

SYSTEMATIC REVIEW OF PROCESSES FOR ADVANCED TREATMENT OF
BREWERY WASTEWATER FOR WATER REUSE PURPOSES

Iwalda Bezuidenhout

A research report submitted to the 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.

Johannesburg, South Africa

August 2019

DECLARATION

I declare that this research project is my own unaided work. It is submitted in accordance to the fulfilment of the requirements necessary to obtain the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been handed in previously for any degree or examination to any other Institution.



.....

Iwalda Bezuidenhout

22nd day of August 2019

ABSTRACT

Water scarcity becomes more apparent every day. As such, the consideration of making use of available advanced treatment technology for the reuse of wastewater must be encouraged. In 1982 it was reported that it was time for South Africa to develop a guide for the planning, design and operation of water reclamation schemes as conventional water sources were predicted to soon be insufficient to meet water needs. The malt brewing industry is one of the largest industrial water users in South Africa. All plants of Anheuser-Busch InBev (AB InBev) in South Africa (previously known as South African Breweries (SAB) and Sedibeng Breweries), which represent 99% of the market share, have some form of wastewater treatment works at their breweries. This study systematically reviews available literature on advanced wastewater treatment technologies with the aim of identifying additional process(es) to existing wastewater treatment works to treat effluent to potable standards for internal reuse.

The review's design parameters include capital and operational cost of technology, operational skills level required and final effluent quality achieved. Following the rigorous systematic review as defined by the 2009 Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA), 863 pieces of literature were initially identified, 152 of which were analysed. A number of relevant technologies were identified as processes to add onto existing wastewater treatment works including: stand-alone Ultra-Filtration (UF) or Nano-Filtration (NF) membranes; UF Membrane Bio Reactor (MBR); expanded granular sludge bed; Anaerobic MBR (AnMBR); Reverse Osmosis (RO) Electro Coagulation (EC); Microbial Fuel Cells (MFC); advanced flocculation using Magnesium (Mg)-sericite or Carbon Nano Tubes (CNTs) as flocculants; and fortified clay filtration. Further investigation and / or pilot studies are required to narrow down the best technology for the relevant effluent.

‘When the well's dry, we know the worth of water.’

Benjamin Franklin

Dedicated to my soulmate, Wynand, and our children, Johan and Sonja

ACKNOWLEDGEMENTS

Special thanks to my supervisor, Dr. Precious Biyela, for her input and calm direction.

Special gratitude for access and information from the study's target brewery, who preferred to stay unnamed in this report.

To Aurecon, my employer, thank you for granting me both the funds, as well as the time, to pursue this study.

LIST OF ACRONYMS AND ABBREVIATIONS

AnMBR	Anaerobic Membrane Bioreactor
AS	Activated Sludge
BNR	Biological Nutrient Removal
BOD	Biological Oxygen Demand
C:N:P	Carbon:Nitrogen:Phosphate ratio
Ca	Calcium
CAPEX	Capital Expenditure
CAS	Conventional Activated Sludge
CIP	Clean-In-Place
CNTs	Carbon Nano tubes
COD	Chemical Oxygen Demand
CP	Cleaner Production
CSTR	Continuous Stirred-Tank Reactor
DO	Dissolved Oxygen
DPR	Direct Potable Reuse
DWS	Department of Water and Sanitation
EC	Electrocoagulation
EGSB	Expanded Granular Sludge Bed reactor
FS	Flat Sheet
GAC	Granular Activated Carbon
IPR	Indirect Potable Reuse
MBR	Membrane Bioreactor
MF	Micro-Filtration
Mg	Magnesium
MFC	Microbial Fuel Cell
MWCO	Molecular Weight Cut Off
NF	Nano-Filtration
NH ₄	Ammonium
NO ₃	Nitrate
NPTEL	National Programme on Technology Enhanced Learning
NPV	Net Present Value
OPEX	Operational Expenditure
PFR	Plug-Flow Reactor
PO ₄	Phosphate
PST	Primary Settling Tank
PVC	Polyvinyl Chloride

PVDF	Polyvinylidene Fluoride
QSE	Qualifying Small Enterprises
RO	Reverse Osmosis
RSA	Republic of South Africa
SAnMBR	Submerged Anaerobic Membrane Bioreactor
SANS	South African National Standard
SBR	Sequencing Batch Reactor
SDG	Sustainable Development Goal
SMBR	Submerged Membrane Bioreactor
SO ₄	Sulphate
SOC	Synthetic Organic Compounds
SS	Suspended Solids
TBD	To Be Determined
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
UASB	Up-flow Anaerobic Sludge Blanket reactor
UF	Ultra-Filtration
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
WITS	University of the Witwatersrand
WRC	Water Research Commission
WTW	Water Treatment Works
WWTW	Wastewater Treatment Works
ZLD	Zero Liquid Discharge

DEFINITIONS

Note: All definitions are from Metcalf & Eddy (2014) unless otherwise specified.

Activated sludge (AS)	An aerobic treatment process of wastewater which includes three typical steps: 1) a reactor in which the microorganisms responsible for treatment are aerated and kept in suspension; 2) liquid-solids separation, mostly in a sedimentation tank; and 3) a recycling system for returning solids removed from the liquid-solids separation unit back to the reactor.
Advanced wastewater treatment	Removal of dissolved and suspended materials remaining after typical biological treatment when required for various water reuse applications. 'Advanced treatment' is often referred to as part of 'tertiary treatment'.
Biological oxygen demand (BOD)	The measurement of the dissolved oxygen used by microorganisms in the biochemical oxidation of organic material; may be reported after a 5-day measurement period (so-called BOD ₅)
Chemical oxygen demand (COD)	A measurement of the overall oxygen equivalent utilised to chemically oxidise all of the organic compounds using dichromate in an acid solution.
Direct potable reuse (DPR)	Represents the introduction of treated wastewater (with or without retention in engineered storage) into a drinking-water supply without prior discharge to an environmental buffer. The treated wastewater may be blended with raw water from a river, lake, reservoir or aquifer immediately before a drinking-water treatment plant; blended with treated water downstream of a conventional drinking water treatment plant; or introduced

	directly into a drinking water distribution system (World Health Organization, 2017b).
Fenton's reagent	A solution of hydrogen peroxide with ferrous iron as a catalyst that is used to oxidise contaminants or waste waters. Fenton's reagent can be used to destroy organic compounds such as trichloroethylene (TCE) and tetrachloroethylene (perchloroethylene, PCE) (Kahoush et al., 2018).
Indirect potable reuse (IPR)	Represents the planned addition of treated wastewater into water bodies used as sources of drinking water. The water bodies, which can include rivers, lakes, reservoirs and aquifers, are referred to as environmental buffers. Water containing a proportion of treated wastewater is taken from the environmental buffer and further treated to provide drinking water (World Health Organization, 2017b).
Life cycle cost	The sum of all costs incurred during the life time of an item, i.e. the total of procurement and ownership costs (Dhillon, 2013).
Membrane bioreactor (MBR)	A process that combines a suspended growth process with a membrane separation system within the process aeration tank; membrane separation is accomplished by either microfiltration or ultrafiltration.
Meta-analysis	A melding of data from multiple studies, usually involving additional mathematical analyses, with the goal of utilising this synergy of information and data size to answer questions that cannot be answered by existing individual studies or to improve the certainty or impact of known findings by increasing the sample size. Meta-

	analyses are often performed as part of a systematic review (Zumsteg et al., 2012).
Molecular weight cut-off (MWCO)	MWCO is defined as the lowest molecular weight (in Daltons) at which greater than 90% of a solute with a known molecular weight is retained by the membrane. It is a method of characterisation used in filtration to describe pore size distribution and retention capabilities of membranes (Cole-Palmer, n.d.).
Preliminary treatment	Removal of wastewater constituents including rags, sticks, floatables, grit and grease that may cause maintenance or operational challenges with the treatment operations, processes and ancillary systems.
Primary treatment	Removal of a portion of the suspended solids and organic matter from the wastewater.
Recalcitrant	Any compound or molecule that persists in nature for long time and resists degradation under a given set of environmental conditions.
Secondary treatment, with nutrient removal	Removal of biodegradable organic matter (in solution or suspension) and suspended solids. Removal of nutrients (nitrogen and phosphorous) and disinfection can be included in either secondary or tertiary treatment.
Sequencing batch biofilm reactor (SBBR)	A SBR to which solid media has been added to allow attached biomass to accumulate in the treatment reactor
Systematic review	A structured evaluation of the literature with the goal of answering a specific research or application question with a synthesis of the best available evidence. Generally published to share these results with a wide audience for consideration and implementation (Zumsteg et al., 2012).

Tertiary treatment	Removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or micro-screens. Removal of nutrients (nitrogen and phosphorous) and disinfection can be included in either secondary or tertiary treatment.
TKN total Kjeldahl nitrogen (N)	Includes ammonia-N and organic-N.
Total solids (TS)	The residue remaining after a wastewater sample has been evaporated and dried at a specified temperature (103 to 105°C)
Total suspended solids (TSS)	Portion of the TS retained on a filter with a specified pore size, measured after being dried at a specified temperature (105°C). The filter used most commonly for the determination of TSS is the Whatman glass fibre filter which has a nominal pore size of about 1.58µm
Up-flow anaerobic sludge blanket (UASB)	A common anaerobic treatment reactor
Wastewater	Liquid or water-carried wastes removed from residences, institutions, commercial and industrial establishments, often including groundwater, surface water and stormwater.
Water reclamation	The production of water from wastewater for a particular reuse application
Water recycling	The direct reuse of treated wastewater at an earlier stage in a sequence of use.

Water system integration	The consideration of water utilisation processes in an enterprise as an organic whole. It considers how to allocate the water quantity and quality reasonably to each water using process, so that water reuse is maximised within the system, simultaneously minimising wastewater generation (Feng et al., 2009).
--------------------------	---

Table of Contents

DECLARATION	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	vi
LIST OF ACRONYMS AND ABBREVIATIONS	vii
DEFINITIONS	ix

Chapter one

1	Introduction and background	1
1.1	Wastewater treatment technologies	5
1.1.1	Preliminary and primary treatment	6
1.1.2	Secondary treatment	7
1.1.3	Advanced / tertiary treatment	8
1.1.4	Potable reuse schemes	8
1.2	Industrial wastewater reuse	9
1.3	Wastewater reuse in the brewery industry	11
1.4	Legislation affecting wastewater reuse in the South African brewing industry	14
1.4.1	National Policies	14
1.4.2	Municipal by-laws	17
1.5	Brewery wastewater constituents	17
1.5.1	Oxygen demand	20
1.5.2	Total Suspended Solids	22
1.5.3	pH	22
1.5.4	Inorganic Pollutants, including heavy metals	22
1.6	Aims of strategic literature review	23
1.6.1	Current layout of target brewery	24
1.6.2	Discharge quality of target brewery	25
1.6.3	Potable water quality standards	26

Chapter two

2	Methodology including results and meta-analysis	29
2.1	PRISMA flow diagram – summary of study selection	29
2.2	Identifying key words	30
2.3	Identifying relevant databases	32
2.4	Identifying relevant publications	33
2.4.1	Final keyword – Wastewater treatment	33
2.4.2	Final keyword – Advanced treatment	33
2.4.3	Final keyword – Reuse	33
2.4.4	Final keyword – Cost	36
2.4.5	Final keywords – Energy and Skills with Developing country	36
2.5	Selection of studies for further review	37
2.6	Removing duplicate studies	37
2.7	Assessing the relevance of studies based on design threshold	38
2.8	Meta-analysis of studies for detail review	40
2.8.1	Reference types	40
2.8.2	List of journals for full review	40
2.8.3	Date of publication of journals for full review	42
2.8.4	Scoring of literature for full review	43

Chapter three

3	Meta-analysis of relevant technology	46
3.1	Reasons for exclusion of literature	46
3.2	Number of studies for Qualitative analysis	47
3.2.1	List of journals for Qualitative analysis	47
3.2.2	Date of publication of journals for Qualitative analysis	48
3.3	Technologies identified in detailed review	48
3.4	Results of meta-analysis of relevant technology	52
3.4.1	Parameters for comparison	52

3.4.2	COD reduction	54
3.4.3	Financial analyses	55
3.4.4	Feasibility	62
3.5	Technologies applied in treating brewery wastewater	66
3.5.1	Membranes: MF, UF, NF and RO	66
3.5.2	Membrane bioreactors (MBR)	70
3.5.3	Carbon nanotubes	72
3.5.4	Advanced oxidation	73
3.5.5	Microbial Fuel Cells (MFCs)	75
3.5.6	Advanced flocculants	76
3.5.7	Fortified clay filtration	77
3.5.8	Electrochemical treatment	78
Chapter four		
4	Findings, discussion, recommendations and conclusion	80
4.1	Findings and discussion	80
4.1.1	Effective secondary treatment	82
4.1.2	Existing advanced treatment in place at breweries	84
4.1.3	Feasibility	85
4.2	Recommendations and conclusion	88
4.2.1	Conclusion on the methodology	88
4.2.2	Conclusions of systematic review	89
4.2.3	Recommendations for further studies	92
REFERENCES		94

Figures

Figure 1	Mass balance from Unicer SA Breweries (Götz, Geißen et al. 2014).....	12
Figure 2	Brewery wastewater treatment works process flow diagram	25
Figure 3	PRISMA flow diagram, adapted from reference Moher, Liberati et al. (2009) ..	30
Figure 4	Initial relevance assessment results	40
Figure 5	Reference types for full review.....	40
Figure 6	Publication date of studies for full review	42
Figure 7	Scoring overview of studies for detail review	43
Figure 8	Overview of scoring of design threshold parameters.....	45
Figure 9	Reasons for exclusion from analysis	46
Figure 10	Publication date of studies for Qualitative analysis.....	48
Figure 11	Summary of advanced treatment technologies found in research.....	50
Figure 12	Number of studies per membrane pore size.....	51
Figure 13	Number of studies per MBR type	51
Figure 14	Publication dates of MBR studies	52
Figure 15	Scoring of cost parameters of studies for full review	55
Figure 16	Capex cost / m ³ for smaller plant capacities	60
Figure 17	Capex cost / m ³ for all plants reporting 100% reduction of COD	61
Figure 18	Opex cost / m ³ for smaller plant capacities	61
Figure 19	Opex cost / m ³ for all plants reporting 100% reduction of COD	62
Figure 20	Water purchased at target brewery.....	64
Figure 21	Development stages of water management in breweries (Götz, Geißen et al. 2014)	65
Figure 22	Tangential filtration chart (Seneviratne 2006)	68
Figure 23	MBR process flow compared to conventional process (Ji, Liu et al. 2015) ..	70
Figure 24	Illustration of membrane configurations for MBRs	71
Figure 25	Schematic diagram of a conventional Microbial Fuel Cell (Lopez Zavala, Torres Delenne et al. 2014)	75

Tables

Table 1	Classification of water pollutants.....	18
Table 2	Impact of specific types of pollution from industrial wastewater	19
Table 3	Concentration of heavy metals in brewery effluent samples	23
Table 4	Target brewery discharge license conditions and average discharge quality ..	26
Table 5	Comparison of potable water quality guidelines	27
Table 6	Identifying keywords.....	31
Table 7	Identifying relevant databases	32
Table 8	Database search results	35
Table 9	Database search results - 'skills'	36
Table 10	Design threshold for full review	39
Table 11	Journals containing reviews rated high	41
Table 12	Summary of scoring according to the design treshold	43
Table 13	Journals with articles for Qualitative analysis	47
Table 14	Relevant technologies identified in detailed research.....	49
Table 15	Parameters referenced in qualitative analysis	52
Table 16	Reported COD reduction.....	54
Table 17	List of studies with cost data for analyses.....	56
Table 18	Annual interest rates per country	57
Table 19	Comparison of capital and operational NPV	59
Table 20	Cost of purchased water at target brewery	64
Table 21	Typical characteristics of membrane processess	67
Table 22	Membrane and process configurations	68
Table 23	Target brewery's problem pollutants	81
Table 24	Alternative technology for secondary treatment of brewery wastewater	83
Table 25	Existing breweries treating wastewater for internal reuse	84
Table 27	High level comparison of possible pay-back periods	87
Table 28	Full list of studies scored 'High'	101

Appendices

Appendix A

Literature search results

CHAPTER ONE

1 Introduction and background

With the rapid growth in population and industrial activities across the globe and diminishing natural water resources, conventional water and wastewater management have had to adapt in order to provide for the growing need (Donnenfeld et al., 2018; Wehn and Montalvo, 2018; Blesing and Pelekani, 2016; Zhou and Smith, 2001). A study published in the *Geoscientific Model Development* journal introduces the first scenarios from the International Institute for Applied Systems Analyses (IIASA) Water Futures and Solutions (WFaS) initiative. This study indicated that, if current trends are followed towards the future, domestic and industrial water demand would have doubled by the year 2050, and is expected to increase thereafter (Wada et al., 2016). South Africa is not immune to water scarcity problems. As the Western Cape government implemented its emergency procedures in an attempt to push 'Day Zero' (when useable water runs out) from the foreseeable future, the alarming fact that the earth's water resources are finite, becomes apparent (Jones, 2018).

The Institute for Security Studies (ISS) reported in its 2017 update to the Water Research Commission (WRC) that South Africa's water demand will outpace supply every year from 2017 to 2035 due to factors such as population growth and changing lifestyles due to urbanisation. Alarming, this will be the reality even if every possible reduction measure and large-scale water South African reconciliation strategy is implemented in time (Donnenfeld et al., 2018). A reasonable argument to address and manage water scarcity in South Africa can include the measures to be taken to contribute towards the availability of sufficient and sustainable resource. The agricultural and industrial sectors of South Africa account for a combined total of 90% of the country's water demand/use. As such, the application of efficient water conservation practices through a variety of methods may significantly influence the awareness and consumption (Department of Water and Sanitation, 2017). For industry, water efficient

practices could include practices such as continuous loop water management systems, reduced cooling requirements and good housekeeping practices including leak repairs (United States Environmental Protection Agency, 2000; Saha et al., 2004). In agriculture, the aim could be to avoid unnecessary run-off, which can be achieved through the implementation of drip irrigation and efficient short furrows (Denison and Manono, 2007).

In a media release, Jones (2018) reports that City of Cape Town's water consumption more than halved from 1 200 Mega Litres per Day (Mℓ D) in February 2015 to 511 Mℓ D in March 2018. He further reports that this significant reduction was largely due to water demand management strategies implemented by the City of Cape Town. These strategies included stringent water restrictions, reduced water pressure, installation of water monitoring and management devices (water meters) and making water use information publicly available (Jones, 2018). Further measures include active leakage control, prevention of illegal connections and consumer awareness and education programmes (van der Berg, 2016). Undeniably the first avenue of response lies in educating users to conserve water and thereby reduce demand. Policy measures, including tiered water pricing structures and review of bylaws, should be accompanied with campaigns to increase awareness about water use and conservation (Donnenfeld et al., 2018; Rambarran, 2017). As Professor Neil Armitage, a civil engineer at UCT, points out 'reducing demand for water massively reduces the scale of augmentation required' (Jones, 2018).

The need for additional water sources still remains a global endeavour (Gurria, 2017). For South Africa, the most reasonable solutions lie in responsible groundwater extraction, wastewater treatment for reuse and desalination (Cilliers, 2016; Blesing and Pelekani, 2016; Sonnenfeld et al., 2018).

As early as 1982 Barnard and Law (1982) recommended that it was time for South Africa to develop a guide for the planning, design and operation of water reclamation schemes as conventional water sources were predicted to soon be insufficient to meet water needs.

Following the World Water Week conference in Stockholm in August 2017, the then Minister of Water and Sanitation, Ms Nomvula Mokonyane, stated that through improved wastewater treatment and innovative solutions, large volumes of water can be put back into the system for use (Ndamase, 2017). This was in line with global trends (Zhang et al., 2017; Cloete, 2017; Bansal, 2017; Huang, 2017; Binz et al., 2016; Adapa et al., 2016), especially finding traction through World Water Week's 2017 theme: Water and Waste: reduce and reuse (United Nations World Water Assessment Programme, 2017)

In its report: 'Strategic overview of the water sector in South Africa', the Department of Water and Sanitation points out that many settlements still have insufficient water resources (Department of Water and Sanitation, 2017).

When wastewater in the economically productive, industrial sector is treated for reuse, it not only satisfies stringent national laws and local by-laws for wastewater effluent quality, it can be argued that less pressure is placed on the local water service provider, as it frees water that would otherwise be used in industry, for domestic use.

In turn this will relieve the strain on the municipal sector, which is already struggling under institutional capacity constraints (Department of Water and Sanitation, 2017), to identify new water resources. This will significantly contribute to South Africa's commitment to achieving Sustainable Development Goal (SDG) 6.1 and 6.3 relating to safe and affordable drinking water for all and substantially increasing recycling and safe reuse of water by 2030.

Increasingly, across the globe, potable reuse is considered as an alternative water source (Zhang et al.; 2017, Cloete, 2017; Bansal, 2017;

Huang, 2017; Binz et al., 2016; Adapa et al., 2016). A significant advantage of wastewater reuse is that it is largely climate independent as well as a sustainable resource. It further encourages environmentally responsible behaviour through effective wastewater treatment (World Health Organization, 2017b).

Schelmetic (2012) identified the largest global industrial water users as those within the power generation, textile and garments, meat production and beverage industry sectors.

Ramukhwatho et al. (2016) reported that a total of 3,515 million litres of beer was produced in South Africa in 2014. Guidelines of the Brewers Association, USA, indicates a typical water use of 4 to 10 litres of water per litre of beer brewed (BrewersAssociation, 2011). New Belgium Brewing Company reports their water consumption as 4.11 per litre beer in 2016, with a goal of 3.5 per litre beer produced in 2020 (New Belgium Brewing Company, 2018). This corresponds well with the average water consumption of 6.8 litre per litre beer for eight breweries studied, with an industry best in South Africa of 3.2 litre per litre beer reported in the same document (Ramukhwatho et al., 2016).

In South Africa, the major brewing industry players, AB InBev, previously known as South African Breweries (SAB), and Sedibeng breweries, have 99% of the market share. To meet the effluent discharge standards set by the National Water Act, all major players treat wastewater generated at their plants before discharge (Ramukhwatho et al., 2016). In reviews of brewery wastewater treatment technologies, Jaiyeola and Bwapwa (2016) and Eyvaz (2016) had found a number of technologies which could potentially be used to treat brewery wastewater for reuse. Of these technologies, the application of carbon nanotubes (CNTs) and the use of membrane bio-reactors (MBRs), amongst other technologies, appear to have the potential to achieve highly desirable results. They conclude that the best solution possibly lies in the combination of different technologies.

However, they have not found adequate analysis of capital and operating costs to recommend the most effective treatment option.

This research study aims to systematically review technology that might be added to a target brewery's existing treatment works, leading to the achievement of advanced treatment producing an effluent water quality that can be reused within the brewery, and by so doing reduce the dependency on external water service providers.

An average of 4.5 Mℓ wastewater is treated per day at this study's target brewery. Current water consumption at this brewery is reported to be 5.3 litre per litre of beer produced. Internal reuse of water can contribute significantly to their target of 3.5 litre per litre beer brewed.

Typically, brewery effluent contains, amongst other contaminants, high levels of organic constituents which requires extensive treatment before reuse can be considered (Jaiyeola and Bwapwa, 2016). Effluent quality for the period June 2016 – June 2017 from the target brewery is available and will be regarded as the intake quality for advanced treatment. Advanced technology identified should have the ability to treat the proposed intake quality to potable standards.

1.1 Wastewater treatment technologies

As this review is mainly interested in advanced treatment technologies, this section will distinguish between different levels of technology to isolate the technology focused on.

Metcalf & Eddy Inc. (2004) define wastewater as 'a combination of the liquid or water-carried wastes removed from residences, institutions, commercial and industrial establishments, together with groundwater, surface water and stormwater that may be present.' Metcalf and Eddy indicate that if left untreated, wastewater can become a nuisance and pose a risk to both the environment and human health. However, treating wastewater for reuse could provide solutions to issues such as security and scarcity of water supply and increased costs for potable water from conventional sources.

Wastewater treatment works typically include preliminary, primary and secondary treatment and may include advanced treatment (sometimes identified as tertiary treatment) (World Health Organization, 2017b; Metcalf & Eddy Inc., 2004).

The following section briefly discusses each of these treatment-segments to serve as background to the further investigation of advanced treatment options for this particular case study.

1.1.1 Preliminary and primary treatment

Primary treatment is predominantly composed of essentially physical treatment processes which removes suspended solids (SS) and biological oxygen demand (BOD). It also removes some organic nitrogen, phosphorus (5-15% removal) and heavy metals but only provides limited removal of microbial pathogens (World Health Organization, 2017b; Michigan Department of Environmental Affairs, 1999).

Metcalf & Eddy Inc. (2004) distinguishes between preliminary and primary treatment as follow: preliminary treatment - removal of wastewater constituents such as rags, sticks, floatables, grit and grease that may cause maintenance or operational problems with the treatment operations, processes and ancillary systems; while primary treatment is defined as: removal of a portion of the suspended solids and organic matter from the wastewater.

Typically a primary sedimentation tank (PST) follows screens and grit removal. The PST generally removes 30 to 40% of the total BOD and 50 to 70% of SS from the raw sewage (Ghangrekar, 2009). Efficiency of removal of SS and BOD from industrial wastewater will differ significantly depending on the nature of the wastewater.

Technologies used for preliminary and primary treatment include screening, sedimentation, hydro-cyclones, primary settling, filtration, dissolved air flotation and centrifugation (Seneviratne, 2006).

1.1.2 Secondary treatment

This is generally carried out through biological treatment and often includes some form of activated sludge (AS) process, also known as Conventional Activated Sludge (CAS) process or trickling filters. An AS process can be defined as an aerobic treatment process of wastewater which includes three basic steps: 1) a reactor in which the microorganisms responsible for treatment are kept in suspension and aerated; 2) liquid-solids separation, usually in a sedimentation tank; and 3) a recycle system for returning solids removed from the liquid-solids separation unit back to the reactor. It removes organic materials by digestion and should reduce biochemical oxygen demand (BOD) and suspended solids (SS) by 85% or more (Metcalf & Eddy, 2014; Levine et al., 2010). Maintaining longer solids retention times in AS based processes can further reduce many trace organic contaminants (Clara et al, 2005; Gerrity et al, 2013a as cited in World Health Organization (2017b)).

