	kg	Undefined	
Nitrogen dioxide		0.0036	kg	Undefined	
Add					

Figure B.5 Input of inventories in Lime Stabilization

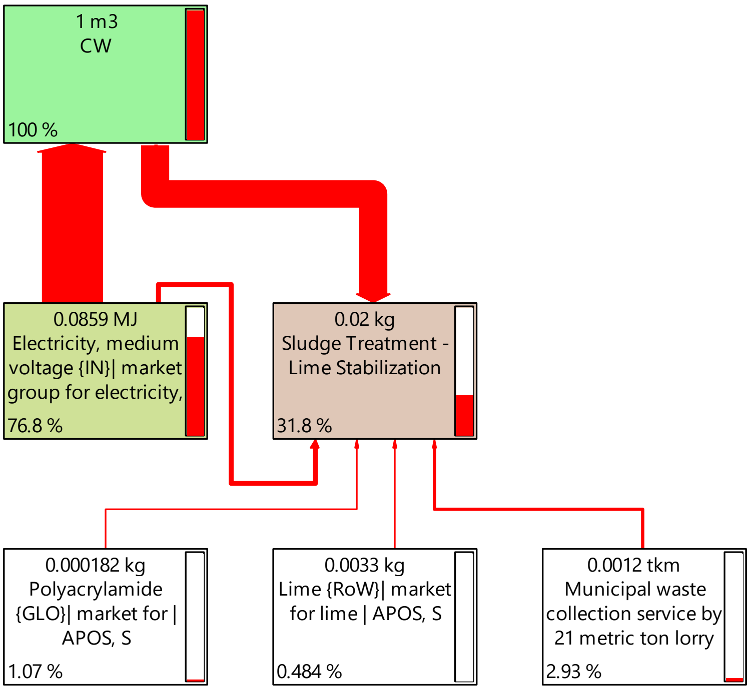
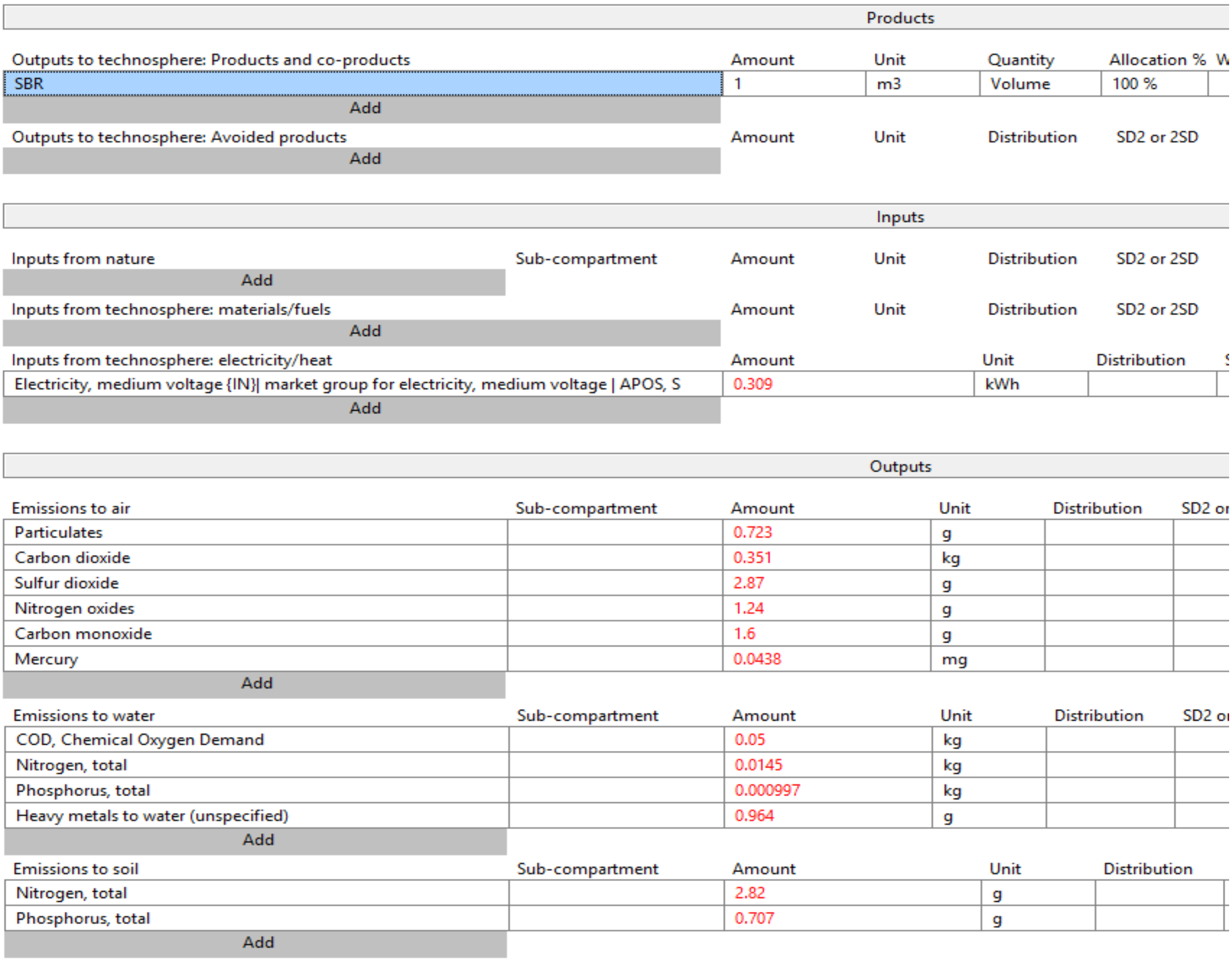


