UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Sewage Treatment Technology Selection using Life Cycle Assessment

Research report

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Submitted to

School of Civil and Environmental Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering

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January, 2021

DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination or to any other University.

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ABSTRACT

Global demand for freshwater continues to increase due to accelerated population growth, consequently several attempts has been made to increase its availability. Wastewater treatment remains an attractive alternative for freshwater replenishment. Traditionally, sewage wastewater treatment technology selection has been based on economic factors with little consideration to other sustainability criteria such as the environment and society. In this study, the Life Cycle Assement (LCA) method was utilised to determine and compare the environmental performance of a sequential batch reactor (SBR) and extended activated sludge (EASP) sewage wastewater treatment technologies located in South Africa. The LCA data was analysed using SimaPro® software, a registred trademark of Pre consultants, using ReCiPe midpoint method.

Electricity was responsible for the majority of process contribution towards the environmental burden of both treatment technologies, with contributions >90% on the freshwater ecotoxicity and human toxicity impact categories. The operational phase was a significant contributor towards the environmental burden on all impact categories compared to the construction phase (<10%). SBR facility performed better than EASP on freshwater ecotoxicity and human toxicity impact categories except for freshwater eutrophication. The use of renewable energy, plant optimization and conducting more Wastewater Treatments Plants (WWTP) LCA studies to improve inventory data specific to South Africa were recommended for this study to improve the environmental performance of the facilities.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to God, for the good health, understanding and wellbeing that were necessary for the completion of this work.

Furthermore, I would like to direct my special appreciation and thanks to the following people without whom this study would not have been possible:

- Prof K.G Harding, for his remarkable supervision, motivation and immense knowledge. His guidance and availability to assist has been invaluable throughout the research and writing of this research report.

- Mr K.R Nemutandani, for his encouragement and insightful comments. Thank you for reminding me to do my work and cheering for me while doing it.

- ESKOM Further study, for funding my research.

- Last but not least, I would like to express my profound gratitude to my family: My Parents (Malindi and Mashudu Mamaṱhoni), my brothers (Khuliso and Munangwa Mamaṱhoni), my sister (Fulufhelo Mamaṱhoni) for providing me with unfailing love and for genuinely supporting me in all my endeavours.

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LIST OF ABBREVIATIONS

ASP	Activated Sludge Process
A^2/O	Anaerobic/Anoxic/Oxic
BOD	Biological Oxygen Demand
EASP	Extended Activated Sludge Process
CMA	Catchment Management Agencies
C&I	Control and Instrumentation
COD	Chemical Oxygen Demand
DWS	Department of Water and Sanitation
EF	Ecological Foot printing
EPI	Environmental Pressure Indicators
FE	Freshwater Eutrophication
FEC	Freshwater Ecotoxicity
GA	General Arrangement
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HT	Human Toxicity
ISO	International Organization of Standards
ISS	Institute for Security Studies
IWA	International Water Association
HDI	Human Development Indicators
LCA	Lifecycle Assessment
LCCA	Lifecycle Cost Analysis
LCI	Lifecycle Inventory
LCIA	Lifecycle Inventory analysis
MBR	Membrane Bio-Reactor
N	Nitrogen
OEM	Original Equipment Manufacturer
P	Phosphorus
PEA	Product Energy Analysis
PFD	Process Flow Diagram
P&ID	Process and Instrumentation Diagram
RWQO	Receiving Water Quality Objects

SAICE	South African Institute of Civil Engineers
SETAC	Society for Environmental Toxicology and Chemistry
SBR	Sequential Batch Reactor
SFI	Substance Flow Indicators
SPF	Solar Photo Fenton
TCTA	Trans Caledon Tunnel Authority
WRC	Water Research Commission
WECD	World Commission on Environment and Development
WWAP	World Water Assessment Program
WWTP	Wastewater Treatments Plants
UNEP	United Nation environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPVC	Un-Plasticised Polyvinyl Chloride
US-EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds

1. INTRODUCTION

1.1 Outline of the chapter

This chapter highlights the basic concepts and the background of the study followed by the problem statement and the importance of the study. The research objectives conclude the chapter.

1.2 Background of the study

Water demand is predicted to increase globally over the coming decades due to accelerated urbanisation and economic development amongst many other factors (Arfanuzzaman and Rahman, 2017; Hubacek *et al*., 2009). Consequently, as the demand for water increases the production of wastewater and its pollution load also increases. The current wastewater treatment trends reveal that developed countries treat about 70% of their wastewater while semi-developed countries and underdeveloped countries treat about 28% and 8% of their wastewater respectively (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2017).

The Water Act 54, of 1956, made it mandatory for all wastewater in South Africa to be treated to satisfactory standards before being returned to water bodies or being reused (Morrison *et al*., 2001). Since then, South African wastewater treatment plants (WWTP) have increased to about 1363 and it is estimated that South Africa currently treats about 54% of its municipal wastewater (Institute for Security Studies [ISS], 2018).

Wastewater treatment facilities were introduced in cities in the late 1800 after Louis Pasteur discovered that sewage borne bacteria were the source of various infectious diseases (Henze & Harremoes, 1983). In the past human waste was disposed through open defecation and in cases of large volumes, large farms were acquired and sewage was spread over the land or alternatively discharged into water bodies (McGhee, 1991). According to Topare *et al*. (2011) the latter attempts relied on the general assumption that the earth was an indefinite sink that has an ability to restore itself.

However, as human population increases wastewater exceeded the self purification bodies and led other methods of treatment to be developed (Topare *et al*. 2011).

Wastewater treatment is not only an integral part of water management cycle; it offers a reliable alternative source of freshwater. If wastewater is not treated it has adverse environmental impacts that include (Cheremisnoff, 2002):

- Production of malodorous gases from the decomposition of organic material;
- Depletion of dissolved oxygen in the water bodies;
- Excessive growth of aquatic plant due to excessive nutrients; and
- Development of pathogenic microorganism in the water source.

Methods to quantify and manage these environmental impacts were developed by several organisations such as: Club of Rome, ISO (Organisation for Standardisation), SETAC (Society for Environmental Toxicology and Chemistry), World Bank, United Nation Environmental Programme (UNEP), United States Environmental Protection Agency (US-EPA) (Harding, 2008). Life Cycle assessment (LCA) has been the valuable tool used in various studies to evaluate the environmental impact of wastewater and water treatment processes (Goga, 2016; Masindi *et al*., 2018; Lopes *et al*., 2018; Buonocore, et al., 2018; Tarpani and Azapagic, 2018; Pradel and Aissani, 2019).

LCA gives a full assessment of environmental impacts of products, services and systems from withdrawal through production and operations to the final disposal or recycling (Buonocore, et al., 2018). The calculated environmental impacts are used to identify the opportunities for pollution prevention and reduction of resource consumption (Rebitzer *et al*., 2004). Corominas *et al*. (2013), after analysing 45 peer reviewed papers dealing with LCA and WWT, confirmed that LCA is an effective tool to assess environmental impacts of wastewater plants but input data collection can be time consuming.

1.3 Problem statement

Majority of the existing WWTP in South Africa have reached their end of life and are mostly malfunctioning (Mitchell et al., 2014). According to (South African Institute for Civil Engineering, 2011), South African WWTP require either an upgrade or replacement estimated to be approximately R573 billion.Therefore it is necessary to conduct assessments to evaluates sustainable WWTP technologies in South Africa, that are able to handle the increasing loads due to increasing urbanisation at the same time protecting the health of the people and ecosystem. This study will conduct a Life Cycle Assessment (LCA) on sequential batch reactor (SBR) and extended activated sludge process (EASP) treatment technologies to evaluate technology section based on their environmental impacts in South Africa. The findings of the study will provide insights on the environmental hotspots of the treatment technologies and identify areas of improvements.

Below are research questions :

- What are the environmental impacts of sequential batch reactor technology?
- What are the environmental impacts of extended activated sludge technology?
- How the environmental impacts of the two technologies compare?

1.4 Research Objectives

The main objectives of this study are to:

- Conduct a Life Cycle Assessment for the sequential batch reactor technology;
- Conduct a Life Cycle Assessment for the extended activated sludge technology; and
- Compare the detailed environmental impacts of the two technologies.

1.5 Research Report Outline

This report is divided into 5 chapters as described below:

Chapter 1 (Introduction)

This chapter highlights the basic concepts and the background of the study, research objectives, problem statement and the importance of the study.

Chapter 2 (Literature review)

This chapter outlines the theoretical background and literature from previous studies. It highlights advantages, disadvantage, strengths and weaknesses of the Life Cycle Assessment and sewage wastewater treatment.

Chapter 3 (Methodology)

This chapter outlines the methods used to execute the Life Cycle Assessment for the study. The guidelines and principles stipulated in ISO14040:2006 and ISO14044:2006 followed to formulate the LCA are discussed.

Chapter 4 (Results and discussions)

The outcomes of the study are presented and interpreted in line with the objectives of the study. The aim is to answer the research questions posed by the study. The findings of the study were compared with other related studies.

Chapter 5 (Conclusions and recommendation)

In this chapter the summary of the study findings is presented in line with the objectives of the research. The limitations and implication of the study are highlighted and furthermore recommendations for future research are made.

2. LITERATURE REVIEW

2.1 Outline of the chapter

This chapter outlines the theoretical background and literature from previous studies. It reviews the current trends, state of the global wastewater sector, wastewater treatment technologies and their application across different wastewater sectors. The South African wastewater sector is reviewed. Thereafter, sustainability and the tools used to measure its effectiveness are reviewed and compared to each other in the technical sphere. LCA as the sustainability assessment tool is then reviewed to understand its history, its advantages and disadvantages. The chapter concludes by reviewing LCA studies in the wastewater treatment sector coupled with their limitations and strengths.

2.2 Overview of Wastewater

Wastewater is defined as effluent combination from one or more of: residential and commercial areas, agricultural runoff, industrial discharges and stormwater runoffs (Raschid-Sally and Jayakody, 2008). Wastewater treatment is an integral part of water cycle (Figure 2.1) as it provides an alternative source of fresh water after having undergone suitable treatment.

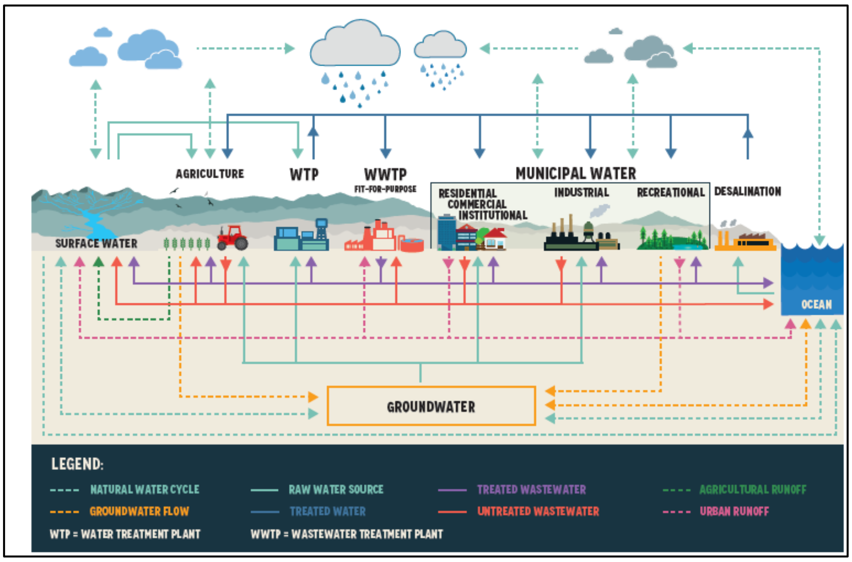

Figure 2.1: The source and fate of wastewater in the water cycle (World Water Assessment Program [WWAP], 2006)

About 80% of the world's wastewater flows back into the ecosystem without being treated or reused (International Water Association , 2018). The disposal of untreated wastewater into the environment (Figure 2.2) has a negative impact on human health, ecosystem and economic productivity (United Nation Environment Programme [UNEP], 2015).

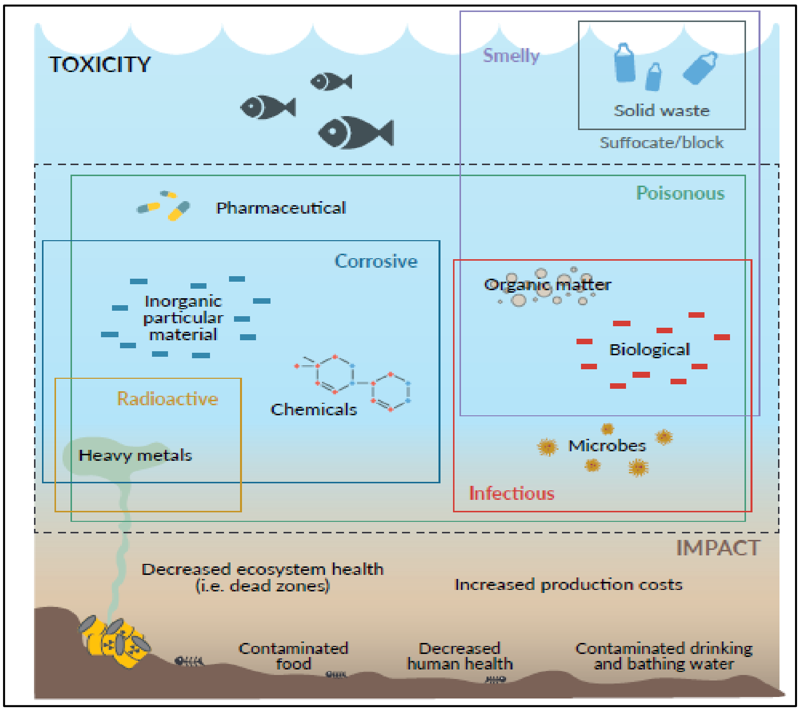

Figure 2.2: Wastewater composition and their impact on the environment (Corcoran et al., 2010)

Societal and environmental pressure have led to a reduction in wastewater and to improved treatment before discharge over years (Popovic *et al*., 2013). Between 1900 and 1970 wastewater treatment objectives were concerned with the removal of suspended material, treatment of biodegradable organics and the elimination of pathogenic microorganisms (Rosen *et al*., 1998; Spellman, 2000). Between 1970 to 1990, treatment objectives were concerned with the environmental effects caused by wastewater discharge and long term effects caused by some of the specific constituents in wastewater (Zhou and Smith, 2002; Barbose and Santanna, 1989). Since early 1990s, the wastewater treatment objectives began to focus on the effective recovery of energy, resources and water (MetCalf and Eddy, 2014). Thus the agenda is to view wastewater treatment plants as a net exporter of energy instead of a consumer of energy (McGhee, 1991; Meltcalf and Eddy, 1991; Rowe and Abdel-Magid, 1995

2.3 Wastewater treatment technologies

The main aim of wastewater treatment is to remove contaminants from wastewater so that water can be reused or returned to the ecosystem with less negative environmental impacts (UNESCO, 2017). According to Su *et al.* (2019), WWTP processes can be classified to environmental (high energy intensive processes with huge capital investment requirements) or ecological (exploits natural processes to treat wastewater with lower pollution loads). Environmental processes include processes such as ASP, SBR, Anaerobic/Anoxic/Oxic (A^2/O), membrane bioreactor (MBR) and oxidation ditches (Su *et al*., 2019). Ecological processes incorporate processes such as stabilization ponds, constructed wetland slowrate systems, trickling filters and land application systems (Su *et al*., 2019).

Wastewater treatment are further classified to physical, chemical and biological process to remove wastewater pollutants (Topare *et al*., 2011). The physical treatment processes (screening, mixing, flocculation, sedimentation, flotation, adsorption, filtration and similar processes) implies the application of natural forces to remove contaminants (Meltcalf and Eddy, 1991). Meanwhile chemical treatment processes (precipitation, gas transfer, absorption, disinfection and related processes) removes contaminants by the use of chemicals to remove wastewater constituents (Meltcalf and Eddy, 1991). Biological treatment processes (aerobic biodegradation, anaerobic biodegradation and anaerobic digestion amid others) bring about the degradation of wastewater constituents by reproducing the natural process that occurs rivers and lakes (International Water Association , 2018). It is worth noting that in practice, these treatment processes do not operate in isolation but as a combination depending on the treatment objectives and regulations.