Targeted nutrient reduction processes are often included in the design of AS processes, e.g. biological nutrient reduction (BNR). Nitrification and denitrification processes can greatly improve water quality for downstream processes such as advanced oxidation and chlorination by removing ammonia and nitrate, respectively (Marshall, 2008).

Progressively, secondary treatment has seen increased use of membrane bio-reactors (MBRs) where membrane filtration, microfiltration (MF) or ultrafiltration (UF) is integrated with biological treatment in the form of a suspended growth bioreactor. The membranes reject solids generated by the biological process resulting in the production of clarified secondary effluent. The membrane filters provide enhanced effluent quality with the extent of pathogen removal depending on pore size (Gebreyohannes et al., 2016; Calabria, 2014; Edwards et al., 2013; Lin et al., 2012). More details on MBRs are provided in chapter 3.

Following stricter regulation of restrictions on nitrogen and phosphorus discharge into the environment, some suppliers have developed

membranes for retrofitting existing infrastructure, to switch from the conventional activated sludge process (CAS) to a MBR while maintaining the treatment capacity by using only existing CAS reactors (Brindle et al., 1999; Brown, 2007; Calabria, 2014; Judd and Judd, 2011; Poyatos et al., 2011).

Metcalf & Eddy (2004) points out that removal of nutrients (nitrogen and phosphorous) can be included in either secondary or tertiary treatment.

1.1.3 Advanced / tertiary treatment

This stage follows secondary treatment and will remove any residual suspended solids, usually by granular medium filtration or micro-screens. Removal of nutrients (nitrogen and phosphorous) and disinfection can be included in either secondary or tertiary treatment. The purpose of this additional treatment stage, also referred to as 'tertiary treatment', is to further improve effluent quality, often for reuse. It typically includes a range of processes of the type used in drinking-water treatment plants, such as, amongst others, oxidation, adsorption, media filtration, membrane filtration and disinfection (Metcalf & Eddy, 2014; Zhou and Smith, 2001).

1.1.4 Potable reuse schemes

Although different water quality can be considered for different uses, this study will focus on advanced treatment technologies that can treat water of the final effluent quality at the target brewery to potable standards.

Categories of treatment employed in potable reuse schemes are biological processes, physical separation (filtration and adsorption), chemical oxidation and disinfection processes which is usually achieved through chemical oxidation processes. Multiple combinations of these processes are possible. Typically, advanced treatment processes such as membrane filtration, advanced oxidation and activated carbon will follow a biological wastewater treatment process such as activated sludge or membrane bioreactor (MBR).

When industries in coastal regions consider technology for the reuse of wastewater, they tend to adopt treatment trains incorporating reverse

osmosis (RO), as large volumes of brine generated by RO can easily be discharged into the ocean. In the absence of ocean discharges, inland communities have preferred non-RO based schemes and selected combinations of oxidation processes, activated carbon filtration, bio-filtration and membrane filtration (Metcalf et al., 2014).

World Health Organization (2017a) reported that, increasingly, the number of potable reuse plants are growing, especially in response to expanding populations and climate pressures. They further report that the technological and scientific basis for potable reuse schemes is established.

Several authors, such as Swartz et al. (2015) and World Health Organization (2017b) list a number of special considerations when considering reuse schemes compared to conventional potable water systems, such as the involvement of multi-disciplinary teams (water and wastewater), multiple-barrier treatment trains, advanced monitoring and response systems, increased public education and stakeholder engagement, amongst others.

An initiative with the aim of educating the general public and creating awareness of potable reuse of wastewater, is the AZ Pure Water Brew Challenge. A mobile package plant on a state wide tour through Arizona, USA, marks the first time wastewater is being treated to potable standards to produce beer (The Associated Press, 2017).

1.2 Industrial wastewater reuse

Seneviratne (2006) points out that for many years, industrial wastewater treatment was seen as a regulatory requirement and the potential of the wastewater as valuable resource, was neglected. Consequently, only the minimum treatment required to comply with discharge regulations was fulfilled. However, this viewpoint has been changing, as factors such as security of water supply, drought, scarcity of water and increased costs for potable water and sewer discharge are forcing some users to rethink this minimalist strategy. As a result, the notion of recycling and reusing water

has become appealing. Still, high upfront capital investment is necessary. For reuse to be feasible, the proposed treatment technologies need to be reliable, economical, particularly with low energy costs, and meet water-quality specifications of the use it will be applied for (Seneviratne, 2006; Kahoush et al., 2018; Bennett, 2014).

One of the sustainability trends gaining traction globally is the drive for Zero Liquid Discharge (ZLD). Alnouri et al. (2018) explains the achievement of ZLD as incorporating technologies through which industrial wastewater is reduced to dry solids/salts. This approach will generally aim to prevent any liquid effluent or wastewater discharge into surface waters. ZLD would typically involve the application of wastewater reuse strategies that attain near-zero discharge levels, or may involve the inclusion of additional processing steps that reduce any wastewater effluent to dry solids/salts. Wastewater treatment, coupled with an additional ZLD processing stage, may assist in achieving enhanced wastewater reuse, whilst eliminating wastewater discharge.

When the objective is to minimise wastewater, the main focus will be on maximizing wastewater reuse, either through direct wastewater reutilisation schemes, or by integrating wastewater treatment options. Wastewater treatment is often used to recondition and enhance wastewater quality before reuse. In this light, a case study by Van der Bruggen and Braeken (2006) was presented to a brewery in Flanders Belgium, which allows for significant reductions in water consumption through an approach that identifies wastewater reuse in less demanding installations, as a step towards a zero-discharge scheme, considering that complete ZLD was shown to be infeasible.

When wastewater in the industrial sector is treated for reuse, it not only satisfies progressively more stringent national laws and local by-laws for wastewater discharge, but it can also be argued that less pressure is placed on the local water service provider which frees water from industrial use for domestic use. In South Africa, there still remains many settlements

without sufficient water resources (Department of Water and Sanitation, 2017). Thus, by focussing on the currently more productive economic sector, industry, as opposed to the municipal sector struggling under institutional capacity constraints (Department of Water and Sanitation, 2017) both innovative technology and capacity are developed while potable water resources is being freed for domestic uses. This will significantly contribute to South Africa's commitment to achieving Sustainable Development Goal (SDG) 6.1 and 6.3 relating to safe and affordable drinking water for all and substantially increasing recycling and safe reuse of water by 2030.

To develop a reuse scheme, full knowledge and measurements of all water consuming processes, including amongst others, production, cooling, cleaning-in-place (CIP) operations and rinsing is required. For most industries, this is a very complex task. Once movement of water is known, it is typically possible to combine processes by reusing waste water of one process as incoming water for other processes requiring a lesser quality of water, for example cooling processes, tank cleaning and truck cleaning. Finally, regeneration of wastewater, using relevant wastewater treatment technology, can be included for wastewater to be recycled to more processes (Majozi et al., 2011; Faria, 2009; Hawkins, 2007).

Although not all industrial processes require water of a potable standard, the current study is only interested in technologies with the potential to treat brewery wastewater to potable standards.

1.3 Wastewater reuse in the brewery industry

Cleaner production (CP) is continuously advocated for in brewery industry from production process, products and services during production, in order to reduce consumption and emissions. For an effective CP, brewer should go green by adopting new brewing technology with efficient energy consumption, reduction in odour emission, efficient water consumption for cleaning and cooling purposes, the prevention of losses, and the reuse of

treated wastewater. As discussed earlier in this study's introduction, a number of studies identify the malt brewing industry as a user of significant amounts of freshwater. The mass balance below illustrates input and output values per m³ of beer produced at the Unicer SA breweries, as cited in Götz et al. (2014):

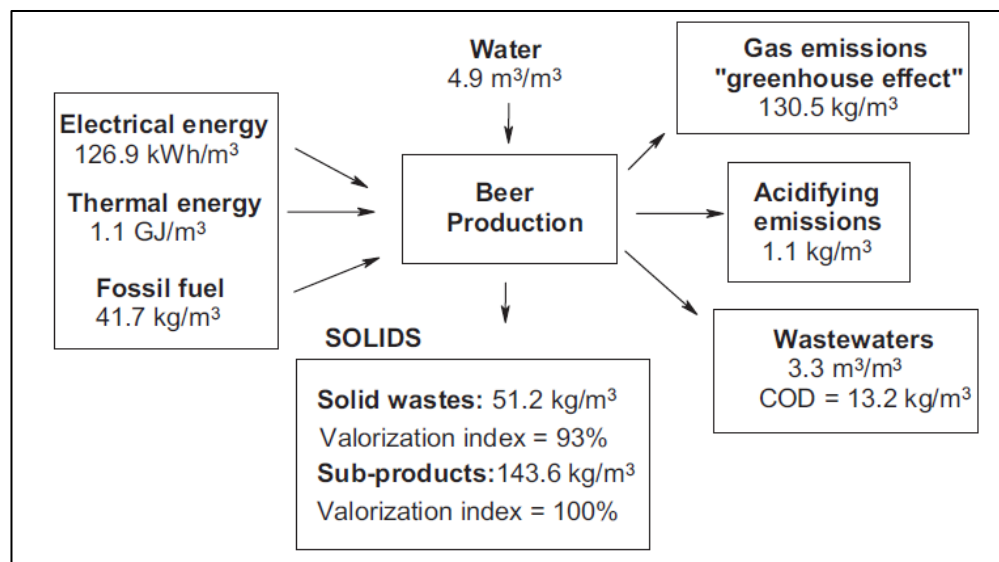


Figure 1 Mass balance from Unicer SA Breweries (Götz et al., 2014)

The reuse of wastewater could provide the opportunity to increase beer production, with resulted economic benefits, once the allocation limit of potable water has been reached (Labs, 2015; Götz et al., 2014).

When considering water-consuming applications in a brewery, volume and quality of both intake and effluent are important. Producing beer consists of mainly three processes: malting, brewing and packaging. This includes water for the product, heating and cooling, cleaning packaging vessels, production machinery and process areas, cleaning vehicles, and sanitary water. One of the largest contributors to brewery effluent results from cleaning processes. Typically, automated CIP systems are used for vessel and pipelines cleaning. Although all these processes require water, Feng et al. (2009) points out that they do not all require the same quality water. However, because brewing beer falls within the food production industry, it requires special safety considerations for all water using processes (Van

der Bruggen and Braeken, 2006; Feng et al., 2009). The highest quality of water is required for brewing, and should be considered separately from process water. It is by far the most substantial ingredient of beer, constituting 90 – 95% of its mass and it can influence not only the taste of beer but also the brewing efficiency (Massen, 2011; Olajire, 2012; van der Merwe and Friend, 2002).

A number of studies such as Götz et al. (2014); Feng et al. (2009) and Fillaudeau et al. (2006) have investigated water management within breweries using detailed water balances. The purpose was to identify opportunities to recycle water from one process for use in another needing a lesser quality water, i.e. crate washing, pre-coating of filters as backwashing etc. (van der Merwe and Friend, 2002, Silver et al., 2017). Interestingly, of all the waste generated by breweries, wastewater is probably the most significant waste product resulting from brewery operations. Approximately 3 – 10l of wastewater is generated per liter of beer produced (Olajire, 2012; Kanagachandran and Jayaratne, 2006).

This study is particularly interested in the end of pipe technology-solutions that will generate potable water from wastewater for reuse and therefore to reduce dependency on external water service provider.

In their review of brewery wastewater treatment technologies, Jaiyeola and Bwapwa (2016) have found a number of technologies which could potentially be used to treat brewery wastewater for reuse. Of these technologies, the application of carbon nanotubes (CNTs) and the use of membrane bio-reactor (MBR), amongst other technologies, appear to have the potential to achieve highly desirable results. They conclude that the best solution possibly lies in the combination of different technologies. However, the authors have not found adequate analysis of capital and operating cost to recommend the most effective treatment option.

1.4 Legislation affecting wastewater reuse in the South African brewing industry

The South African government has a three tier system: national, provincial and local (municipal level) government. Increasingly, stricter environmental control is seen not only from national legislation, but also through the adoption of by-laws at the local government level where industries function. This localised approach has strengthened the implementation of effective environmental management systems. Ramukhwatho et al. (2016) summarises the legislation affecting the brewing industry at the different levels as follows:

1.4.1 National Policies

South African citizens have the right to a safe environment, water, access to information, and just administrative action as specified in The Bill of Rights in the Constitution of the Republic of South Africa (Act 108 of 1996). Particularly section 25 of this Act enshrines the concept of sustainability. These rights and other requirements are further legislated through the National Water Act (NWA) (Act 36 of 1998). The NWA provides the legal basis for water management in South Africa by ensuring ecological integrity, economic growth, and social equity when managing water use.

The NWA further describes the concept of Integrated Water Resource Management (IWRM), which provides for resource and source directed measures to manage the aquatic environment. Resource directed measures aim to protect and manage the environment that receives water, while source directed measures aim to control the quality and quantity of the resource that will impact the receiving environment by preventing pollution, reusing water, and treating wastewater. The integration of resource and source directed measures forms the basis of the hierarchy aimed at mitigating the effect of waste generation:

- Priority 1: Pollution Prevention

- Priority 2: Minimisation of impacts (*water reuse and reclamation water treatment*)
- Priority 3: Discharge or disposal of waste and/or waste water (*Site specific risk based approach and polluter pays principle*)

Environmental

The Constitution of the Republic of South Africa (Act 108 of 1996) declares that everyone has the right to an environment that is not harmful to his or her health or well-being and the right to have the environment protected, for the benefit of present and future generations through reasonable legislative and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development. Protecting these rights are the responsibility of the Department of Environmental Affairs (DEA).

Regulations that are the most relevant to the malt industry are the National Environmental Management Act, 1998 (Act 107 of 1998), the National Environmental Management: Waste Act (Act 59 of 2008), and the National Environmental Management: Air Quality Act (Act no. 39 of 2004).

Generally speaking, these Acts outline the requirements for the treatment and storage of waste onsite, licensing requirements, the establishment of waste management plans, the setting of limits for air emissions, and the setting of penalties for offences.

Water

The Department of Water and Sanitation (DWS) is the water and sanitation sector leader in South Africa. DWS is the custodian of all water resources within South Africa's jurisdiction. They are also the custodian and regulator of the National Water Act (NWA) (Act 36 of 1998) and the Water Services Act (WSA) (Act 108 of 1997).

The NWA prescribes the legal framework for the effective and sustainable management of water resources with the aim to protect, use, develop,

conserve, manage and control water resources as a whole. It further promotes the integrated management of water resources with the participation of all stakeholders.

The WSA deals with the rights of access to basic water supply and basic sanitation and has water conservation as a key objective. It provides local government with powers to enforce water conservation and demand management, which in turn impacts on all water users. Each Water Services Authority at local government level should develop by-laws which outline the water supply and effluent discharge regulations and tariffs for that area.

Wastewater

Norms and standards for the treatment of wastewater or effluent, prior to discharge have been set in the NWA. These consist of general and special standards and set limits for several contaminants such as pH, temperature, COD, suspended solids, heavy metals etc. Test methods to be used to determine these levels are also specified. All public and private generators of wastewater, that discharges to the environment, must comply to these limits. In turn, the entity operating a wastewater treatment works must set limits for industries discharging to their works such that the DWS final discharge limits can be met.

The author could find no South African legislation or policies guiding the food and beverage industry on the reuse of wastewater for use in its products.

Health and Safety

The malt brewing industry, as part of the food industry, must meet threshold standard for human consumption, and therefore, should comply with the Foodstuffs, Cosmetics, and Disinfectants Act (FCDA) of 1972 (Act No. 54 of 1972; Amendment Act, No. 39 of 2007). The National Department of Health regulates issues on food safety to ensure fitness for human consumption.

The Department of Labour promulgated the Occupational Health and Safety Act (OHSA) of 1993 (No. 85 of 1993; Amendment Act, No. 181 of 1993) to safeguard the safety of all workers and other persons, and also applies to the safety of all brewery workers. The OHSA aims to provide for the health and safety of persons at work as well as those who use the plant and machinery.

Trade and Licencing

In South Africa, the liquor industry is governed by the Department of Trade and Industry's Liquor Act of 2003 (No. 59 of 2003). The main aims of this Act are to reduce socio-economic and other costs of alcohol abuse by setting essential national norms and standards in the liquor industry.

These regulate the manufacture and wholesale distribution of liquor. This includes the regulation of retail sales and micro-manufacture of liquor. It also provides for public participation in the consideration of applications for registration. It further aims to promote the development of a responsible and sustainable liquor industry in a manner that facilitates entry of new, diverse participants into the industry.

1.4.2 Municipal by-laws

Municipalities provide water and sanitation services to most industrial users. As such, the malt beer industry is also governed by by-laws and tariffs which are municipality specific. The Water Service Authority (either a District or Local municipality) sets out the regulatory framework for institutions tasked with the supply of water services. Calculation of industrial effluent tariffs are determined by the cost recovery systems of the municipalities, types of industries discharging to the municipal sewer and the wastewater treatment that will have to treat the effluent (Ramukhwatho et al., 2016).

1.5 Brewery wastewater constituents

In its webcourse on 'Classification Of Water Pollutants And Effects On Environment', The National Programme on Technology Enhanced Learning (NPTEL), offers the following major classification of water pollutants: (1)

Organic pollutants, (2) Pathogens, (3) Nutrients and agriculture runoff, (4) Suspended solids and sediments (organic and inorganic), (5) Inorganic pollutants (salts and metals), (6) Thermal Pollution, and (7) Radioactive pollutants. The table below summarises the impact of each of these pollutants.

Table 1 Classification of water pollutants (NPTEL - National Programme on Technology Enhanced Learning, 2018)

	Pollutants	Impact
1.	Organic pollutants • Oxygen demanding wastes • Synthetic organic pollutants • Oil	Depletion of the DO will be a serious problem adversely affecting aquatic life, if the DO falls below 4.0 mg/l. Most of these compounds are toxic and biorefractory organics. It also makes water unfit for different uses. This pollutant is also responsible for endangering water birds and coastal plants due to coating of oils and adversely affecting the normal activities which cause reduction of light transmission and photosynthesis.
2.	Pathogens	Diseases are transmitted by pathogens occurring in wastewater
3.	Nutrients	When these are disposed in the aquatic environment, they can lead to the growth of undesirable aquatic life. When they are discharged on land they can cause groundwater pollution.
4.	Suspended solids and sediments	Presence of suspended solids can block sunlight penetration into the water, which is required for photosynthesis by in-the-water vegetation. Finer suspended solids such as silt and coal dust may injure the gills of fishes and cause asphyxiation.
5.	Inorganic pollutants	These pollutants include mineral acids, inorganic salts, trace elements, metals, metals compounds, complexes of metals with organic compounds, cyanides, sulphates, etc. They have adverse effect on aquatic flora and fauna and may constitute a public health problem.
6.	Thermal pollutants	When organic matter is also present, the bacterial action increases due to rise in temperature; hence, resulting in rapid decrease of DO. It also results in thermal stratification which alters spectrum of organisms.
7.	Radioactive pollutants	These isotopes are toxic to the life forms; they accumulate in the bones, teeth and can cause serious disorders

When considering technology to treat any wastewater, it is of utmost importance to understand the composition of the incoming wastewater (influent). It is also important, after treatment, to understand the effect that the resulting effluent could have on the environment. While the table above considers the different categories of pollutants and their impacts, in general, the table below by Barnard and Law (1982) summarises the effects and specific types of pollution from industrial wastewater.

Table 2 Impact of specific types of pollution from industrial wastewater (Barnard and Law, 1982)

Pollutant	Pollution source	Potential impact of pollution
Colour	Pulp and paper, textiles, abattoirs, steel, dairy	Visually objectionable
Solids	Pulp and paper mills, textile factories, tanneries, canning, breweries, steel mills, boiler-house operations, mining, drainage from mine dumps, abattoirs	Blockage of sewer lines and equipment, damage to rivers by deposit of solids and depletion of oxygen
Oil and grease	Abattoirs, wool-washeries, tanneries, metal finishing, dairy plants, steel mills, oil refineries, railway workshops, locomotive, truck and aircraft washing, engineering works	Blockage of sewer lines and equipment, floating scum on water which prevents transfer of oxygen, anaerobic conditions, unpleasant smell and attraction of flies
Organic wastes,	Pulp and paper, textiles, abattoirs, tanneries, canning, brewery, starch and yeast factories	Overloading of conventional sewage treatment plants, depletion of oxygen in rivers
Insecticides, pesticides	Chemical, food and textile factories	Toxic to bacterial and aquatic life, puts Sewage treatment works out of action
Heavy metals & cyanide	Pickling, plating, metal finishing, cooking, refineries	
Chemical wastes	Coking, synthetic dyes, chemicals, plastics solvents, textile finishing, Kraft and sulphite pulp	Unpleasant taste and odour, toxic to aquatic life
Acids (mineral and organic)	Steel pickling, chemicals, food processing, acid mine drainage	Corrosion of concrete structures
Alkalis, sodium	Metal finishing, plating, textile and pulp mills, tanneries, water	Toxic to fish, rendering water unsuitable for irrigation by

Pollutant	Pollution source	Potential impact of pollution
	softening, ion-exchange installations	causing brack conditions due to imbalance of ions
Nitrogen, phosphorus Carbohydrates	Fertilizer plants, synthetic detergents Fruit and vegetable canning, sugar milling	Rapid growth of aquatic organisms, algae <i>Sphaerotilus natans</i>
Heat	Cooling, all processes	Stimulates organic growth and reduces oxygen in water
Detergents	Textiles, metal finishing	Foaming
Pathogens, viruses, worm eggs	Hospitals, abattoirs	Spreading of disease

Brewery effluent can be classified as a very high strength waste, specifically in terms of chemical oxygen demand (COD) and biological oxygen demand (BOD) (Kanagachandran and Jayaratne, 2006). Depending on the type of beer produced, brewery wastewater quality varies significantly. In general, the organic load of wastewaters from facilities producing high fermentation beers is higher than for low fermentation beers; the same conclusions can be made on suspended solids (Van der Bruggen and Braeken, 2006). Most breweries are required to treat their wastewater on site before discharging into municipal sewers or the environment, as a number of constituents typically far exceed the regulated limits for discharge. Of these, the most troublesome constituents for breweries include chemical oxygen demand (COD) and total suspended solids (TSS) (Massen, 2011; Feng et al., 2009, Simate et al., 2011). Extensive treatment is required before reuse can be considered (Jaiyeola and Bwapwa, 2016).

This section will detail the nature of each of these compounds in brewery wastewater, as well as pH and inorganic pollutants.

1.5.1 Oxygen demand

Chemical Oxygen Demand (COD) is a measurement of the amount of dissolved oxygen required to oxidize all organic materials present in a

water or wastewater. The brewing process generates wastestreams of different organic loading. Wastewater from the malting process has a COD of around 800-1,200 mg/l. The highest concentrations are found in effluent from the brewhouse. The brew kettle, fermenter, as well as cleaning operations, contribute to concentrated COD loading. Residues such as trub, spent grain, kieselguhr and yeast are major waste items from the brewing process. Typical COD values are within the 3,000-6,000 mg/l range. Further, waste loading results from rinsing and cleaning of process and bottling equipment, as well as bottle washing. Bottle washing produces a wastewater with moderate COD values of 2,000-3,000 mg/l and temperatures of 25°C to 30°C. Fluctuations in COD (and pH) values result from the various cleaning processes and Clean-in-Place (CIP) systems. Product at various stages of production can enter the effluent stream as a result of leakage and breakage. The very high COD of beer-spillages is the main cause for peak loadings in brewery wastewater treatment works and precautions should be taken to minimise or divert these spills from wastewater.¹

Biological oxygen demand (BOD) is an indicator of the amount of dissolved oxygen used by microorganisms in the biochemical oxidation of available organics in wastewater. Brewery effluents are generally characterised as having a high BOD, ranging around 1,200 – 3,600 mg/l, with a typical value of 1,500 mg/l. This is due to organics that enter the waste stream during the brewing process; primarily in the form of maltose, dextrose, soluble starches, ethanol, and volatile fatty acids. BOD represents a fraction of COD. The average brewery effluent is generally related by a BOD/COD ratio of approximately 0.6 – 0.7; this does not reflect the ratio of contributing waste streams (Massen, 2011; Driessen and Vereijken, 2003; Simate et al., 2011; Braeken et al., 2004).

¹ For the period July 2016 – June 2017, the case study brewery's maximum COD measurement for influent entering the wastewater works was 13,470 mg/l. On 17 days of this year, the maximum value exceed 6,000 mg/l, of which only 3 days were above 10,000 mg/l. The average COD for the same period was 2,786 mg/l.

1.5.2 Total Suspended Solids

Brewery solids, expressed as total suspended solids (TSS) mostly originates from spent grain, kieselguhr, trub, surplus yeast, and label pulp - all of which are primarily organic in nature. TSS are generally found to be >300 mg/ℓ, ranging from 200 – 1,000 mg/ℓ). The organic portion of the TSS significantly contributes to the BOD and COD loading. Dissolved solids are mainly from beer, wort, and cleaning / sanitising solutions (Driessen and Vereijken, 2003; Massen, 2011).