Figure B.6 Sankey diagram of CWs process

B.3 Sequential Batch Reactor inventory in Simapro



Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	W
SBR	1	m3	Volume	100 %	

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.309	kWh	

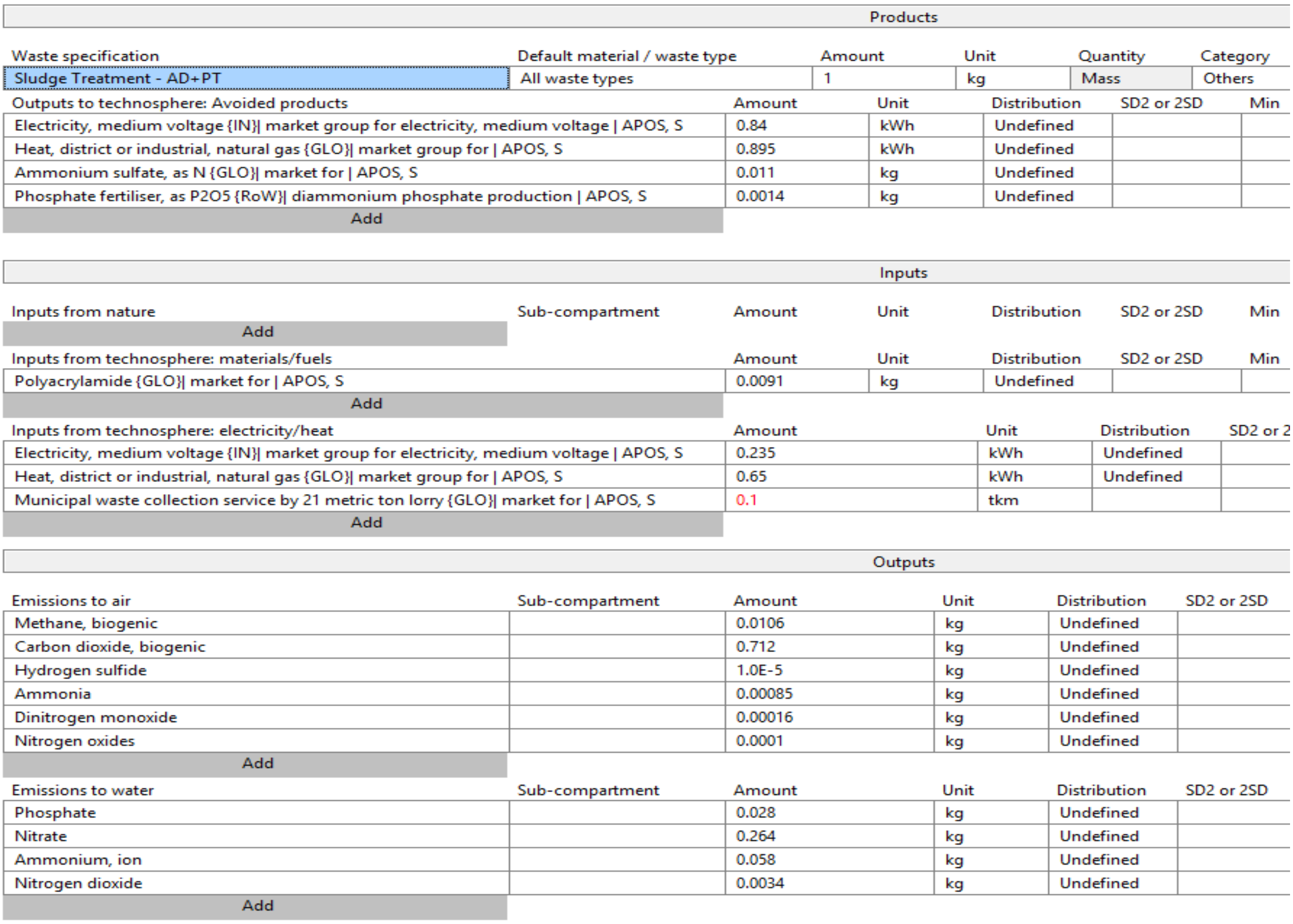
Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 o
Particulates		0.723	g		
Carbon dioxide		0.351	kg		
Sulfur dioxide		2.87	g		
Nitrogen oxides		1.24	g		
Carbon monoxide		1.6	g		
Mercury		0.0438	mg		

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 o
COD, Chemical Oxygen Demand		0.05	kg		
Nitrogen, total		0.0145	kg		
Phosphorus, total		0.000997	kg		
Heavy metals to water (unspecified)		0.964	g		

Emissions to soil	Sub-compartment	Amount	Unit	Distribution
Nitrogen, total		2.82	g	
Phosphorus, total		0.707	g	

Figure B.7 Input of inventories in CW



Products

Waste specification	Default material / waste type	Amount	Unit	Quantity	Category
Sludge Treatment - AD+PT	All waste types	1	kg	Mass	Others

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.84	kWh	Undefined		
Heat, district or industrial, natural gas {GLO}| market group for | APOS, S	0.895	kWh	Undefined		
Ammonium sulfate, as N {GLO}| market for | APOS, S	0.011	kg	Undefined		
Phosphate fertiliser, as P2O5 {RoW}| diammonium phosphate production | APOS, S	0.0014	kg	Undefined		

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min
Polyacrylamide {GLO}| market for | APOS, S	0.0091	kg	Undefined		

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.235	kWh	Undefined	
Heat, district or industrial, natural gas {GLO}| market group for | APOS, S	0.65	kWh	Undefined	
Municipal waste collection service by 21 metric ton lorry {GLO}| market for | APOS, S	0.1	tkm		

Add

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Methane, biogenic		0.0106	kg	Undefined	
Carbon dioxide, biogenic		0.712	kg	Undefined	
Hydrogen sulfide		1.0E-5	kg	Undefined	
Ammonia		0.00085	kg	Undefined	
Dinitrogen monoxide		0.00016	kg	Undefined	
Nitrogen oxides		0.0001	kg	Undefined	

Add

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Phosphate		0.028	kg	Undefined	
Nitrate		0.264	kg	Undefined	
Ammonium, ion		0.058	kg	Undefined	
Nitrogen dioxide		0.0034	kg	Undefined	