The selection of the most suitable wastewater treatment process depends on incoming raw wastewater pollution load, expected use of treated wastewater and socio-economic factors (Abbassl and Al Baz, 2008). Table 2.1 compares some of the common WWTP technologies that are largely used based on their energy consumption, removal efficiency, capital costs and land use.

Table 2.1: Comparison of wastewater treatment technologies (Sue et al., 2019)

Wastewater Treatment Technology	Energy (kWh/m^3)	BOD % removal	N % removal	P% removal	Capital cost (US$/ resident)	Land use (m^2/ resident)
Anaerobic/Anoxic/Oxic	0.31	76-99	72-94	94-96	16.9	0.11
Anoxic/oxic	0.28	94.8	75	20-49	ND	0.48
Activated Sludge Process	0.22-0.31	85-93	30-40	30-45	60-120	0.2-0.3
Constructed wetland	0-0.25	68-92	38-84	41-60	3.7-15.2	2.5
High-rate trickling filter	0.5-1	80-90	30-40	30-45	40-70	0.3-0.45
Low-rate trickling filter	0.2-0.6	85-93	30-40	30-45	50-90	0.6-0.7
Membrane Bioreactor	0.66-4.24	>97	36-80	62-97	2.14	2.5
Overland flow	~ 0	85-95	10-80	20-50	5-15	1.2
Oxidation ditches	0.20-0.30	90-98	40-78	50-96	9.6-22.1	0.13-0.43
Rapid infiltration	~ 0	86-98	10-80	30-99	5-15	1-6
Sequential Batch Reactor	0.23 -0.31	85-95	30-40	30-45	50-80	0.2-0.3
Slow-rate infiltration	0.04	94-99	65-95	75-99	10-20	10-50
Stabilization pond	~ 0.04	75-90	30-50	20-60	10-30	0.3-13.3
Subsurface infiltration	~ 0	90-98	10-40	85-95	5-15	1-5
Upflow anaerobic sludge blanket reactor	~ 0	60-80	10-25	10-20	20-40	0.05-0.1

The ASP (Figure 2.4) is the most common biological wastewater treatment technology for municipal wastewater treatment plants (Jeppsson, 1996). According MetCalf and Eddy (2014), the technology was developed by Clark and Gage in 1913 (Lawrence experiment station, Massachusetts) and by Arden and Lockett in 1914 (Davyhulme sewage works, Manchester). In the ASP process, activated mass of microorganism is mixed with influent wastewater in an aerobic condition in order to stabilize waste of which a portion is recycled back to the feed while the other portion is wasted (MetCalf and Eddy, 2014).

Many configurations of ASP have been developed since its inception, the notable one being the introduction of biological selectors and staged ASP in order to prevent settling problems due to filamentous bacteria (Chudob *et al*., 1973). MetCalf and Eddy (2014) reported significant advancement that occurred in the 1990s through the introduction of the MBR, whereby a membrane unit is immersed with sufficient head in the activated sludge compartment. SBR (Figure 2.3) is a variation of ASP over a series of operational steps (fill, react, settle, decant, idle) in a batch reactor without the returned activated sludge stream and the secondary sedimentation tank (MetCalf and Eddy, 2014). The SBRs benefit over other ASP technologies is the small land requirements and high resilience towards organic shock. However, the drawback is the high level of control and instrumentation (C and I) for its operation (Abdel-Kader, 2009).

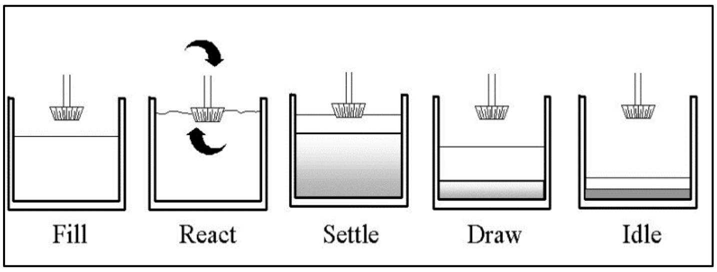

Figure 2.3: The configuration of the Sequential Batch Reactor **(Kinross, 2008)**

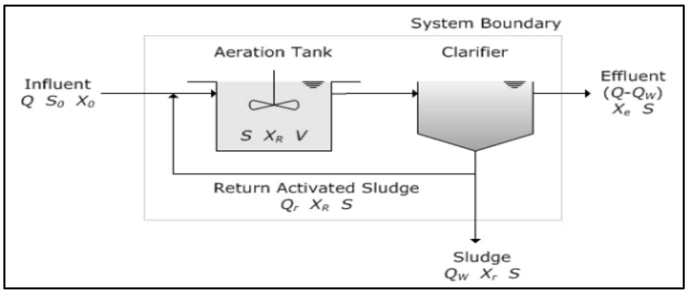

Figure 2.4: Schematic diagram of the Activated Sludge process **(Lenntech, 2019)**

2.4 The State of the South African wastewater sector

In 2015, approximately 73% of South Africans had access to basic and safely managed sanitation, mainly in the form of latrines, septic tanks and sewer connections (Joint Monitoring Programme [JMP], 2017). The National Water Act of 1998 and the Water Service Act of 1997 are the two legal frameworks that govern Department of Water and Sanitation (DWS) in developing policies and strategies for the water sector (Department of Water Affairs, 2015). The current water usage in South Africa is estimated to be 16 billion m^3/annum with agriculture having the biggest share at 62% (Department of Water Affairs, 2015). DWS is the custodian of water resource management (security, utilization, development and preservation) and water service supply (sustainable water and sanitation provision) to all residents of South Africa (National Treasury, 2008). Table 2.2 shows the partners that enable DWS to fulfil its constitutional mandate.

Table 2.2: Enabling structures that supports DWS in fulfilling its constitutional mandate (DWS, 2015)

Supporting Partners	**Functions**
Catchment Management Agencies (CMA)	Delegates water resource management to the regions for different uses
Water Boards	Responsible for regional bulk water distribution to the municipalities
Municipalities	Provides water and sanitation to areas of jurisdiction
Water Research Commission (WRC)	Does research for DWS
Trans Caledon Tunnel Authority (TCTA)	Finance and implement bulk raw water infrastructure

2.5 Regulation of the South African wastewater sector

For many years South Africa relied on regulation that presented targets that must be complied to and negative sanction in case of non-compliance (command and control mechanism) to enforce water and sanitation standards (Ntombela, 2013). Although the command and control mechanism monitors endpoint non-compliance, it is criticized for being reactive instead of being proactive in addressing non-conformance (Morris *et al*., 2017). In 2008, DWS introduced the green drop program (wastewater quality management) and the blue drop program (drinking water quality management) as an incentive-based program with the aim of improving operation, management and regulation of the water and sanitation sector (Ntombela *et al*., 2016). The green drop criteria and the respective percentage weightings that are used to grade municipalities performance are displayed in Table 2.3

Table 2.3: Green Drop Criteria used to evaluate the performance of wastewater treatment plants (Department of Water Affairs, 2013)

Performance criteria	**Percentage weighting**
Process control, maintenance and management skills	20
Wastewater sample analysis	10
Submission of wastewater quality results	12
Wastewater quality compliance	35
Wastewater quality failure response management	20
Wastewater treatment works capacity	5
TOTAL	**100**

Although there is an improvement in the performance of wastewater facilities through the green drop program, the delay in releasing the green drop results to the public negatively affects the transparency and the credibility of the green drop program (Ntombela *et al.,* 2016). A lack of capacity in terms of skills and knowledge required to run wastewater facilities was identified by South African Institute of Civil Engineers [SAICE], (2017) as the flaw that affects the green drop scores.

Wastewater treatment plants are designed such that effluent quality does not decrease the ability of receiving water bodies to support the economic, environmental and societal needs (Morris *et al*., 2017). Options available to ensure that effluent water quality standard is met include: optimum treatment processes, efficient wastewater reclamation processes, influent contamination load control and population behaviour control (Luo *et al*., 2014). The water quality parameters in most of South African water resources are under pressure with eutrophication (excessive nutrients), salinisation (excessive salts), acid mine drainage, sedimentation, urban runoff pollution and emerging pollutants (nanoparticles, antibiotics, endocrine disrupting chemicals) as priority water quality issues (Department of water and sanitation, 2018).

According to Department of Water and Sanitation (2015), 1363 of WWTP are registered in South Africa owned by the municipalities (897), private sector (393) and Department of Public works (73). Most of the WWTP in South Africa are small plants, with 93% having a capacity less than 25 ML/day and only 7% with a capacity greater than 25 ML/day (Department of Water Affairs and Forestry, 2008). It is estimated that the South African water sector requires an investment of about R1.4 billion each year to maintain and operate the current infrastructure (Zhuwakinyu, 2012). Most of the south African wastewater treatment facilities have reached end of life and require either an upgrade or replacement which is estimated to be approximately R573 billion (SAICE, 2011).

2.6 Sustainability in the wastewater treatment sector

The term sustainability has multidisciplinary meanings and applications. According to Muga and Mihelcic (2008) it can be summarised as the capability of a system to endure and maintain itself for the economic wellbeing, protection of the environment and the equitable use for all. Since the 1980s, the term sustainability has been used in the sense of human sustainability, which led to the concept of sustainable development being defined as "*development that meets the needs of the present without compromising the ability of the future generation to meet their own needs*" (WECD, 1987).

The concept of sustainability development is embedded in three pillars namely environment, economy and society, which implies that for a particular process to be sustainable it should not cause irreversible change to environment; it should be economically viable and should benefit society (Rodriguez *et al*., 2002). Balkema (2003) defined sustainable design and engineering as the process of thinking and implementation of ideas that embraces sustainability principles (Figure 2.5 and Table 2.4) with the aim of creating products and services that benefits society and the environment.

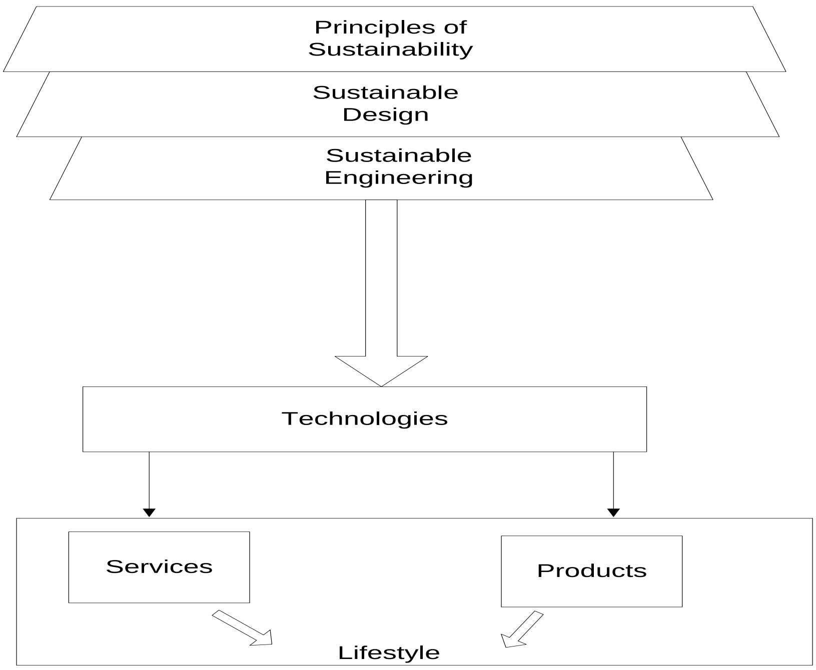

Figure 2.5: Fedkin hierarchy of sustainability in the technical spheres (Fedkin, 2018)

Table 2.4: Comparison of traditional engineering and sustainable engineering (Fedkin, 2018)

TRADITIONAL ENGINEERING	SUSTAINABLE ENGINEERING
Considers object or process	Considers the whole system in which the object or process will be used
Focus on technical issues	Considers both technical and non-technical issues
Solves immediate problem	Strives to solve the problem for the infinite future (forever)
Considers the local context	Considers global context
Assumes others will deal with political, ethical and societal issues	Acknowledges the need to interact the experts in other disciplines related to the problem

Water resource systems that are on par with demands from present and future generation without deteriorating are sustainable (American Society of Civil Engineers [ASCE], 1998). Thus, WWTP sustainable solutions seeks to have a long-term view and do not stimulate similar or new problems in the future (Meneses *et al*., 2010). In order for WWTP to be sustainable it must: (a) reduce cost, (b) recover and reuse resources (energy, water, sludge and nutrients), (c) optimise the wastewater treatment processes, (d) minimise toxic waste streams and (e) ignite sustainable behaviour (Balkema, 2003).

Sustainability assessment tools measures the attainment of sustainable goals, and since their inception, better application guidelines have been developed (Kasemir *et al*., 2003). The sustainability assessment tools have been defined by Devuyst *et al*. (2001) as tools that can help decision makers and policy makers decide which action they should take or should not take in an attempt to make society more sustainable.

Ness *et al.* (2007) developed a framework for categorising sustainability assessment tools (Table 2.5) that consisted of three general categorisations namely: indicators and indices; product related assessment and integrated assessment.

Table 2.5: The characteristics of sustainability assessment tools, adapted from (Ness *et al*., 2007)

Assessment Tool	**Method of assessment**	**Application**	**Types**
Indicators and Indices	Continuously measured, calculated and aggregated to get an index	Used for short term projections and decision making for the future	Environmental Pressure Indicators (EPIs), Human Development Indicators (HDI), Gross Domestic Product (GDP), Ecological Foot printing (EF), Substance Flow Indicators (SFI)
Product related Process	Considers the flow in connection with production and consumption of goods and services	They evaluate resource use and environmental impacts along the production chain	Life Cycle Assessment (LCA), Lifecycle Cost Analysis (LCCA) and Product Energy Analysis (PEA)
Integrated Assessment	These tools are based on systems analysis approaches and integrate nature, economic and society aspects	Supports decision related to policy or a project in a specific region	Risk Analysis (RA), Cost Benefit Analysis (CBA), Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA)

2.7 Background of Life Cycle Assessment (LCA)

LCA has passed many stages (Figure 2.7) of development to reach a place where it is known and widely used across different sectors of the economy. According to Hunt and Franklin (1996), LCA started in the 1960s as a means for companies to manage their resources. The energy crisis in the 1970s led more companies to adopt the lifecycle thinking and this carried to the 1980s (McManus and Taylor, 2015). In the 1990s and 2000s, the global environmental agenda was gaining attention and this led to the Society of Environmental Toxicology and Chemistry (SETAC) developing the first standards (McManus and Taylor, 2015).