1.5.3 pH

Considerable fluxes in effluent pH are found due to the caustic and acidic effluents from regular clean in place (CIP) operations, caustic-laden water from sanitising rinses in the bottling area, and discharges of beer at various stages of fermentation. Water for cleaning is reported to be between 45 % (Massen, 2011) up to 80% (Van der Bruggen and Braeken, 2006) of the total water use in a brewery. Beer has a pH of around 4, and inevitably gets discharged to drain during regular operations and accidental spills. The pH of brewery effluent is reported to range from 4.5 – 12 (Driessen and Vereijken, 2003)

1.5.4 Inorganic Pollutants, including heavy metals

The inorganic portion of brewery wastewater include phosphorous, ammonia and sulfide compounds, of which the most troublesome is phosphorous (Massen, 2011). These ions are mainly derived from malt, nutrient additives, yeast and acid-based CIP procedures. Ammonium salts are commonly used to promote yeast growth. Because industrial wastewaters such as paper mill effluent and brewery effluent lack N and P, it should be added in the form of urea, superphosphate or ammonium phosphate to maintain optimal biomass conditions. Seneviratne (2006) reports that the minimum BOD to N and P ratio required for optimal microbial growth in the aeration tank as, BOD:N:P = 100:5:1. The addition of these nutrients should prevent the sludge bulking often reported in brewing and food-processing industries which probably results due to nutrient imbalance (Seneviratne, 2006).

Vessels requiring more thorough cleaning often employ acid CIP processes over caustic rinses. Nitric (HNO_3) and phosphoric (H_3PO_4) acids are favoured as these elements are already present in the beer. Concentrations of inorganic phosphorus in brewery wastewater may range from 10-100 mg/l (Massen, 2011; Driessen and Vereijken, 2003).

Controlling phosphorous discharged from wastewater treatment plants is a key factor in preventing eutrophication of surface waters. Phosphorous is one of the major nutrients contributing in the increased eutrophication of lakes and natural waters. Its presence causes many water quality problems including increased purification costs, decreased recreational and conservation value of impoundments, loss of livestock and the possible lethal effect of algal toxins on drinking water (Lenntech, n.d.).

Other inorganic chemicals introduced into brewery wastewater include potassium and calcium salts as well as silicates derived from diatomaceous earth (Massen, 2011; Driessen and Vereijken, 2003).

Typically, brewery wastewater contains only low concentrations of heavy metals, as can be seen in Table 3.

Table 3 Concentration of heavy metals in brewery effluent samples (Inyang U.E. et al., 2012)

Parameter	Concentration (mg/l)
Iron (Fe)	0.46
Aluminium (Al)	0.118
Chromium (Cr)	0.16
Copper (Cu)	0.11
Cyanide (CN)	0.76
Lead (Pb)	0.030
Zinc (Zn)	0.040
Barium (Ba)	0.31
Mercury (Hg)	0.022
Manganese (Mn)	0.017
Cadmium (Cd)	0.04

However, these are toxic to microbes which could result in the malfunctioning of biological treatment plants and should therefore

be taken into consideration in the design of biological treatment components. (Inyang U.E. et al., 2012)

1.6 Aims of strategic literature review

The aim of this study is primarily to systematically review advanced brewery wastewater treatment processes. As a consequence, this study will make recommendations to an existing large-scale brewery, for the improvement of wastewater effluent quality to increase the opportunities for wastewater reuse.

After considering the advantages and disadvantages of different treatment technologies for industrial wastewater, Prajapati and Chaudhari (2015) concluded that no single technology can be employed in isolation. The treatment they recommend, should be comprehensive and considerate of a variety of sequential technologies

The methodology employed in this study is discussed in Chapter 2.

1.6.1 Current layout of target brewery

As illustrated in Figure 2, the existing treatment works incorporates an up flow anaerobic sludge blanket (UASB) reactor, followed by sequential batch reactor (SBR). For the purpose of reviewing applicable advanced treatment technology, the study assumes that the influent quality is equal to the current discharge license agreement set out by the Department of Water and Sanitation (DWS).

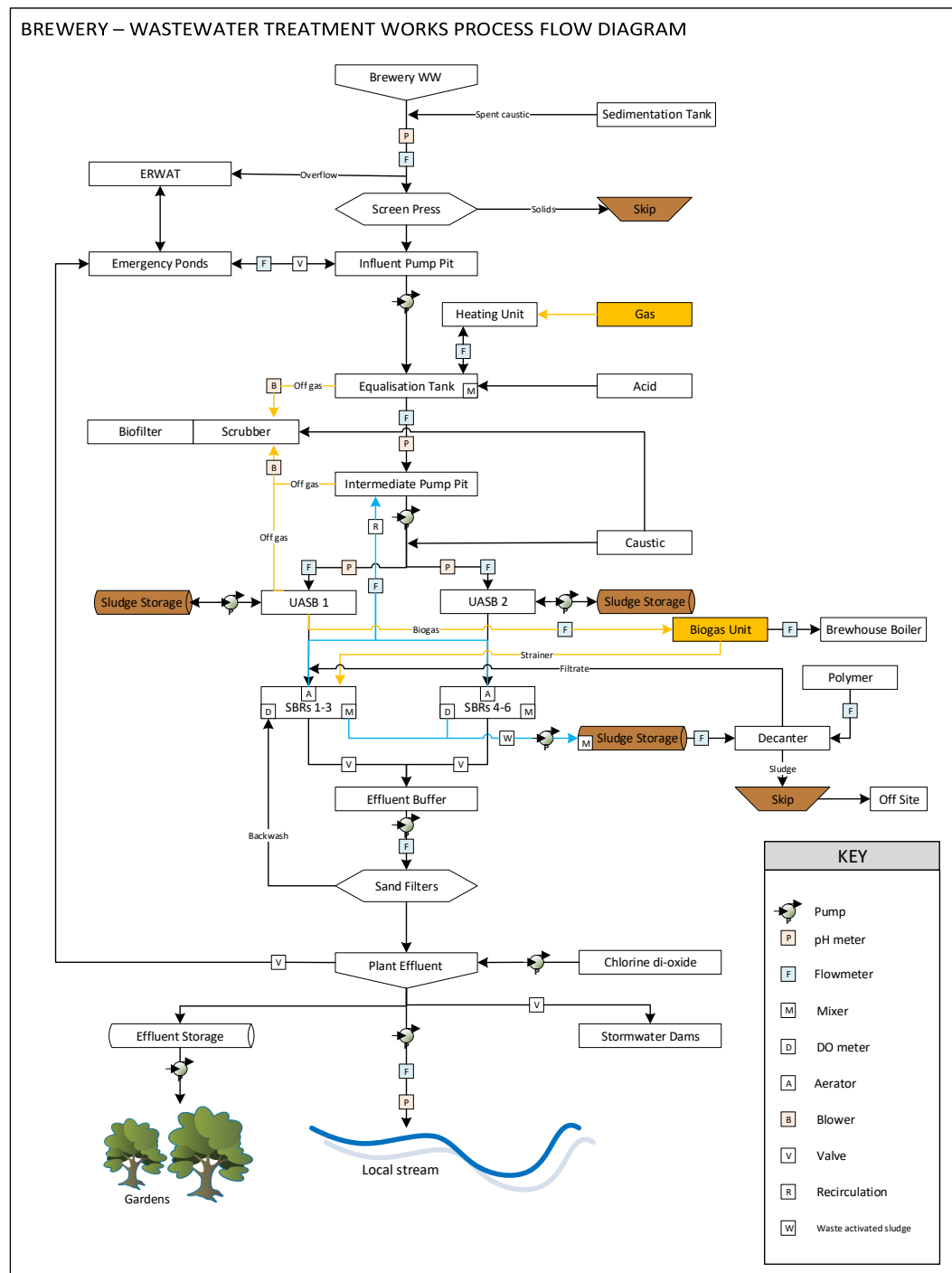


Figure 2 Brewery wastewater treatment works process flow diagram

1.6.2 Discharge quality of target brewery

For the period June 2016 to June 2017, the target brewery mostly achieved the discharge limits as set out in the Department of Water and Sanitation (DWS)' discharge licence agreement. The average quality achieved is shown in Table 4.

Table 4 Target brewery discharge license conditions and average discharge quality

Determinant	Unit	Brewery discharge license	Discharge average Jun 2016 – Jun 2017	SA wastewater discharge limits	
				General limit	Special limit
Ammonia	mg/l NH ₃ as N	1.5	0.8	<3	<2
Chemical Oxygen Demand (COD)	mg/l	70	78.3	<75	<30
Electrical Conductivity at 25°C *	m/S/m	< (Intake + 75)	198.4		
Fluoride (F)	mg/l	1	0.1		
Dissolved Oxygen (DO)	mg/l	>3	5.5	75% saturation	
pH – Value at 25°C *	mg/l	6.5 - 9	8.7	5.5-9.5	5.5 -7.5
Phosphate (PO₄ as P)	mg/l	2	4.7	10	1
Suspended Solids	mg/l	25	31.0	<25	<10
Dissolved Iron (Fe)	mg/l	1	5.1		
Sodium (Na)	mg/l	350	461.0	Intake + 90	Intake + 50
Total dissolved solids (TDS)	mg/l	1000	1039.8		
Chlorides (Cl)	mg/l	200			
Sulphate (SO₄)	mg/l	350			

1.6.3 Potable water quality standards

Discussion around technology will include its potential to treat water to potable standards. Table 5 compares potable standards set out by different institutions / users.

Table 5 Comparison of potable water quality guidelines

Determinand	Unit	Limits for Potable Water			
		SANS 241:2015 ²	WHO ³	Goreangab Reclamation ⁴	Reclamation guide ⁵
Physical and aesthetic determinands					
Colour	Mg/l Pt-Co	≤ 15	≤ 15	≤ 10	NS
Chemical Oxygen Demand (COD)	mg/l	NS	NS	≤ 15	≤ 15
Dissolved Organic Carbon	mg/l	NS	NS	≤ 5	NS
Electrical Conductivity at 25°C *	m/S/m	≤ 170	NS	NS	NS
Total dissolved solids (TDS)	mg/l	≤ 1 200	≤ 1 000	≤ 1 000	Incoming plus ≤ 500
Turbidity, operational	NTU	≤ 1	≤ 5	≤ 0.2	≤ 0.4
pH – Value at 25°C *	mg/l	≥ 5 to ≤ 9.7			
Chemical determinands					
Aluminium (Al)	mg/l	NS	≤ 0.2	NS	NS
Ammonia	mg/l NH3 as N	≤ 1.5	≤ 1.5	≤ 0.1	≤ 0.5
Barium (Ba)	mg/l	≤ 0.7	≤ 0.7	NS	NS
Cadmium (Dd)	mg/l	≤ 0.003	≤ 0.003	NS	NS
Chlorides (Cl)	mg/l	≤ 300	NS (taste ≤ 250)	≤ 250	NS
Chromium (Cr)	mg/l	NS	≤ 0.05	NS	NS
Combined nitrate + nitrite	mg/l	≤ 1	≤ 11	≤ 10	NS
Copper (Cu)	mg/l	≤ 2	≤ 2	NS	NS
Cynanide CN)	mg/l	≤ 0.2	NS	NS	NS
Fluoride (F)	mg/l	≤ 1.5	≤ 1.5	NS	NS
Iron (Fe)	mg/l	≤ 0.3	NS (taste ≤ 0.3)	≤ 0.1	NS
Lead (Pb)	mg/l	≤ 0.01	≤ 0.01	NS	NS
Manganese (Mn)	mg/l	Health ≤ 0.4 Taste ≤ 0.1	Health ≤ 0.4 Taste ≤ 0.1	NS	NS
Mercury (Hg)	mg/l	≤ 0.006	≤ 0.006	NS	NS
Nitrate as N	mg/l	≤ 11	≤ 50 (short exposure)	NS	≤ 10
Nitrite as NO2-	mg/l	≤ 0.9	≤ 3 (short exposure)	≤ 0.05	NS
Phosphate (PO ₄ as P)	mg/l	NS	NS	NS	≤ 0.5
Sodium (Na)	mg/l	≤ 200	NS (taste ≤ 200)	NS	NS
Sulphate (SO ₄ ²⁻)	mg/l	≤ 250	NS (taste ≤ 250)	≤ 200	NS
Zinc (Zn)	mg/l	≤ 0.005	NS	NS	NS

² SABS STANDARDS DIVISION 2015. South African National Standard (SANS) 241-1:2015. Drinking Water, Part 1: Microbiological, physical, aesthetic and chemical determinands. Pretoria: SABS.

³ WORLD HEALTH ORGANIZATION 2011. Guidelines for Drinking-water Quality - 4th ed. Fourth ed. Geneva: World Health Organization.

⁴ WOLZ K.D., DU TOIT A. & VAN DER WALT C. 1998. Goreangab water reclamation plant - Process train report. Stuttgart: FMG Goreangab JV.

⁵ BARNARD, J. L. & LAW, I. B. 1982. A guide for the planning, design and implementation of a water reclamation scheme. Water Research Commission.

Determinand	Unit	Limits for Potable Water			
		SANS 241:2015 ²	WHO ³	Goreangab Reclamation ⁴	Reclamation guide ⁵
Microbiological determinands					
E. coli	Per 100ml	ND	ND	ND	NS
Faecal coliforms	Per 100ml	ND	ND	ND	NS
Total coliforms	Per 100ml	≤ 10	ND	ND	ND
Protozoan parasites Cryptosporidium species Giardia species	Per 10l	ND	NS	ND	NS
Heterotrophic plate count	Per 1ml	≤ 1 000	NS	≤ 100	≤ 100
Somatic coliphages	Per 100ml	ND	NS	ND	ND

NS: No standard; ND: Not detected

It is interesting to note that the Goreangab Reclamation plant, in Windhoek, treats to standards more stringent than the standards set by SANS 241. Should the reuse of water be considered for brewing within the target brewery, they will have to agree on a standard acceptable to their own operational standards.

The brewery in question has reached the limit of their potable water allocation from the local water services provider, with no possibility of increasing their allocation in the near future. The reuse of wastewater could provide the opportunity to increase beer production (Labs, 2015). Ultimately, treated wastewater for reuse could result in the case study brewery reducing its dependency on an external water service provider. Therefore, the research objectives are:

- To systematically review published literature on advanced treatment options available for the brewery industry in general;
- To review treatment technology from literature, comparing: infrastructure capital cost, operational cost, energy requirements, level of operator skills required and effluent quality achievable;
- To report the most appropriate technologies for the case study brewery as recommended by literature and/or suggest possible avenues for further investigation.

CHAPTER TWO

2 Methodology including results and meta-analysis

A systematic review of advanced wastewater treatment technologies was conducted in order to identify and compare advanced wastewater treatment technologies capable of treating the effluent from this study's target brewery to potable standard.

Moher et al. (2009) and Zumsteg et al. (2012) define a systematic review as a structured evaluation of the literature with the goal of answering a specific research or application question with a synthesis of the best available evidence. Generally, results are published to a wide audience for consideration and implementation. Statistical methods (meta-analysis) may or may not be used to analyse and summarise the results of the included studies.

In disciplines such as medicine, ecology and software engineering, standardised protocols have been developed for systematic reviews. Increasingly, a similar approach is being applied in sectors such as Life Cycle Assessment (LCA) and environmental sciences (Zumsteg et al., 2012; Hutton et al., 2015). No widely recognised guidelines for systematic reviews within the environmental engineering sector could be found. The researcher has therefore based this review, as far as applicable, on the 2009 Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement as described by Moher et al. (2009) and also followed the 'Five steps for Systematic Review' closely as suggested by Khan et al. (2003). PRISMA can also be used as a basis for reporting systematic reviews of research other than in the field of clinical medicine, particularly for evaluations of interventions (Moher et al., 2009).

2.1 PRISMA flow diagram – summary of study selection

Figure 3 displays the typical PRISMA flow diagram summarising the literature review process. This chapter then further discusses in detail how

literature was identified and selected for detail review, as well as show meta-analysis of the studies reviewed.

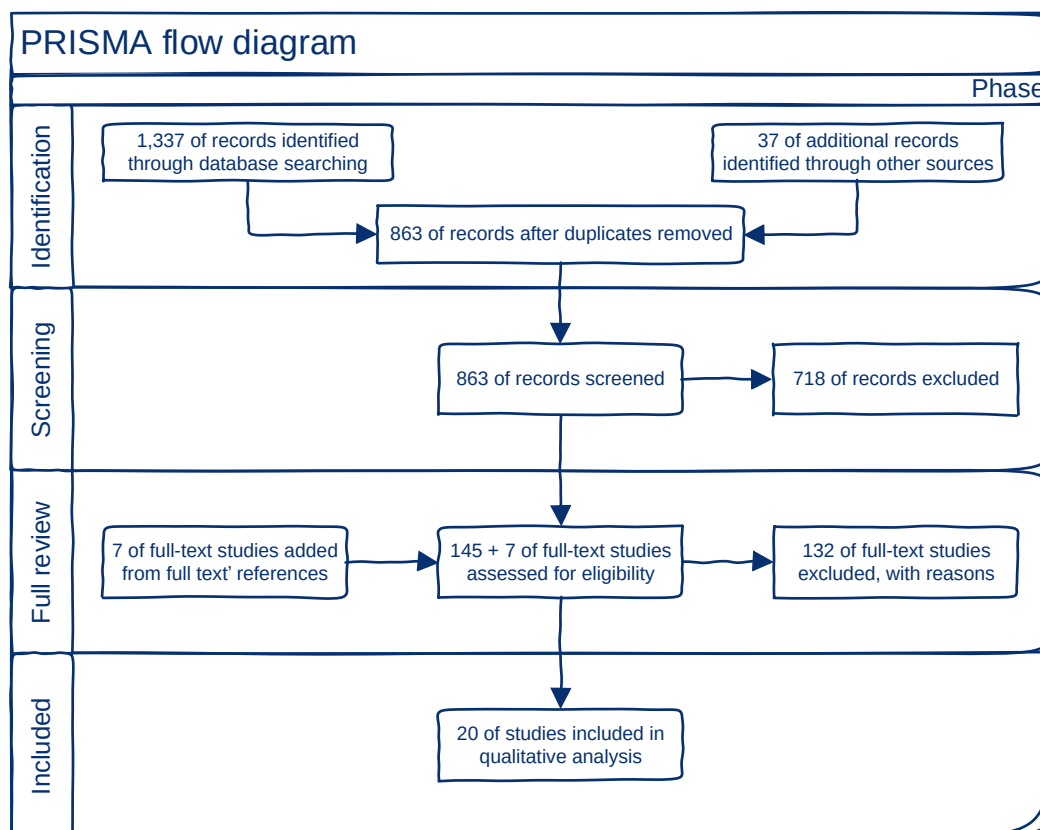


Figure 3 PRISMA flow diagram, adapted from reference Moher et al. (2009)

2.2 Identifying key words

The University of the Witwatersrand (WITS) has an extensive library with subscriptions to a wide range of resources. All literature was sourced using the WITS library.

Prior to the systematic review illustrated in the summarising figure above, an open search was conducted for studies on 'brewery wastewater reuse'. The purpose of this initial search was to identify the most relevant key words listed within literature and evaluate each study's alignment to the research question, thus identifying the most appropriate key words to use for the systematic review.

The results from evaluating the abstracts and / or final discussion of the initial 73 studies:

- Duplicates – 16 studies

- Directly applicable to research question – 33
- Relevant to study background, i.e. water scarcity, wastewater reuse etc. – 16
- Possibly applicable – abstract does not contain sufficient information – 6
- Not relevant at all – 2

The initial search produced 59 keywords. Only the keywords that appeared at least three times are listed below, as well as the total count for each:

Table 6 Identifying keywords

	Keyword	Count
1	Water purification / treatment	6
2	Brewery wastewater	5
3	Life cycle assessment	5
4	Water / Wastewater reuse / reclamation	4
5	Environmental information / Environment	4
6	Capital costs	3
7	Industrial / other wastewater	3
8	Environment	3
9	Models, theoretical / mathematical / kinetic	3
10	Sustainable community planning / Sustainability	3
11	Waste disposal	3
12	Membrane technology / filtration / separation	3

From the keyword identification process and through consideration of the appropriateness of studies found, the following keywords were used for the full, systematic review: wastewater treatment, advanced treatment, brewery, reuse and cost

2.3 Identifying relevant databases

Using the WITS library, relevant databases were identified by selecting those databases that were listed in all three of the following library LibGuides categories:

- Engineering: Environmental
- Engineering: Chemical
- Engineering: Civil

Table 7 Identifying relevant databases

Engineering: Environmental	Engineering: Chemical	Engineering: Civil
ScienceDirect	Web of Science	ScienceDirect
ICE Virtual Library	SCOPUS	Institution of Civil Engineers Virtual Library
Web of Science	ScienceDirect	ASCE Journals
Springer Collection	American Chemical Society	Web of Science
Scopus	Royal Society of Chemistry Publishing	EBSCO Host
IEEE Xplore	Institute of Physics Journals (IOP)	Scopus
EBSCO: Environment Complete	Wiley Online Library	Springer Collection
Proquest	PubMed	Cement and Concrete
Compendex	Reaxys	IEEE Xplore
SA ePublications	Springer Collection	Compendex
Sabinet Online	SciFinder Scholar	ProQuest
	Proquest	Sabinet Online
	Sabinet Online	SA e-Publications
	Compendex	Sabinet Legal

The overlapping databases that were used for the full, systematic review were:

- ScienceDirect
- Web of Science

- Springer Link
- Scopus
- Proquest
- Sabinet Online

2.4 Identifying relevant publications

The results (number of literature items) from the extensive search, using the keywords identified in the previous section, are shown in the tables below. The discussion below explains the approach taken and should be read together with Table 8 and Table 9.

2.4.1 Final keyword – Wastewater treatment

As shown in Table 6, both ‘water treatment’ and ‘wastewater treatment’ emerged as plausible keywords. The first two result columns, for the ScienceDirect database, show the results using either ‘water treatment’ or ‘wastewater treatment’ as the first keyword (a) search. The following keywords (b, c, d, e etc.) were then searched within the listed results. It was subsequently decided to use only ‘wastewater treatment’ as the first keyword, as the number of applicable studies was still sufficient for this review.

2.4.2 Final keyword – Advanced treatment

Within the ScienceDirect database, searches were done using either ‘advanced treatment’ or ‘advanced technology’. The keyword with the greater search result, ‘advanced treatment’, was used going forward.

2.4.3 Final keyword – Reuse

The initial review discussed earlier when identifying keywords, also exposed the keyword ‘reclamation’ as an alternative for ‘reuse’. Levine et al. (2010) explain the terms reclamation and reuse are often used in various contexts to mean different things. Water reclamation is the

treatment or processing of wastewater to make it reusable with definable treatment reliability and meeting appropriate water quality criteria, while water reuse is the use of treated wastewater (or reclaimed water) for a beneficial purpose. Considering the results from using either 'reclamation' or 'reuse' within the ScienceDirect database, it was decided to use only 'reuse' within the remaining databases as by definition it is the more appropriate term addressing the research objective and produced a larger number of studies.

Table 8 Database search results

		Keyword	Science-Direct Water Treatment	Science-Direct Wastewater Treatment	Web of Science	Springer Link	Scopus	Proquest	Sabinet Reference - All	TOTAL
a	a	Waste / water Treatment	2 087 930	148 595	58 237	56 882	126 245	461 241	57 178	908 378
a+b	b	Advanced Treatment	293 332	32 191	4 596	19 644	25 081	64 447	2 935	148 894
a+c	c	Advanced Technology	131 975	24 302						24 302
a+b+d	d	Brewery	1 264	604	7	509	429	1 509	4	3 062
a+b+d+e	e	Reuse, OR	338	262	3	228	168	580	471	1 712
a+b+d+f	f	Reclamation	116	95		78				173
a+b+d+e+g	g	Cost (reuse)	294	228		204	99	550	116	1 337
a+b+d+e+h	h	Capital cost	149	126						126
a+b+d+e+i	i	Infrastructure cost	82	67						67
a+b+d+e+j	j	Operational cost	165	142						142
a+b+d+e+k	k	Capital & Operational cost	115	98						98
a+b+d+e+g+m	m	Energy	274	213		195	71	527	50	1 056
a+b+d+e+g+m+o	o	Developing country	181	142		140	9	346	10	647
a+b+d+e+g+n	n	Skills	52	34		53	0	237	3	327
a+b+d+e+g+n+o	o	Developing country	42	30		46	0	214	1	291

2.4.4 Final keyword – Cost

As illustrated in Table 8, the keyword ‘cost’ was replaced by ‘capital cost’, ‘infrastructure cost’, ‘operational cost’ and ‘capital and operational cost’ to get an indication whether ‘cost’ on its own covers all the aspects of ‘cost’. Testing this in the ScienceDirect database only, it was accepted the term “cost” encompasses all aspects of ‘cost’ and was therefore the only ‘cost’ keyword used in the remaining databases.

2.4.5 Final keywords – Energy and Skills with Developing country

As per the research objective, this review aims to compare advanced treatment technology on several parameters, including energy needs and level of skills needed. Therefore the studies found at “cost” were searched for the keywords “energy’ then ‘developing country’ as well as ‘skills’ and ‘developing country’ to test that these concepts were covered in the studies included.

However, it was acknowledged that final results for ‘skills’ were only after ‘cost’ was searched. To ensure no relevant studies were excluded another keyword order was used to ensure the important topic of ‘level of skills’ was not overlooked. The following table shows the results for the two larger databases: ScienceDirect and Proquest.

Table 9 Database search results - 'skills'

		Keyword	Science-Direct Wastewater Treatment	Proquest	TOTAL
a	a	Wastewater Treatment	148 595	126 245	274 840
a+b	b	Advanced Treatment	32 191	25 081	57 272
a+b+l	l	Reuse	9 688	14 600	24 288
a+b+l+m	m	Skills	460	3 428	3 888
a+b+l+m+n	n	Developing country	355	2 784	3 139
a+b+l+m+n+o	o	Brewery	33	214	247

Although the final number of relevant studies using either keyword combination were remarkably similar, it was decided to include studies from this last search in the evaluation phase to follow.

2.5 Selection of studies for further review

As discussed in the previous section, reaching the keyword 'cost', included a number of studies with reference to the main elements to compare advanced treatment technology when considering reuse of brewery wastewater.

As can be seen from the line in Table 8, the total of number of studies addressing the identified keywords, is 1,337.