Add

Figure B.8 Input of inventories in Anaerobic Digestion with Pre-treatment

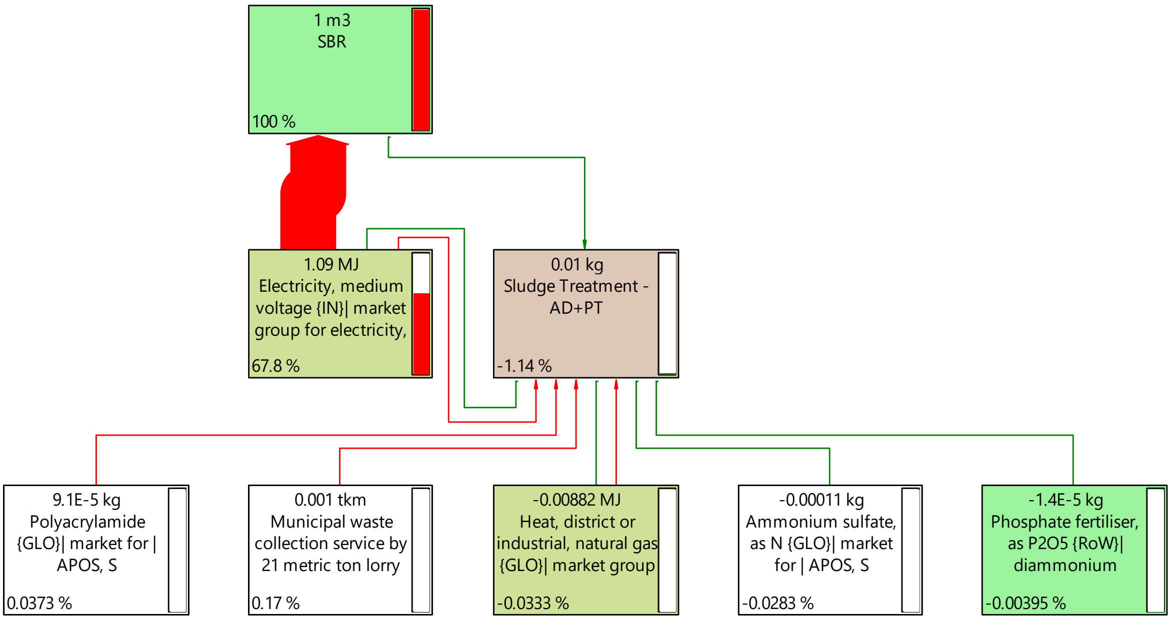
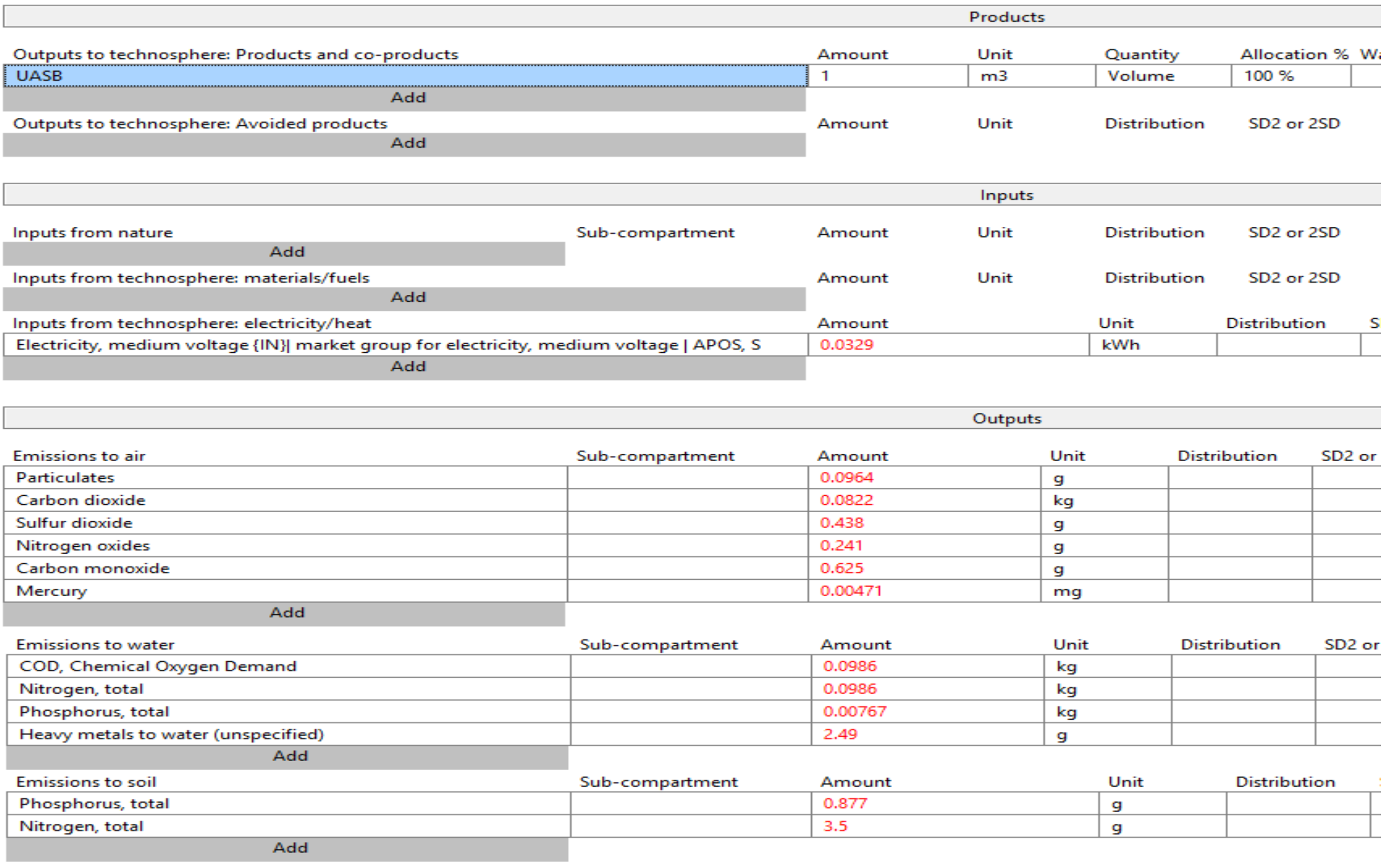


Figure B.9 Sankey diagram of SBR process

B.4 Up-flow Anaerobic Sludge Blanket inventory in Simapro



Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	W
UASB	1	m3	Volume	100 %	

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	S
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.0329	kWh		

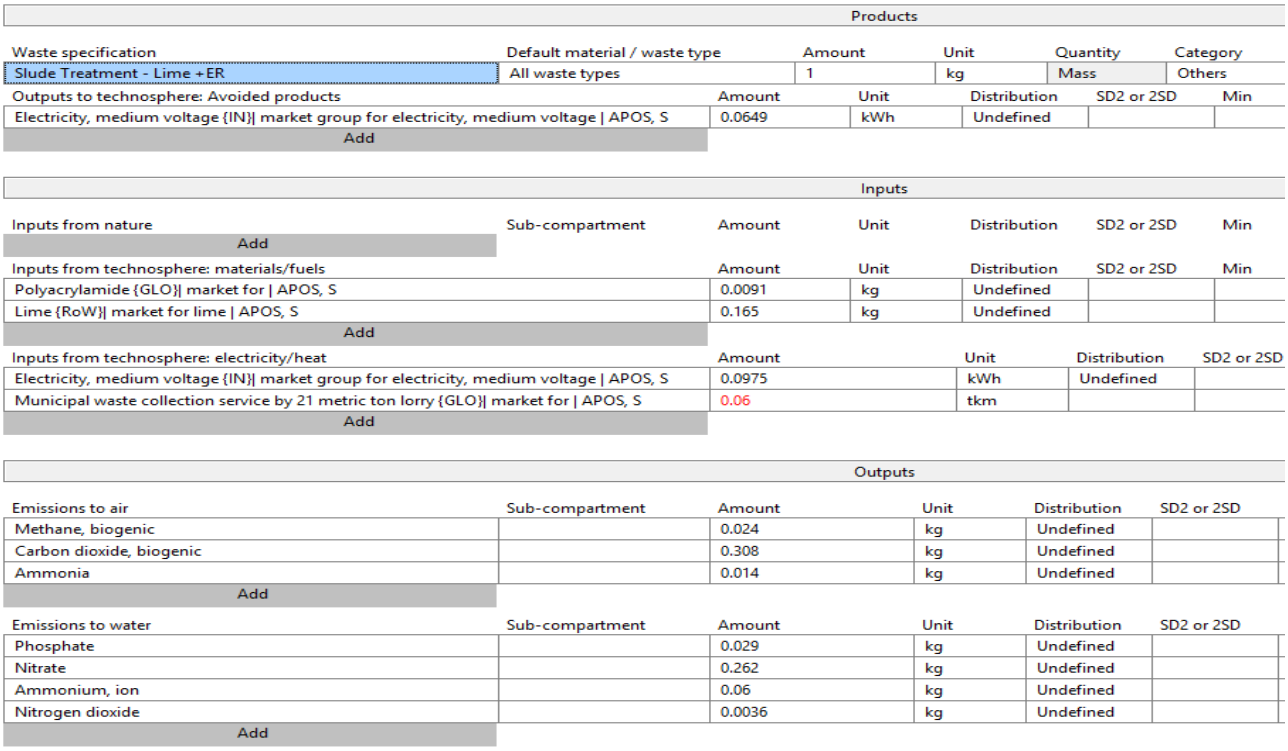
Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or
Particulates		0.0964	g		
Carbon dioxide		0.0822	kg		
Sulfur dioxide		0.438	g		
Nitrogen oxides		0.241	g		
Carbon monoxide		0.625	g		
Mercury		0.00471	mg		