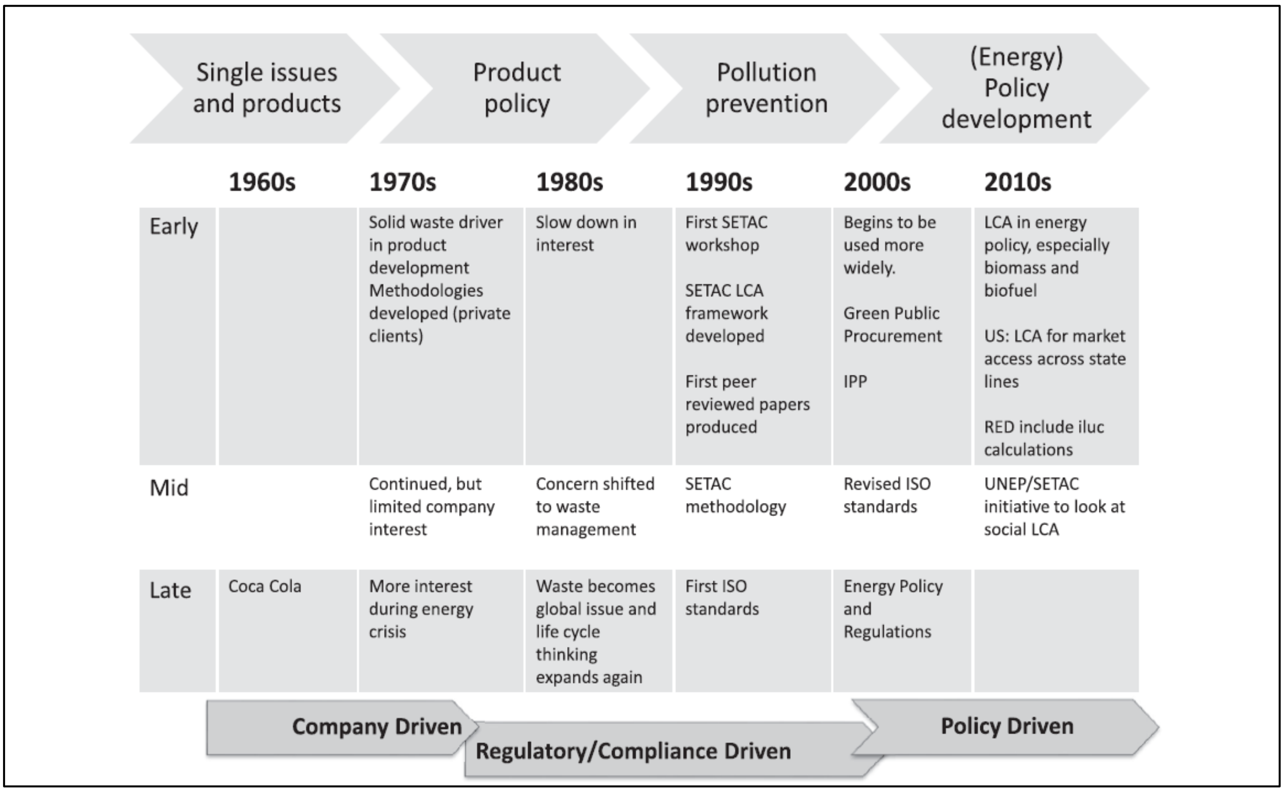

Figure 2.6: Evolution of Life Cycle Assessment from the 1960s to 2010s (McManus and Taylor, 2015)

Life Cycle Assessment (LCA) is the study that analyses real and potential burdens that materials, products or services have on the environment during raw material acquisition, production processes, use and disposal (Lindfors *et al*., 1995). The findings from LCA studies guides the selection of designs and improvement of material, product and services based on environmental trade-offs (Fava, 1997).

LCA studies are extensively used in public policy discussions and in informing public decision-making processes (Tukker, 2000). Private sector use LCA study to inform their eco-labelling databases that awards tags to products that satisfies some environmental criteria (Cowell *et al*., 2002). The prominent strengths (Figure 2.7) of LCA includes the ability to comprehensively asses the environmental impacts (negative and positive) of the entire life cycle of a system (product, material and services) in an analytical manner (Curran, 2014). The weaknesses (Figure 2.7) of LCA encompasses the difficulty in accessing inventory data, consequently leading to different results from seemingly the same product (Curran, 2013).

Table 2.6: Comparison of barriers and benefits of conducting LCA identified by the built environment communities [adapted from Saunders et al. (2013)]

BENEFITS	**BARRIERS**
Follows ISO standards	Times it takes to conduct an LCA
Use scientific and structured approach	Complexity of an LCA
Compares alternative products	Lack of integration with the current design tools
Informs decision making	Availability and accessibility of data can be limiting
Could drive government regulation	Assumptions are used to conduct LCA
Promotes a product for the green market	Cost of conducting an LCA may be prohibitive to small firms
Advanced triple bottom line framework of sustainable development	There are no governmental incentives for conducting LCA in most jurisdiction

Due to the growing interest of LCA in the 1990s, ISO (International Organization of Standards) developed standards (Table 2.6) in order to harmonise the application of LCA (Finnveden *et al*., 2009).

Table 2.7: ISO Life Cycle Assessment standards (ISO, 2019)

ISO Catalogue	**DESCRIPTION**
ISO 14040: 2006	LCA principles and framework
ISO 14044: 2006	LCA requirements and guidelines

LCA is an iterative process (Figure 2.6) that consists of four stages (goal and scope definition, inventory analysis, impact assessment and interpretation) (ISO, 2006).

- The goal and scope: describe the system boundaries, functions, the intended application and functional unit of the study.
- Inventory analysis: input and output data of the study is modelled and inventory table is generated.
- Impact assessment: computes the environmental impacts caused by emission from the inventory analysis stage.
- Interpretation: evaluates results and communicates to stakeholders and decision makers.

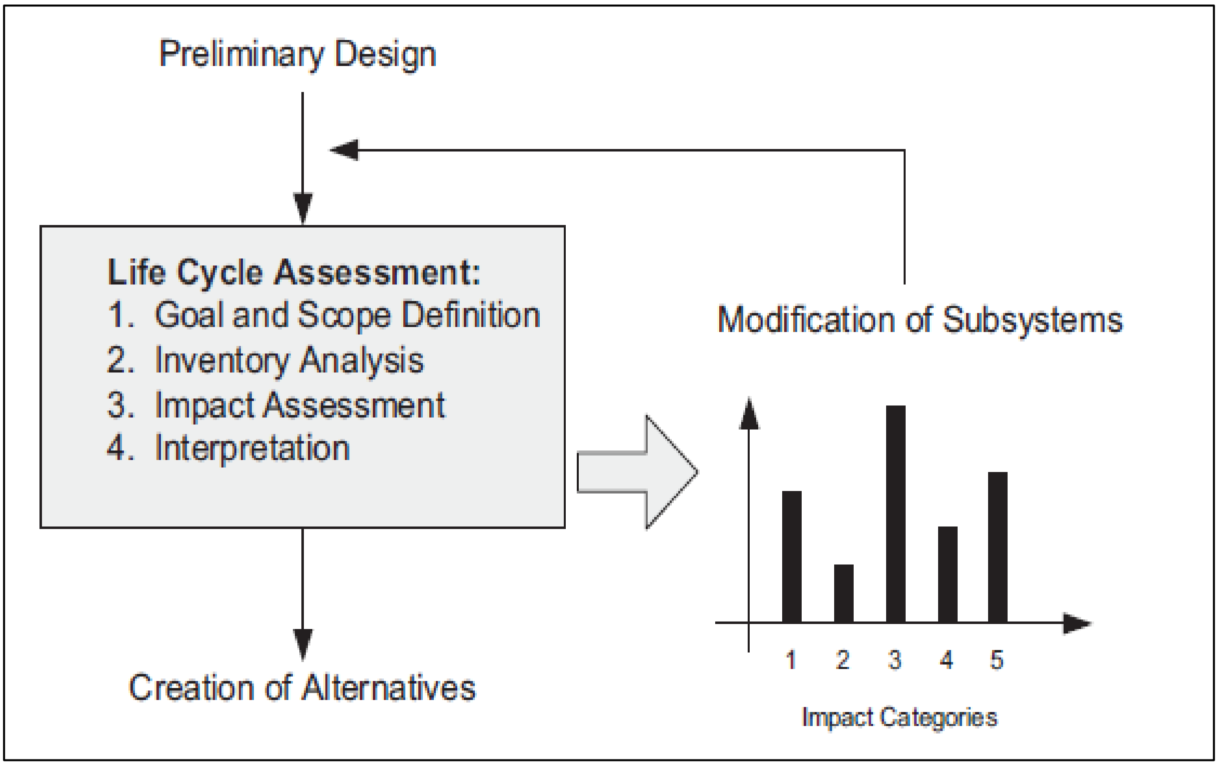

Figure 2.7: Feedback loop indicating LCA iterative nature in designs (Pryshlakivsky and Searcy, 2013)

2.8 Life Cycle Assessment in the wastewater treatment sector

LCA is an invaluable tool that has been widely used for the evaluation of environmental sustainability of wastewater systems since the 1990s (Sabeen *et al*., 2018).The review of published articles by Gallego-Schmid and Tarpani (2019) on the application of LCA on WWTP of the developing countries revealed that significant stages such as construction, sludge management and accountability of direct greenhouse gases emissions on the inventory level were often missing. On the latter study only two studies out of 43 reviewed articles were from South Africa, which confirms that there are few WWTP LCA studies conducted in the South Africa. It was found that majority of environmental impacts of the South African WWTP were attributed to electricity which is dominated by fossil fuel (Mavhungu et al., 2020). Moreover it was concluded that energy integration and energy efficiency devices do reduce the environmental impact for WWTP in South Africa (Fernández-Torres et al., 2012).

WWTP LCA framework (Figure 2.7) commonly consist of wastewater collection & transport, construction & operation and dismantling stage (Zang *et al.,* 2015). Several LCA studies (Table 2.8) have been conducted with varying scales and technologies from different locations to quantify environmental impacts of WWTP

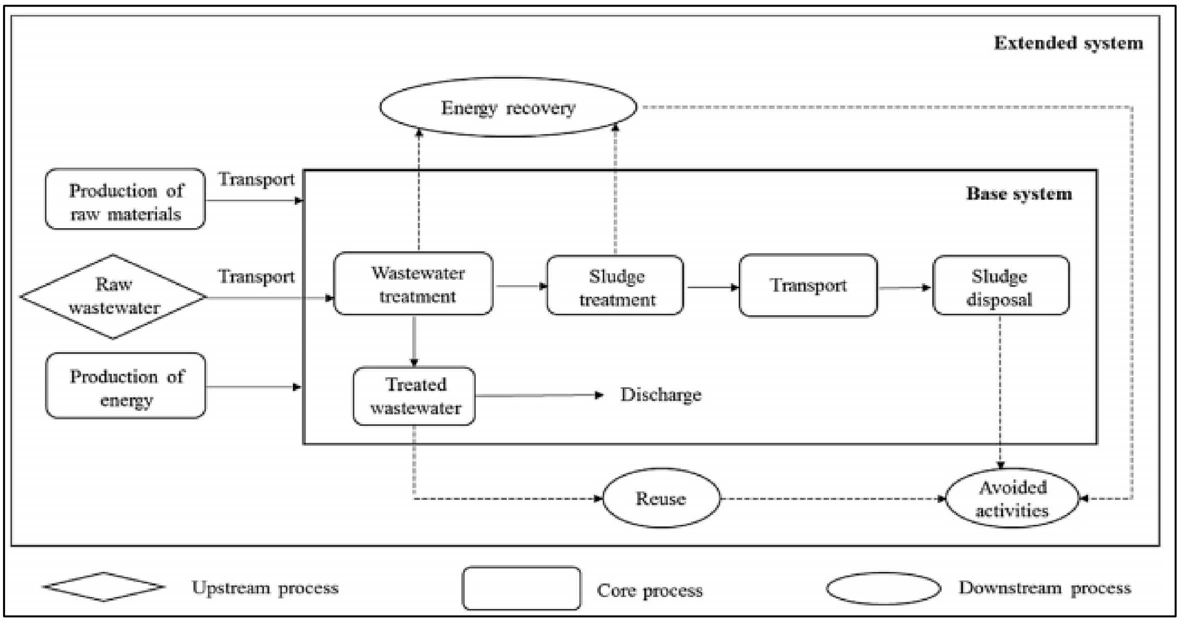

Figure 2.8: WWTP material and energy flow framework for conventional treatment systems

Table 2.8: Wastewater treatment LCA studies in the wastewater sector

LCA Study	Functional Unit	Location	Impact Assessment Method	Results	Key Finding	Reference
"Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries"	$1m^3$ of treated wastewater	Gamasa, Egypt	CML 2000	Significant contributors (normalised) for ASP were Global Warming Potential (59.4%), Eutrophication (27.4%) and Abiotic depletion (4.63%)	Electricity is the main contributor towards the environmental impacts of ASP because of the mechanical aeration	Awad *et al*. (2019)
"Life Cycle Assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds"	$1m^3$ of water	Catalonia, Spain	ReCiPe midpoint	ASP electrical consumption was 1.26 kWh/m^3	Electricity consumption for ASP was responsible for low environmental performance compared to nature-based treatment technologies	Garfi *et al*. (2017)

LCA Study	Functional Unit	Location	Impact Assessment Method	Results	Key Finding	Reference
"A procedure for evaluating the most environmentally sound alternative between two on-site small-scale wastewater treatment systems"	15 Population Equivalent (PE)	Campania, Italy	ReCiPe(endpoint), Ecological footprint and IPCC 2007, 100 YEAR	Constructed wetland environmental impacts were the best in 93% comparison of the impact assessment methods used	Electricity consumption had the high influence of the performance of ASP	De Feo and Ferrara (2017)
"Life Cycle Assessment of a municipal wastewater treatment plant: a case study in Suzhou, China"	10^5 m^3/day over 50 years	*Kunshan, China*	CML Baseline 2000	Hotspot (normalised) impacts were: Eutrophication (6E-03), Abiotic resource depletion (1E-03), Acidification (6E-04) and Global Warming (1E-04)	Electricity generation from renewable energy sources decrease the environmental impacts of Kunshan WWTP	Li *et al*. (2013)

LCA Study	Functional Unit	Location	Impact Assessment Method	Results	Key Finding	Reference
"Life Cycle Assessment of an intensive sewage treatment plant in Barcelona (Spain) with focus on energy aspects"	50 000 PE	*Barcelona*, Spain	CML 2 Baseline 2000	Climate change (5,164 kg CO_2 eq) was the significant environmental impact followed by abiotic depletion (26.27 kg Sb-eq)	electricity consumption and direct GHG emissions were the greatest contributors towards environmental impacts of WWTP	Bravo and Ferrer (2011)
"Environmental performance of wastewater treatment plants for small populations"	1 PE/ Year	Galicia, Spain	CML 2 Baseline 2000	Electricity consumption made (96.4 %) significant contribution toward abiotic depletion	Electricity consumption was the chief contributor towards the environmental performance of WWTP	Gallego *et al.* (2008)

3. METHODOLOGY

3.1 Outline of the chapter

This chapter outlines the methods used to execute the Life Cycle Assessment for the study at hand. The guidelines and principles stipulated in ISO14040:2006 and ISO14044:2006 were followed to formulate the LCA. Methodological framework details for conducting LCA are summarised in appendix A

3.2 Goal and scope definition

The goal of this LCA was to evaluate the environmental impacts associated with sewage wastewater treatment plants (Extended Activated Sludge Process (EASP) and Sequential Batch Reactor (SBR)) both located in Limpopo province, South Africa. The study also aimed at comparing the two plants environmental performance and to identify the treatment processes that have significant environmental impacts. For both technologies, construction and operation phase were considered while the decommissioning phase was not considered due to its negligible contribution towards wastewater LCA (Lopsik, 2013; Machado *et al*., 2007). The outcome of the study will provide input to intended audiences (Table 3.1) for future projects.

Table 3.1: The potential uses of the LCA study by various stakeholders

Intended stakeholders	**Potential use of LCA outcomes**
Water sector professionals (engineers, operators, managers, researchers)	Knowledge on environmental performance of their systems and future studies
Government (DWS and its key partners)	Selection of sewage treatment technologies
Civil society	Understanding environmental impacts associated with sewage treatment technologies

System description of EASP plant

The plant is designed to treat 2700 m^3/ day of raw sewage wastewater from an industrial site, collected from four pump stations. Large suspended matter are removed through the mechanical bar screen installed upstream of the balancing tank. Sewage is pre-aerated in the balancing tank to ensure that sewage that is pumped to the biological aeration tanks with uniform flow for stable operating conditions. In the aeration tank sewage is aerated in order for nutrients and organic matter to be digested biologically. Moreover, soda ash is dosed in the aeration tank to keep pH at 6.8 (optimum pH for biological treatment). Bar mechanical screens are installed upstream and downstream of the aeration tank to remove any residual suspended solid matter and screenings thereof are disposed to the landfill.

The mixed liquor from the aeration tank is gravity fed to the clarifier, which is fitted with a skimming device to remove any floating matter and also to assists with settling of sludge. A portion of the sludge is returned to the aeration tank to provide an active sludge to raw sewage and the rest is wasted through the sewage drying beds. Dried sludge is then transported to the landfill for disposal. Clarified water overflow into the chlorine contact tank, whereby chlorine is injected to disinfect water before being discharged to irrigation dams. Potable water is used as motive water to ensure constant supply pressure for chlorine gas ejectors. The plant is designed to treat sewage wastewater to the South African general limit for wastewater (National Water Act No.36 of 1998, section 39)

System description of SBR plant

Raw sewage from an industrial plant passes through a mechanical screen before being pumped to the balancing tank at the design flowrate of 1700 m^3/hr. The mechanical screen is equipped with the flushing system (potable water tank and two pumps) to flush any debris that might be left during the screening operation. Ferric chloride is dosed in the balancing tank in order to precipitate inorganic form of phosphates to suspended solids. From the balancing tank, sewage is pumped to the splitter box which gravity feeds the three sequential batch reactors (SBR), each equipped with a surface aerator. In the SBR, sewage is aerated to biologically oxidise/digest dissolved and suspended waste. After a predetermined time, aeration is stopped and sewage is allowed to settle in the same tank. Once setting has occurred treated effluent is discharged into the chlorine contact, whereby chlorine is dosed to disinfect water before being discharged to the maturation pond. A stream from the contact tank is drawn as motive water to ensure constant supply pressure for chlorine gas ejectors. Settled sludge is wasted to the drying bed whereby is left to dry and thereafter be transported to the landfill for disposal. The plant is designed to treat sewage wastewater to the South African general limit for wastewater (National Water Act No.36 of 1998, section 39)

System boundaries

The system boundaries (Figure 3.1 and Figure 3.2) incorporated inflows and outflows for both construction and operation phases for a period of 50 years. In the operation phase all inputs and outputs associated with primary, secondary and tertiary wastewater treatment stages were considered.