Table 8 Excerpt

	Keyword	Science -Direct	Web of Science	Springer Link	Scopus	Proquest	Sabine t	TOTAL
g	Cost (reuse)	228		204	99	550	116	1 337

Table 9 Excerpt

	Keyword	Science- Direct	Proquest	TOTAL
o	Brewery	33	214	247

Adding the additional studies as shown in Table 9, the total studies to be considered from database search: $1,337 + 247 = 1,584$

2.6 Removing duplicate studies

Full references and abstracts, where available, were downloaded from the WITS library and captured in the software package EndNote. EndNote is a commercial reference management software package, used to manage bibliographies and references for research, essays and articles. It is produced by Clarivate Analytics.

Using a tool within EndNote, duplicate studies were identified and removed. Once this was done, 863 studies remained.

2.7 Assessing the relevance of studies based on design threshold

As set out from the start, the aim of this research was to identify advanced treatment technologies that could be added to an existing treatment works for brewery wastewater in order to improve effluent quality to potable quality. Potential technology identified in literature was reviewed based on the parameters (design threshold) as shown in the table below. The chosen threshold was based on technology assessments done by Adewumi (2011). The assessments include pollutant removal efficiency to meet reuse water quality, capital and O&M costs, ease of O&M and environmental (i.e. power and chemical requirements) Table 10 shows the design criteria used to assess each of the 863 studies. If a study rated 'Low', no further evaluation was done regarding each of the 'Quality categories'. For both 'Moderate' and 'High' ratings, each of the quality categories were scored between '5' (good information) and '0' (no information). All ratings were captured in EndNote.

As illustrated in Figure 4 the outcome of this initial assessment had 145 studies (17%) in the 'High' overall rating, 74 were 'Moderate' (8%) and 644, 75%, were rated 'Low'. All 'Low' studies were discarded at this point. Analyses of the scoring results can be found in Section 2.8.4 of this document. Discussion in the chapters to follow will be based on studies rated 'high'. Those rated 'moderate' didn't rate high on any of the quality categories, but could have overall relevance, mostly in related food industries and were later discarded.

Table 10 Design threshold for full review

Quality category	High (Score = 5)	High-Moderate (Score = 4)	Moderate (Score = 3)	Moderate-Low (Score = 2)	Low (Score = 1)
Reuse / reclamation of wastewater achieved	Reuse for brewing process	Reused at potable standard	Reused within plant, other than product	Reused externally	Reused externally
Quality parameters of influent and effluent given	Full detail available	Details given	Some information given	Little information given	Not clear, promising. Further review needed.
Infrastructure capital & implementation cost. Include monitoring SCADA system	Full detail available	Details given	Some information given	Little information given	Not clear, promising. Further review needed.
Operational cost, energy included	Full detail available	Details given	Some information given	Little information given	Not clear, promising. Further review needed.
Operational skills level needed	Full detail available	Details given	Some information given	Little information given	Not clear, promising. Further review needed.
Anticipated lifespan of technology	Full detail available	Details given	Some information given	Little information given	Not clear, promising. Further review needed.
Other relevant parameters of technology, i.e. footprint needed, daily flow volume, temperature etc. Regulation: WSP, monitoring.	Full detail available	Details given	Some information given	Little information given	Not clear, promising. Further review needed.

Note: “0” = no information, not included in table above.

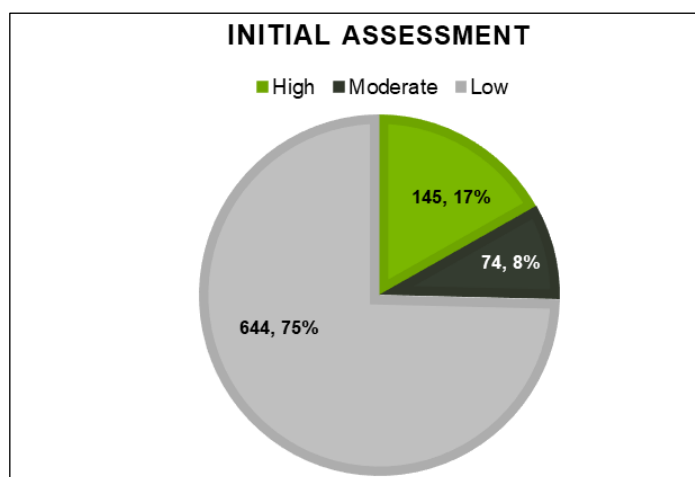


Figure 4 Initial relevance assessment results

2.8 Meta-analysis of studies for detail review

2.8.1 Reference types

Most of the studies rated for detailed review were from journals. More specifically, 106 studies were journal articles, 12 reports, 10 academic theses, 8 newspaper articles, 5 books, 2 web pages and 2 conference proceedings.

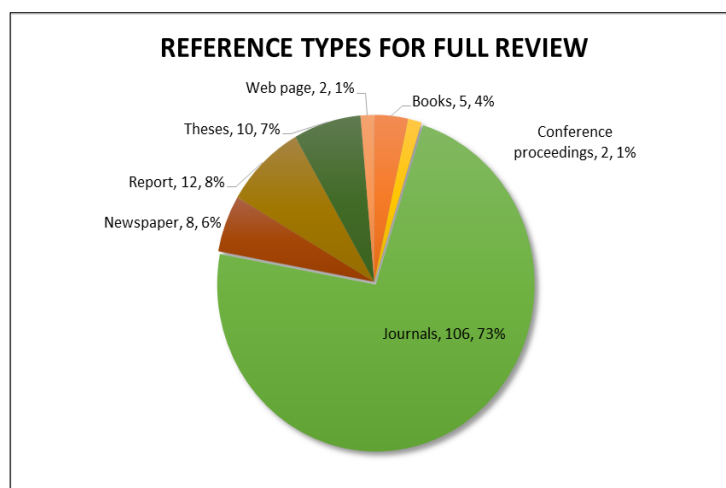


Figure 5 Reference types for full review

2.8.2 List of journals for full review

The journals from which studies for detailed review were selected, covered a range of disciplines, but came mostly from chemical engineering, water treatment and environmental engineering journals. Table 11 lists all

journals from which high rated articles came as well as the number of articles from the journal.

Table 11 Journals containing reviews rated high

Title of Journal & Number of studies from Journal		Title of Journal & Number of studies from Journal	
Water Environment Research	29	Energy Conversion and Management	1
Chemical Engineering Journal	6	Environment International	1
Desalination	6	Environmental Engineering Science	1
Journal of Cleaner Production	6	Environmental Monitoring and Assessment	1
Journal of Water Process Engineering	3	Environmental Technology (United Kingdom)	1
Renewable and Sustainable Energy Reviews	3	Filtration + Separation	1
WRC Knowledge Hub	3	Industrial and Engineering Chemistry Research	1
Applied Clay Science	2	International Journal of Electrochemical Science	1
Bioresource Technology	2	Journal of Environmental Health Science and Engineering	1
Food Engineering	2	Journal of Environmental Management	1
Journal of Hazardous Materials	2	Journal of Industrial and Engineering Chemistry	1
Reviews in Environmental Science and Biotechnology	2	Journal of Membrane Science	1
Separation and Purification Technology	2	Journal of Molecular Liquids	1
Water Research - IWA	2	Manufacturers' Monthly	1
Applied Microbiology and Biotechnology	1	MOJ Ecology & Environmental Sciences	1
Biochemical Engineering Journal	1	Process Biochemistry	1
BrewingScience	1	Progress in Natural Science	1
Canadian Journal of Civil Engineering	1	Reactive and Functional Polymers	1
Chemical Engineering Communications	1	Resources, Conservation and Recycling	1
Civil Engineering	1	Revista Ambiente & Água	1
Critical Reviews in Environmental Science and Technology	1	Science of the Total Environment	1

Title of Journal & Number of studies from Journal		Title of Journal & Number of studies from Journal	
Current Opinion in Chemical Engineering	1	South African Journal of Science	1
Ecological Engineering	1	Technological Forecasting and Social Change	1
Ecotoxicology and Environmental Safety	1	Waste and Biomass Valorization	1
Energy	1	Water Resources and Industry	1

2.8.3 Date of publication of journals for full review

As the review focused on advanced treatment technologies, as well as the increasing need to reuse wastewater, it was anticipated more studies would be found in more recent years. Figure 6 shows the dates of publications ranged from 1982 to 2018, with two records not dated. As anticipated more relevant studies emerged in recent years, which possibly confirms the notion of increased need to treat wastewater for potable reuse.

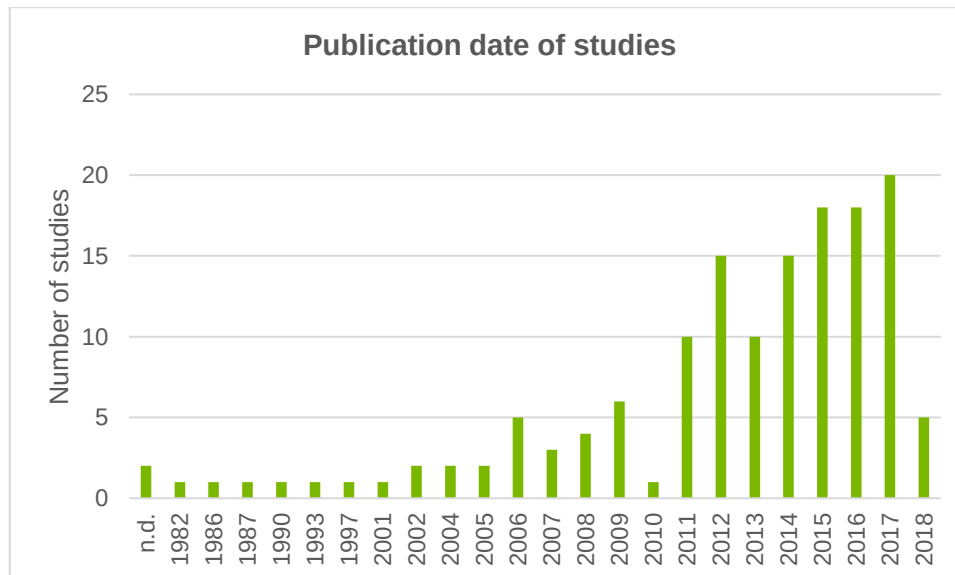


Figure 6 Publication date of studies for full review

Further analysis regarding the content of the studies being reviewed in detail will be included in the next chapter.

2.8.4 Scoring of literature for full review

Of the 152 literature sources selected for full review, 141 could be scored according to the design threshold given in Table 10. The 11 documents not scored were either reference documents used for background information or comprehensive text books. The table below summarises the scoring results of all documents scored. The numbers reflect the number of studies with the particular rating for the particular category. 90% of the studies had a scoring of 3 or above for 'reuse'.

Table 12 Summary of scoring according to the design threshold

	Reuse		Quality		Capital Cost		O&M Cost		Skills		Lifespan		Other	
5	36	26%	7	5%	1	1%	3	2%	0	0%	0	0%	21	15%
4	66	47%	28	20%	9	6%	9	6%	0	0%	0	0%	27	19%
3	24	17%	80	57%	32	23%	24	17%	4	3%	22	16%	66	47%
2	9	6%	16	11%	58	41%	65	46%	46	33%	12	9%	24	17%
1	3	2%	8	6%	34	24%	32	23%	71	50%	88	62%	2	1%
0	3	2%	2	1%	7	5%	8	6%	20	14%	19	13%	1	1%

Figure 7 below provides an overview of the scoring summary as displayed above. More in depth analyses per rating follows after this graph.

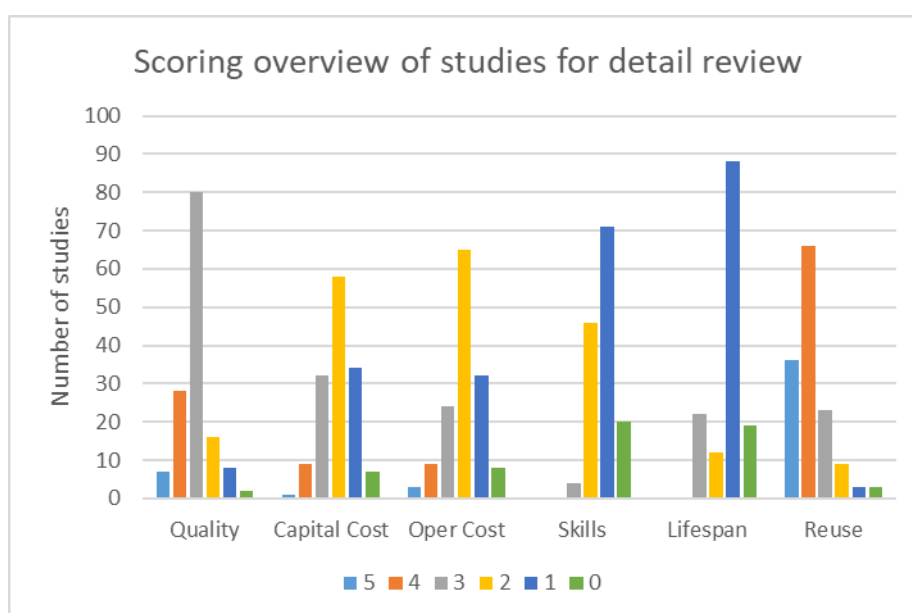


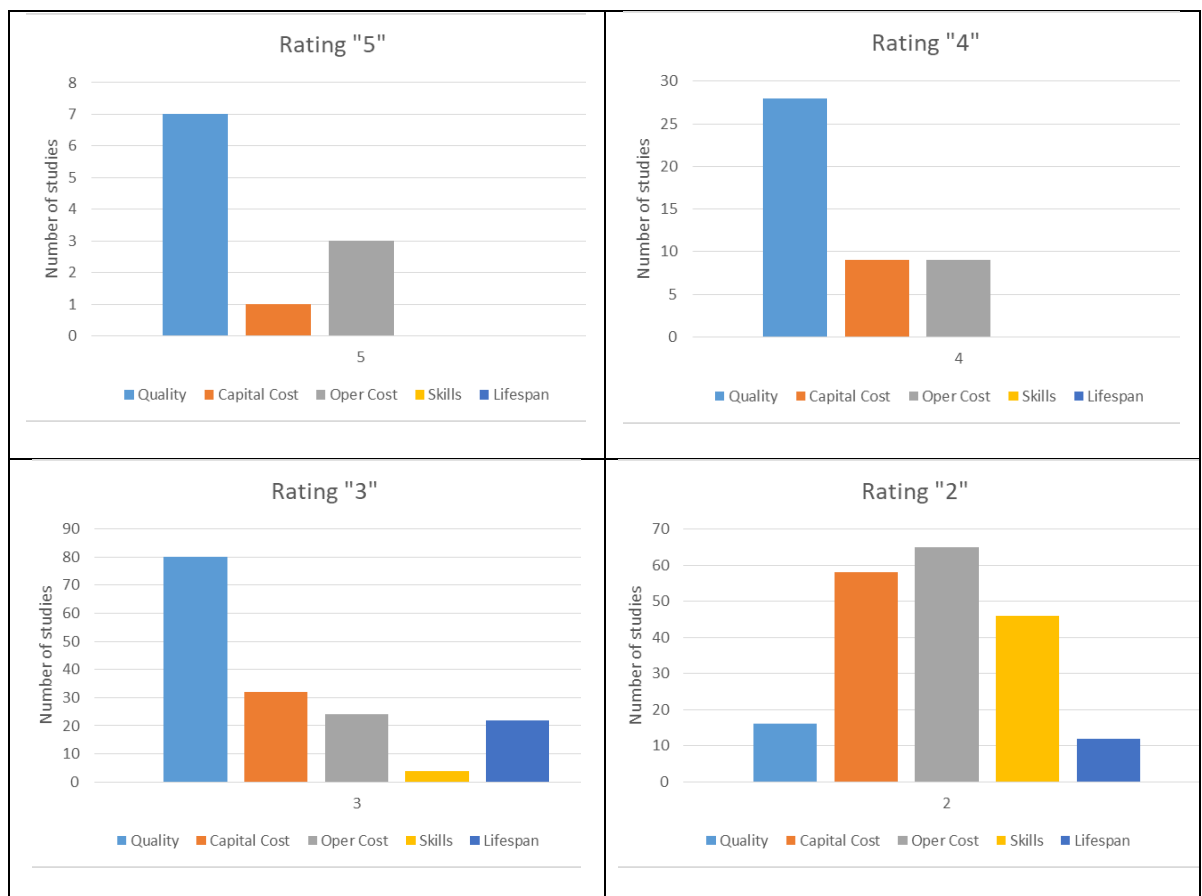
Figure 7 Scoring overview of studies for detail review

Figure 8 clearly indicates that the selected studies focused greatly on the quality of wastewater and treated effluent. 82% of all studies reviewed had at least a score of 3 showing it included information on quality of wastewater.

Although 'reuse' is a main search criteria to identify relevant technology, it is not a feature for comparison of technology. All further evaluation was only done on the parameters for comparison, namely: quality, capital cost, operational cost, level of skills required and lifespan of technology.

Besides the parameter 'quality', only 'capital cost' and 'operational cost' received scores of 5 or 4. Only 30% of the studies included sufficient reference to 'capital cost' to attract a scoring of 3 or above, while 25% of studies had a rating of 3 or above for the parameter 'operational cost'.

The selected studies had very little, or insignificant reference to the parameters of 'skills' and 'lifespan'.



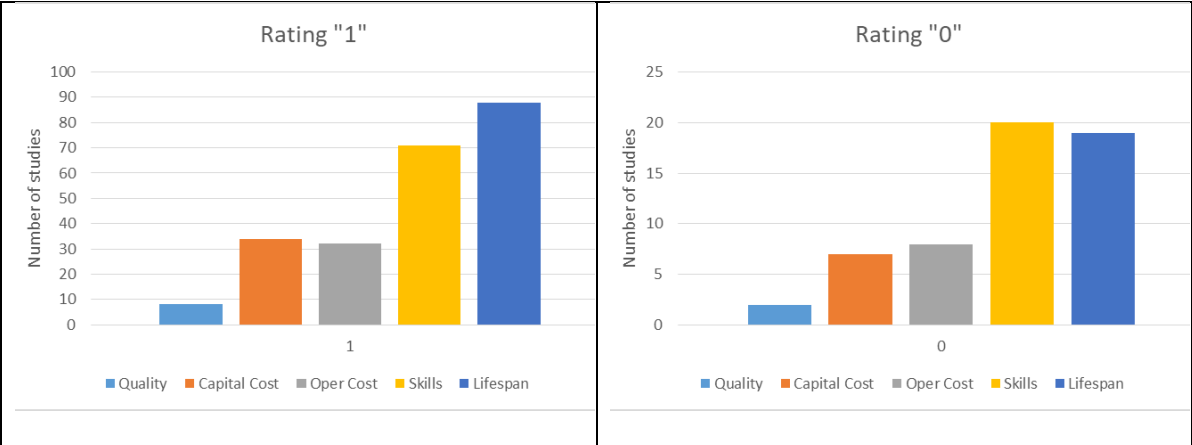


Figure 8 Overview of scoring of design threshold parameters

CHAPTER THREE

3 Meta-analysis of relevant technology

Following the systematic identification of literature meeting the design parameters, this chapter provides results from the more detailed review of relevant literature with Qualitative analysis of selected studies. As per the research objectives set out earlier, the qualitative analysis was done to:

1. Identify relevant, advanced treatment technology
2. Where available, compare treatment technology with regards to
 - a. infrastructure capital cost;
 - b. operational cost;
 - c. energy requirements;
 - d. effluent quality achievable;
 - e. any other relevant characteristics.

3.1 Reasons for exclusion of literature

As shown in the earlier PRISMA summary (Figure 3), 132 sources of literature selected for full review, were eventually excluded from analysis. The graph below shows the reasons for exclusion, as well as the number of studies per reason.

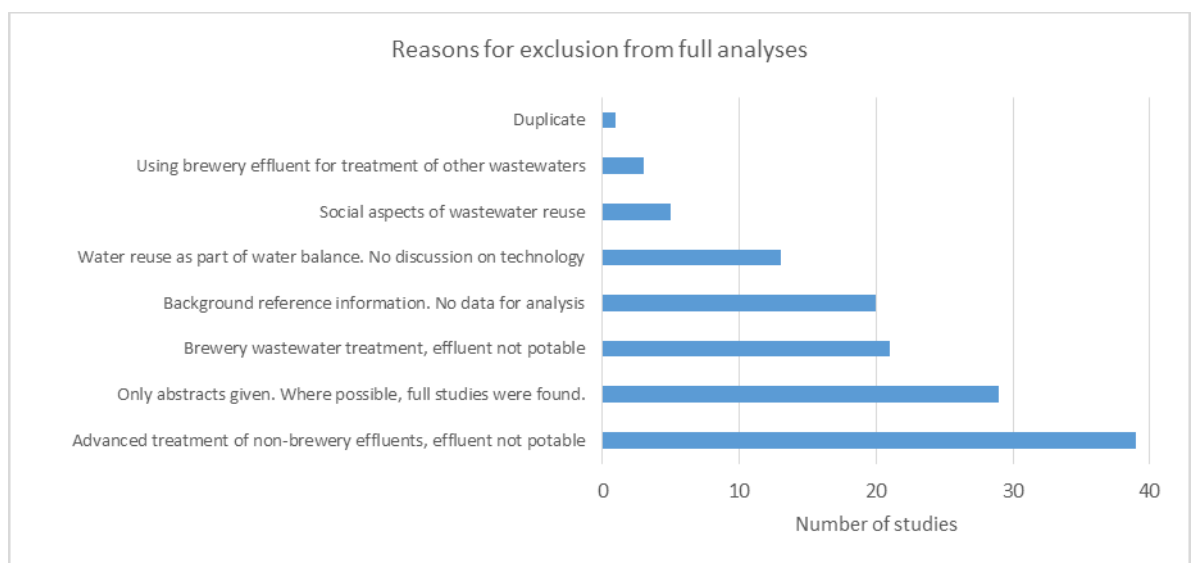


Figure 9 Reasons for exclusion from analysis

3.2 Number of studies for Qualitative analysis

Following the initial screening of 863 studies, 145 studies were identified according to the design threshold described in Table 10 for full review. From these another 7 studies were added which were identified from the references given within the relevant studies. Thus, 152 studies were fully reviewed searching specifically for advanced treatment technologies that could be added to this study's target brewery's current treatment train to achieve wastewater treatment to potable standard for reuse consideration.

Of the 152 studies reviewed in full, only 20 studies included relevant information for Qualitative analysis. Although most of the studies reviewed only one possible technology, several studies included more than one.

3.2.1 List of journals for Qualitative analysis

The journals containing studies with sufficient data for Qualitative analysis, covered a range of disciplines, but came mostly from chemical engineering, water treatment and environmental engineering journals. Table 13 lists all journals from which high rated articles came as well as the number of articles from the journal.

Table 13 Journals with articles for Qualitative analysis

Title of Journal & Number of studies from Journal	
Desalination	3
Applied Microbiology and Biotechnology	2
Applied Clay Science	1
Biochemical Engineering Journal	1
Canadian Journal of Civil Engineering	1
Food Engineering	1
Industrial and Engineering Chemistry Research	1
International Journal of Electrochemical Science	1
Journal of Industrial and Engineering Chemistry,	1
Journal of Membrane Science	1
Journal of Water Process Engineering	1
Journal of Zhejiang University-SCIENCE B	1

Title of Journal & Number of studies from Journal	
Modern Applied Science	1
Reactive and Functional Polymers	1
Renewable and Sustainable Energy Reviews	1
Waste and Biomass Valorization	1
Water Research	1

3.2.2 Date of publication of journals for Qualitative analysis

Figure 10 shows the dates of publications ranged from 2001 to 2017, with 75% (15/20 studies) since 2010. As anticipated more relevant studies emerged in recent years, which still confirms the notion of increased need to treat wastewater for potable reuse.

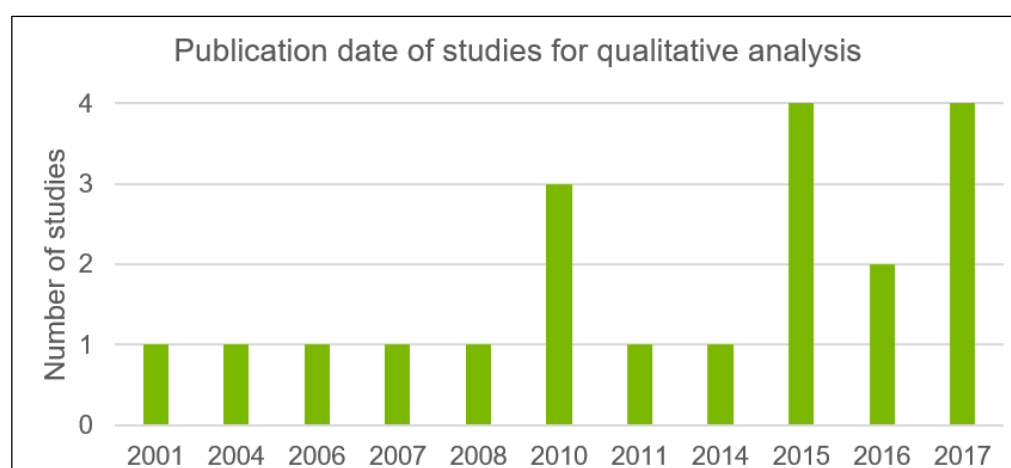


Figure 10 Publication date of studies for Qualitative analysis

3.3 Technologies identified in detailed review

Globally, there are many wastewater treatment methods for brewery wastewater in operation currently. Some are for treating to discharge standards, others are for reuse purposes. Progressively, according to reviews done by Eyvaz (2016) as well as Jaiyeola and Bwapwa (2016), the conventional aerobic methods have been replaced by treatment methods such as microbial fuel cells (MFC), upflow anaerobic sludge blanket (UASB), MBR, food chain predation, aerobic hydrolytic process, quenched plasma, nanofiltration, reverse osmosis and coagulation-

flocculation. Conventional separation methods (coagulation, gravity separation) are concluded to be incapable of complete COD removal and generate secondary pollutants. They further report that advanced treatment methods often have large scale design requirements and high capital investment.