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or
COD, Chemical Oxygen Demand		0.0986	kg		
Nitrogen, total		0.0986	kg		
Phosphorus, total		0.00767	kg		
Heavy metals to water (unspecified)		2.49	g		

Emissions to soil	Sub-compartment	Amount	Unit	Distribution
Phosphorus, total		0.877	g	
Nitrogen, total		3.5	g	

Figure B.10 Input of inventories in CW



Products

Waste specification	Default material / waste type	Amount	Unit	Quantity	Category
Slude Treatment - Lime +ER	All waste types	1	kg	Mass	Others

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.0649	kWh	Undefined		

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min
Polyacrylamide {GLO}| market for | APOS, S	0.0091	kg	Undefined		
Lime {RoW}| market for lime | APOS, S	0.165	kg	Undefined		

Add

Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD
Electricity, medium voltage {IN}| market group for electricity, medium voltage | APOS, S	0.0975	kWh	Undefined	
Municipal waste collection service by 21 metric ton lorry {GLO}| market for | APOS, S	0.06	tkm		

Add

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Methane, biogenic		0.024	kg	Undefined	
Carbon dioxide, biogenic		0.308	kg	Undefined	
Ammonia		0.014	kg	Undefined	

Add

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD
Phosphate		0.029	kg	Undefined	
Nitrate		0.262	kg	Undefined	
Ammonium, ion		0.06	kg	Undefined	
Nitrogen dioxide		0.0036	kg	Undefined	

Add

Figure B.11 Input of inventories in Lime Stabilization with Energy Recovery

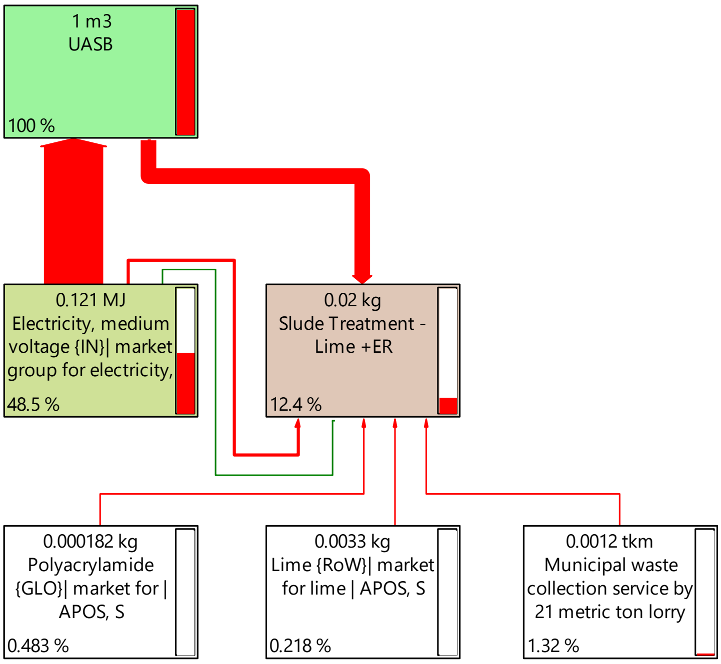


Figure B.12 Sankey diagram of UASB process

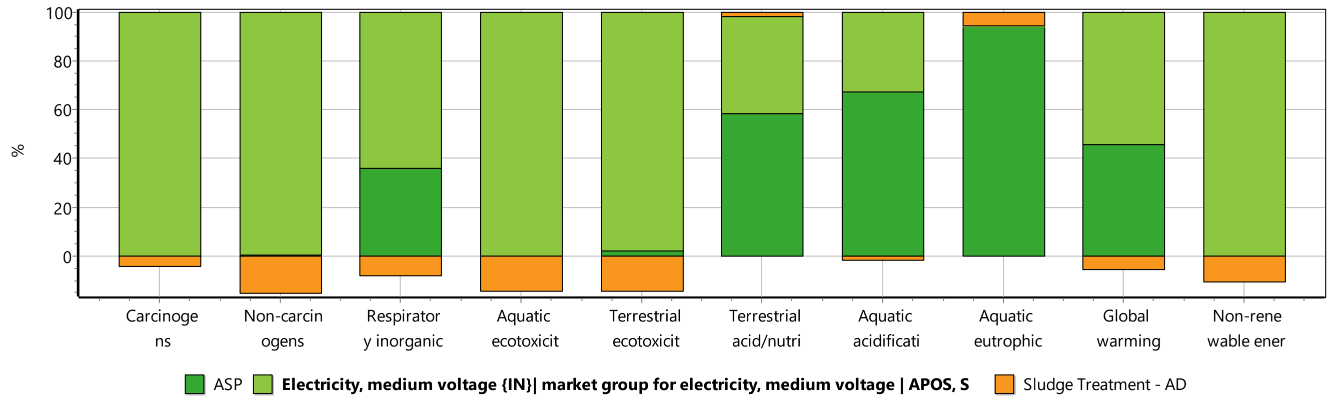
APPENDIX - C

CHARACTERIZATION VALUES OF ALL WWT METHODS

C.1 Activated Sludge Process

Table C.1 Midpoint characterization values of ASP

Impact category	Unit	Total	ASP	Electricity	Sludge Treatment - AD
Carcinogens	kg C2H3Cl eq	0.001145688	0	0.001197368	-5.17E-05
Non-carcinogens	kg C2H3Cl eq	0.004147697	9.62E-06	0.004891508	-0.000753426
Respiratory inorganics	kg PM2.5 eq	0.000717008	0.000282197	0.000499929	-6.51E-05
Aquatic ecotoxicity	kg TEG water	17.496026	0.01981964	20.480444	-3.0042379
Terrestrial ecotoxicity	kg TEG soil	4.1776481	0.096798485	4.778955	-0.69810538
Terrestrial acid/nutri	kg SO2 eq	0.009351084	0.00547103	0.003702564	0.00017749
Aquatic acidification	kg SO2 eq	0.003080251	0.002112877	0.001027014	-5.96E-05
Aquatic eutrophication	kg PO4 P-lim	0.024437858	0.023038466	4.61E-05	0.001353268
Global warming	kg CO2 eq	0.40866499	0.19872274	0.23496396	-0.025021709
Non-renewable energy	MJ primary	2.7168616	0	3.0487461	-0.33188447