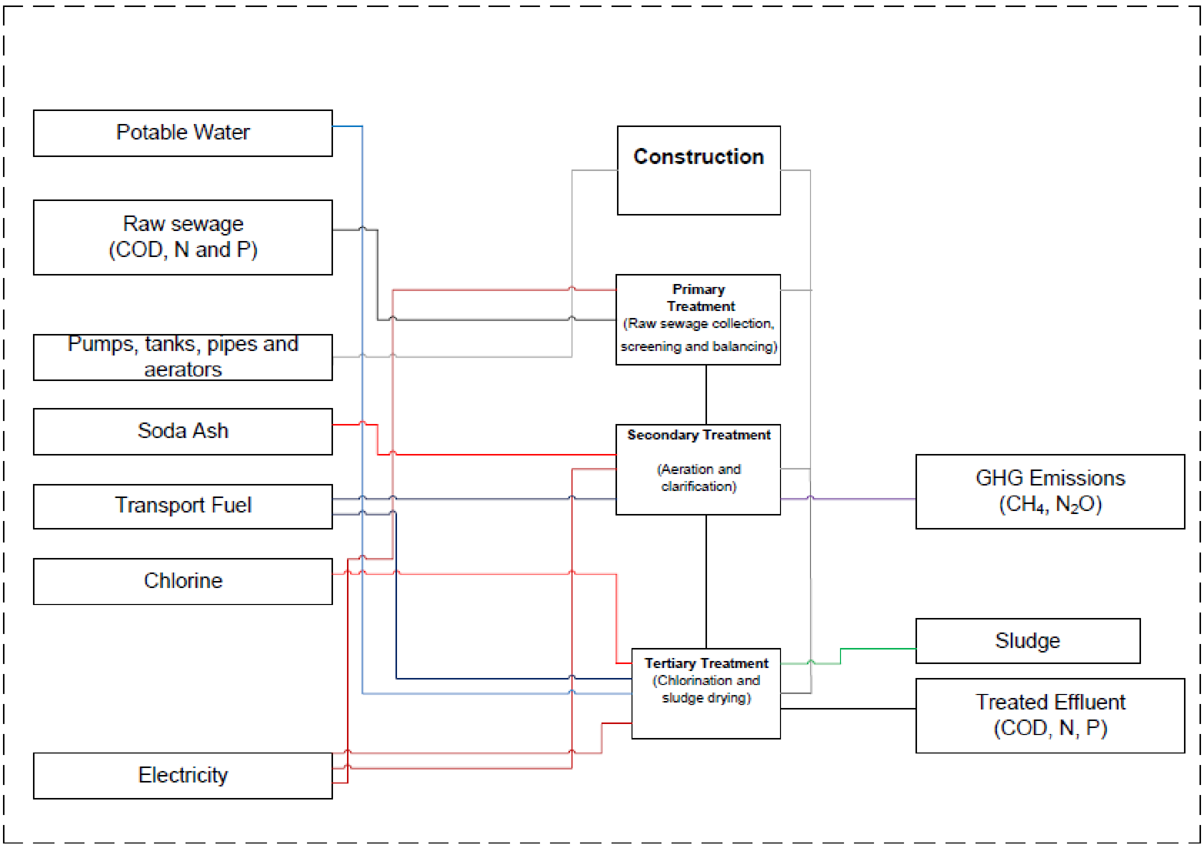

Figure 3.1: The system boundary for extended activated sludge process

COD (Chemical Oxygen Demand), N (Nitrogen) and P (Phosphorus) were the only considered parameters in the composition of raw sewage and treated effluent as both plants were designed to remove these contaminants. Sludge treatment processes after being disposed to the landfill were not considered in this study as that was viewed as wastewater management instead of wastewater treatmentDirect Greenhouse Gases [GHG], (CH_4 and N_2O) released during biological wastewater treatment processes were considered as they contribute towards the climate change of wastewater treatment plant (Lopsik, 2013). CO_2 emitted during wastewater treatment was not accounted for as it is considered of biogenic origin (IPCC, 2007) therefore rendering it as climate neutral.

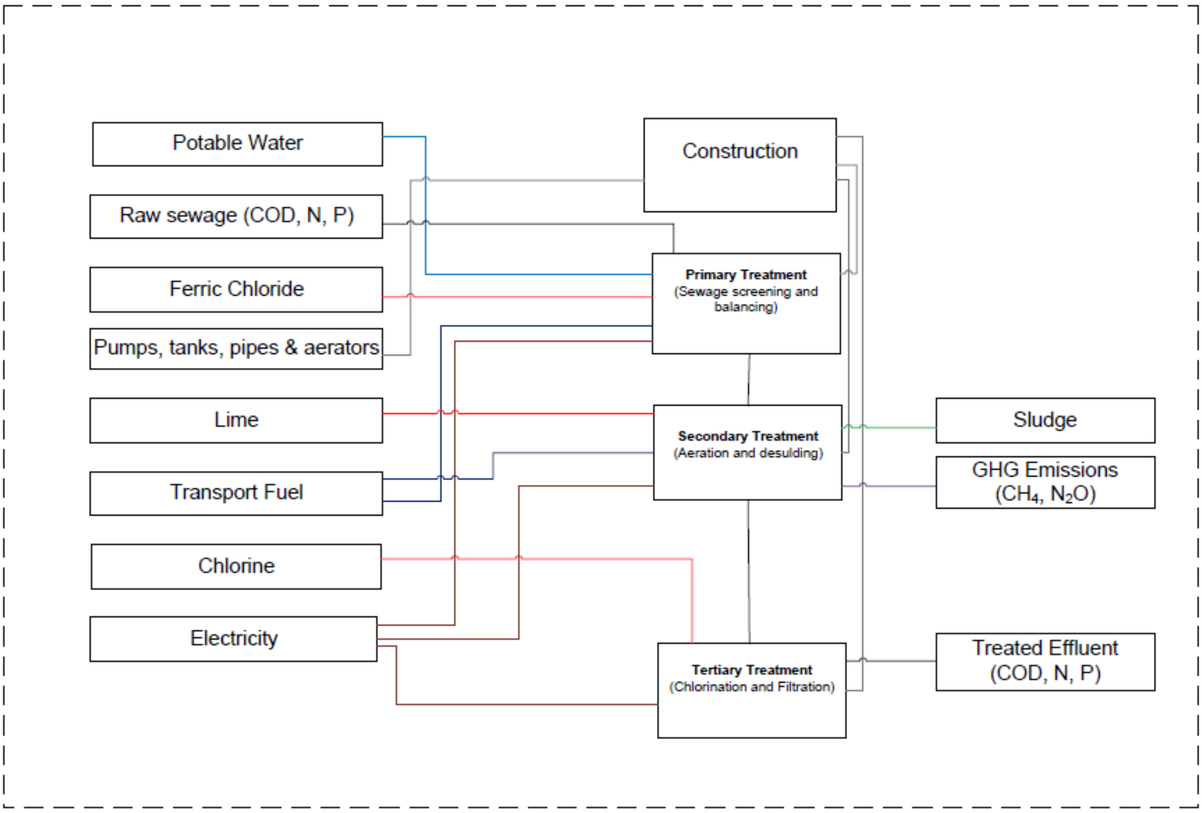

Figure 3.2: The system boundary for sequential batch reactor technology

<u>Functional unit</u>

The function of both wastewater treatment technologies is to remove contaminants from sewage wastewater in order to meet the South African general limit for wastewater as per section 39 of the National Water Act No.36 of 1998 (Appendix B) The functional unit for both treatment technologies is 1m^3 water.

Foreground and Background data

Majority of operation phase foreground data such as electricity consumption, material and chemical requirements were collected from the plant monitoring logs and nameplates of equipment. Foreground data utilised was the average for three years (2016 to 2019) covering all different seasons of the year with varying weather conditions in Limpopo province, South Africa. In cases were nameplates were missing; foreground data was attained from equipment datasheets, design reports, operations manuals, maintenance manuals, P&ID (Process and instrumentation diagrams) and GA (General arrangements) drawings. Suppliers and manufacturers of pumps and were also contacted for power ratings that were not available in the manuals.

For construction phase, most of the foreground data related to pipes, concrete, steel, plastics, glass and other related materials were not available due to commercial confidentiality from the manufacturers. Consequently Ecoinvent 3.0 database library was utilised to gather background data on material extraction, manufacturing and production processes related to materials and energy. Transportation fuel background data was calculated based on the fuel consumption of the type of truck used and the distance travelled from the manufacturer to the plant.

3.3 Lifecycle Inventory

The data collection started by compiling a PFD (Process flow diagram) which shows the general unit operations and major equipment of the plant. Thereafter, the spreadsheet was developed that shows the material and energy flows in and out of each unit operation. Inflow and outflow were then related to the functional unit (1 m^3 of water). Detailed inventory analysis (foreground and background data) for the material and energy utilised in both treatment technologies is shown in Chapter 4 with the following assumptions:

Electricity

The electricity background data was attained from the ecoinvent 3.0 database library based on the South African medium voltage mix. Running hours for equipment that are actuated or driven by electric current were collected from the operators log sheets. Thereafter electricity consumption was calculated from the kWh rating of equipment and the hours of operation. Energy input was expressed in terms of kWh/m^3 of treated effluent water.

Material

Background data (construction material production and chemicals production) were obtained from ecoinvent 3.0 database library. The average quantities of chemicals and sewage flows were collected from operator plant log sheets. COD, N and P concentrations were taken from the laboratory analysis reports from the respective plants. The direct GHG emission from the plant were collected from the review study conducted by Campos *et al*. (2016) due to the difficulty of measuring this type of emissions in the plant. It was assumed that an 8-ton truck with 30L/km fuel consumption was utilised to transport material from the manufacturers to the plants. This was based on the average weight of trucks that were transporting material to the two plants from the plant's weighbridge log book. Material inflows and outflows were expressed in terms of kg/m^3 of treated effluent water.

3.4 Lifecycle Impact Assessment (LCIA)

In this study all mandatory steps of LCIA (selection of impact categories, classification and characterisation) were followed while optional steps (grouping and weighting) were ignored, only normalisation was followed. SimaPro 8.5.2.0 Software and ReCipe 16 method were used to assess the environmental impact of the LCAs. The following impact categories (Huijbregts *et al*., 2016) were assessed for this study based on the pressing environmental concerns in the region where the plants are located:

- Freshwater ecotoxicity [Freshwater ecotoxicity potential, kg (1,4-DB $_{eq}$)]: Points out the potential for chemicals released into freshwater bodies to affect species in water bodies
- Freshwater eutrophication [Freshwater eutrophication potential, kg (P $_{eq}$)]: Outlines the potential for nutrients discharged into soil or freshwater bodies to increase the concentration of P.
- Terrestrial acidification formation [Terrestrial acidification potential, kg (SO_2 $_{eq}$)]: Defines the potential of atmospheric deposition of inorganic substances to change soil concentration of H^+ ion.
- Photochemical oxidation formation [Ozone formation potential, kg (NMVOC)]: Describes the potential for gases emitted to the atmosphere to form photochemical reactions.
- Fossil depletion [Fossil depletion potential, kg (oil eq)]: Highlights the impact of fossil resources extraction to the natural resource scarcity
- Human toxicity [Human toxicity potential, kg (1,4-DB $_{eq}$)]: Defines the potential for chemicals released into the atmosphere to affect species in the terrestrial environment
- Climate change [Global warming potential, kg (CO_2 $_{eq}$)]: Refers to the potential of GHGs to release radioactive forces that leads to an increase in the global mean temperatures.

3.5 Interpretation

The findings from inventory analysis and impact assessment were interpreted in line with the defined goal and scope in order to reach conclusions (See chapter 4)

4. RESULTS AND DISCUSSION

4.1 Outline of the chapter

The chapter commences by presenting the Process Flow Diagram (PFD) and the inventory lists for the LCAs conducted. Thereafter the results of LCAs were presented and discussed.

4.2 Process flow diagrams for LCA technologies

To evaluate the environmental impacts associated with a Sequential Batch Reactor (SBR) and an Extended Activated Sludge Process (EASP), the process inputs and outputs flows were constructed on PFD drawings (Figure 4.1 and Figure 4.2). The process streams have been colour coded for ease of identification: blue (potable water), red (chemicals) and black (sewage wastewater).

EASP has three pump stations (Figure 4.1) compared to one pump station (Figure 4.1) for SBR. This translates to more energy (pumps and aerators) and material (pipes, pumps, tanks, valves and other related materials) owing to two additional sewage wastewater streams. SBR has three chemical inputs (ferric chloride, lime and chlorine), while EASP has two chemical input (soda ash and chlorine).

SBR was designed to treat of 1700 m^3/day of raw sewage with an average loading of COD (750 mg/l), N (40 mg/l), and P (5 mg/L). EASP was designed to treat 2736 m^3/day of raw sewage with an average loading of COD (800 mg/l), N (45 mg/l) and P (5 mg/l). EASP SBR emits CH_4 (7.5 mg/l) and N_2O (3 mg/l) as GHG while EASP releases CH_4 (8 mg/l) and N_2O (3.375 mg/l) respectively. The SBR sludge (170 kg/day) is more than that produced by EASP (110 kg/day). This is due to the use of ferric chloride to remove phosphorus in SBR, which results in phosphates precipitates which are removable as sludge.