Table 14 lists the technologies identified in this study's review. This review confirm findings from earlier reviews done by Eyvaz (2016) and Jaiyeola and Bwapwa (2016). Some additional methods of treatment were found, such as Fungi treatment with *T. Harzianum* and advanced flocculation using Mg-sericite.

Table 14 Relevant technologies identified in detailed research

Technology	Sub-category	Reference
1. Fungi treatment, <i>T. Harzianum</i>	Advanced biological	Hultberg and Bodin (2017)
2. RO component (following AS)	Membranes only	Herman et al. (2017)
3. Pilotscale external ocrossflow UF AnMBR	MBR, including membranes	Massara et al. (2017)
4. Lab scale Expanded Granular Sludge Bed	Advanced biological	Massara et al. (2017)
5. Labscale SAnMBR 0.04 um (GE Water and Process Technologies,	MBR, including membranes	Chen et al. (2016)
6. Electrocoagulation (EC) using Alternating Pulse Current (APC) Labscale	Electrocoagulation (EC)	Eyvaz (2016)
7. Mg-sericite flocculant	Advanced flocculation	Choi (2015)
8. MBR + RO	MBR, including membranes	Labs (2015)
9. CNTs added to coagulation/flocculation tanks and filter bed	Advanced flocculation	Simate (2015)
10. UF-Bioreactor (MBR)	MBR, including membranes	Ji et al. (2015)
11. NF flat, Koch membrane, MPS-34	Membranes only	Götz et al. (2014)
12. Pilotscale external ocrossflow UF AnMBR	MBR, including membranes	Lin et al. (2011)
13. MFC, double chamber, air cathode	Microbial Fuel Cells (MFC)	Wen et al. (2010)

Technology	Sub-category	Reference
14. MBR + RO	MBR, including membranes	Dai et al. (2010)
15. RO	Membranes only	Gude et al. (2010)
16. MFC, single chamber, air cathode	Microbial Fuel Cells (MFC)	Feng et al. (2008)
17. NF & RO, following primary & secondary treatment	Membranes only	Hafez et al. (2007)
18. Fortified clay, Double column treatment (DCT), lab scale	Advanced filter media	Oladoja et al. (2006)
19. Electrochemical	Electrocoagulation (EC)	Vijayaraghavan et al. (2006)
20. NF, flat membrane UTC-20 (Toray, Japan)	Membranes only	Braeken et al. (2004)
21. UF-Bioreactor (MBR)	MBR, including membranes	Zhou and Smith (2001)

As shown in Figure 11, technologies including either membranes on their own, or in combination with biological reactors as Membrane Bio-Reactors (MBR), dominated the review results. 75% of the relevant results included the use of membranes.

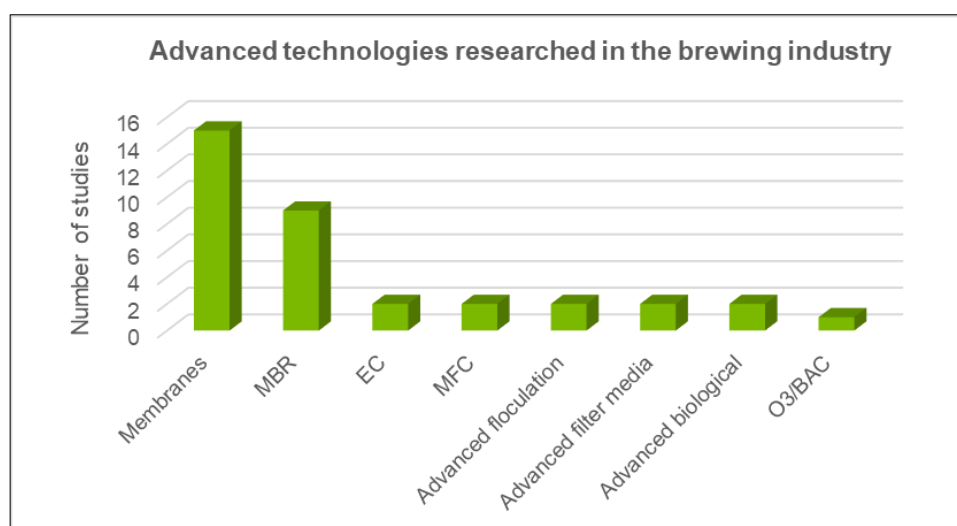


Figure 11 Summary of advanced treatment technologies found in research

Of the studies referring to membranes, Figure 12 illustrates the number of studies per reported pore size of the membrane.

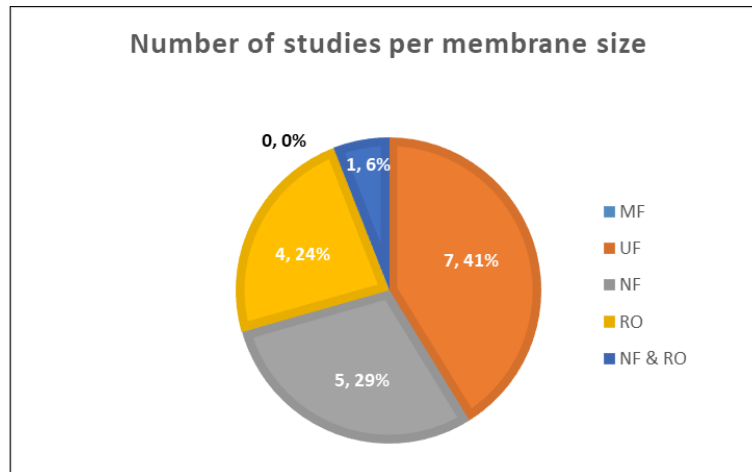


Figure 12 Number of studies per membrane pore size

Where MBR technology was discussed, Figure 13 illustrates that 5 out of the 9 relevant studies, which equates to 56% of the times, the membranes were used in combination with anaerobic biological treatment. 4 out of the 9 studies (44%) indicates membranes with aerobic biological treatment.

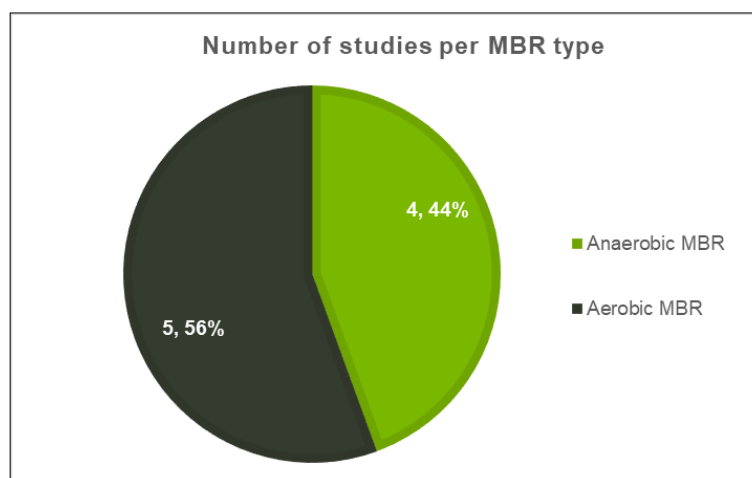


Figure 13 Number of studies per MBR type

Recent research shows a preference for anaerobic treatment as opposed to conventional aerobic treatment. Findings presented in Figure 14 seems to confirm this trend.

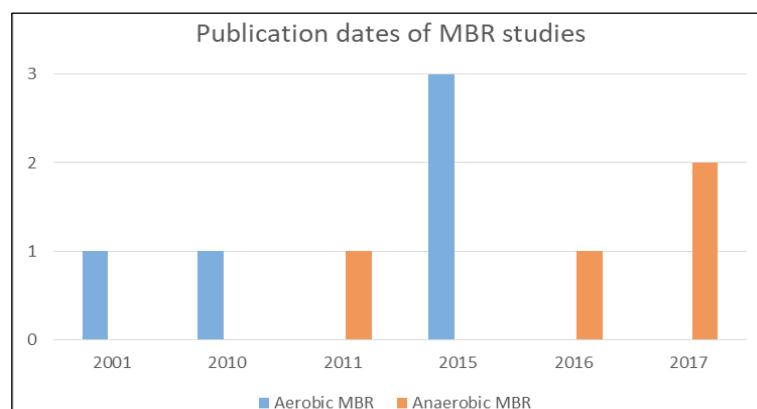


Figure 14 Publication dates of MBR studies

3.4 Results of meta-analysis of relevant technology

This section reports on results of Qualitative analysis of relevant technology.

3.4.1 Parameters for comparison

To achieve the evaluation of categories as shown in the design criteria in Table 10, a list of parameters were identified for detailed, Qualitative analysis. Any information concerning these parameters were captured in an extensive Excel spreadsheet for analysis.

Table 15 lists a summary of these parameters, as well as the number of studies containing detail of the particular parameter. The table is split into 'Influent' and 'Effluent' parameters. The table is further sorted to show the most commonly reported parameters first.

Table 15 Parameters referenced in qualitative analysis

INFLUENT				EFFLUENT			
Parameter	Unit	No of studies referenced		Parameter	Unit	No of studies referenced	
Chemical Oxygen Demand (COD)	mg/l	19	76%	Chemical Oxygen Demand (COD)	% reduction	19	76%
Volume reported		15	60%	Chemical Oxygen Demand (COD)	mg/l	15	60%
pH		14	56%	pH – Value at 25°C	mg/l	7	28%
Temp		11	44%	Ammonia	% reduction	6	24%

INFLUENT				EFFLUENT			
Parameter	Unit	No of studies referenced		Parameter	Unit	No of studies referenced	
Conductivity	uS/cm	7	28%	Electrical Conductivity at 25°C	% reduction	5	20%
NH ₄ -N	mg/l	6	24%	Sodium (Na)	% reduction	5	20%
Pressure (membranes)	kPa	6	24%	Ammonia	mg/l NH ₃ as N	4	16%
TN		6	24%	Biological Oxygen Demand (BOD)	mg/l	4	16%
Cl	mg/l	5	20%	Electrical Conductivity at 25°C	m/S/m	4	16%
HRT	days	5	20%	Sodium (Na)	mg/l	4	16%
MWCO	Dalton (Da)	5	20%	Phosphate (PO ₄ as P)	% reduction	3	12%
Na	mg/l	5	20%	Suspended Solids	mg/l	3	12%
BOD / COD		4	16%	Suspended Solids	% reduction	3	12%
SS	mg/l	4	16%	Biological Oxygen Demand (BOD)	% reduction	2	8%
TP		4	16%	Phosphate (PO ₄ as P)	mg/l	2	8%
BOD		3	12%	TN reduction	%	2	8%
PO ₄ -P		2	8%	TP reduction	%	2	8%
Organic loading rate (OLR)	kg COD /m ³ /d	1	4%	Dissolved Oxygen (DO)	mg/l	0	0%
Volume potable purchased		0	0%	Fluoride (F)	mg/l	0	0%
				Sludge production		0	0%

As eluded to in Section 1.5, brewery wastewater is regarded as a strong wastewater containing high concentrations of COD. The notion that the treatment of COD in brewery wastewater is the guiding principle governing treatment solutions for brewery wastewater is clearly confirmed in Table 15 by illustrating that most of the literature on brewery wastewater was referring to COD. In fact, the literature sources referred to that had no reference to COD were of a financial nature only.

3.4.2 COD reduction

As discussed in the previous section, reduction in levels of COD is the guiding principle governing the treatment solutions for brewery wastewater. To achieve potable standards acceptable for the food industry, it is imperative that COD is completely removed, i.e. a 100% reduction⁶. From the results shown in Table 16, only a handful of technologies claim to remove 100% of COD. All of these include membrane technology. It is important to note, however, that the same technologies, in other consulted studies, report less than 100% reduction in COD.

Table 16 Reported COD reduction

	Technology	COD influent	COD effluent	% Reduction
62	NF & RO, following primary & secondary treatment	1,786	0	100%
1655	NF, flat membrane UTC-20 (Toray, Japan)	Initially, 2800 - 8700, 72, post CAS & UF	0	100%
1655	NF flat membrane UTC-60 (Toray, Japan)	Initially, 2800 - 8700, 53, post CAS & UF	0	100%
1655	NF flat membrane Desal-HL-51 (Osmonics, USA)	Initially, 2800 - 8700, 46, post CAS & UF	0	100%
1655	NF flat membrane Desal-5-DK (Osmonics, USA)	Initially, 2800 - 8700, 43, post CAS & UF	0	100%
125	Fortified clay, Double column treatment (DCT), lab scale	729	10	99%
1422	Lab scale SAnMBR 0.04 um (GE Water and Process Technologies,	17,000	171	99%
1486	Mg-sericite flocculant	1,250		99%
1437	Pilot scale external crossflow UF AnMBR	8000 - 9000		97%
1581	Electrochemical	2,470	64	97%
3	CNTs added to coagulation/flocculation tanks and filter bed	597	24	96%
1657	MBR + RO	Initially, 2000 - 2500, 500 - 1000, post UASB	<40	96%

⁶ Chapter 1, Table 5, lists COD <15mg/l as acceptable for reuse.

	Technology	COD influent	COD effluent	% Reduction
1660	MFC, double chamber, air cathode	1,249	54	96%
24	NF flat, Koch membrane, MPS-34	2,945	194	93%
1462	Electrocoagulation (EC) using Alternating Pulse Current (APC) Labscale	3,440		90%
141	Fungi treatment, T. Harzianum	5,567	612	89%
32	Pilotscale external ocrossflow UF AnMBR	425	51	88%
1659	MFC, single chamber, air cathode	2,250	292	87%
1437	Lab scale Exoanded Granular Sludge Bed	7,300 & 5,200		85% & 73%
1587	UF-Bioreactor (MBR)			82%

The following section (Section 3.5) will discuss each of these technologies in more detail, highlighting the advantages and disadvantages of each.

3.4.3 Financial analyses

As described in Chapter 2, the majority of studies did not include actual financial data. Figure 15 illustrates only 30% and 25% of studies scored 3 and above for the parameters - capital cost and operational cost respectively.

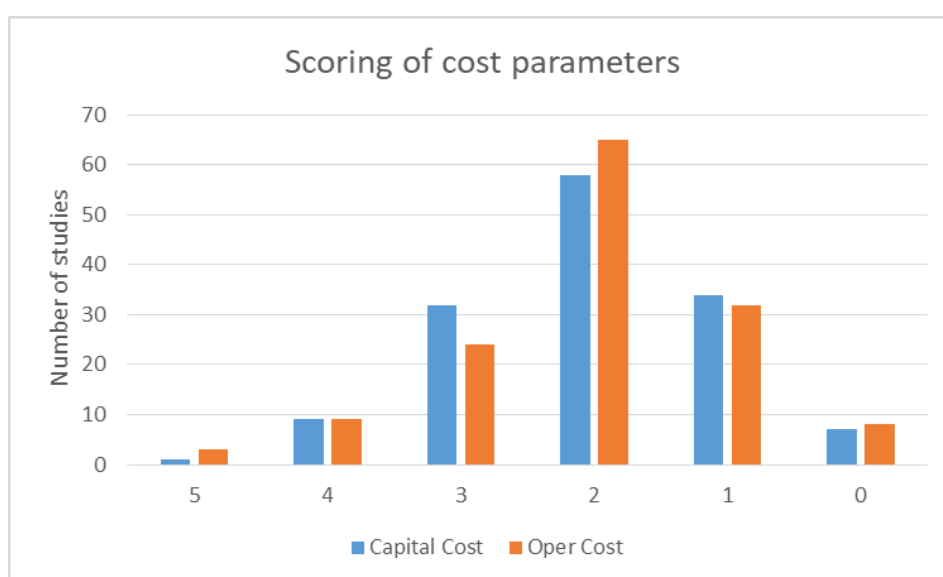


Figure 15 Scoring of cost parameters of studies for full review

Almost all alluded to the importance of proper financial information before implementation. One of the main reasons given for lack of financials was the fact that their study reported on work done either in a laboratory or at pilot scale and would not accurately reflect cost at full scale. Table 17 lists the sources that included breakdown of capital and O&M cost of described technologies.

Table 17 List of studies with cost data for analyses

Endnote ref no	Document title	Source	Reference
#58	The costs of direct and indirect potable water reuse in a medium-sized arid inland community	Journal of water process engineering	(Herman et al., 2017)
#46	Wastewater Reclamation for Potable Reuse	Water Research Commission	(Metcalf et al., 2014)
#32	Feasibility evaluation of submerged anaerobic membrane bioreactor for municipal secondary wastewater treatment	Journal: Desalination	(Lin et al., 2011)
#1509	Present situation of wastewater treatment in the Iranian industrial estates: Recycle and reuse as a solution for achieving goals of eco-industrial parks	Journal: Resources, Conservation and Recycling	(Piadeh et al., 2014)
#1462	Treatment of brewery wastewater with electrocoagulation: Improving the process performance by using alternating pulse current	International Journal of Electrochemical Science	(Eyvaz, 2016)

In order to compare, the net present value (NPV) was calculated using standard formulas used for decades to compare NPV (McCulloch, 1936)

$$FV = PV(1 + r)^T$$

FV = Future value

PV = Present value

r = nominal interest rate / return on capital

T = number of accounting periods

$$AF_T = \frac{(1+r)^T - 1}{r(1+r)^T}$$

AF = Annuity factor

T = number of accounting periods

r = nominal interest rate / return on capital

The nominal interest rate (r), was calculated using an average from published annual interest rates of the years from study date to 2017, as

found at www.tradingeconomics.com, for the relevant country. The table below summarises the annual interest rates used.

Table 18 Annual interest rates per country

	USD US Dollar	ZAR South African Rand
2001	8.617	10.917
2002	10.539	12.333
2003	7.584	11.417
2004	6.4616	7.833
2005	6.3806	7.125
2006	6.7796	7.667
2007	7.0625	9.667
2008	8.264	11.542
2009	8.444	8.250
2010	7.3324	6.333
2011	7.2702	5.500
2012	8.2206	5.250
2013	9.6588	5.000
2014	10.8605	5.625
2015	12.7721	5.917
2016	14.7129	6.958
2017	13.3209	6.75

Source: www.tradingeconomics.com (Trading Economics, 2018)

Once the value was grown to NPV, it was converted to ZAR, using the following exchange rates:

- 1 USD = 13 ZAR

Although studies were from different countries, the only reported currencies used were USD and ZAR.

This study followed the same comparative approach as Piadeh et al. (2014). In Piadeh's study the capital and O&M cost of 8 advanced treatment schemes for potable reuse were compared. For O&M cost, actual annual totals were used. When investigating these figures, it can be seen that the plants were not operated at full capacity every day of the year. Days at full capacity ranged from 98 – 256 with an average of only 175 days per year at full capacity. Following suit and for reasonable comparative results, where only operational unit cost, per m³, was reported the author has conservatively assumed annual operation at full capacity on 250 days. When only a total annual cost was given, operation at full capacity on 150 days were assumed.

Table 19 summarises the available financial information found in studies selected for detail review. The final values for comparison are:

- NPV Capital cost / m³
- NPV O&M cost / m³
- The annual operational cost for a plant of 5Mℓ/day, the capacity of current target brewery.

Unfortunately not all of the studies used for financial comparison included sufficient information on quality of effluent achieved.

Table 19 Comparison of capital and operational NPV

Reference	Study location	Advanced treatment	COD		pH	TSS		Capacity m ³ /day	Capital cost, 2017		Operational cost, 2017	
			mg/l	% reduction		mg/l	% reduction		NPV	Capex / m ³	Opex / m ³	Annual value for 5 Ml /d
(Piadeh et al., 2014)	Shokuhiye, Iran	SF + MBR + O ₃ + AC + RO	264	100%	8.10	134	100%	300	R8,502,510	R28,341.70	R20.19	R21,952,786
	Aq-qala, Iran	SF + MBR + AC + RO	111	100%	7.78	64	100%	170	R10,062,615	R59,191.85	R31.50	R26,041,046
	Semnan, Iran	SF + MBR + AC + RO	106	100%	7.63	70	100%	350	R8,502,510	R24,292.89	R17.33	R18,816,674
	Murche khurt, Iran	SF + UF + AC + RO	158	100%	7.82	17	100%	500	R14,727,708	R29,455.42	R12.96	R7,949,722
	Bushehr 2, Iran	DAF + MF + AC + RO	56	100%	7.86	193	100%	300	R8,737,762	R29,125.87	R28.33	R36,252,239
	Shahid Salimi, Iran	C&F + O ₃ + AC + MF + RO	200	100%	6.87	60	100%	660	R12,538,256	R18,997.36	R11.45	R9,312,923
	Mobarake, Iran	SF + MF + AC + RO	114	100%	7.33	50	100%	500	R25,482,212	R50,964.42	R25.62	R19,612,831
	Oshtorjan, Iran	SF + MBR + O ₃ + AC + RO	100	100%	7.50	122	100%	354	R19,290,321	R54,492.43	R21.70	R10,655,825
(Lin et al., 2011)	China	Retrofit membranes to have external ocrossflow UF AnMBR	425	88%	7.60	294	100%	20,000	R255,813,764	R12,790.69	R1.25	R1,565,527
	China	Retrofit membranes to have external ocrossflow UF MBR						20,851	R266,698,640	R12,790.69	R4.21	R5,257,254
(Herman et al., 2017)	New Mexico	RO (following CAS)						5,000	R543,012,679	R108,602.54	R2.50	R1,872,168
	New Mexico	O ₃ / BAC (following CAS)						5,000	R362,008,453	R72,401.69	R0.08	R59,468
(Metcalf et al., 2014)	Darvil, RSA	MBR + RO + UV		100%			100%	100,000	R1,078,357,040	R10,783.57	R2.83	R4,558,029
	Darvil, RSA	MBR + O ₃ /GAC + NF + UV		100%			100%	100,000	R1,148,734,026	R11,487.34	R3.33	R5,343,418
(Eyvaz, 2016)	Turkey	Electrocoagulation (EC) using Alternating Pulse Current (APC) Labscale		90%	6.9			1	no data		R18.48	R23,097,750

SF: Sand Filter; C&F: Coagulation & filtration; DAF: Dissolved air flotation; MBR: Membrane bio reactor; MF: Micro-filter; RO: Reverse Osmosis; AC: Activated carbon; BAC: Biologically activated carbon; O₃: Ozonation

The studies reported on a wide range of operational capacity, from 0.17 Mℓ/day to 100 Mℓ/day. It is also apparent that the data displays a wide variability for capital and O&M costs. Similar results found by Herman et al. (2017) were thought to be because of unknown variables included or excluded such as chemical addition, full energy costs, inclusion of all treatment components, etc.

As this study's interest is in advanced technology for treatment of secondary effluent to potable standards, the anyalysis below only includes the technology for which 100% reduction in COD was reported. Figure 16 and Figure 17 illustrates firstly the Capex cost per m³ for the smaller plants and then the same information adding the only other plant (100 Mℓ/day capacity) reporting 100% reduction in COD. The graphs were split to accommodate the different scales needed as the capacity ranges are significantly different.

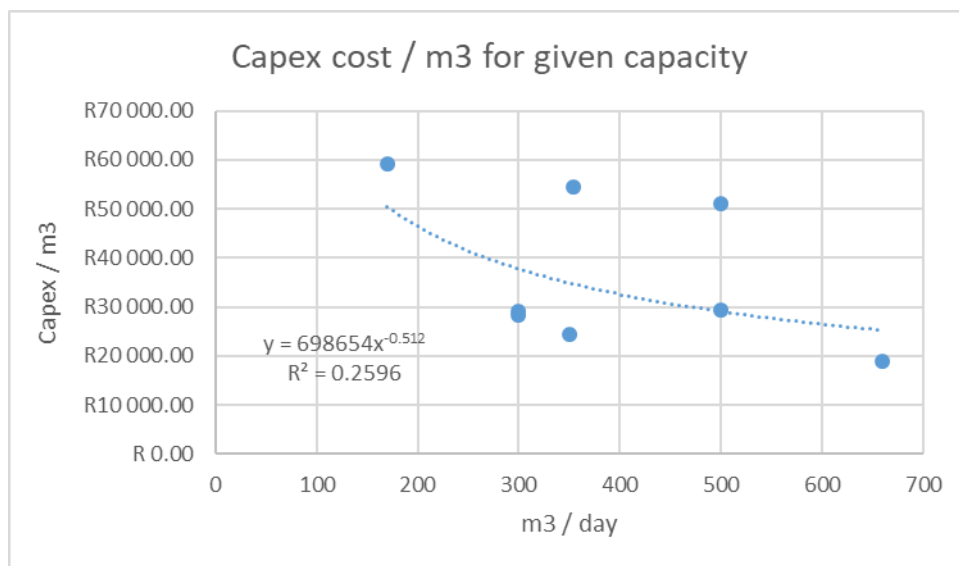


Figure 16 Capex cost / m³ for smaller plant capacities

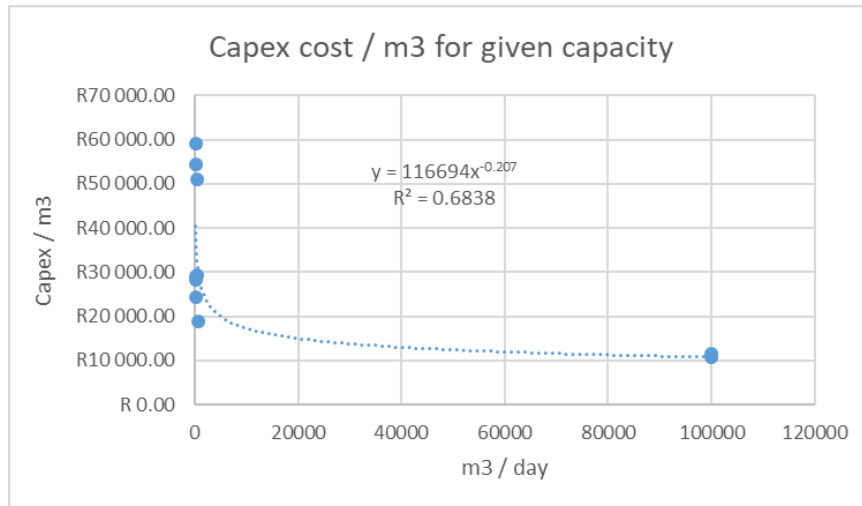


Figure 17 Capex cost / m³ for all plants reporting 100% reduction of COD

Figure 18 and Figure 19 illustrates firstly the Opex cost per m³ for the smaller plants and then the same information adding the only other plant (100 Ml/day capacity) reporting 100% reduction in COD. The graphs were split to accommodate the different scales needed as the capacity ranges are significantly different.