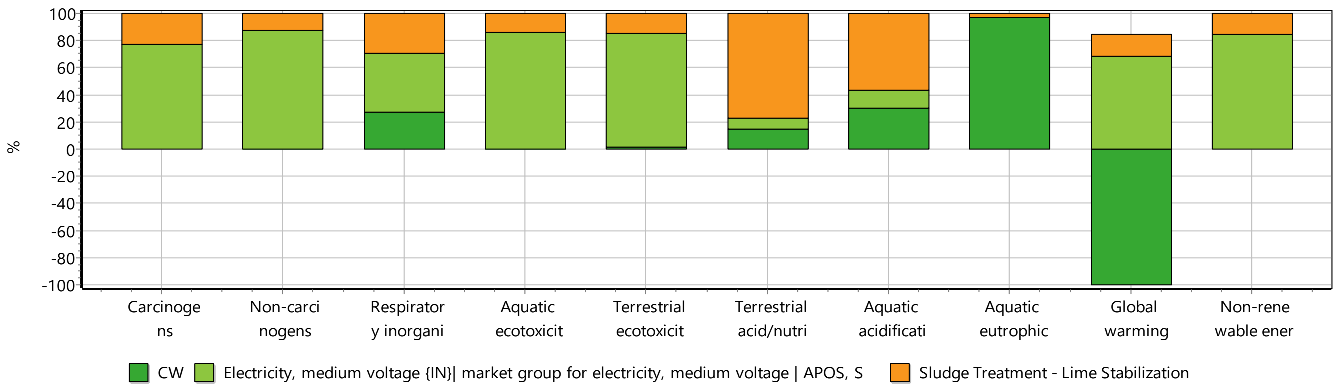
Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 m3 'ASP';

Figure C.1 Midpoint characterization bar chart

C.2 Constructed Wetlands

Table C.2 Midpoint characterization values of CW

Impact category	Unit	Total	CW	Electricity	Sludge Treatment – Lime Stabilization
Carcinogens	kg C2H3Cl eq	0.000197	0	0.000151566	4.50E-05
Non-carcinogens	kg C2H3Cl eq	0.000712	1.25E-06	0.000619178	9.15E-05
Respiratory inorganics	kg PM2.5 eq	0.000145	3.94E-05	6.33E-05	4.26E-05
Aquatic ecotoxicity	kg TEG water	3.023697	0.002585	2.5924613	0.42865012
Terrestrial ecotoxicity	kg TEG soil	0.723703	0.012626	0.60493102	0.10614624
Terrestrial acid/nutri	kg SO2 eq	0.005593	0.000821	0.000468679	0.004304049
Aquatic acidification	kg SO2 eq	0.000977	0.000296	0.000130002	0.000550676
Aquatic eutrophication	kg PO4 P-lim	0.019331	0.018744	5.84E-06	0.000580806
Global warming	kg CO2 eq	-0.00663	-0.04349	0.029742273	0.007114426
Non-renewable energy	MJ primary	0.456964	0	0.38591723	0.071046862



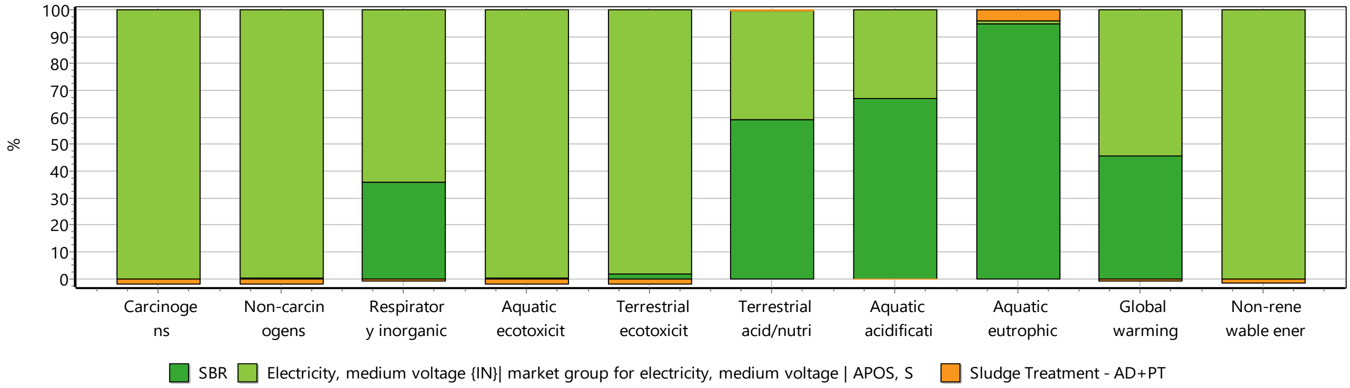
Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 m3 'CW';

Figure C.2 Midpoint characterization bar chart

C.3 Sequential Batch Reactor

Table C.3 Midpoint characterization values of SBR

Impact category	Unit	Total	SBR	Electricity	Sludge Treatment – AD +PT
Carcinogens	kg C2H3Cl eq	0.002096	0	0.002138	-4.23E-05
Non-carcinogens	kg C2H3Cl eq	0.008576	1.67E-05	0.008734	-0.00017
Respiratory inorganics	kg PM2.5 eq	0.001375	0.000497	0.000893	-1.45E-05
Aquatic ecotoxicity	kg TEG water	35.9117	0.034469	36.56667	-0.68944
Terrestrial ecotoxicity	kg TEG soil	8.543755	0.168345	8.532552	-0.15714
Terrestrial acid/nutri	kg SO2 eq	0.016329	0.009667	0.006611	5.12E-05
Aquatic acidification	kg SO2 eq	0.005559	0.003738	0.001834	-1.23E-05
Aquatic eutrophication	kg PO4 P-lim	0.006675	0.006314	8.24E-05	0.000278
Global warming	kg CO2 eq	0.766217	0.353197	0.419515	-0.00649
Non-renewable energy	MJ primary	5.351989	0	5.443363	-0.09137