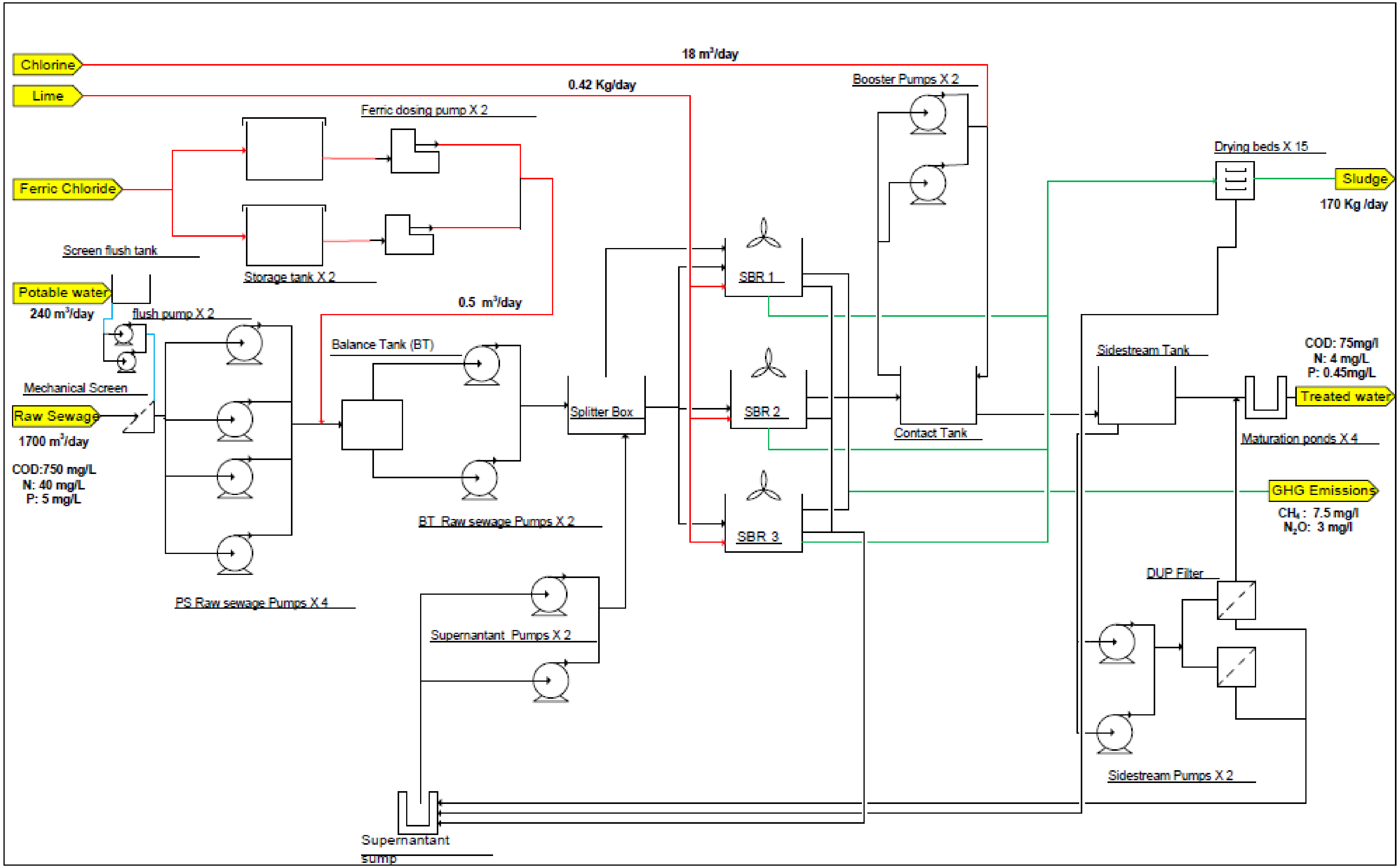

Figure 4.1: Process Flow Diagram for Sequential Batch Reactor technology

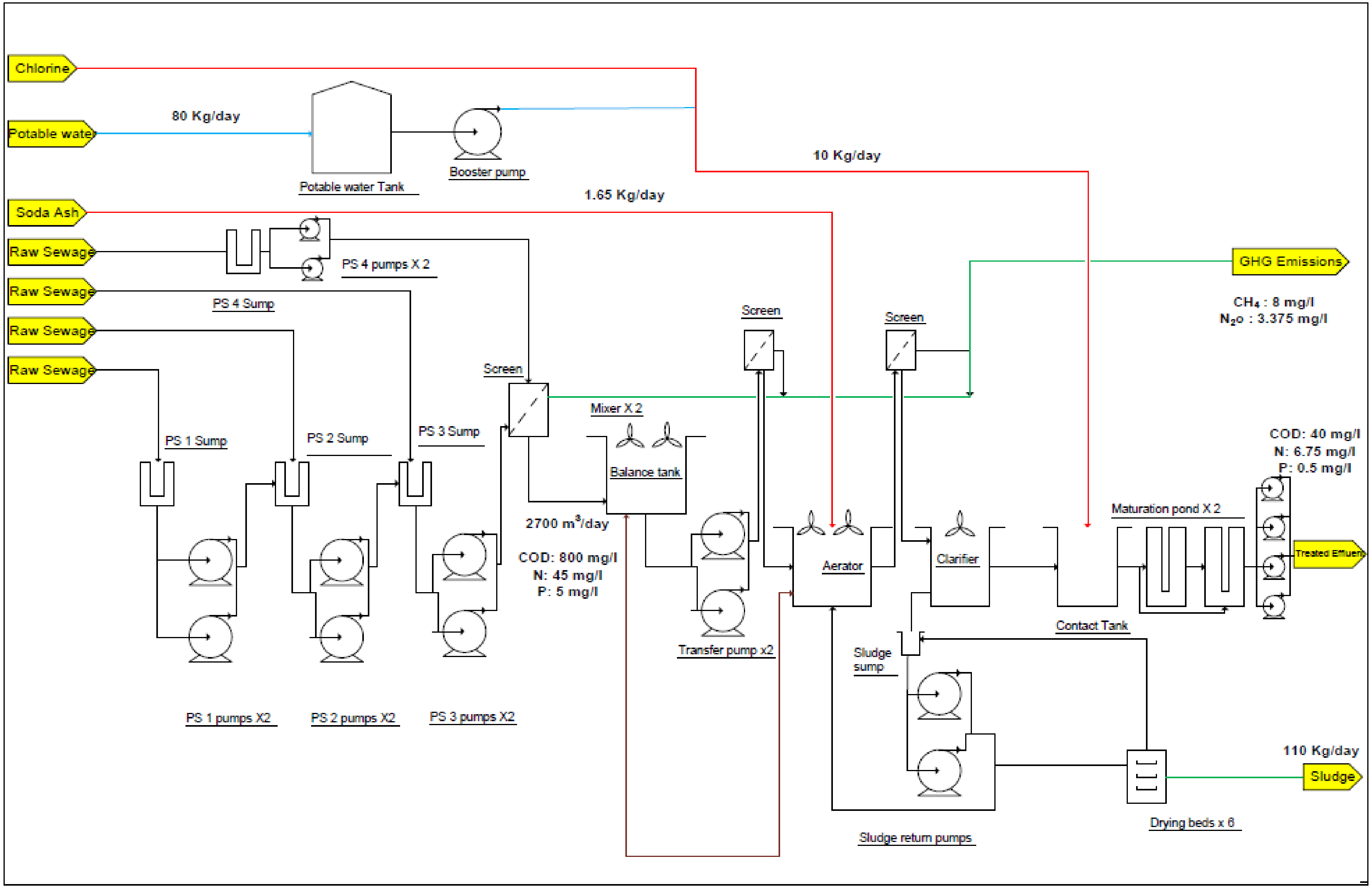

Figure 4.2: Process Flow Diagram for Extended Activated Sludge Process technology

4.3 Inventory lists for LCA of SBR and EASP

Inventory lists of treatment technologies (SBR and EASP) were populated with foreground and background data referred to the functional unit (1m^3 of water) from the ecoinvent 3 database. Electricity consumptions (Figure 4.1 and Figure 4.2) were the highest input on both treatment technologies, 1.04 kWh/m^3 was calculated for SBR treatment while 7.01 kWh/m^3 was calculated for EASP. Previous studies have also shown values of electricity consumption for biological wastewater treatment which are close to those of SBR treatment technology (0.3–1 kWh/m^3 (Soares *et al*., 2017); 0.38–1.12 kWh/m^3 (Wakeel *et al*., 2016) and 0.33–1 kWh/m^3 (Wang *etal*., 2016)). The electricty consumption for EASP was 7 times that of SBR treatment technology due the additional recycle activated sludge pumps (x2), balancing tank aerators (x2), and additional raw sewage pumps (x2).

The SBR sludge was almost 50%(volume) more than that produced by EASP owing to the use of ferric chloride to remove inorganic phosphorus in SBR, which results in phosphates precipitates which are removable as sludge. SBR further consumed more chemicals (Ferric Chloride, Lime and Chlorine) than EASP (Soda Ash and Chlorine). This was attributed to the additional use of ferric chloride to remove inorganic phosphorus. Moreover, due ferric chloride acidic nature; its use necessitates the use of pH correction chemical (lime) in order to maintain the optimum pH for treatment. The direct greenhouse gases (N_2O (7.5% N, inlet); CH_4 (1% COD, inlet)) emission were calculated from correlations adopted from Campos *et al*. (2016).

Wastewater treatment technologies yielded treated wastewater and sludge as outputs. The sludge was viewed as waste product as it was not further processed to recover material or energy. Consequently, allocation methods were ignored as sludge did not have any economic value.

Table 4.1: Inventory Table for Sequential Batch Reactor (SBR) technology

INPUT			Ecoinvent Library /Data Source
Primary Treatment			
Cast Iron	3.2E-04	kg/m^3	Cast iron {GLO}| market for | Conseq, U
Mild Steel	1.4E-04	kg/m^3	Steel, low-alloyed {GLO}| market for | Conseq, U
Stainless Steel 304	3.6E-05	kg/m^3	Steel, chromium steel 18/8 {GLO}| market for | Conseq, U
Polypropylene	3.2E-06	kg/m^3	Polypropylene, granulate {GLO}| market for | Conseq, U
Polyvinylchloride	2.8E-04	kg/m^3	Polyvinylchloride, emulsion polymerised {GLO}| market for | Conseq, U
Polyethylene	1.4E-05	kg/m^3	Polyethylene, high density, granulate {GLO}| market for | Conseq, U
Reinforced Concrete	2.3E-07	m^3/m^3	Concrete, 25MPa {GLO}| market for | Conseq, U
Electricity	2.02E-01	kWh/m^3	Electricity, medium voltage {ZA}| market for | Conseq, U
Ferric chloride	3.41E-02	kg/m^3	Iron (III) chloride, without water, in 14% iron solution state {GLO}| market for | Conseq, U
Potable water (flush of mechanical screen)	9.80E-02	kg/m^3	Tap water {GLO}| market group for | Conseq, U
Diesel for transporting Ferric Chloride	5.9E-06	kg/m^3	Diesel {GLO}| market group for | Conseq, U
Secondary Treatment			
Reinforced Concrete (25 Mpa)	1.5E-06	m^3/ m^3	Concrete, 25MPa {GLO}| market for | Conseq, U
Mild Steel	7.2E-05	kg/m^3	Steel, low-alloyed {GLO}| market for | Conseq, U
Cast Iron	7.9E-04	kg/m^3	Cast iron {GLO}| market for | Conseq, U
Polyvinylchloride	1.8E-06	kg/m^3	Polyvinylchloride, suspension polymerised {GLO}| market for | Conseq, U
Electricity	6.2E-01	kWh/m^3	Electricity, medium voltage {ZA}| market for | Conseq, U
Lime	8.8E-02	kg/m^3	Lime, hydrated, packed {GLO}| market for | Conseq, U
Diesel for transporting Lime	3.0E-04	kg/m^3	Diesel {GLO}| market group for | Conseq, U
Tertiary Treatment			

Stainless Steel 304	2.2E-05	kg/m^3	Steel, chromium steel 18/8 {GLO}| market for | Conseq, U
Mild Steel	1.4E-04	kg/m^3	Steel, low-alloyed {GLO}| market for | Conseq, U
Cast Iron	3.3E-05	kg/m^3	Cast iron {GLO}| market for | Conseq, U
Polyvinylchloride	1.6E-05	kg/m^3	Polyvinylchloride, suspension polymerised {GLO}| market for | Conseq, U
Reinforced Concrete (25 Mpa)	3.8E-04	m^3/m^3	Concrete, 25MPa {GLO}| market for | Conseq, U
Electricity	2.2E-01	kWh/m^3	Electricity, medium voltage {ZA}| market for | Conseq, U
Chlorine	4.0E-03	kg/m^3	Chlorine, liquid {GLO}| market for | Conseq, U
Diesel for transporting Chlorine	3.0E-04	kg/m^3	Diesel {GLO}| market group for | Conseq, U
OUTPUT			
COD	7.5E-02	kg/m^3	Quality monitoring foreground data from the plant
N	4E-03	kg/m^3	Quality monitoring foreground data from the plant
P	4.5E-04	kg/m^3	Quality monitoring foreground data from the plant
CH_4	7.5E-03	kg/m^3	Correlation background data from Campos et al. (2016)
N_2O	3E-03	kg/m^3	Correlation background data from Campos et al. (2016)
Sludge	9.5E-02	kg/m^3	Quality monitoring foreground data from the plant
Treated wastewater	1	m^3/m^3	Functional unit

Table 4.2: Inventory Table for Extended Activated Sludge Process (EASP) technology

INPUT			Ecoinvent Library
Primary Treatment			
Cast Iron	8.0E-04	kg/m^3	Cast iron {GLO}| market for | Conseq, U
Galvanised Steel	6.5E-06	kg/m^3	Steel, low-alloyed {GLO}| market for | Conseq, U
Reinforced Concrete	1.0E-06	m^3/m^3	Concrete, 25MPa {GLO}| market for | Conseq, U
Polyvinylchloride	3.8E-06	kg/m^3	Polyvinylchloride, emulsion polymerised {GLO}| market for | Conseq, U
Electricity	5.36E+00	kWh/m^3	Electricity, medium voltage {ZA}| market for | Conseq, U
Secondary Treatment			
Carbon Steel	6.5E-06	kg/m^3	Steel, low-alloyed {GLO}| market for | Conseq, U
Stainless Steel 304	2.0E-07	kg/m^3	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Conseq, U
Cast Iron	6.6E-06	kg/m^3	Cast iron {GLO}| market for | Conseq, U
Galvanised Steel	2.2E-06	kg/m^3	Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U
Reinforced Concrete	2.9E-06	m^3/m^3	Concrete, 25MPa {GLO}| market for | Conseq, U
Asbestos Cement	6.6E-06	kg/m^3	Asbestos, crysotile type {GLO}| production | Conseq, U
Polyvinylchloride	2.5E-06	kg/m^3	Polyvinylchloride, suspension polymerised {GLO}| market for | Conseq, U
Electricity	8.0E-01	kWh/m^3	Electricity, medium voltage {ZA}| market for | Conseq, U
Soda Ash	6.0E-04	kg/m^3	Soda ash, light, crystalline, heptahydrate {GLO}| market for | Conseq, U
Diesel for transporting Soda ash	1.8E-04	kg/m^3	Diesel {GLO}| market group for | Conseq, U
Tertiary Treatment			
Cast Iron	2.0E-05	kg/m^3	Cast iron {GLO}| market for | Conseq, U
Stainless Steel 304	2.0E-06	kg/m^3	Steel, chromium steel 18/8 {GLO}| market for | Conseq, U

Fibre glass	5.1E-06	kg/m^3	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Conseq, U
Reinforced Concrete	1.5E-04	m^3/m^3	Concrete, 25MPa {GLO}| market for | Conseq, U
Polyvinylchloride	1.0E-04	kg/m^3	Polyvinylchloride, suspension polymerised {GLO}| market for | Conseq, U
Electricity	8.5E-01	kWh/m^3	Electricity, medium voltage {ZA}| market for | Conseq, U
Chlorine	3.7E-03	kg/m^3	Chlorine, liquid {GLO}| market for | Conseq, U
Diesel for transporting Chlorine	1.6E-03	kg/m^3	Diesel {GLO}| market group for | Conseq, U
Potable water for Chlorine injection	9.8E-02	kg/m^3	Tap water {GLO}| market group for | Conseq, U
OUTPUT			
COD	1.60E-02	kg/m^3	Quality monitoring foreground data from the plant
N	7.65E-03	kg/m^3	Quality monitoring foreground data from the plant
P	5.0E-04	kg/m^3	Quality monitoring foreground data from the plant
CH_4	8.0E-03	kg/m^3	Correlation background data from Campos et al. (2016)
N_2O	3.38E-03	kg/m^3	Correlation background data from Campos et al. (2016)
Sludge	4.92E-02	kg/m^3	Quality monitoring foreground data from the plant
Treated wastewater	1	m^3/m^3	Functional unit

4.4 Impact assessment results for LCAs

The characterised LCIA results (Figure 4.3) showed that EASP environmental impact was more than SBR in all impact categories besides climate change and freshwater eutrophication. SBR climate change and freshwater eutrophication were 1.2 and 1.3 times greater than those of EASP respectively. The significant impacts of SBR and EASP on climate change were due to greenhouse gas emitted due to the South African coal-based electricity mix coupled with the direct greenhouse gases released during biological treatment. A study conducted by Li et al. (2013) in China, found the climate change impact of 5.45E+08 kg CO_2-eq from ASP treatment technology, which was 8 times more than the one from SBR (3.3E+00 kg CO_2-eq) and EASP (2.8E+00 kg CO_2-eq). The greater contribution on the latter study was attributed to the large size (10^5 m^3/day) of the wastewater treatment plant and difference in the electricity mix of South Africa and China.