In both cases (Opex and Capex) the R² value of the second graphs match the line of regression sufficiently to propose using the formula for future estimates of Capex and Opex works, where similar technology is considered.

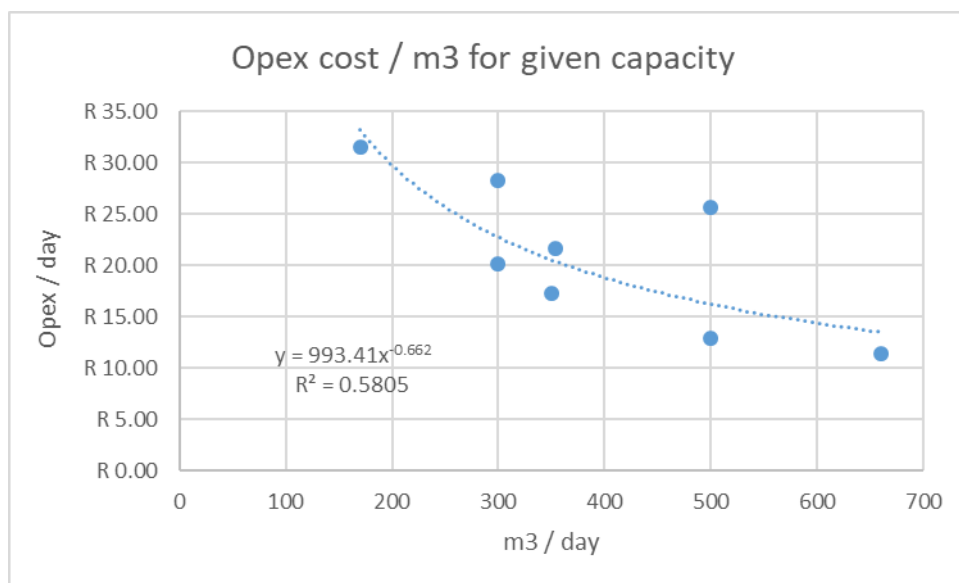


Figure 18 Opex cost / m³ for smaller plant capacities

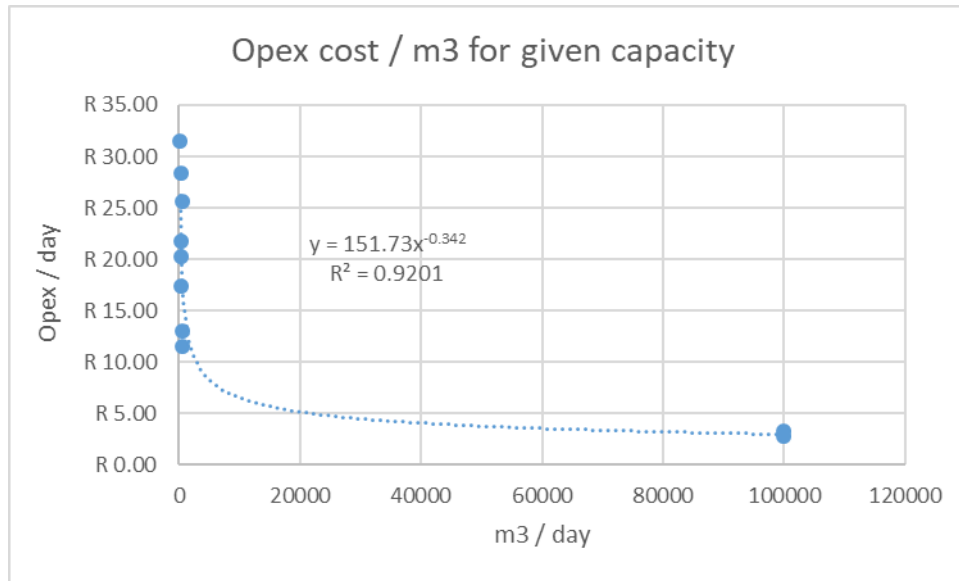


Figure 19 Opex cost / m³ for all plants reporting 100% reduction of COD

3.4.4 Feasibility

Business Directory (n.d.) defines 'Life cycle cost' as the sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life. When selecting the appropriate treatment technology, it is important to compare the full life cycle cost of different options.

For example, Gude et al. (2010) found the full life cycle cost to produce potable water from treatment of secondary municipal effluent, using RO technology, half the cost of desalination from seawater (SWRO).

Operational cost to consider within life cycle cost of a brewery, includes:

- cost of energy: aeration and permeate suction / backflush when membranes are used. Cost of energy amounts to around 80% of total operational cost (Lin et al., 2012)
- sludge and / or brine treatment and disposal

- chemicals
- staff
- building maintenance
- equipment maintenance
- supervisory control and data acquisition (SCADA) systems and instrumentation
- laboratory and monitoring work
- replacement of membranes
- purchase price of water
- cost / penalties to discharge non-compliant effluent to the environment (Herman et al., 2017; Lin et al., 2012; Gude et al., 2010)

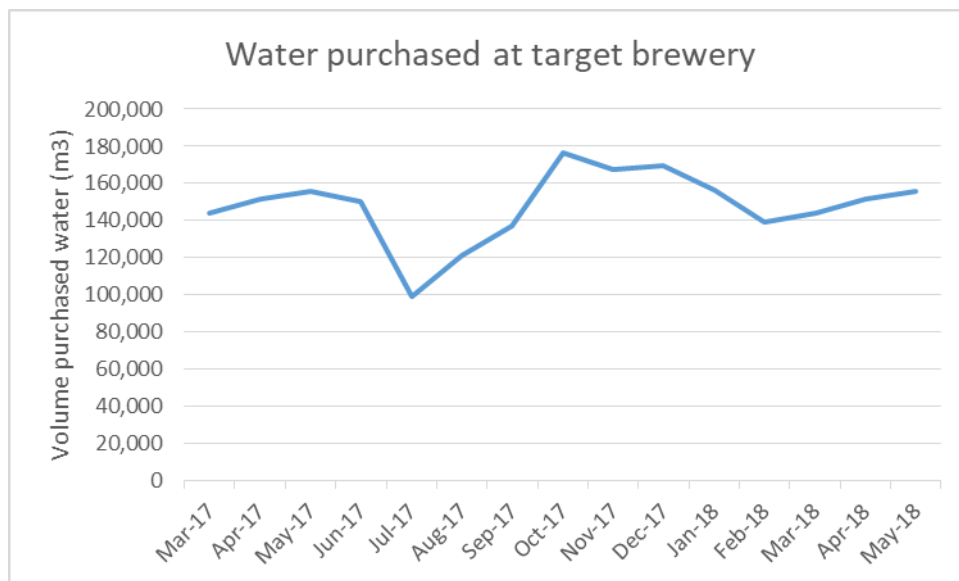
Especially where the last two mentioned costs are very high, the cost of treating wastewater for reuse can become economically feasible through offset of initial capital investment and O&M cost by reuse. Return on investment of less than five years have been reported (Li et al., 2015; 2030 Water Resources Group, 2015).

At the Polar Brewery in Venezuela, Bennett (2014) reports a 'very limited time' for return on investment on vertical, tube-shaped UF membrane modules positioned on the exterior of the bioreactor. Bennet further reports recycling wastewater in the cleaning and rinsing process of the brewery, released potable water for production not otherwise available from their supplier, which in turn increased beer production to meet its market demands. shows the volume and cost of water purchased by this study's target brewery from March 2017 – May 2018.

Table 20 Cost of purchased water at target brewery

Month	Volume purchased (m ³)	R/m ³	Cost in Rands	Comments
Mar-17	144,260	7.64	1,102,182	
Apr-17	151,370	7.64	1,156,504	
May-17	155,480	7.64	1,187,906	
Jun-17	150,335	8.41	1,264,317	
Jul-17	99,240	8.41	835,042	Shut down
Aug-17	121,245	8.41	1,019,670	
Sep-17	136,900	8.41	1,151,927	
Oct-17	176,200	8.41	1,482,611	Peak
Nov-17	167,780	8.41	1,411,763	Peak
Dec-17	169,560	8.41	1,426,740	Peak
Jan-18	156,680	8.41	1,318,363	Peak
Feb-18	139,157	7.64	1,063,159	
Mar-18	144,260	7.64	1,102,182	
Apr-18	151,370	7.64	1,156,504	
May-18	155,480	7.64	1,187,906	

Figure 20 clearly shows the typical seasonal variation as beverage demand declines in colder months.

**Figure 20 Water purchased at target brewery**

Regardless of season, breweries are completely dependent on the availability of water for their business.

Figure 21, as cited by Götz et al. (2014), illustrates the increase in cost of wastewater treatment as the dependence on an external water service provider decreases. At the same time the reduction in water consumption is only possible when technical effort increases. The pivotal factor in this delicate balance is undoubtedly the availability of water to accommodate the market's demand.

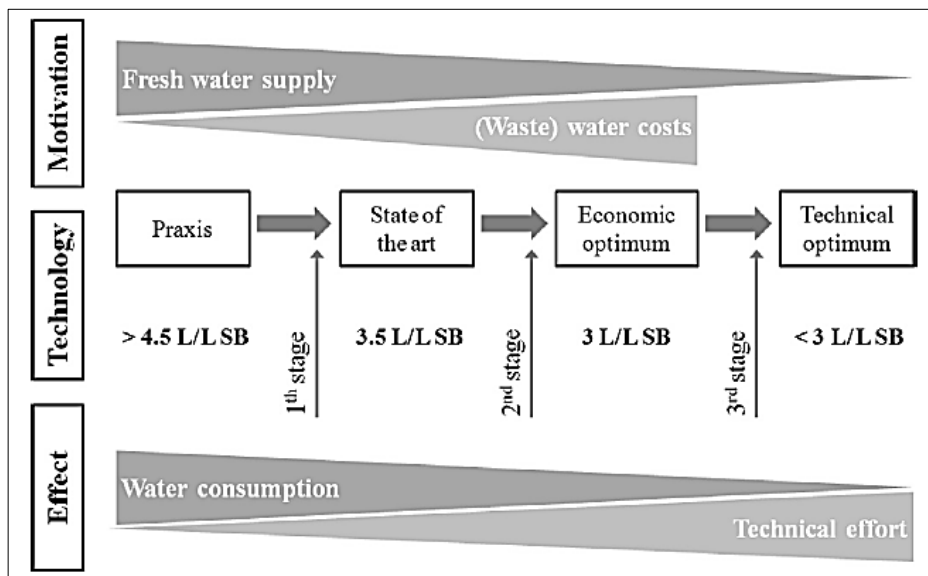
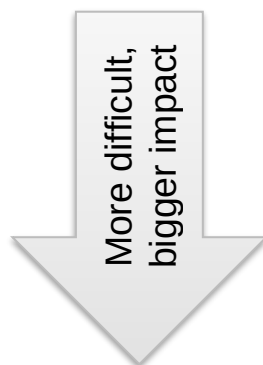


Figure 21 Development stages of water management in breweries (Götz et al., 2014)

When analysing the cost and difficulty of implementation against the gains, BrewersAssociation (2011) found the following order of impact:



- Adjust water flow
- Modify existing equipment or install water-saving devices
- Change to more water-efficient equipment
- Reuse of recycle water (treat, if needed)
- Shift to a low-water or waterless process

With this increasing impact in mind, when considering wastewater reuse for industrial use, Edwards et al. (2013) recommended the following initiatives to support decision making before full-scale interventions:

- Onsite piloting trials must be conducted to provide long-term optimisation and scalability data;
- Cleaner production and waste minimization audits should be conducted in parallel to capitalize on increased long-term savings potential;
- Stream segregation analysis should be implemented during the latter phases of pilot trials if a decision to implement a treatment strategy at full-scale is considered;
- Full-scale implementation should be done using a modular approach to match expansion requirements when necessary;
- Based on the calculated OPEX savings potential, overall savings taking into account full-scale CAPEX and OPEX should translate into an ROI/ROC period of approximately 5-7 years with an overall savings potential of 25-50% calculated on a cost-per-kL basis calculated over the 10-year operating period (NOTE: this excludes any additional savings related to implementing cleaner production and waste minimisation audits which would optimise raw material usage, energy requirements, and production manufacturing.)

3.5 Technologies applied in treating brewery wastewater

This section aims to give an overview of relevant technology with specific reference to its application in advanced treatment of brewery wastewater. It is by no means an exhaustive discussion of the technology.

3.5.1 Membranes: MF, UF, NF and RO

Metcalf & Eddy (2014) define a membrane as a device, usually made of an organic polymer, that allows the passage of water and certain constituents, but rejects others above a certain physical size or molecular weight.

Usually, the pore size of membranes guides the categorisation of membranes, and divides them into four categories from largest to smallest

pore size: microfiltration, ultra-filtration, nanofiltration and hyperfiltration. Similar to the pore-size classification, nominal molecular weight cut-off (MWCO) can also be used to characterise a membrane, and is often preferred when describing nanofiltration membranes. Some overlap can be found between the different categories. Besides the pore size classification, membranes can also be classified according to the material they are made of, with three major categories being polymeric, metallic, and inorganic (ceramic). Amongst the most widely used materials are celluloses, polyamides, polysulphone, charged polysulphone and other polymeric materials such as polyacrylonitrile (PAN), polyvinylidene difluoride (PVDF), polyethylsulphone (PES), polyethylene (PE), and polypropylene (PP). The polymeric materials have a desirable chemical and physical resistance, but are also hydrophobic. As most interactions between the membrane and the foulants are hydrophobic in nature, hydrophobic membranes are more prone to fouling than hydrophilic ones. All commercially available membranes are therefore modified by chemical oxidation, organic chemical reaction, plasma treatment, or by grafting to achieve more hydrophilic surface. This modification process, as well as the method of fabrication, usually differentiates one membrane from another (Radjenović et al., 2008; Simate et al., 2011).

The table below, as cited by Simate et al. (2011), lists typically important characteristics when considering membranes for wastewater treatment.

Table 21 Typical characteristics of membrane processes

Process	Operating pressure (bar)	Pore size (nm)	Molecular weight cut-off (MWCO) range	Size cut-off range (nm)
Microfiltration	<4	100–3000	>500,000	50–3000
Ultrafiltration	2–10	10–200	1,000–1,000,000	15–200
Nanofiltration	5–40	1–10	100–20,000	1–100
Reverse osmosis (hyperfiltration)	15–150	<2	<200	<1

Source: The treatment of brewery wastewater for reuse: State of the art (Simate et al., 2011)

Further illustrating the concept of pore size and associated rejection, is the diagram below from Seneviratne (2006)

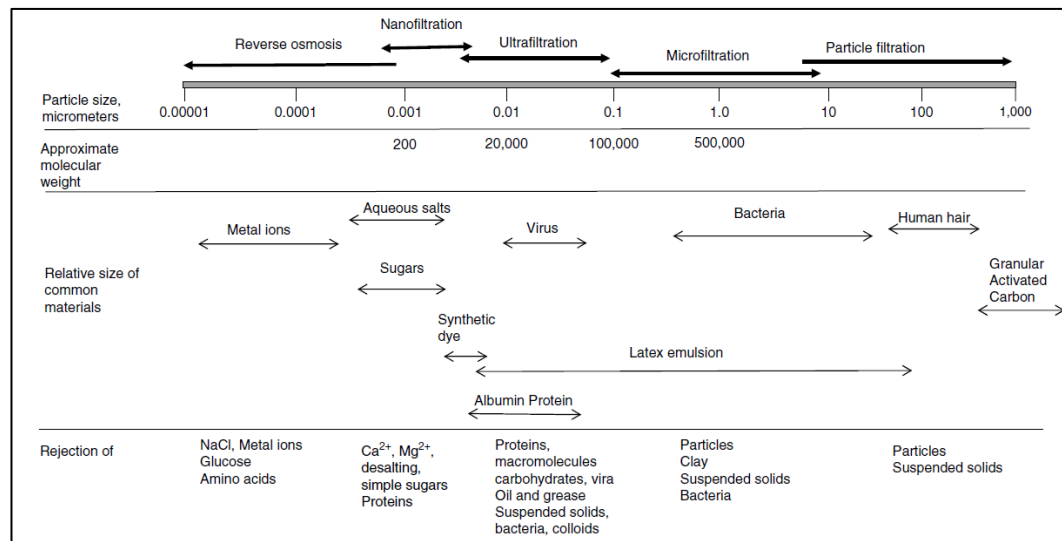


Figure 22 Tangential filtration chart (Seneviratne, 2006)

Different membrane and process configurations are available from a growing number of manufacturers. The table below illustrates those commonly available currently, globally.

Table 22 Membrane and process configurations

		Process Configuration	
		Submerged	Sidestream
Membrane Configuraton	Flat Sheet (FS)	Brightwater Toray Kubota	Novasep-Orelis
	Hollow Fibre (HF)	Asahi-Kasei Koch Puron Mitsubishi Rayon Pall Corporation Siemens Memcor Zenon	
	Multitube (MT)	Millennimpore	Norit-Xflow

Source: Wastewater Reclamation for Potable Reuse (Metcalf et al., 2014)

The use of membranes include a number of notable advantages in the brewing industry, including compact design (reduced footprint), ease of operation and short start-up period (Seneviratne, 2006; Edwards et al., 2013).

Although the use of membranes for advanced treatment has grown significantly, there still remains operational challenges of which the most troublesome is membrane fouling. The treatment of wastewater upfront of the membranes, either at generation (split source) or combined wastestream, is critical to ensure efficient and viable functioning of membranes (Dizge et al., 2018; Simate, 2015; Götz et al., 2014). In fact, Braeken et al. (2004) reports that membranes on their own, without secondary biological treatment, can not produce effluent for reuse consistently.

A number of studies investigated new and / or combinations of coagulation / flocculation prior to the membranes to enhance membrane performance. Section 3.5.6 has some discussion on the use of Mg-sericite as flocculant for brewery wastewater treatment (Choi, 2015). It has also become a fairly common practice in wastewater treatment and water reclamation plants to use a combination of membranes in series of decreasing poresize. This configuration gradually reduces the pollution load and minimises fouling along the way. Membrane treatment requires high pressure, with resulting high energy demand, to push water through membranes. Range of 7 – 14 bar is reported while generally, performance improves as pressure increases. (Gude et al.; 2010, Hafez et al.; 2007, Alnouri et al., 2018). Besides improved effluent quality, the combination of membranes also reduces the pressure, number of backwash cycles and chemical cleaning required, which in turn reduces the overall operational cost (Li et al., 2015)

Besides fouling, the greatest concern when using membranes for water treatment, is the generation of brine. Typically only 60% of the water is recovered for reuse, while a concentrated brine (reject) is generated. When considering the use of membranes, careful consideration is needed to either treat or dispose of the brine. Implementing options for Zero Liquid Discharge (ZLD) resulted as a solution to the problem of brine generation. (Alnouri et al., 2018).

3.5.2 Membrane bioreactors (MBR)

Since the 1960s, membrane treatment technology focused on advanced treatment of secondary effluents to improve effluent quality. However, from around the turn of the current century, Membrane Bioreactors (MBRs) have emerged as an advanced treatment technology, incorporated in secondary treatment (Radjenović et al., 2008).

Metcalf & Eddy (2014) defines MBR as a process that combines a suspended growth process with a membrane separation system within the process aeration tank; membrane separation is accomplished by either microfiltration or ultrafiltration.

As illustrated in Figure 23, one of the advantages of a MBR system, is significant reduction in footprint, as compared to conventional activated sludge (CAS) wastewater treatment process. The CAS treatment process typically comprises of a multi-step process involving more space, facilities and chemicals and longer operating time. MBR simplifies the process by combining the activated sludge with the membrane filtration process in one bioreactor. Some of the advantages of this combination includes higher biomass concentration and less sludge carry-over. The reduced biomass concentration results in a more compacted system with smaller footprint, while the decrease in sludge carry-over simplifies the polishing step before either discharge or reuse. This has led to a significant growth in global demand for MBR systems for the treatment of both industrial and municipal wastewater (Ji et al., 2015).

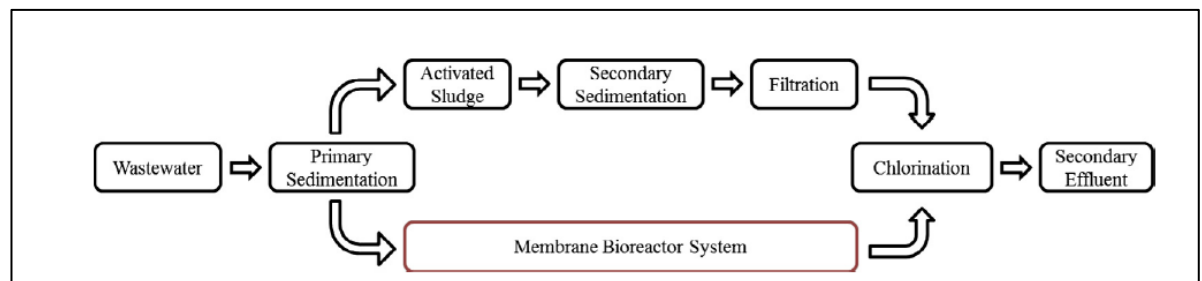


Figure 23 MBR process flow compared to conventional process (Ji et al., 2015)

As illustrated in Figure 24, different membrane configurations for MBR systems are possible: submerged in the biological reactor, external as a

separate system or in airlift configuration (Lin et al., 2012; Labs, 2015; Seneviratne, 2006).

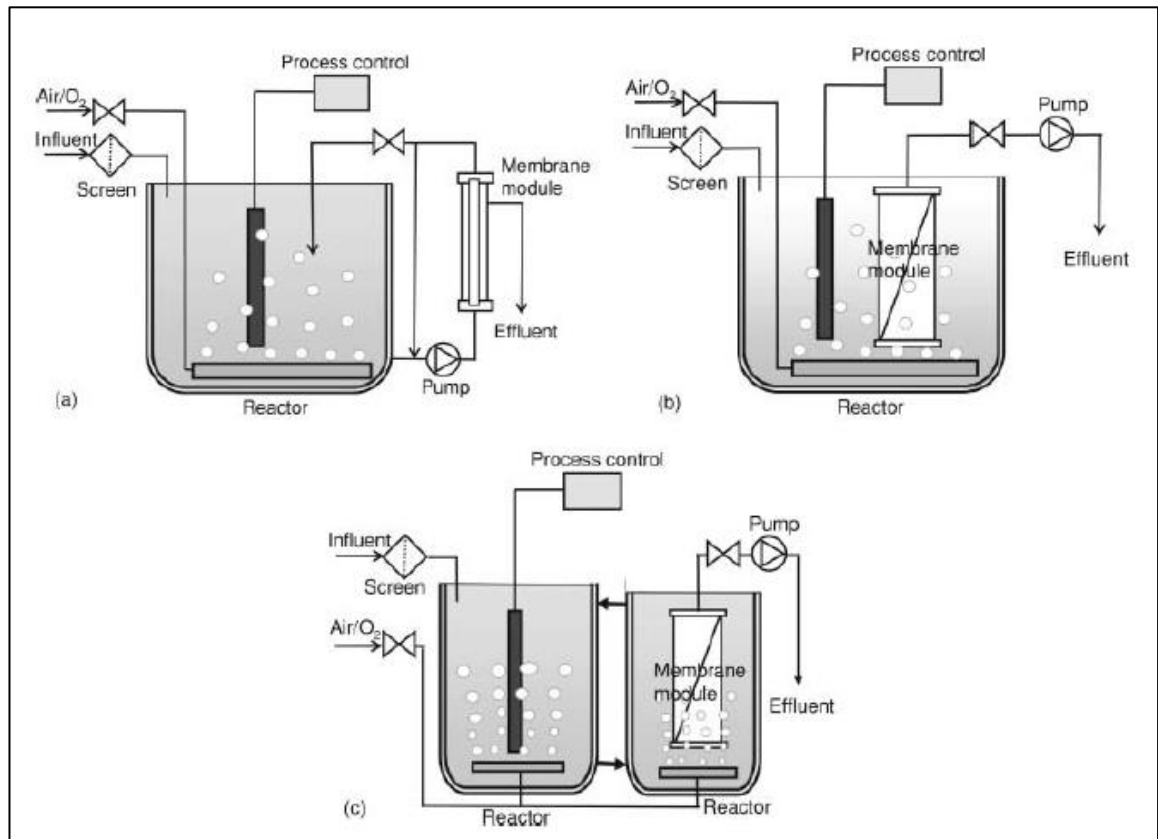


Figure 24 Illustration of membrane configurations for MBRs
a) External configuration; b) Submerged configuration; c) Airlift configuration (Lin et al., 2012)

It has been found that industrial wastewaters, such as brewery wastewater, characterized by high temperature, high organic strength, extreme pH, high toxicity, and low filterability, are more suited to external MBRs.

A significant development in MBR technology for food industry wastewater treatments, was the submerged anaerobic MBR (AnMBR). Similar to MBR, the AnMBR also boasts significantly reduced footprint requirement, stable operation and providing 3–5 times the biomass concentration of the conventional digesters.

Lin et al. (2012) reports on a number of different reactors that have been tested using MBRs for industrial wastewater. These include Continued

stirred tank reactors (CSTR), plug-flow reactors (PFR), sequencing batch reactors (SBR) and Uplow anaerobic sludge blanket reactors (UASB).