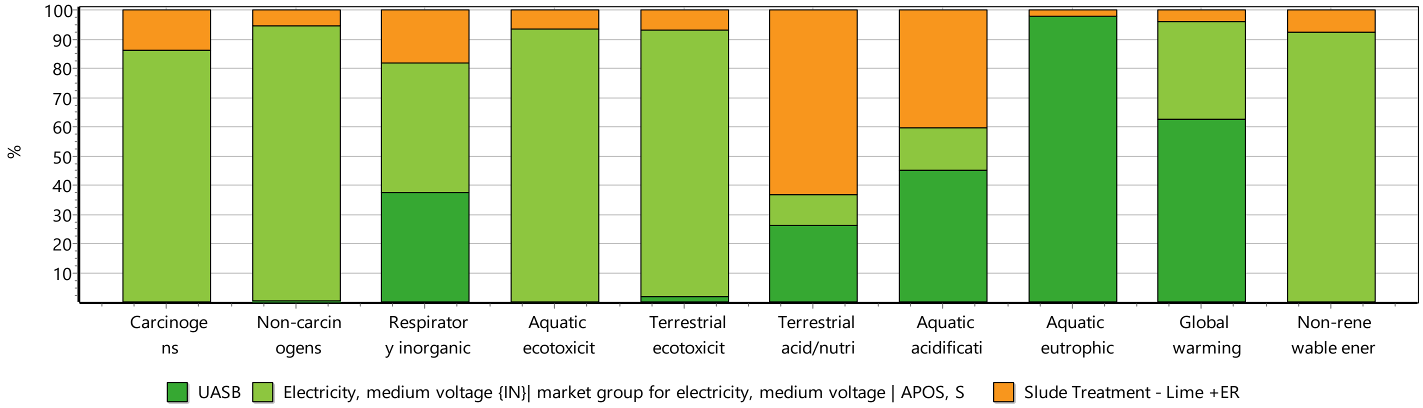
Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 m3 'SBR';

Figure C.3 Midpoint characterization bar chart

C.4 Up-flow Anaerobic Sludge Blanket

Table C.4 Midpoint characterization values of UASB

Impact category	Unit	Total	UASB	Electricity	Sludge Treatment – Lime +ER
Carcinogens	kg C2H3Cl eq	0.000263	0	0.000227	3.61E-05
Non-carcinogens	kg C2H3Cl eq	0.000985	1.80E-06	0.000929	5.49E-05
Respiratory inorganics	kg PM2.5 eq	0.000214	8.07E-05	9.49E-05	3.88E-05
Aquatic ecotoxicity	kg TEG water	4.167519	0.003705	3.888692	0.275121
Terrestrial ecotoxicity	kg TEG soil	0.995815	0.018097	0.907397	0.070321
Terrestrial acid/nutri	kg SO2 eq	0.006741	0.001761	0.000703	0.004276
Aquatic acidification	kg SO2 eq	0.001345	0.000607	0.000195	0.000543
Aquatic eutrophication	kg PO4 P-lim	0.028916	0.028327	8.76E-06	0.00058
Global warming	kg CO2 eq	0.133139	0.083172	0.044613	0.005353
Non-renewable energy	MJ primary	0.627068	0	0.578876	0.048192



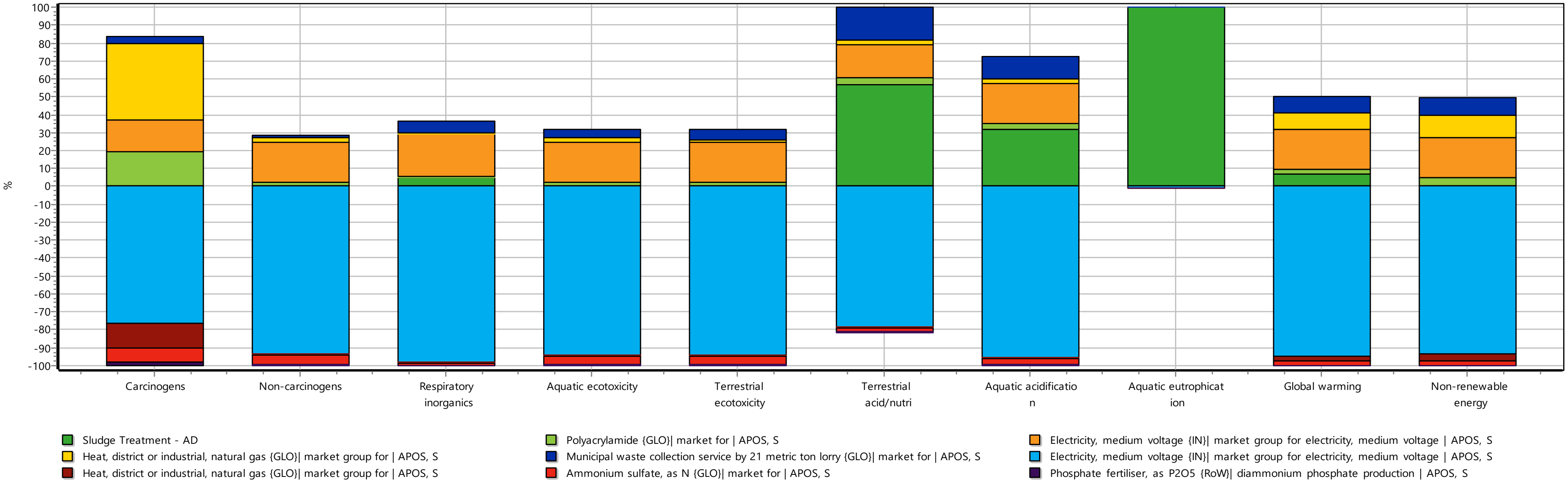
Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 m3 'UASB';

Figure C.4 Midpoint characterization bar chart

C.5 Anaerobic Digestion

Table C.5 Midpoint characterization values of AD

Impact category	Unit	Total	AD	Polyacrylamide	Electricity	Heat	Transport	Electricity (Avoided Product)	Heat (Avoided Product)	Ammonium Sulfate (Avoided Product)	Phosphate Fertiliser (Avoided Product)
Carcinogens	kg C2H3Cl eq	-0.00103	0	0.001209	0.001147	0.002690	0.000239	-0.00484	-0.00088	-0.00048	-0.00012
Non-carcinogens	kg C2H3Cl eq	-0.01507	3.88E-05	0.000444	0.004689	0.000521	0.000393	-0.01978	-0.00017	-0.00108	-0.00013
Respiratory inorganics	kg PM2.5 eq	-0.0013	9.52E-05	2.18E-05	0.000479	1.80E-05	0.000139	-0.00202	-5.87E-06	-2.42E-05	-4.89E-06
Aquatic ecotoxicity	kg TEG water	-60.0848	0.002730	2.274143	19.63465	2.148047	3.956038	-82.7967	-0.69923	-3.75329	-0.85111
Terrestrial ecotoxicity	kg TEG soil	-13.9621	0.006861	0.492645	4.581596	0.286462	1.177108	-19.32	-0.09325	-0.99367	-0.09988
Terrestrial acid/nutri	kg SO2 eq	0.00355	0.010908	0.000652	0.003549	0.000507	0.003505	-0.01497	-0.00017	-0.00037	-6.68E-05
Aquatic acidification	kg SO2 eq	-0.00119	0.001390	0.000137	0.000984	0.000116	0.000542	-0.00415	-3.78E-05	-0.00014	-3.04E-05
Aquatic eutrophication	kg PO4 P-lim	0.027065	0.0272	7.71E-06	4.42E-05	6.68E-07	6.89E-06	-0.00019	-2.17E-07	-2.79E-06	-4.66E-06
Global warming	kg CO2 eq	-0.50043	0.069685	0.02466	0.225260	0.088942	0.092916	-0.94989	-0.02895	-0.02095	-0.0021
Non-renewable energy	MJ primary	-6.63769	0	0.633668	2.922840	1.666068	1.366859	-12.3252	-0.54234	-0.31765	-0.04191