Table 4.3: LCA characterisation results for EASP and SBR with 1 m^3 of water as a functional unit

Impact category	Unit	SBR	EASP
Climate change	kg CO2 eq	3.3	2.8
Human toxicity	kg 1,4-DB eq	2.3 × 10-1	1.3
Fossil depletion	kg oil eq	1.2 × 10-1	6.2 × 10-1
Freshwater ecotoxicity	kg 1,4-DB eq	2.1 × 10-2	1.4 × 10-1
Terrestrial acidification	kg SO2 eq	2.4 × 10-3	1.5 × 10-2
Photochemical oxidant formation	kg NMVOC	2.7 × 10-3	9.4 × 10-3
Freshwater eutrophication	kg P eq	8.2 × 10-3	6.3 × 10-3

Human toxicity and terrestrial acidification for EASP were roughly 6 times higher than SBR. EASP Freshwater ecotoxicity was about 7 times more than SBR. Fossil depletion was almost 5 times more than SBR, while photochemical oxidation formation was about 3 times that of SBR. High energy demand for EASP (7.01 kWh/m^3) compared to SBR (1.04 kWh/m^3) was responsible for the latter environmental burdens on EASP technology.

To better understand the magnitude of impact categories, environmental impacts results were normalised (Figure 4.3) using ReCiPe 16 midpoint world reference method. The most significant impact categories for EASP were freshwater ecotoxicity (3.14E-02), followed by freshwater eutrophication (2.17E-02) and human toxicity (4.02E-03). For SBR, freshwater eutrophication (2.83E-02), freshwater ecotoxicity (4.97E-03) and human toxicity (6.94E-04) were the significant impact categories. The normalised results for EASP and SBR were fairly consistent with those found by Niero et al. (2014) for conventional activated sludge treatment on freshwater eutrophication (3.56E-04), freshwater ecotoxicity (1.85E-03) and human toxicity (4.67E-02).

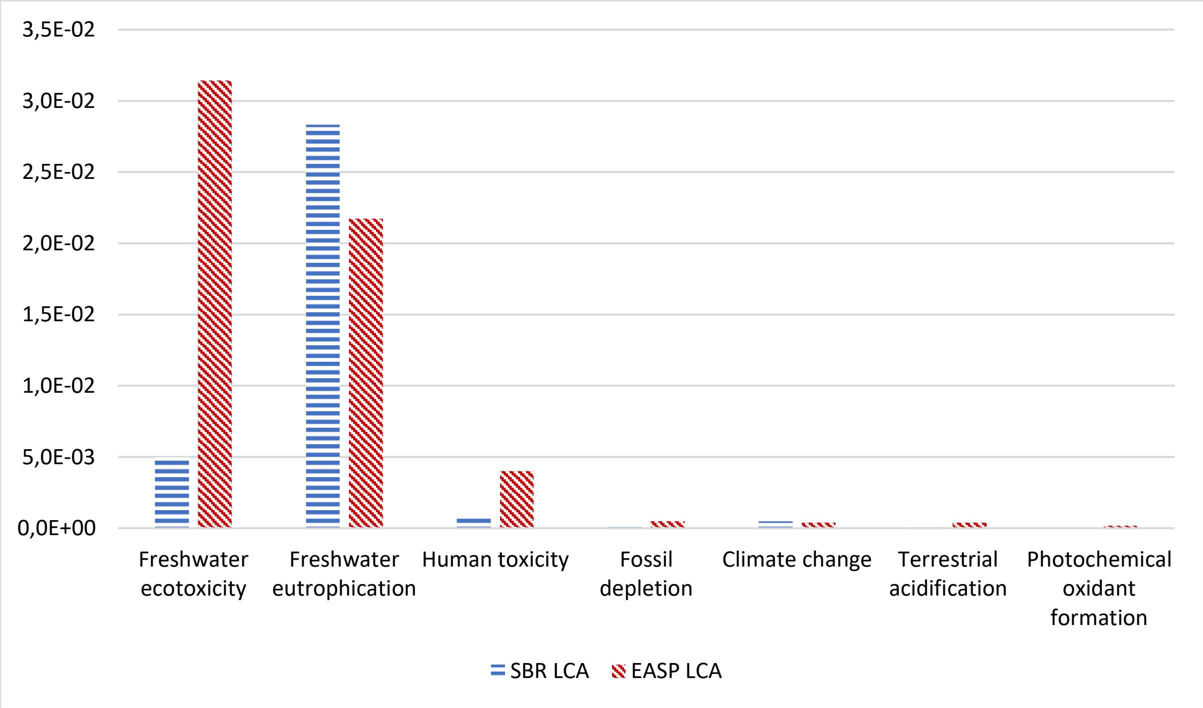

Figure 4.3: Normalised impact assessment results for EASP and SBR LCA

The contributions by treatment stages on impact categories for EASP (Figure 4.4) and SBR (Figure 4.5) both revealed that secondary treatment stage (82% (EASP), 99% (SBR)) was the main contributors towards freshwater eutrophication impact category. An effect that was a consequence of residual Phosphorus, Nitrogen and COD compound in effluent treated wastewater. For other impact categories, primary treatment stage contributed more than 65% towards EASP environmental burdens.

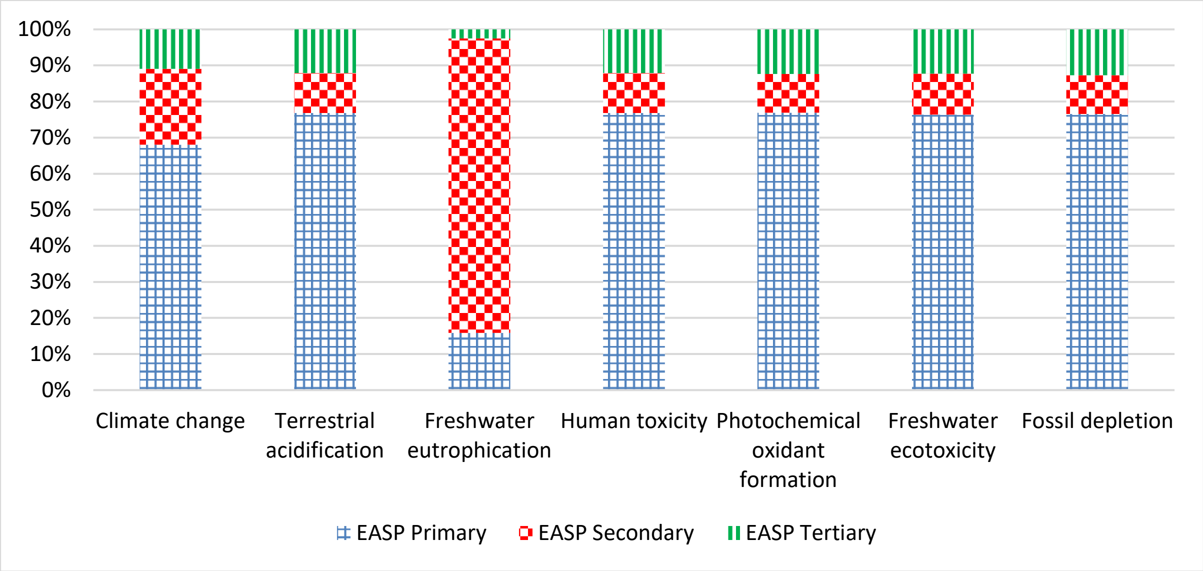

Figure 4.4: Impact assessment results for EASP with treatment stages contributions

For SBR treatment technology (Figure 4.5), secondary treatment stage contributed more than 50% of environmental burden across all impact categories. For climate change and freshwater eutrophication, secondary treatment stage specifically contributed 93% and 99% of environmental burden respectively. The emission of direct GHGs (N_2O and CH_4) from SBR biological treatment tied with the use of coal-based South African electricity mix for secondary treatment (0.62 kWh/m^3) were responsible for the pronounced burden towards climate change impact category. For both treatment technologies, Freshwater eutrophication (Figure 4.4 and Figure 4.5) was the impact category of significance. These results agree with other LCAs (Gallego et al. (2008); Lassaux et al. (2007)) for wastewater treatment.

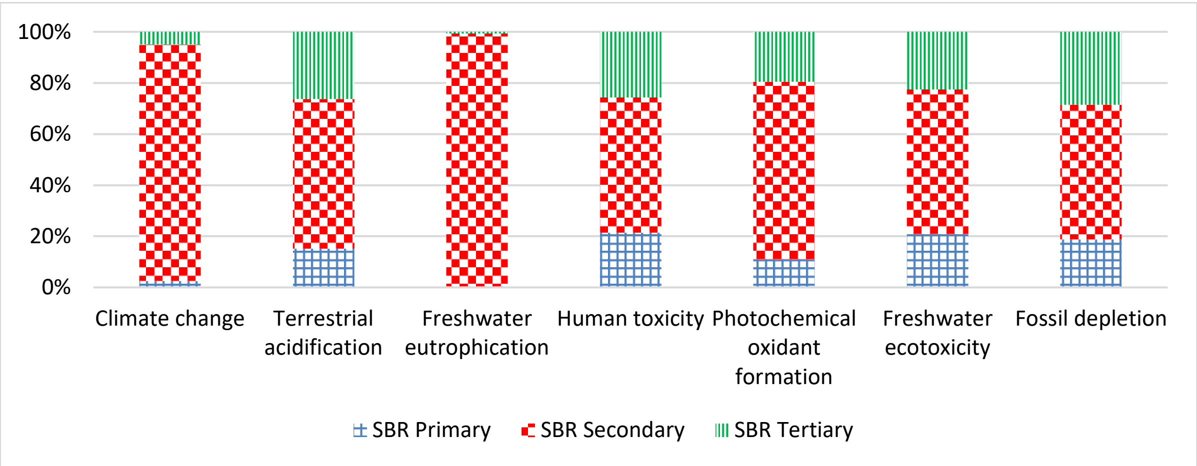

Figure 4.5: Impact assessment results for SBR with treatment stages contribution

4.5 Process contribution analysis for LCAs impact categories

To investigate process contributions made by key impact categories (freshwater eutrophication, freshwater ecotoxicity and human toxicity) determined from normalised LCAs results, sunburst diagrams were utilised (Harding, 2013). This style accounts for all direct and indirect processes that contributes toward the LCIA scores. The percentage contribution of processes greater than 5% of the LCA impact categories (negative and positive impacts) were investigated. The process contributions for other evaluated impact categories are displayed on Appendix D.

4.5.1 Freshwater eutrophication

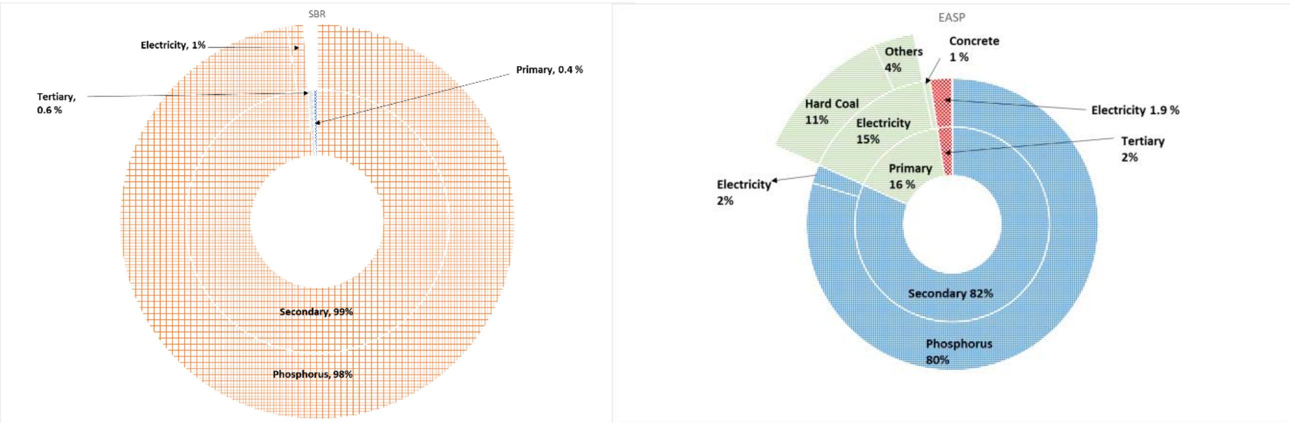

Figure 4.6: Life Cycle Assessment process contribution of SBR and EASP towards freshwater eutrophication impact category using ReCipe midpoint method

For freshwater eutrophication (Figure 4.6), secondary treatment was the largest contributor in both treatment technologies, 82% was contributed for EASP and 98% for SBR. The effect in the secondary treatment was mainly due to the residual phosphorus (Figure 4.1 and Figure 4.2) left in the treated wastewater effluent after biological treatment in both treatment technologies. Electricity was the dominating process contributor on the primary treatment stage (SBR [95%]; ASP [93%]) and tertiary treatment stage (SBR [76%]); ASP [99%]). This was mostly from electricity generated from coal, the main source of electricity generation in South Africa.

4.5.2 Freshwater ecotoxicity

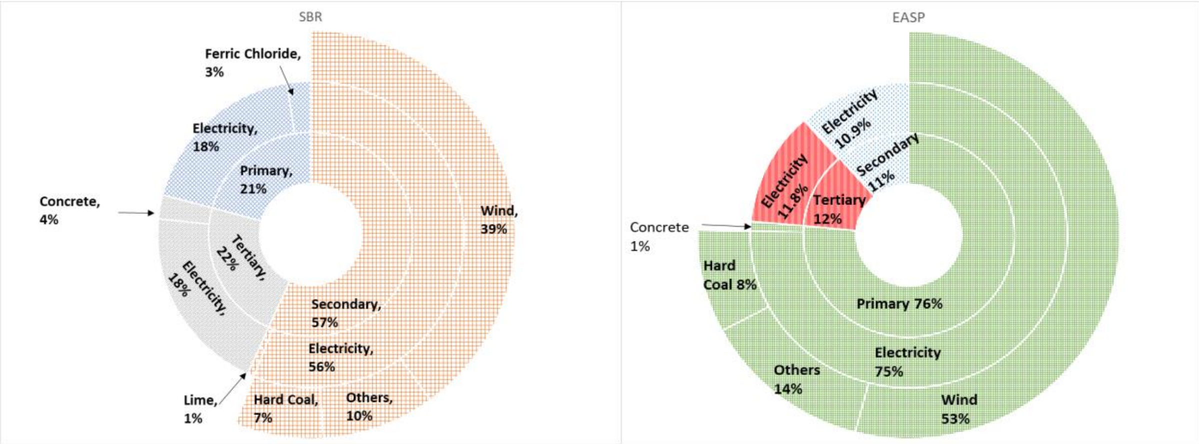

Figure 4.7:Life Cycle Assessment process contribution of SBR and EASP towards freshwater ecotoxicity impact category using ReCipe midpoint method

Primary treatment (78%) dominated the environmental contribution of freshwater ecotoxicity (Figure 4.7) on EASP. In the primary treatment stage of EASP, electricity (84%) and concrete (16%) were the significant process contributors. SBR treatment was dominated by secondary treatment (57%). Significant Process contributor to secondary treatment of SBR was electricity (98%). Wind electricity (70%) was the dominant process contributor for SBR (secondary treatment) and EASP (primary treatment). This was due to the release of heavy metals (Nickel, vanadium and Barium) to water and air during the manufacturing process of metals used in wind turbines (Razdan & Garrett, 2015)

4.5.3 Human toxicity

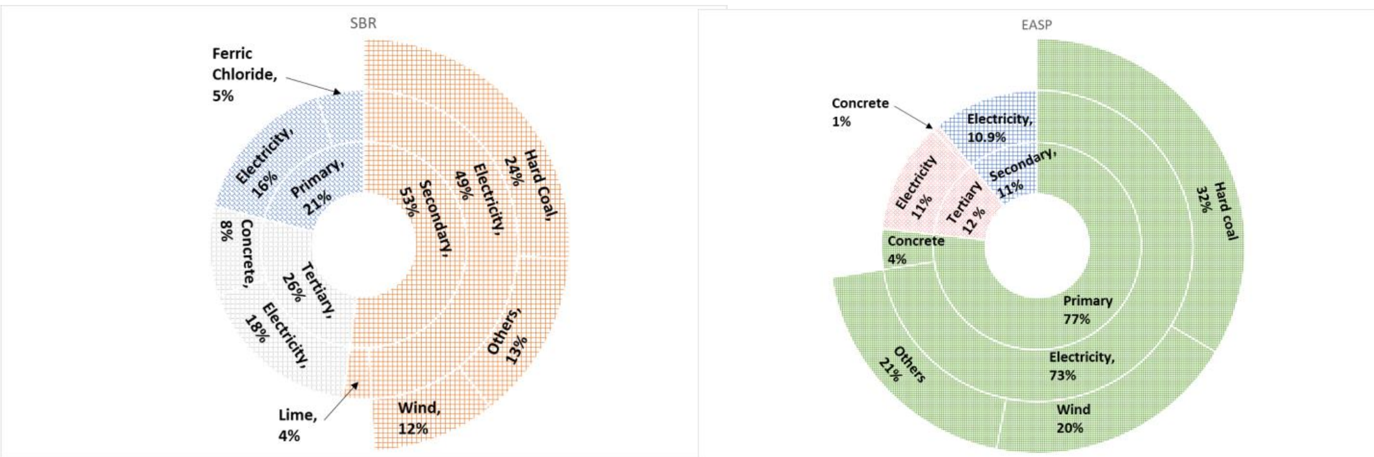

Figure 4.8: Life Cycle Assessment process contribution of SBR and EASP towards human toxicity impact category using ReCipe midpoint method

Human toxicity environmental burden (Figure 4.8) was predominantly due to primary treatment (77%) of EASP and secondary treatment (53%) of SBR. Coal electricity was the significant process contributor (50%) on both SBR secondary treatment and EASP primary treatment. Concrete provided 5% contribution alongside each electricity contribution for EASP primary treatment (94%) and EASP tertiary (95%) treatment. Chemicals that were utilised in the SBR treatment technology made contribution on areas where they were dosed: primary treatment stage (ferric chloride, 23%), secondary treatment stage (lime, 6%) and tertiary treatment stage (chlorine, -5%). The negative contribution by chlorine on the SBR tertiary treatment was due to the environmental credit for the removal of trace nutrients in treated wastewater by chlorine.