As mentioned in the previous section, up-stream (or secondary) treatment of high strength wastewater is critical prior to membrane filtration. Aerobic MBR treatment has been found by a number of food industry users to be sufficient on its own to prepare wastewater for Reverse Osmosis (RO) systems (Labs, 2015). Through comparison in a laboratory of effluent from an anaerobic reactor with, and without a submerged membrane, it was found that the membrane increases overall COD removal from brewery wastewater by around 10% (Chen et al., 2016)

3.5.3 Carbon nanotubes

Simate et al. (2011) describes Carbon nanotubes (CNTs) as honeycomb structures of graphene sheets rolled up into cylinders with a diameter of a few nanometers. It has a length of several micron or even centimeters. Many methods and carbon sources for the growth of CNTs have been pursued in the past few years. The two typical forms of CNTs are single-walled CNT (SWCNT) and multi-walled CNTs (MWCNT) and differ in the number of rolled up graphene layers that form the tube.

CNTs unique properties can be attributed to their special atomic and electronic structures which make them useful in a number of water treatment applications, described below:

Nanosorbents

Carbon nanotubes have shown exceptionally good adsorption capability and high adsorption efficiency for various organic pollutants, inorganic pollutants such as fluoride and heavy metals. The CNTs effectiveness as adsorbent can be explained because of their hollow and layered structure giving them a large surface areas while very small in size. They can be used with various chemical groups to increase their affinity towards target compounds. CNTs can adsorb various impurities from wastewater which can be extended to the removal of COD from brewery wastewater.

Besides adsorbent, CNTs are also a functional coagulant and can therefore effectively be applied to the treatment of brewery wastewater to remove dissolved organics by adsorption, and suspended solid organic by heterogeneous coagulation (bridging and neutralization), simultaneously.

Although CNTs effectiveness has been proven in a laboratory, traditionally used ferric chloride was found to be a more effective coagulant in the treatment of brewery wastewater than both the pristine and functionalised CNTs. Other challenges in using CNTs include its lack of dispersion and solubility, excessive cost and most notably its potential impact on human health and ecosystems due to its nano-size. They may be able to enter the human body through the skin, lung and gastrointestinal tract. They could rapidly pass through the blood circulation system and accumulate in the lungs, liver, and bladder. This is not only true for CNTs but also for many other chemicals and therefore the critical importance to use all treatment chemicals within water regulation guidelines. (Simate et al., 2011; Simate et al., 2012a; Simate et al., 2012b).

Nanofilters

CNT filtration membranes consist of hollow cylinders with radially aligned carbon nanotube walls. Billions of these tubes act as the pores in the membrane. CNTs also displayed super-hydrophobicity and super oleophilicity, which gives CNTs excellent separation ability, ideal for hydrophobic and oleophilic liquids such as high strength, in terms of COD, brewery wastewater. It was also found to improve a column sandfilter when sandwiching CNTs within the sandfilter. No CNTs were found in the effluent. Its absence was important to not effect human health (Simate et al., 2011; Simate, 2015)

3.5.4 Advanced oxidation

Advanced oxidation processes (AOPs) can be used to treat and eliminate trace constituents that can't be completely oxidized by conventional oxidants. They have been found very effective in degrading recalcitrant pollutants.

Unlike conventional treatments which either separate the pollutants from the wastewater stream or convert them to some intermediate compounds, AOPs mineralize organic pollutants to water (H_2O) and carbon dioxide (CO_2). Typical AOPs include Fenton and Fenton-like processes, photocatalysis, electrochemical oxidation, Ozonation and ultrasound cavitation. AOPs use strong oxidizing agents such as Ozone (O_3), Hydrogen Peroxide (H_2O_2) and/or catalysts like Fe, Mn and TiO_2 , typically joined with high energy radiation, e.g. UV irradiation. AOPs predominantly involve the generation of a powerful and non-selective oxidizing specie, the hydroxyl radical ($OH^\bullet$) for the destruction of recalcitrant and often hazardous pollutants (Metcalf & Eddy, 2014). Studies have shown the enhancement of H_2O_2 's organic degradation efficiency when combined with UV due to $OH^\bullet$ generation caused by the photolysis of H_2O_2 , the so-called photo-Fenton process (de Sena et al., 2009).

A significant advantage of this complete degradation caused by AOPs, is the absence of a secondary waste stream or sludge. Despite their advantages, there are still many disadvantages to these methods, such as the need for large amounts of chemicals and high energy consumption which has a direct impact on the cost of the operation as well as the surrounding environment (Kahoush et al., 2018).

Ozonation is a well established technology and it has been the focus of attention in literature in the last few years as an option for advanced wastewater treatment (Bello et al., 2017; Metcalf & Eddy, 2014). Ozone is an expensive oxidant, but its ability to mineralize organic matter, alone or in combination with hydrogen peroxide, is attractive for wastewater reuse purposes (Munoz et al., 2009).

The choice of a reactor is also important to ensure all chemical reactions needed for the generation of oxidant. Reactors such as fluidized bed reactor (FBR) have been described as effective reactors for AOPs (Bello et al., 2017).

3.5.5 Microbial Fuel Cells (MFCs)

One of the most promising technologies in the field of wastewater treatment coupled with renewable energy production is Microbial Fuel Cells (MFCs). Because MFCs don't need an external energy supply, they have the potential to be energy self-efficient. Moreover, MFCs allow for direct clean electricity production, with no additional conversion needed.

Zinadini et al. (2017) describes the typical structure of traditional MFCs as consisting of two chambers, an anaerobic anodic chamber and an aerobic cathodic chamber. These are separated by a proton exchange membrane (PEM) which is a selectively permeable membrane restraining diffusion of oxygen into the anode chamber, while allowing proton transfer from anode to cathode. Figure 25 illustrates the typical MFC configuration.

Microorganisms, in the anode chamber, oxidize organic matter producing protons and electrons. The electrons produced move through an external circuit to the cathode, forming the electrical current. The protons pass through the PEM membrane to the cathode chamber, where electrons, protons and electron acceptor, mainly oxygen, combine to produce water.

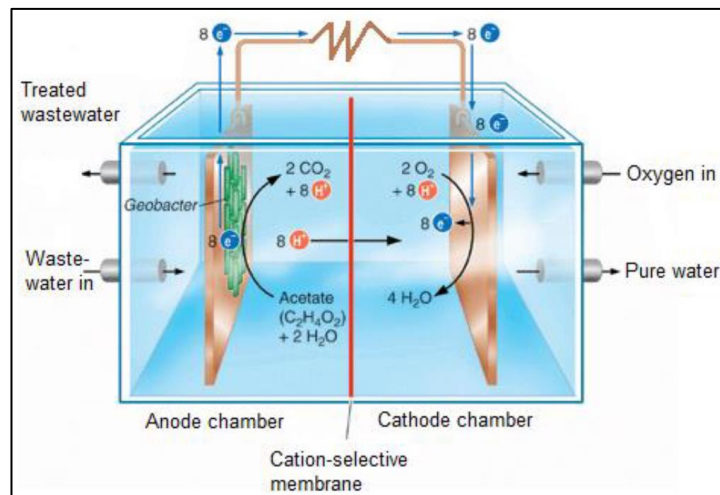


Figure 25 Schematic diagram of a conventional Microbial Fuel Cell (Lopez Zavala et al., 2014)

Besides its energy sufficiency, efficient treatment is possible across a broad COD range with reduced need for aeration. It has further been demonstrated that MFC systems can remove recalcitrant organics,

nutrients, sulphur compounds and metals. Another advantage is the very short start-up times with a stable power output within a few days, which is a much shorter time than for typical anaerobic digestion.

Despite dual function advantage of simultaneous wastewater treatment and generation of electricity, its high cost and low power density still prevents commercialization. In MFCs, the membrane plays a pivotal role determining its performance and significantly affects its overall cost and power density. The membrane must have good ability for exchanging protons. Besides the typical problems with membrane technology, as described in earlier section, such as high costs and biofouling, MFC membranes have further challenges such as oxygen leakage from the cathode to the anode chamber, cation transport and accumulation rather than that of protons and substrate losses.

MFC technologies still have the potential to become the most promising anaerobic treatment technique as they are more favorable to competitive anaerobic digestion (Zinadini et al., 2017; Toczyłowska-Mamińska, 2017).

3.5.6 Advanced flocculants

Magnesium (Mg)-sericite

The biopolymer, Magnesium (Mg)-sericite, was found to be a promising flocculant when treating brewery wastewater. At low doses, 98 – 100% COD removal was reported, which warranted inclusion of this flocculant with other advanced treatment technologies. A reduction of up to 99% of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ was also reported. The motivation to research the application of modified sericite in wastewater treatment includes its high specific surface area, chemical and mechanical stability, variety of structural and surface properties, higher values of cation exchange capacities, biocompatibility and attractive adsorption properties. It is a non-toxic, non-corrosive material that is safe to handle. Because it does not contaminate treated wastewater, it is safe to use for wastewater reuse.

Research results indicated that approximately 12.3 mg/L, 11.0 mg/L, 1.0 mg/L, 0.5 mg/L, 0.3 mg/L and 0.4 mg/L of COD, BOD, TN, NH₄-N, TP and PO₄-P were removed by 1 mg/L Mg-sericite, respectively.

Mg-sericite was more effective at COD and BOD removal compared to conventionally used alum and FeCl₃. Although polymer flocculants did require lower dosages for COD removal, the removal effect of Mg-sericite was greater than that of polymer flocculants (Choi, 2015).

Flocculent yeast: *Hansenula anomala* J224 PAWA

Following the anaerobic treatment (UASB) at the target brewery, the need remains to remove nutrients, phosphorus and nitrogen. Physicochemical treatment, such as precipitation, is needed. A flocculent yeast, *Hansenula anomala* J224 PAWA, bred as a mutant of the wild typ *H. anomala* J224 in a study to enhance the phosphorus-accumulating activity of *H. anomala* J224, accumulated twice as much phosphorus as the wild type. In a semi-batch continuous experiment this strain removed both phosphorus and the majority of organic matter from alcoholic distillery wastewater.

Over a 30-d period, PAWA removed 70–80% of dissolved total phosphorus while the wild type removed only 30%. Because PAWA cells resulted in large flocks that rapidly settled, sludge was easily seperated (Watanabe et al., 2009).

3.5.7 Fortified clay filtration

Various studies on raw and treated wastewater samples using fortified soil-clay columns reported that it had high potential for water and industrial wastewater treatment. The mineralogical assemblage, high surface area and plant morphology, all directly contribute to the treatment efficiency. It has the ability to closely pack in columns, serving as primary barriers to solids in the aqueous medium.

Clay samples, fortified with pebbles of aproximately 20mm diameter, have been used as a wastewater filter. The peblles were needed to increase flow rates as water does not drain through clay easily otherwise. The pebbles also served as inert media for microbial attachment.

Microorganisms are therefore partially retained in the system as the water passes through, assisting in the digestion of solids in the wastewater, thereby reducing the TS content.

Two types of cation exchange capacity (CEC) have been identified in clays. The first being permanent CEC, caused by isomorphous substitution and it predominates at pH below 6.0. The second, pH dependent CEC, predominates at pH above 6.0. During these cation exchange reactions, alkali earth metals and hydrogen ions can exchange for cationic pollutants in the aqueous phase. It was found that for treatment of the brewery wastewater, permanent CEC occurred more. At an optimal clay:pebbles ratio of 3:1, COD removal of between 78.15-95.98% was achieved.

When more than one fortified clay column is used, significant improvement in water quality could be achieved. Although the results showed that fortified soil-clays have potential to remove contaminants from industrial wastewater, further pilot scale studies are required to determine long term effectiveness of the media and to further develop the technology. (Oladoja et al., 2006)

3.5.8 Electrochemical treatment

The practise of utilising electricity to treat water was first proposed in the UK in 1889. Electrochemical treatment includes applications such as electrocoagulation (EC), electrochemical Fenton, electro-Fenton, peroxi-coagulation, electrophotooxidation and electrodisinfection, amongst others.

Electrochemical processes can be applied for the treatment of different wastewaters and are referred as benign technologies since the main reagent are electrons. The most important advantages of electrochemical processes include that chemicals are not applied during treatment, thus avoiding secondary pollution and the automatic operation of these technologies that decreases costs of operation and maintenance. The disadvantages are the formation of metal hydroxide sludge, the need for electricity and expensive electrode replacement. However, through

extensive research over the past two decades, electrochemical technologies have reached a state where it is not only comparable with other technologies in terms of cost but can also be more efficient and more compact. (Ghanbari and Moradi, 2015; Chen, 2004).

Electrocoagulation, first applied on large scale for drinking water treatment in the USA in 1946, involves the generation of coagulants in situ by dissolving electrically either aluminum or iron ions from respectively aluminum or iron immersed electrodes using direct current (DC). The generation of metal ions takes place at the anode while hydrogen gas is released from the cathode. The hydrogen gas would then help to float the flocculated particles out of the water. When metal hydroxides are used as coagulant and/or adsorbents for removal of inorganic and organic contaminants and pathogens, it provides 100 times greater adsorption capacity on in situ hydroxides rather than on preprecipitated hydroxides. Compared to other conventional process, EC generates lower quantity of sludge while it can effectively destabilise small colloidal particles (Ghanbari and Moradi, 2015; Eyvaz, 2016).

Eyvaz (2016) found electrocoagulation (EC), using alternating pulse current, could completely remove turbidity, TSS, color, TN and TP and about 90 % of COD from relatively low-medium strength brewery effluent.

Another application of electrochemical reaction for the treatment of brewery wastewater included the in situ generation of hypochlorous acid (HClO) through introduction of sodium chloride concentrations of 2% and 3%. It was generated in an undivided electrolytic cell that consisted of two sets of graphite as the anode and stainless sheets as the cathode. The generated hypochlorous acid served as an oxidizing agent reducing COD by 97.3% (Vijayaraghavan et al., 2006).

CHAPTER FOUR

4 Findings, discussion, recommendations and conclusion

The aim of this study was primarily to make recommendations for an existing large-scale brewery, for the improvement of wastewater effluent quality to increase the opportunities for wastewater reuse. Literature on advanced wastewater treatment technologies was reviewed systematically with the aim of recommending additional process to add onto the existing treatment works, currently discharging up to 5 Ml of wastewater per day.

Besides the identification of relevant technology, some notable findings will be discussed in this section.

4.1 Findings and discussion

When advanced treatment is considered, the quality of effluent received from the upstream primary and secondary processes must be known and efficiently controlled. For this study, the effluent was considered to be compliant with the target brewery's discharge license. However, as illustrated in Table 23, in reality this was not always the case. Therefore it is accepted as best practise to consider employing advanced treatment technology that can accommodate small margins of failure.

Discharge limits set for the target brewery are stricter than general South African discharge limits, presumably as the target brewery is discharging into a stream which is a sink for wastewater discharges from other industries in the area. To limit the cumulative effect of pollutant build-up, strict limits were set.

Although results show predominantly effective treatment, for the period between June 2016 and June 2017, discharge limits were not consistently met. Of the parameters exceeded, COD and PO₄ failures are discussed in more detail below.

Table 23 Target brewery's problem pollutants

Determinant	Unit	Brewery discharge license	Discharge average Jun 2016 – Jun 2017	Standard deviation	SA wastewater discharge limits	
					General limit	Special limit
Ammonia	mg/l NH ₃ as N	1.5	0.6	1.4	<3	<2
Chemical Oxygen Demand (COD)	mg/l	70	80.2 ⁷	184.24 ⁷	<75	<30
Electrical Conductivity at 25°C *	m/S/m	< (Intake + 75)	195.3	122		
Fluoride (F)	mg/l	1	0.11	0.034		
Dissolved Oxygen (DO)	mg/l	>3	5.53	1.39	75% saturation	
pH – Value at 25°C *	mg/l	6.5 - 9	8.71	0.56	5.5-9.5	5.5 -7.5
Phosphate (PO ₄ as P)	mg/l	2	4.72	3.2	10	1
Suspended Solids	mg/l	25	27.56	40.53	<25	<10
Dissolved Iron (Fe)	mg/l	1	0.37	0.36		
Total dissolved solids (TDS)	mg/l	1000	1219.05	202.04		
Chlorides (Cl)	mg/l	200				
Sulphate (SO ₄)	mg/l	350				

Closer scrutiny of raw data shows that the COD standard of 70mg/l was exceeded only 26.6% of the time, with 10.7% of the results having COD concentrations that exceeded 100mg/l. Over a twelve month period, the three highest readings were 2830, 427 and 378mg/l. Depending on the chosen technology, the brewery will have to set an operational upper limit of, say, 100mg/l, failing which effluent is recycled to head of works and not routed to advanced treatment.

The goal of advanced treatment will be potable standards, which, for COD, as discussed in Table 5, is <15mg/l. Therefore technology considered must be able to consistently reduce COD from the chosen operational upper limit to <15mg/l.

As shown in Figure 2, treatment at the target brewery includes anaerobic UASB treatment, followed by aerobic SBR treatment. This sequence is

⁷ Of the 243 measurements used for this calculation, there was only one extremely high value of 2830. Replacing this with the second highest value of 427, lowers the average to 70.3 and standard deviation to 55.7.

important to ensure the removal of nutrients, especially phosphorus and nitrogen. Physicochemical treatment, such as precipitation, is needed following anaerobic treatment. Table 23 shows a PO_4 average of 4.7mg/l. Although significantly lower than the general discharge standard, this still does not comply to the discharge limit set for the target brewery of 2mg/l. As pointed out in Chapter 1 when discussing brewery effluent contaminants, phosphorous is often found by breweries to be troublesome to sufficiently remove. Although scrutiny of raw data shows significant reduction of nutrients, the discharge exceeds the strict limit of 2mg/l for 77% of the time, with 45% of readings >4mg/l and 6.4% >10mg/l (general discharge limit). The maximum value recorded over a twelve month period was 18.6mg/l.

Although adding advanced treatment such as NF will remove all PO_4 , introducing an effective flocculant could produce sufficient flocs to further decrease PO_4 through settling or UF. Watanabe et al. (2009) reports that a flocculent yeast, *Hansenula anomala* J224 PAWA, bred as a mutant of the wild type *H. anomala* J224 in a study to enhance the phosphorus-accumulating activity of *H. anomala* J224, accumulated twice as much phosphorus as the wild type. In a semi-batch continuous experiment, this strain removed both phosphorus and the majority of organic matter from alcoholic distillery wastewater. Over a 30 day period, PAWA removed 70–80% of dissolved total phosphorus while the wild type removed only 30%. Because PAWA cells resulted in large flocks that rapidly settled, sludge was easily separated.

4.1.1 Effective secondary treatment

A number of widely used and some novel treatment options for secondary treatment of brewery wastewater are described in literature. Before advanced treatment technologies can be introduced, it is essential that primary and secondary treatment is effective as the final effluent produced by advanced technology is dependent on the quality of the influent. For this study, it was assumed existing treatment at the case-study brewery

consisting of a UASB reactor, followed by SBR is working efficiently and that the brewery's current discharge standards are met.

Although this study is particularly interested in advanced treatment technologies that can be added onto existing treatment to further treat effluent to potable standards, some of the novel secondary treatment options discussed in literature are worth mentioning. Literature shows results from testing technology in treatment of high strength brewery wastewater, but there is no discussion of the same technology's effectiveness if given a low strength stream. In other words, would the same technology be able to function as advanced treatment option, removing contaminants entirely if influent was at lower strength? The table below lists some of these alternative technologies.

Table 24 Alternative technology for secondary treatment of brewery wastewater

Technology	COD influent (mg/l)	COD effluent (mg/l)	COD Reduction (%)	Reference
Electrochemical methods	2,470	64	97	(Vijayaraghavan et al., 2006)
Microbial fuel cells	2,250	292	87	(Feng et al., 2008)
Microbial fuel cells	1,249	54	95.7	(Wen et al., 2010)
Non-thermal quenched plasma	1,018*	20*	98	Cited in (Simate et al., 2011)
Nano-filtration	3,692	143	96	(Braeken et al., 2004)
Fungi T. Harzianum			89	(Hultberg and Bodin, 2017)
Horizontal flow constructed wetland		<75		(Vymazal, 2014)

*BOD values.

As reported in the meta analysis of relevant technology, in chapter 3, the technology with the ability to produce potable water all included membrane technology. Further discussion of membranes, in the same chapter, points out the importance of reliable, consistent secondary treatment upstream of the membranes to ensure effective advanced treatment.

4.1.2 Existing advanced treatment in place at breweries

Through researching advanced treatment options for brewery wastewater, a number of breweries were found already treating wastewater to potable standards for brewing beer. The technologies used, correlate well with what research identified as relevant solutions. Table 25 lists these breweries and the technologies they are using.

Table 25 Existing breweries treating wastewater for internal reuse

Year	Brewery	Production site	Advanced technology	Reference
2017	Half Moon Bay brewing company	Berkeley, California	MF, RO, UV disinfection & AOP (H ₂ O ₂)	(Bansal, 2017)
2017	Pure Water Brew pilot study	Flagstaff, Arizona	UF, RO, UV disinfection & AOP	(The Associated Press, 2017)
2016	Lagunitas Brewing Company	Petaluma, California	Ecovolt Reactor, Ecovolt MBR, RO	(Silver et al., 2017)
2014	Bear Republic Brewing Company	California	Ecovolt BioEnergy system	(Mier, 2014)
2014	Sociedade Central de Cervejas (SCC) e Bebidas, part of the HEINEKEN Group	Vialonga, Portugal	Multi-media filters & RO	(Staley, 2014, 2030 Water Resources Group, 2015)
2010	Bluetongue brewery	Warnervale, Australia	MBR + RO	(Götz et al., 2014)
2009	Lion Nathan's Castlemaine Perkins	Brisbane, Australia	MF + RO	(Götz et al., 2014)
2009	ABIn Bev Tanzania breweries	Dar es Salaam, Tanzania	MBR + RO	(Götz et al., 2014)
2008	Cerveceria Polar	Caracas, Venezuela	MBR + RO	(Götz et al., 2014)
2007	Boon Rawd brewery	Khon Kaen, Thailand	UF + RO	(Götz et al., 2014)
2007	Martens brewery	Bocholt, Belgium	MBR + RO + UV	(Götz et al., 2014)
2006	Konig brewery	Duisburg, Germany	MBR + RO	(Götz et al., 2014)
2004	Foster's CUB Yatala	Yatala, Australia	MF + RO	(Götz et al., 2014)

4.1.3 Feasibility

Business Directory (n.d.) defines 'Life cycle cost' as the sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life. When selecting the appropriate treatment technology it is important to compare the full life cycle cost of different options.

Similar to earlier studies, results from the financial review were too varied to come to accurate conclusions. The reasons for the variation is possibly due to the fact that initial studies were not consistent in the variables they considered to be included in the cost of treatment.

The table below considers a few high level scenarios in order to illustrate the possible payback period for capex investment to treat wastewater to potable standards for reuse. The shortest payback period calculated was just more than 6 years. The following assumptions were made:

- The brewery will always need potable water from an external service provider. Scenarios of purchasing either 75%, 50% or 35% were considered
- The actual rate for purchased water at the study's target brewery of R8.41/m³ was used for all purchased water
- Taking the earlier financial analyses in Chapter 3 into consideration, opex rates of either R4.00 or R3.00 / m³ were considered for treated wastewater
- Similarly, taking the earlier financial analyses into consideration, capex rate of either R14,000 or R12,000 / m³ was used.
- No financing cost was considered in the calculation
- Only the calculated savings due to reduced water purchases was used as return on capex investment

- The current target brewery has the option to pump any non-compliant effluent to neighbouring municipal wastewater treatment works without cost from the municipality. This is a unique situation as typically a cost would have been incurred for such a service. Alternatively, a cost / fine would have been payable for non-compliant effluent discharge to the environment. Many studies list this cost as one of the main economical drivers for choosing advanced treatment of wastewater. Should this cost have been taken into consideration, the payback period is expected to decrease significantly.
- Currently, the target brewery can't expand on production as its service provider can't provide more water. In a detailed return on investment, the potential for increased production should also be seen as a return on investment.

Actual totals 12 months: m³/annum 1,768,207 Cost / annum R14,420,184			
Scenario 1 Purchased water 75% Rate/m³ 1,326,155 R8.41 R11,152,966 Potable treated wastewater 25% Rate/m³ Opex 442,052 R4.00 R1,768,207 Capex Capacity (m³/d) 4,000 R14,000.00 R56,000,000 Years to break-even 37.36 Savings / annum R1,499,011			
Scenario 2 Purchased water 50% Rate/m³ 884,104 R8.41 R7,435,310 Potable treated wastewater 50% Rate/m³ Opex 884,104 R4.00 R3,536,414 Capex Capacity (m³/d) 4,000 R14,000.00 R56,000,000 Years to break-even 16.24 Savings / annum R3,448,460			
Scenario 3 Purchased water 35% Rate/m³ 618,872 R8.41 R5,204,717 Potable treated wastewater 65% Rate/m³ Opex 1,149,335 R4.00 R4,597,338 Capex Capacity (m³/d) 4,000 R14,000.00 R56,000,000 Years to break-even 12.13 Savings / annum R4,618,128			
Scenario 4 Purchased water 75% Rate/m³ 1,326,155 R8.41 R11,152,966 Potable treated wastewater 25% Rate/m³ Opex 442,052 R3.00 R1,326,155 Capex Capacity (m³/d) 3,000 R12,000.00 R36,000,000 Years to break-even 18.55 Savings / annum R1,941,063			
Scenario 5 Purchased water 50% Rate/m³ 884,104 R8.41 R7,435,310 Potable treated wastewater 50% Rate/m³ Opex 884,104 R3.00 R2,652,311 Capex Capacity (m³/d) 3,000 R12,000.00 R36,000,000 Years to break-even 8.31 Savings / annum R4,332,563			
Scenario 6 Purchased water 35% Rate/m³ 618,872 R8.41 R5,204,717 Potable treated wastewater 65% Rate/m³ Opex 1,149,335 R3.00 R3,448,004 Capex Capacity (m³/d) 3,000 R12,000.00 R36,000,000 Years to break-even 6.24 Savings / annum R5,767,463			

4.2 Recommendations and conclusion

This section will reflect both on the process of systematic review used for this study, as well as the results from this study.

4.2.1 Conclusion on the methodology

Using the PRISMA methodology was found to be a usefull and thorough methodology. Although no other systematic reviews in the field of civil and process engineering could be found, it can be recommended for similar reviews in these fields.