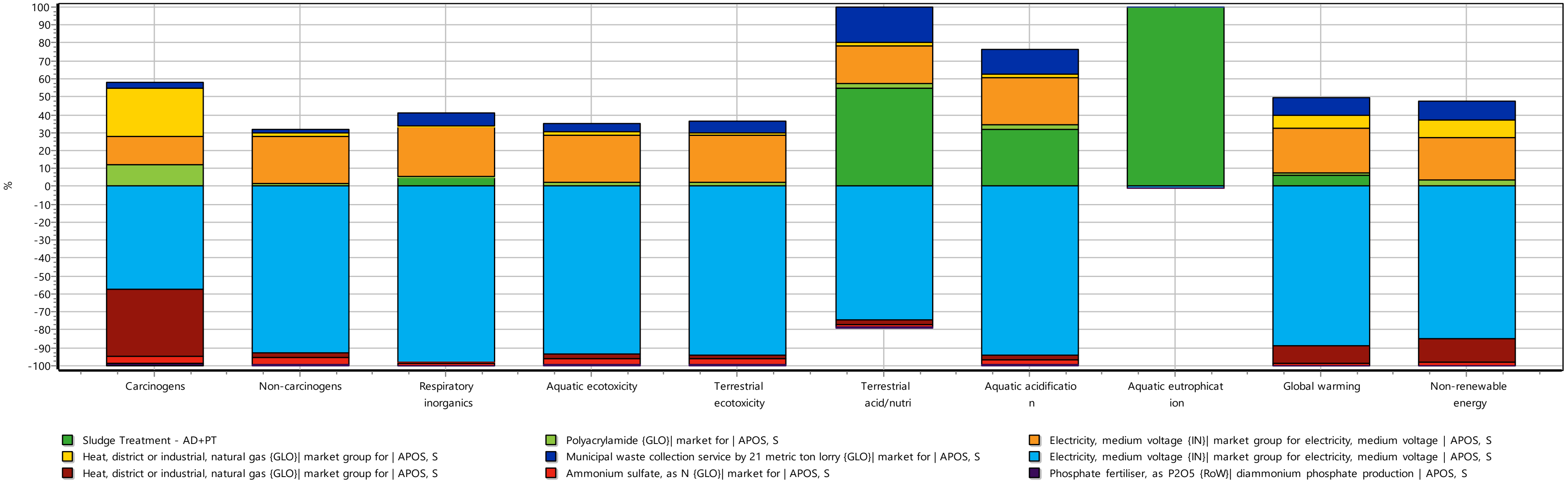
Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 kg 'Sludge Treatment - AD';

Figure C.5 Midpoint characterization bar chart

C.6 Anaerobic Digestion with Pre-treatment

Table C.6 Midpoint characterization values of AD + PT

Impact category	Unit	Total	AD + PT	Polyacrylamide	Electricity	Heat	Transport	Electricity (Avoided Product)	Heat (Avoided Product)	Ammonium Sulfate (Avoided Product)	Phosphate Fertiliser (Avoided Product)
Carcinogens	kg C2H3Cl eq	-0.004230	0	0.001209	0.001625	0.002733	0.000323	-0.00581	-0.00376	-0.00044	-0.0001
Non-carcinogens	kg C2H3Cl eq	-0.017373	4.64E-05	0.000444	0.006639	0.00053	0.000532	-0.02373	-0.00073	-0.00099	-0.00012
Respiratory inorganics	kg PM2.5 eq	-0.001454	0.000115	2.18E-05	0.000679	1.83E-05	0.000188	-0.00243	-2.52E-05	-2.22E-05	-4.28E-06
Aquatic ecotoxicity	kg TEG water	-68.94411	0.003315	2.274143	27.79605	2.181611	5.345998	-99.3561	-3.00391	-3.44052	-0.74472
Terrestrial ecotoxicity	kg TEG soil	-15.71424	0.008331	0.492645	6.485995	0.290939	1.590687	-23.184	-0.4006	-0.91086	-0.08739
Terrestrial acid/nutri	kg SO2 eq	0.0051194	0.013262	0.000652	0.005025	0.000515	0.004736	-0.01796	-0.00071	-0.00034	-5.84E-05
Aquatic acidification	kg SO2 eq	-0.001234	0.001686	0.000137	0.001394	0.000118	0.000732	-0.00498	-0.00016	-0.00013	-2.66E-05
Aquatic eutrophication	kg PO4 P-lim	0.0278489	0.028	7.71E-06	6.26E-05	6.78E-07	9.31E-06	-0.00022	-9.34E-07	-2.56E-06	-4.08E-06
Global warming	kg CO2 eq	-0.649479	0.07637	0.02466	0.318893	0.090333	0.125562	-1.13987	-0.12438	-0.01921	-0.00184
Non-renewable energy	MJ primary	-9.137383	0	0.633668	4.137756	1.6921	1.847107	-14.7903	-2.32989	-0.29118	-0.03667



Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 kg 'Sludge Treatment - AD+PT';

Figure C.6 Midpoint characterization bar chart

C.7 Lime Stabilization

Table C.7 Midpoint characterization values of Lime

Impact category	Unit	Total	Lime	Polyacrylamide	Electricity	Lime	Transport
Carcinogens	kg C2H3Cl eq	0.002252	0	0.001209	0.000674	0.000176	0.000194
Non-carcinogens	kg C2H3Cl eq	0.004576	0.000715	0.000444	0.002754	0.000345	0.000319
Respiratory inorganics	kg PM2.5 eq	0.002129	0.0017	2.18E-05	0.000282	1.28E-05	0.000113
Aquatic ecotoxicity	kg TEG water	21.43251	0.054616	2.274143	11.5324	4.363746	3.207599
Terrestrial ecotoxicity	kg TEG soil	5.307312	0.137232	0.492645	2.690998	1.032026	0.954412
Terrestrial acid/nutri	kg SO2 eq	0.215202	0.209395	0.000652	0.002085	0.000229	0.002842
Aquatic acidification	kg SO2 eq	0.027534	0.02632	0.000137	0.000578	5.91E-05	0.000439
Aquatic eutrophication	kg PO4 P-lim	0.02904	0.029	7.71E-06	2.60E-05	1.01E-06	5.59E-06
Global warming	kg CO2 eq	0.355721	0.1164	0.02466	0.132307	0.007017	0.075337
Non-renewable energy	MJ primary	3.552343	0	0.633668	1.716729	0.093682	1.108264