4.6 Discussion of SBR and EASP LCA results

Electricity was responsible for majority of process contribution towards the environmental performance of SBR and EASP on freshwater ecotoxicity (SBR, 98%; EASP, 99%) and human toxicity (SBR, 93%; EASP, 94%). The significant process contribution by electricity was due to the negative environmental impacts (emission of GHGs, particulate matter, SO_2 and heavy metals) associated with the dominant coal-based South African energy mix. For freshwater eutrophication, phosphorus (treated wastewater) was the dominant process contributor (SBR, 99%; EASP, 97%). This was due the residual phosphorus left after wastewater treatment which leads to excessive plant growth (eutrophication) in freshwater bodies.

LCA study by Awad et al. (2019) on activated sludge treatment process found the following dominant process contributions: freshwater eutrophication (99%, phosphorus); freshwater ecotoxicity (56%, electricity) and human toxicity (55%, electricity). Only freshwater eutrophication from the latter study was within the range of values in SBR and EASP. Electricity process contributions on freshwater ecotoxicty and human toxicity from the latter study were almost 40% less than those of SBR and EASP. The higher electricty for SBR and EASP owes to the coal-based South African electricty mix compared to that of hydro-based in Egypt which was used for the study in Awad et al. (2019).

Concrete made 36% process contribution on freshwater ecotoxicity of SBR tertiary treatment (although it was not the dominant treatment stage). 5% process contribution by concrete was observed on human toxicity of EASP primary treatment. The process contributions by ferric chloride towards the environmental burden of SBR primary treatment were: freshwater eutrophication (5%), freshwater ecotoxicity (12%) and human toxicity (23%). Lime made a process contribution of 6% on human toxicity of SBR secondary treatment. The notable environmental burdens by ferric chloride and lime on the latter impact categories owed to the production processes of ferric chloride and lime that releases chemicals (GHGs, heavy metals and other related materials) into air, soil and water. 30% process contribution by ferric chloride chemical on the environmental burden of toxicity impact categories for wastewater treatment processes were also observed by Niero et al. (2014). There was no significant process contribution (greater than 5%) made by chemicals (soda ash and chlorine) which were dosed on the secondary and tertiary treatment of EASP. Chlorine made a negative process contribution (environmental benefit) on freshwater eutrophication (-9%) and human toxicity (-5%) of SBR tertiary treatment. This was due to the ability of chlorine to remove of trace nutrients in treated wastewater, which reduces eutrophication and toxicity of treated wastewater.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Outline of the chapter

In this chapter the summary of the study findings were presented in line with the objectives of the research. The limitations and implication of the study were highlighted and furthermore recommendations for future research studies were made.

5.2 Conclusions

The objective of this study was to perform a Life Cycle Assessment (LCA) on a Sequential Batch Reactor (SBR) and an Extended Activated Sludge Process (EASP) sewage wastewater treatment technologies. This was done in order to evaluate technology section based on evironmental impacts in South Africa. It was in answering three research questions formulated in chapter 1 that the objectives of the study were examined.

1. <u>What are the environmental impacts of sequential batch reactor technology?</u>

SBR teatment technology had prominent effects on freshwater eutrophication, freshwater ecotoxicty and human toxicity impact categories. The main environmental burderns were attributed to secondary treatment stage on freshwater eutrophication (98%), freshwater ecotoxicty (57%) and human toxicity (53%). Process contributions analysis of secondary treatment on freshwater eutrophication revealed that phosphorus in treated wastewater was the significant contributor (99%). Concerning Secondary treatment on freshwater ecotoxicity, electricity (98%) was the major process contributor. Regarding secondary treatment on human toxicity, Lime (6%) and electricity (93%) were the prominent process contributors. Thus electricity, effluent phosphorus and lime were the significant process contributors towards SBR environmental performance.

2. <u>What are the environmental impacts of extended activated sludge technology?</u>

EASP teatment technology had notable effects on freshwater ecotoxicty, freshwater eutrophication and human toxicity impact categories. The main environmental burderns were attributred to primary treatment stage on freshwater ecotoxicty (76%) and human toxicity (77%). freshwater eutrophication (82%), was mainly attributed to seondary treatment stage. Process contributions analysis of secondary treatment on freshwater eutrophication revealed that phosphorus in treated wastewater was the significant contributor (97%). Concerning primary treatment on freshwater ecotoxicity, electricity (99%) was the major process contributor. Thus electricity, effluent phosphorus and concrete were the significant process contributors towards EASP environmental performance.

3. How the environmental impacts of the two technologies compare?

SBR treatment technology performed better than EASP on freshwater ecotoxicity and human toxicity impact categories except for freshwater eutrophication. On both treatment technologies electricity and phosphorus in the treated wastewater were the largest process contributors. Chemical consumption made a fair environmental burden contribution <6% on the SBR facility mostly due to ferric chloride whereas the impact on EASP was negligible (<1%).

The results and conclusions recommend the following:

- For policy makers, investment in renewable energy and energy efficiency is recommended in South Africa to improve the environmental performance of sewage treatment plants.
- For water sector professionals, plant optimization on process kinetics parameters and improvement on pumping and aeration efficiencies is recommended to improve the removal efficiency of major pollutants (COD, N, P); and
- For LCA practitioners, it is recommended to do more WWTP LCA studies to improve inventory data specific to South Africa.

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APPENDIX A: LCA METHODOLOGY FRAMEWORK

According to ISO 14040:2006, LCA has four stages (Goal and scope definition, Lifecycle Inventory, Lifecycle Impact assessment and Interpretation) as shown in figure A.1

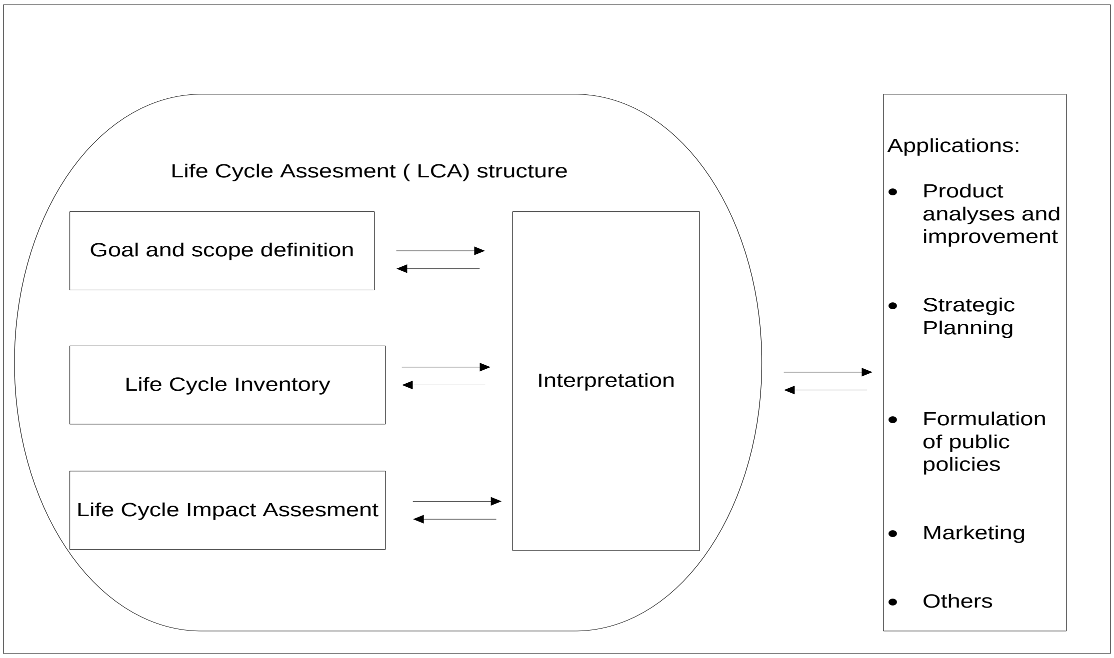

Figure A. 1: LCA Stages according to ISO 14040 **(ISO, 2006)**

1. The goal and scope: describe the system boundaries, functions, the intended application and functional unit of the study.
2. Inventory analysis: input and output data of the study is modelled and inventory table is generated.
3. Impact assessment: computes the environmental impacts caused by emission from the inventory analysis stage.
4. Interpretation: evaluates results and communicates to stakeholders and decision makers.

GOAL AND SCOPE OF THE STUDY

The goal of LCA is to highlight the motives for the study, intended application, and intended stakeholders (ISO, 2006). According to ISO (2006), the scope should address the goal of the LCA. System boundaries define the unit processes that are included in the LCA which are informed by the intended application, assumptions made, cut-off criteria, data, cost constraints and the intended audience (ISO, 2006). Functional unit that will be used to quantify products is defined at the goal and scope stage. In cases of more than one product output, the system should be expanded to include all products and where it is not possible allocation methods should be defined by mass, volume or economic values in order to share the environmental burdens (ISO, 2006).

Data quality requirement

Table A. 1: The matrix of data quality assessment adapted from (Bicalho et al., 2017)

Indicator Score	Excellent	Very Good	Good	Fair	Poor
Reliability	Verified data based on measurement	Verified data partly based on assumptions	Non Verified data partly on assumptions	Qualified estimate	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuation	Representative data > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuation	Representative data from only some sites (< 50%)relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representative unknown or data from a small number of sites and from shorter periods
Temporal correlation	≤ 3 years difference to year of study	3-6 years of difference	5-10 years of difference	10-15 years of difference	Unknown ≥ 15 years of difference
Geographical Correlation	Data from area under study	Average data from large area on which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Data quality requirements specify the characteristics of data needed for the study. It addresses time-related coverage, geographical coverage, technology coverage, precision, completeness, representation of data, sources of data and uncertainty of information (ISO, 2006). Data quality Indicators (DQI's) approach is widely used as the main reference for data quality in LCA (Bicalho *et al*., 2017).

Reliability

This relates to the sources, acquisition methods and verification procedure to obtain data (Weidema & Wesnaes, 1996)

Completeness

This focuses on the representativeness of data and the period of which it was collected (Bicalho *et al*., 2017).

Temporal correlation

This defines the relationship from the year of study and the year at which data was taken (Bicalho *et al*., 2017).

Technological correlation

This relates the technology source from which data was taken in relation to technology under study (Bicalho *et al*., 2017).

INVENTORY ANALYSIS

This stage focuses on data collection and calculation procedure that are used to quantify inputs and outputs of the systems. Data that that are collected are related to the functional unit and reported in the inventory table. Foreground data are collected from the actual processes while background data are those collected from secondary sources.

Lifecycle Impact Assessment (LCIA)

In this phase results of the inventory table are interpreted in terms of the impacts they have on the environment (UNEP, 1996). According to ISO (2006) LCIA consists of three mandatory steps (selection of impact categories, classification, characterisation) and three optional steps (normalisation, grouping, weighting)

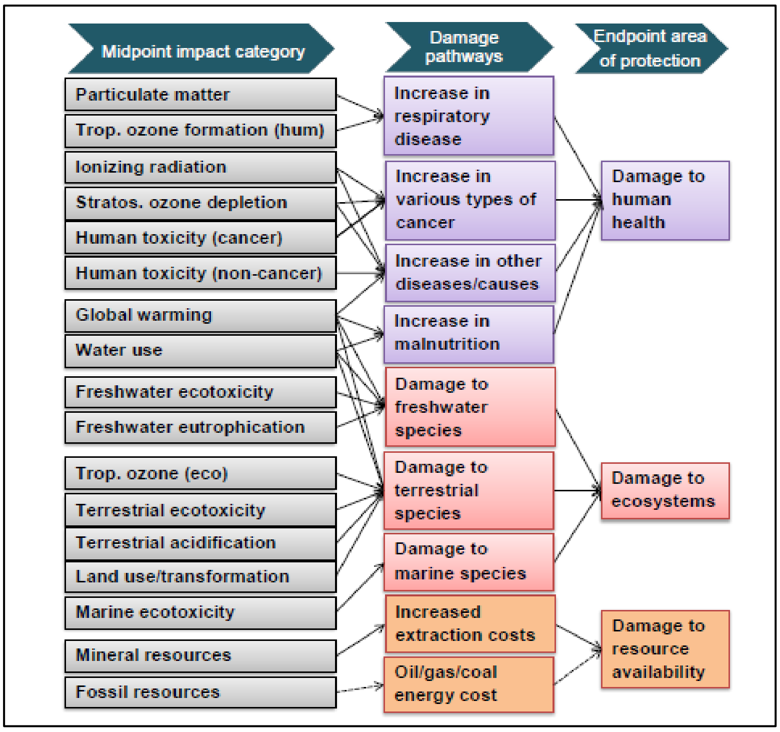

Figure A. 2: Overview of ReCiPe 2016 impact categories (Huijbregts et al., 2016)

<u>Classification</u>

The inputs and outputs are classified according to the environmental problem they contribute (UNEP, 1996). Hence there are also some resources that can contribute to more than one problem.

<u>Characterisation</u>

In this step the contribution to each environmental problem is quantified through conversion factors compared to reference substance such kg (CO_2 eq), kg (P eq) and kg (SO_2 eq). (UNEP, 1996).

Normalisation

In normalisation, the magnitude of each impact category is calculated relative to the reference value such as Europe and world reference in order to better understand the magnitude of each impact category (ISO, 2006).

Grouping

In this stage the large inventory data is grouped into different impact categories such as water use, fossil depletion and terrestrial ecotoxicity using equivalency factors. When impacts are ranked to indicate the environmental problem they are called midpoint categories. When midpoints are added together to show the environmental damage (human health damage, ecosystem damage and resource availability damage) the groupings are called endpoint impact categories.

Weighting

At this stage endpoints impact categories are congregated together to give a single score for all impact categories to indicate the overall environmental performance of the system. The weighting is not encouraged by ISO standard (ISO, 2006).

INTERPRETATION

At this stage the environmental contributions by inventory data and results from impact assessment are analysed in order to understand their effect on the environmental performance of the systems. Furthermore, sensitivity analyses are also conducted in this stage to understand the influence of a material or process on overall environmental performance.

APPENDIX B: Section 39 of South African National Water Act No.36 of 1998

Table B. 1: An extract of the South African discharge limits as stipulated in the National Water Act

SUBSTANCE/PARAMETER	GENERAL LIMIT	SPECIAL LIMIT
Faecal Coliforms (per 100 ml)	1000	0
Chemical Oxygen Demand (mg/l)	75 (i)	30(i)
pH	5,5-9,5	5,5-7,5
Ammonia (ionised and un-ionised) as Nitrogen (mg/l)	6	2
Nitrate/Nitrite as Nitrogen (mg/l)	15	1,5
Chlorine as Free Chlorine (mg/l)	0,25	0
Suspended Solids (mg/l)	25	10
Electrical Conductivity (mS/m)	70 mS/m above intake to a maximum of 150 mS/m	50 mS/m above background receiving water, to a maximum of 100 mS/m
Ortho-Phosphate as phosphorous (mg/l)	10	1 (median) and 2,5 (maximum)
Fluoride (mg/l)	1	1
Soap, oil or grease (mg/l)	2,5	0
Dissolved Arsenic (mg/l)	0,02	0,01
Dissolved Cadm ium (mg/l)	0,005	0,001
Dissolved Chromium (VI) (mg/l)	0,05	0,02
Dissolved Copper (mg/l)	0,01	0,002
Dissolved Cyanide (mg/l)	0,02	0,01
Dissolved Iron (mg/l)	0,3	0,3
Dissolved Lead (mg/l)	0,01	0,006
Dissolved Manganese (mg/l)	0,1	0,1
Mercury and its compounds (mg/l)	0,005	0,001
Dissolved Selenium (mg/l)	0,02	0,02
Dissolved Zinc (mg/l)	0,1	0,04
Boron (mg/l)	1	0,5

APPENDIX C: SAMPLE CALCULATIONS

Reference Flow

- The calculation below show the reference flow for the SBR technology
- The same calculation was used to calculate reference flow for EASP

$Design\ flow/day\ = 1700\ m^3\ /day$

$days/year = 365\ days$

$years/lifespan = 50\ years$

$$Reference\ Flow = \frac{Design\ flow}{day} \times \frac{days}{year} \times \frac{years}{lifespan\ of\ the\ plant}$$

$$= 31\ 025\ 000 \frac{m^3}{plant\ lifetime}$$

$$Functional\ unit\ = 1m^3\ of\ water$$

Electricity

- Below is sample power consumption calculation power consumption for raw sewage pump for SBR'S

$pump\ power\ rating = 36\ kW\ X\ 4(\ pumps)$

$pump\ efficiency\ (pe) = 0.75$

$Run\ hours\ /day = \ \ 2.5$

$days/year = 365\ days$

$years/lifespan = 50\ years$

$Reference\ flow = 31\ 025\ 000\ m^3/lifespan$

$$Power\ consumption = \frac{Pump\ rating \times pe \times \frac{run\ hours}{day} \times \frac{days}{year} \times \frac{years}{lifespan}}{Reference\ flow}$$

$P1)\ Raw\ sewage\ Punmps\ power\ consumption\ =\ 0.16 = 1.6E - 01\ kWh/m^3$

$P2)\ Balance\ tank\ pumps\ (\times 2)\ power\ consumption\ =\ 3.9E-02\quad kWh/m^3$

$P3)\ Flusing\ water\ pumps\ (\times 2)\ power\ consumption\ =\ 2.2E-05\quad kWh/m^3$

$P4)\ Mechanical\ screen\ (\times 1)\ power\ consumption\ =\ 3.9E-03\quad kWh/m^3$

$P5)\ Ferric\ dosing\ pumps\ (\times 2)\ power\ consumption\ =\ 2.3E-04\quad kWh/m^3$

$$SBR\ Primary\ treatment\ Power\ consumption = \sum P_I$$

$$= \mathbf{2.02E-01\ kWh/m^3}$$ **(Table 4.1)**

Electricity, medium voltage {ZA}| market for |Conseq, U (ecoinvent reference on Simapro)

<u>Chemicals</u>

- The calculation below shows the chemical consumption of ferric chloride.

$Dosing\ rate = 0.04\ m^3/day$

$days/year = 365\ days$

$years/lifespan = 50\ years$

$Density\ of\ ferric\ chloride =\ 1450\ kg/m^3$

$Reference\ flow = 31\ 025\ 000\ m^3/lifespan$

$$Ferric\ chloride\ \ consumption = \frac{Dosing\ rate \times \frac{days}{year} \times \frac{years}{lifespan} \times Density}{Reference\ flow}$$

$P1)\ Power\ consumption\ =\ 0.034 = \mathbf{3.41E-02\ kg/m^3}$ **(Table 4.1)**

Iron (III) chloride, without water, in 14% iron solution state {GLO}| market for | Conseq, U (ecoinvent reference on Simapro)

Fuel for transporting chemical

- The calculation below shows the truck fuel consumption for delivering ferric chloride
- 1000 m^3 of ferric chloride is deliverd twice a year on each trip
- The shelf life of ferric chloride in 6 months

$Distance\ (from\ supplier\ to\ plant\ with\ return)/trip\ = 740\ km$

$Truck\ (diesel)\ consumption/distance = 30\ L\ /100\ \ km$

$Density\ of\ Diesel\ = 830\ kg/m^3\ = 0.83\ kg/l$

$trips/lifetime\ = 100$

$Reference\ flow = 31\ 025\ 000\ m^3/lifespan$

$$Ferric\ chloride\ \ consumption = \frac{\frac{Distance}{trip} \times \frac{consumption}{Distance} \times \frac{trips}{lifetime} \times Density}{Reference\ flow}$$

$Ferric\ chloride\ \ consumption\ = \ 0.00059 = \mathbf{5.9E-06\ kg/m^3}$ **(Table 4.1)**

Diesel {GLO}| market group for | Conseq, U (ecoinvent reference on Simapro)

APPENDIX D: SUNBURST DIAGRAM FOR OTHER IMPACT CATEGORIES

Figure D. 1: Life Cycle Assessment process contribution of SBR and EASP towards fossil depletion impact category using ReCipe midpoint method

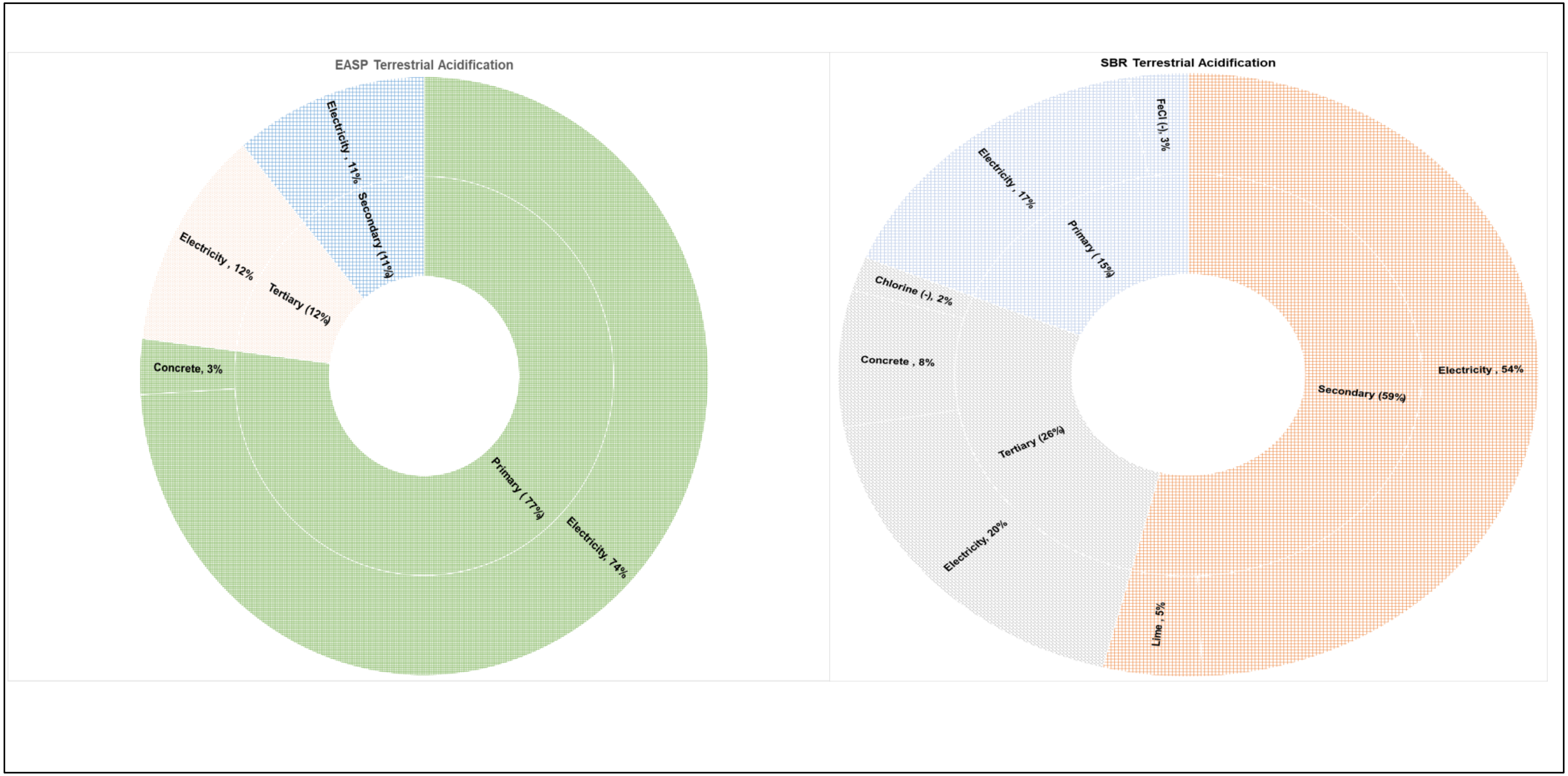

Figure D. 2: Life Cycle Assessment process contribution of SBR and EASP towards terrestrial acidification impact category using ReCipe midpoint method

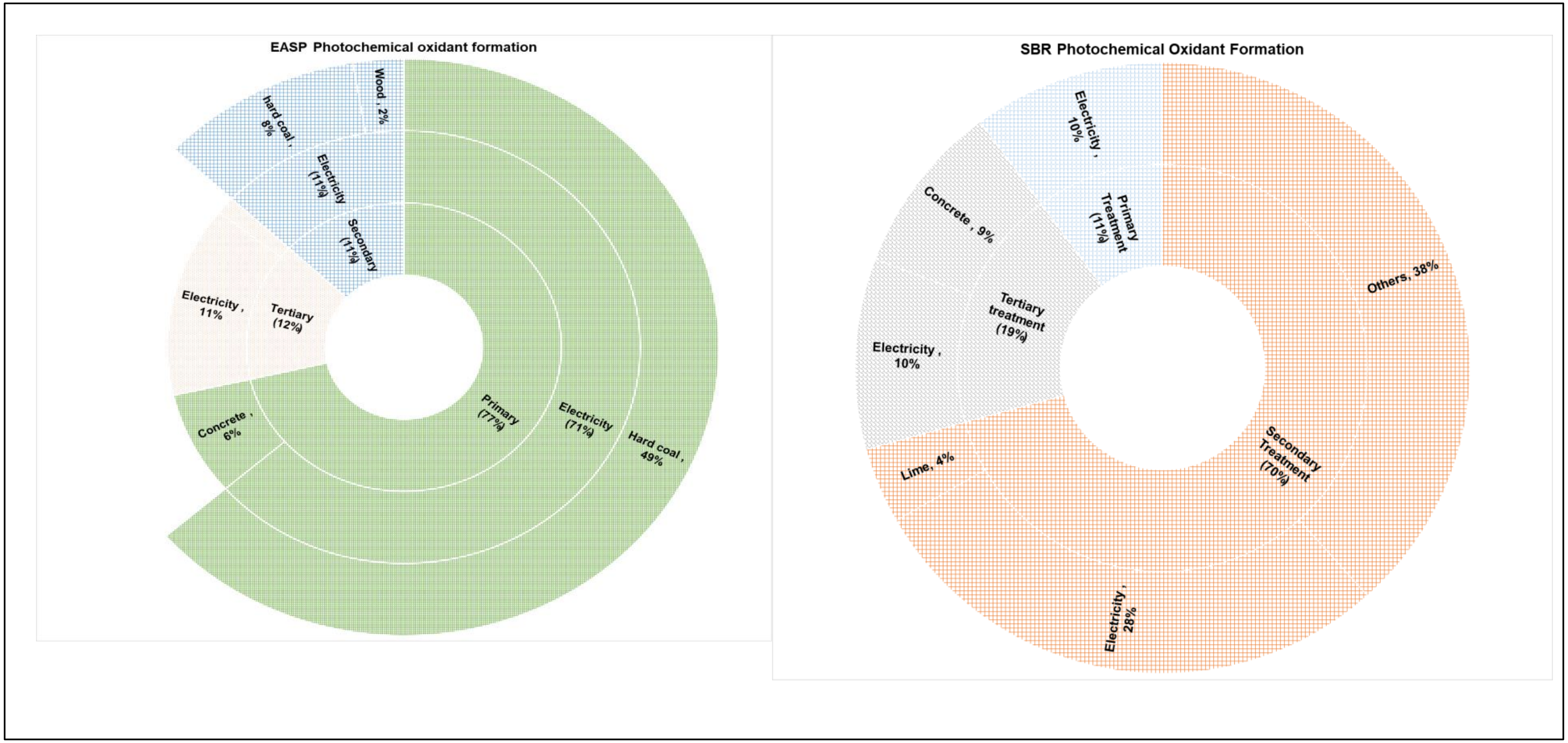

Figure D. 3: Life Cycle Assessment process contribution of SBR and EASP towards photochemical oxidant formation impact category using ReCipe midpoint method

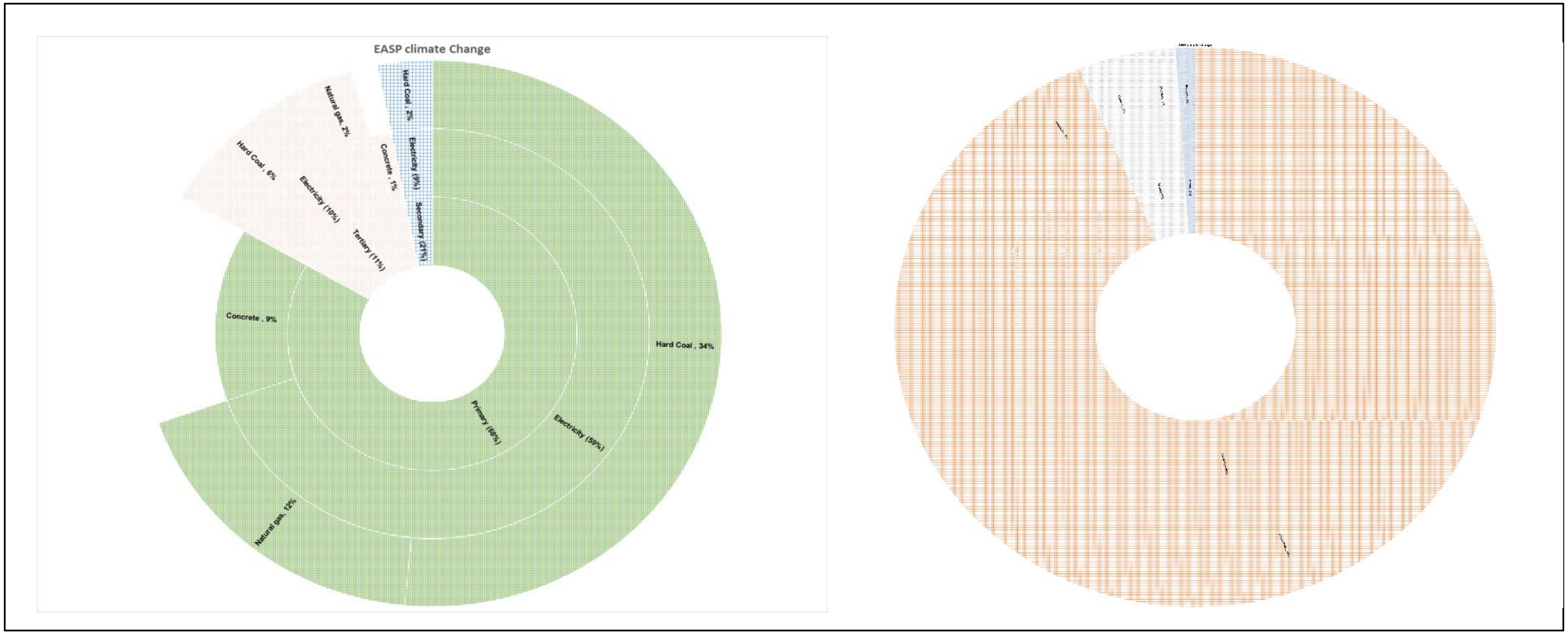

Figure D. 4: Life Cycle Assessment process contribution of SBR and EASP towards climate change impact category using ReCipe midpoint