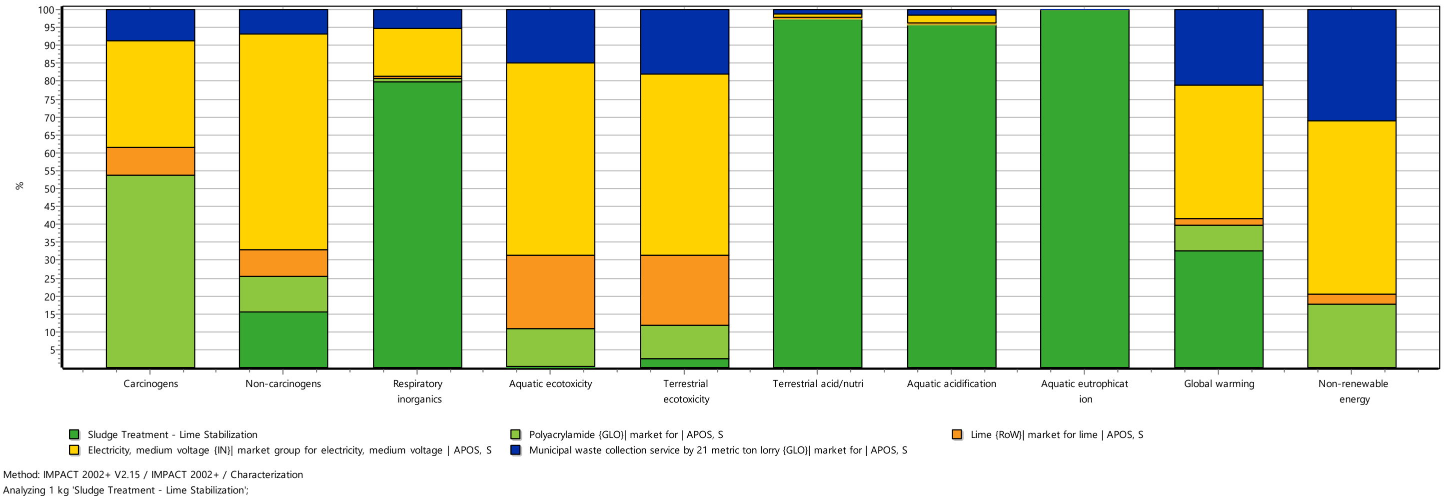
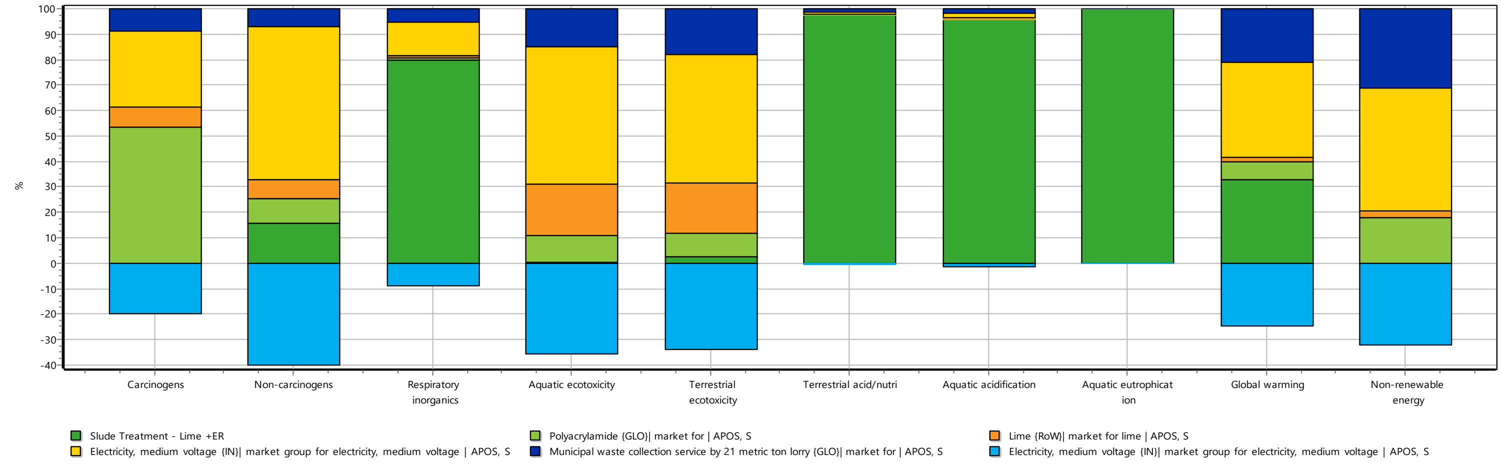


Figure C.7 Midpoint characterization bar chart

C.8 Lime Stabilization with Energy Recovery

Table C.8 Midpoint characterization values of Lime + ER

Impact category	**Unit**	**Total**	**Lime + ER**	**Polyacrylamide**	**Electricity**	**Lime**	**Transport**	**Electricity (Avoided Product)**
Carcinogens	kg C2H3Cl eq	0.001804	0	0.001209	0.000674	0.000176	0.000194	-0.00045
Non-carcinogens	kg C2H3Cl eq	0.002743	0.000715	0.000444	0.002754	0.000345	0.000319	-0.00183
Respiratory inorganics	kg PM2.5 eq	0.001942	0.0017	2.18E-05	0.000282	1.28E-05	0.000113	-0.00019
Aquatic ecotoxicity	kg TEG water	13.75607	0.054616	2.274143	11.5324	4.363746	3.207599	-7.67644
Terrestrial ecotoxicity	kg TEG soil	3.516073	0.137232	0.492645	2.690998	1.032026	0.954412	-1.79124
Terrestrial acid/nutri	kg SO2 eq	0.213815	0.209395	0.000652	0.002085	0.000229	0.002842	-0.00139
Aquatic acidification	kg SO2 eq	0.027149	0.02632	0.000137	0.000578	5.91E-05	0.000439	-0.00038
Aquatic eutrophication	kg PO4 P-lim	0.029023	0.029	7.71E-06	2.60E-05	1.01E-06	5.59E-06	-1.73E-05
Global warming	kg CO2 eq	0.267653	0.1164	0.02466	0.132307	0.007017	0.075337	-0.08807
Non-renewable energy	MJ primary	2.409618	0	0.633668	1.716729	0.093682	1.108264	-1.14273



Method: IMPACT 2002+ V2.15 / IMPACT 2002+ / Characterization
Analyzing 1 kg 'Slude Treatment - Lime +ER';

Figure C.8 Midpoint characterization bar chart