Choosing the appropriate keywords and order of adding keywords to refine the search, is critical to the studies selected. As discussed in detail Chapter two, the final keywords selected were: wastewater treatment > advanced treatment > brewery > reuse > cost > energy > skills. The goal was to identify and compare advanced treatment technologies to be added to an existing brewery's wastewater treatment works. Comparison was proposed to be done on capital and operational cost together with the quality of effluent achieved and skills needed to optimally operate the technology.

Because the cost of energy is one of the main contributors to operational cost, it was selected as a keyword. The author found that using this keyword highlighted many studies where the technology was used to create energy, such as methane producing technologies and microbial fuel cells, which was proposed as advantage to use the particular technology. However, as this review's main focus was to identify technologies for the production of potable water, many of these studies were excluded during the initial review, as the goal of those studies were reducing energy cost, not production of potable water.

Discussion of the results from the initial review can be found in Chapter two as part of the methodology.

Many of the systematic reviews in other fields have used more than one researcher per review. This was both to have a second opinion on the inclusion or exclusion where the relevance is not immediately obvious, as

well as to divide and conquer the time consuming task of initial review. The author strongly recommends this team-approach for similar reviews in future.

4.2.2 Conclusions of systematic review

The aim of this research was to make recommendations for an existing large-scale brewery, for the improvement of wastewater effluent quality to increase the opportunities for wastewater reuse. Literature on advanced wastewater treatment technologies was reviewed systematically with the aim of recommending additional process to add onto the existing treatment works, currently discharging up to 5 Mℓ wastewater per day.

Following a rigorous systematic review as defined by the 2009 Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement as described by Moher et al. (2009) a number of relevant technologies were identified. Detail discussion of the final results can be found in Chapter three as part of the meta analysis of the final review

When considering the advantages and disadvantages of different treatment technologies for strong wastewater, Prajapati and Chaudhari (2015) concludes that no single technology can be employed. The treatment approach should follow a comprehensive approach considering all technologies sequentially.

Table 14, in Chapter three, summarises and references the studies of relevant technology identified as having the capacity to treat the target brewery's effluent to potable standards. These include:

- Adding UF or NF membranes on their own after current treatment
- Retrofitting SBR to develop UF MBR
- Adding expanded granular sludge bed
- Retrofitting UASB to develop AnMBR
- Retrofitting existing treatment to develop MBR and additional RO
- Adding EC using alternating pulse current

- Adding MFC to existing treatment
- Advanced flocculation using MG-sericite flocculant or CNTs as flocculant
- Adding double column fortified clay for final filtration

Of these, the most recurring (75% of relevant studies) were the use of membrane technology either on its own as addition to current treatment train, or as addition to secondary treatment to develop MBR / AnMBR.

As eluded to in Section 1.5, brewery wastewater is regarded as a strong wastewater containing high concentrations of COD. The notion that the treatment of COD in brewery wastewater is the guiding principle governing treatment solutions for brewery wastewater is clearly confirmed in Table 15 by illustrating that most of the literature on brewery wastewater was referring to COD. In fact, the literature sources not containing reference to COD were of a financial nature only. With brewery wastewater being classified as a strong wastewater with typically high COD values, it was expected that most relevant studies will report on the reduction in COD through treatment. This was found to be the case as 76% of the relevant studies did report on COD reduction. The only relevant studies not reporting on COD reduction focussed on the cost of technology rather than the quality of effluent.

Further detail analyses of the documentation revealed that only a few of the listed relevant technology reported 100% reduction of COD. These included:

- NF & RO, following primary & secondary treatment
- NF, flat membrane UTC-20 (Toray, Japan)
- NF flat membrane UTC-60 (Toray, Japan)
- NF flat membrane Desal-HL-51 (Osmonics, USA)
- NF flat membrane Desal-5-DK (Osmonics, USA)

Very promising results, with COD reduction from 96% to 99% were from:

- Fortified clay, Double column treatment (DCT), labscale
- Labscale SAnMBR
- 0.04 um membrane (GE Water and Process Technologies,
- Mg-sericite flocculant
- Pilotscale external ocrossflow UF AnMBR
- Electrochemical
- CNTs added to coagulation/flocculation tanks and filter bed
- MBR + RO
- All potential technology identified in literature was reviewed based on the parameters (design threshold) as shown in the

Table 10. Besides pollutant removal efficiency (mainly COD reduction), capital and O&M costs, skills level and lifespan of technology were also considered.

Although some analysis could be done on the cost of technology, as discussed in Section 3.4 on feasibility of technology, it could at best only be used as background on factors influencing the cost and an indication of the range of costs involved. There are too many unique factors to consider for too many scenarios for this methodology to reach conclusive outcomes on cost. The information found on 'lifespan of technology' and 'skills level' needed for operation was so limited, no analysis could be done on these topics.

From literature it was found a number of industrial users have similar high strength wastewater, with high COD. Arguably these industries could consider results from this review useful when considering advanced treatment technology for treatment of their wastewater effluent. These industries include paper mills, food and beverage factories, textile industry, dairies and abattoirs.

4.2.3 Recommendations for further studies

This review followed guidelines of the PRISMA methodology closely and focussed on design criteria as shown in

Table 10. However, the reuse of wastewater embodies far more than selection of appropriate technology. Some of the factors not considered in this review, but critical to include in comprehensive decision making when considering the reuse of wastewater and therefore warrants proper investigation, include:

- The psychological barrier of using wastewater in food products. Amongst other initiatives, the availability of information on treatment efficiency and strict monitoring was found to generate greater acceptance of the reuse of wastewater in Windhoek (Wolz K.D. et al., 1998).
- Although design criteria focused on effluent quality, it ignored the waste generated by any technology, i.e. brine generated by the use of membrane technology.
- Necessity of pilot-scale studies to select most appropriate technology before large capital investment and to more accurately determine cost of technology. This could include modelling of each treatment stage with removal efficiencies applied to each, simulating results of final effluent to assist in decision making.

REFERENCES

- 2030 WATER RESOURCES GROUP 2015. Maximising water reuse at a brewery. Vialonga, Portugal.
- ADAPA, S., BHULLAR, N. & DE SOUZA, S. V. 2016. A systematic review and agenda for using alternative water sources for consumer markets in Australia. *Journal of Cleaner Production*, 124, 14-20.
- ADEWUMI, J. R. 2011. *A decision support system for assessing the feasibility of implementing wastewater reuse in South Africa* Doctor of Philosophy, Witwatersrand University.
- ALNOURI, S. Y., LINKE, P. & EL-HALWAGI, M. M. 2018. Accounting for central and distributed zero liquid discharge options in interplant water network design. *Journal of Cleaner Production*, 171, 644-661.
- BANSAL, D. G. 2017. TOILET TO TAP? SOME SAY IT'S TIME. *East Bay Times*, 07/06/2017 Jul 06.
- BARNARD, J. L. & LAW, I. B. 1982. A guide for the planning, design and implementation of a water reclamation scheme. Water Research Commission.
- BELLO, M. M., ABDUL RAMAN, A. A. & PURUSHOTHAMAN, M. 2017. Applications of fluidized bed reactors in wastewater treatment – A review of the major design and operational parameters. *Journal of Cleaner Production*, 141, 1492-1514.
- BENNETT, A. 2014. Food & drink: New technologies in feed water and effluent treatment. *Filtration + Separation*, 51, 18-22.
- BINZ, C., HARRIS-LOVETT, S., KIPARSKY, M., SEDLAK, D. L. & TRUFFER, B. 2016. The thorny road to technology legitimization — Institutional work for potable water reuse in California. *Technological Forecasting and Social Change*, 103, 249-263.
- BLESING, J. E. & PELEKANI, C. 2016. Seawater desalination: A sustainable solution to world water shortage. *Australian Water*. Online.
- BRAEKEN, L., VAN DER BRUGGEN, B. & VANDECASTEELE, C. 2004. Regeneration of brewery waste water using nanofiltration. *Water Res*, 38, 3075-82.
- BREWERSASSOCIATION. 2011. *Water Conservation and Wastewater Reduction for Breweries* [Online]. BrewersAssociation. Available: www.allianceforwaterefficiency.org/WorkArea/DownloadAsset.aspx?id=9673 [Accessed 2018/01/20 2018].
- BRINDLE, K., STEPHENSON, T. & SEMMENS, M. J. 1999. Pilot-Plant Treatment of a High-Strength Brewery Wastewater Using a Membrane-Aeration Bioreactor. *Water Environment Research*, 71, 1197-1216.
- BROWN, P. A. 2007. *Influence of anaerobic and anoxic hydraulic retention time on biological nutrient removal in a membrane bioreactor*. 1443052 M.S., Iowa State University.
- BUSINESS DIRECTORY. n.d. *Life cycle cost* [Online]. Available: <http://www.businessdictionary.com/definition/life-cycle-cost.html> [Accessed 24/9/2018].
- CALABRIA, J. L. 2014. *Wastewater Nutrient Recovery Using Anaerobic Membrane Bioreactor (AnMBR) Permeate for Hydroponic Fertigation*. 1569904 M.S.E.V., University of South Florida.
- CHEN, G. 2004. Electrochemical technologies in wastewater treatment. *Separation and Purification Technology*, 38, 11-41.
- CHEN, H., CHANG, S., GUO, Q., HONG, Y. & WU, P. 2016. Brewery wastewater treatment using an anaerobic membrane bioreactor. *Biochemical Engineering Journal*, 105, 321-331.
- CHOI, H. J. 2015. Effect of Mg-sericite flocculant for treatment of brewery wastewater. *Applied Clay Science*, 115, 145-149.
- CILLIERS, J. 2016. Finding solutions to South Africa's water crisis. Institute for Security Studies.
- CLOETE, K. 2017. Recycling wastewater an option to counter water scarcity. *Engineering News*. Johannesburg: Creamer media.
- COLE-PALMER. n.d. *Laboratory Filtration Selection Guide*, [Online]. Available: <https://archive->

- resources.coleparmer.com/TechInfo/HTMLFiles/SelectFiltLab.htm#anchor3
[Accessed 2 July 2018].
- DAI, H., YANG, X., DONG, T., YONGWEN, K. & WANG, T. 2010. Engineering Application of MBR Process to the Treatment of Beer Brewing Wastewater. *Modern Applied Science*, 4, 103-109.
- DE SENA, R. F., TAMBOSI, J. L., GENENA, A. K., MOREIRA, R. D. F. P. M., SCHRÖDER, H. F. & JOSÉ, H. J. 2009. Treatment of meat industry wastewater using dissolved air flotation and advanced oxidation processes monitored by GC-MS and LC-MS. *Chemical Engineering Journal*, 152, 151-157.
- DENISON, J. & MANONO, S. 2007. A rough guide for irrigation development practitioners. Pretoria: Water Research Commission.
- DEPARTMENT OF WATER AND SANITATION 2017. Strategic overview of the water sector in SA 2017. Department of Water and Sanitation.
- DHILLON, B. S. 2013. *Life cycle costing. Techniques, models and applications*. , Canada, Gordon and Breach science publishers.
- DIZGE, N., AKARSU, C., OZAY, Y., GULSEN, H. E., ADIGUZEL, S. K. & MAZMANCI, M. A. 2018. Sono-assisted electrocoagulation and cross-flow membrane processes for brewery wastewater treatment. *Journal of Water Process Engineering*, 21, 52-60.
- DONNENFELD, Z., CROOKES, C. & HEDDEN, S. 2018. A delicate balance: Water scarcity in South Africa. Institute for security studies.
- DRIESSEN, W. & VEREIJKEN, T. 2003. Recent development in biological treatment of brewery effluent. *The institute and guild of brewing convention*. Zambia.
- EDWARDS, W., SHELDON, M. S., ZEELIE, P. J., DE JAGER, D., DEKKER, L. G. & BEZUIDENHOUT, C. C. 2013. Water Reuse using a dual-stage membrane bioreactor for industrial effluent treatment. Water Research Commission.
- EYVAZ, M. 2016. Treatment of brewery wastewater with electrocoagulation: Improving the process performance by using alternating pulse current. *International Journal of Electrochemical Science*, 11, 4988-5008.
- FARIA, D. C. D. 2009. *Advanced optimization tools for the design and retrofit of process plants water networks*. 3379011 Ph.D., The University of Oklahoma.
- FENG, X., HUANG, L., ZHANG, X. & LIU, Y. 2009. Water system integration of a brewhouse. *Energy Conversion and Management*, 50, 354-359.
- FENG, Y., WANG, X., LOGAN, B. E. & LEE, H. 2008. Brewery wastewater treatment using air-cathode microbial fuel cells. *Appl Microbiol Biotechnol*, 78, 873-80.
- FILLAUDEAU, L., BLANPAIN-AVET, P. & DAUFIN, G. 2006. Water, wastewater and waste management in brewing industries. *Journal of Cleaner Production*, 14, 463-471.
- GEBREYOHANNES, A. Y., MAZZEI, R. & GIORNO, L. 2016. Trends and current practices of olive mill wastewater treatment: Application of integrated membrane process and its future perspective. *Separation and Purification Technology*, 162, 45-60.
- GHANBARI, F. & MORADI, M. 2015. A comparative study of electrocoagulation, electrochemical Fenton, electro-Fenton and peroxi-coagulation for decolorization of real textile wastewater: Electrical energy consumption and biodegradability improvement. *Journal of Environmental Chemical Engineering*, 3, 499-506.
- GHANGREKAR 2009. Sedimentation. *Bioenergy Symposium Series at IIT Kharagpur, Vol. 1', 2009*.
- GÖTZ, G., GEIßEN, S.-U., AHRENS, A. & REIMANN, S. 2014. Adjustment of the wastewater matrix for optimization of membrane systems applied for water reuse in breweries. *Journal of Membrane Science*, 465, 68-77.
- GUDE, V. G., NIRMALAKHANDAN, N. & DENG, S. 2010. Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews*, 14, 2641-2654.
- GURRIA, A. 2017. *Putting water at the centre of the global agenda* [Online]. New York Organisation for Economic Co-operation and Development,

- . Available: <https://www.oecd.org/water/SG-Water-lecture-April-2017.pdf> [Accessed 9 December 2018].
- HAFEZ, A., KHEDR, M. & GADALLAH, H. 2007. Wastewater treatment and water reuse of food processing industries. Part II: Techno-economic study of a membrane separation technique. *Desalination*, 214, 261-272.
- HAWKINS, T. R. 2007. *A mixed-unit input-output model for life cycle assessment: Development, uncertainty, and application*. 3257146 Ph.D., Carnegie Mellon University.
- HERMAN, J. G., SCRUGGS, C. E. & THOMSON, B. M. 2017. The costs of direct and indirect potable water reuse in a medium-sized arid inland community. *Journal of Water Process Engineering*, 19, 239-247.
- HUANG, Z. J. 2017. *Using Microbial Electrochemical Methods for Carbon Capture and Utilization During Wastewater Treatment*. 10606047 Ph.D., University of Colorado at Boulder.
- HULTBERG, M. & BODIN, H. 2017. Fungi-based treatment of brewery wastewater--biomass production and nutrient reduction. *Applied Microbiology and Biotechnology*, 101, 4791-4798.
- HUTTON, B., SALANTI, G., CALDWELL, D. M., CHAIMANI, A., SCHMID, C. H., CAMERON, C., IOANNIDIS, J. P., STRAUS, S., THORLUND, K., JANSEN, J. P., MULROW, C., CATALA-LOPEZ, F., GOTZSCHE, P. C., DICKERSIN, K., BOUTRON, I., ALTMAN, D. G. & MOHER, D. 2015. The PRISMA extension statement for reporting of systematic reviews incorporating network meta-analyses of health care interventions: checklist and explanations. *Ann Intern Med*, 162, 777-84.
- INYANG U.E., BASSEY E.N. & INYANG J.D. 2012. Characterization of brewery effluent fluid. *Journal of Engineering and Applied Science*, 4, 11.
- JAIYEOLA, A. T. & BWAPWA, J. K. 2016. Treatment technology for brewery wastewater in a water-scarce country: A review. *South African Journal of Science*, 112, 8.
- JI, J., LIU, F., HASHIM, N. A., ABED, M. R. M. & LI, K. 2015. Poly(vinylidene fluoride) (PVDF) membranes for fluid separation. *Reactive and Functional Polymers*, 86, 134-153.
- JONES, A. 2018. How Cape Town more than halved its water usage. *GroundUp*.
- JUDD, S. J. & JUDD, C. 2011. *The MBR Book*.
- KAHOUSH, M., BEHARY, N., CAYLA, A. & NIERSTRASZ, V. 2018. Bio-Fenton and Bio-electro-Fenton as sustainable methods for degrading organic pollutants in wastewater. *Process Biochemistry*, 64, 237-247.
- KANAGACHANDRAN, K. & JAYARATNE, R. 2006. Utilization Potential of Brewery Waste Water Sludge as an Organic Fertilizer. *Journal of the Institute of Brewing*, 112, 92-96.
- KHAN, K. S., KUNZ, R., KLEIJNEN, J. & ANTES, G. 2003. Five steps to conducting a systematic review. *Journal of the Royal Society of Medicine*, 96, 4.
- LABS, W. 2015. Weighing all the options in wastewater treatment. *Food Engineering*, 87, 77-78,80,82,84,86,88-90,92,94,96,98.
- LENNTech. n.d. *Water treatment: Phosphorous removal from wastewater* [Online]. Netherlands. Available: <https://www.lenntech.com/phosphorous-removal.htm> [Accessed 27 February 2018].
- LEVINE, A. D., LEVERENZ, H. & ASANO, T. 2010. Water reclamation and reuse. *Desalination and water resources. Water Health - Volume II*. United Kingdom: Eolss Publishers.
- LI, L., HU, C., DAI, X., JIN, W., HU, C. & MA, F. 2015. The performance of a biological aerated filter loaded with a novel non-sintered fly-ash ceramsite as pretreatment for dual membrane processes. *Environmental Technology (United Kingdom)*, 36, 2024-2034.
- LIN, H., CHEN, J., WANG, F., DING, L. & HONG, H. 2011. Feasibility evaluation of submerged anaerobic membrane bioreactor for municipal secondary wastewater treatment. *Desalination*, 280, 120-126.

- LIN, H., GAO, W., MENG, F., LIAO, B. Q., LEUNG, K. T., ZHAO, L., CHEN, J. & HONG, H. 2012. Membrane bioreactors for industrial wastewater treatment: A critical review. *Critical Reviews in Environmental Science and Technology*, 42, 677-740.
- LOPEZ ZAVALA, M. A., TORRES DELENNE, P. R. & REYNOSO CUEVAS, L. Hybrid system for wastewater treatment and simultaneous production of electricity and hydrogen: modeling approach. Fifth international symposium on energy from biomass and waste, 2014 Venice, Italy. CISA Publisher.
- MAJOZI, T., ADEKOLA, O. & NONYANE, D. 2011. Water use optimization in industry: development of a mathematical model for wastewater minimization in a multipurpose batch plant. Pretoria: Water Research Commission.
- MARSHALL, R. 2008. Best management practices for nutrient management in effluent treatment. Canada: Forest Products Association of Canada.
- MASSARA, T. M., KOMESLI, O. T., SOZUDOGRU, O., KOMESLI, S. & KATSOU, E. 2017. A Mini Review of the Techno-environmental Sustainability of Biological Processes for the Treatment of High Organic Content Industrial Wastewater Streams. *Waste and Biomass Valorization*, 8, 1665-1678.
- MASSEN, S. J. 2011. *Progressive Brewery Wastewater Management Strategies* ©. MR88931 M.Sc., University of Guelph (Canada).
- MCCULLOCH, L. 1936. Derivation of the equation $PV = RT$. *Journal of Chemical Education*, 13, 393.
- METCALF & EDDY, I. A. A. C. 2014. *Wastewater engineering: Treatment and resource recovery*, New York, McGraw Hill.
- METCALF & EDDY INC. 2004. *Wastewater engineering, treatment and reuse*, New York, McGraw Hill.
- METCALF, G., PILLAY, L., MURUTU, C., CHIBURI, S., GUMEDE, N. & GAYDON, P. 2014. *Wastewater reclamation for potable reuse. Volume 2: Integration of MBR technology with advanced treatment processes*, Pretoria, Water Research Commission.
- MICHIGAN DEPARTMENT OF ENVIRONMENTAL AFFAIRS. The basics of phosphorus removal. Quality Operator Training and Certification 1999. Michigan.
- MIER, S. 2014. Bear Republic Brewing Company and Cambrian Innovation Unveil Pioneering Wastewater Reuse System. *Business Wire*, 01/15/2014 Jan 15.
- MOHER, D., LIBERATI, A., TETZLAFF, J., ALTMAN, D. G. & GROUP, T. P. 2009. *Preferred Reporting Items for Systematic Reviews and Meta-Analysis: The PRISMA Statement* [Online]. PLoS Medicine. Available: <https://doi.org/10.1371/journal.pmed.1000097> [Accessed 2017/10/22 2017].
- MUNOZ, I., RODRIGUEZ, A., ROSAL, R. & FERNANDEZ-ALBA, A. R. 2009. Life Cycle Assessment of urban wastewater reuse with ozonation as tertiary treatment: a focus on toxicity-related impacts. *Sci Total Environ*, 407, 1245-56.
- NDAMASE, M. 2017. World Water Week conference will give traction to SA's ability to achieve SDG 6. Pretoria: South African Department of Water & Sanitation.
- NEW BELGIUM BREWING COMPANY. 2018. *Good water means good beer* [Online]. Colorado. Available: <http://www.newbelgium.com/Sustainability/Environmental-Metrics/Water> [Accessed 2018/01/20 2018].
- NPTEL - NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING. 2018. *Classification Of Water Pollutants And Effects On Environment* [Online]. India: Government of India. Available: <https://nptel.ac.in/courses/105105048/M10L12.pdf> [Accessed 19 August 2018 2018].
- OLADOJA, N. A., ADEMOROTI, C. M. A. & ASIA, I. O. 2006. Treatment of industrial effluents using fortified soil-clay. *Desalination*, 197, 247-261.
- OLAJIRE, A. A. 2012. The brewing industry and environmental challenges. *Journal of Cleaner Production*.
- PIADEH, F., MOGHADDAM, M. R. A. & MARDAN, S. 2014. Present situation of wastewater treatment in the Iranian industrial estates: Recycle and reuse as a solution for achieving goals of eco-industrial parks. *Resources, Conservation and Recycling*, 92, 172-178.

- POYATOS, J. M., ALMECIJA, M. C., GARCÍA-MESA, J. J., MUÑO, M. M., HONTORIA, E., TORRES, J. C. & OSORIO, F. 2011. Advanced Methods for the Elimination of Microorganisms in Industrial Treatments: Potential Applicability to Wastewater Reuse. *Water Environment Research*, 83, 233-46.
- PRAJAPATI, A. K. & CHAUDHARI, P. K. 2015. Physicochemical Treatment of Distillery Wastewater—A Review. *Chemical Engineering Communications*, 202, 1098-1117.
- RADJENOVIC, J., MATOSIC, M., MIJATOVIC, I., PETROVIC, M. & BARCELÓ, D. 2008. Membrane Bioreactor (MBR) as an Advanced Wastewater Treatment Technology. *The Handbook of Environmental Chemistry*. Verlag Berlin Heidelberg: Springer.
- RAMBARRAN, J. 2017. *New study: Better education and data collection can further water (and energy) savings* [Online]. Environmental Defense Fund. Available: <http://blogs.edf.org/energyexchange/2017/12/14/new-study-better-education-and-data-collection-can-further-water-and-energy-savings/> [Accessed 9 December 2018 2018].
- RAMUKHWATHO, F., SEETAL, A. & PIENAAR, H. 2016. Natsurv 1: Water and wastewater management in the malt brewing industry. Water Research Commission: Water Resources Competency Area
- Natural Resources and the Environment
CSIR.
- SABS STANDARDS DIVISION 2015. South African National Standard (SANS) 241-1:2015. Drinking Water, Part 1: Microbiological, physical, aesthetic and chemical determinands. Pretoria: SABS.
- SAHA, N. K., BALAKRISHNAN, M. & BATRA, V. S. 2004. Improving industrial water use: case study for an Indian distillery,. *Resources conservation & recycling*, 12.
- SCHELMETIC, T. 2012. *Down the drain: Industry water use* [Online]. Thomas publishing company. Available: <https://news.thomasnet.com/imt/2012/04/10/down-the-drain-industry-water-use> [Accessed 16 November 2018 2018].
- SENEVIRATNE, M. 2006. Industrial Water Reuse Technologies. *A Practical Approach to Water Conservation for Commercial and Industrial Facilities*. Queensland: Elsevier Science Limited.
- SILVER, M., BAROSKY, M., AVILES, C. & RIXEY, E. 2017. Water audit expands reuse opportunities at Lagunitas brewery. *Water reuse & desalination*, 8, 3.
- SIMATE, G. S. 2015. The treatment of brewery wastewater for reuse by integration of coagulation/flocculation and sedimentation with carbon nanotubes 'sandwiched' in a granular filter bed. *Journal of Industrial and Engineering Chemistry*, 21, 1277-1285.
- SIMATE, G. S., CLUETT, J., IYUKE, S. E., MUSAPATIKA, E. T., NDLOVU, S., WALUBITA, L. F. & ALVAREZ, A. E. 2011. The treatment of brewery wastewater for reuse: State of the art. *Desalination*, 273, 235-247.
- SIMATE, G. S., IYUKE, S. E., NDLOVU, S. & HEYDENRYCH, M. 2012a. The heterogeneous coagulation and flocculation of brewery wastewater using carbon nanotubes. *Water Research*, 46, 1185-1197.
- SIMATE, G. S., IYUKE, S. E., NDLOVU, S., HEYDENRYCH, M. & WALUBITA, L. F. 2012b. Human health effects of residual carbon nanotubes and traditional water treatment chemicals in drinking water. *Environment International*, 39, 38-49.
- STALEY, E. 2014. Portuguese Brewery Saves 72 Million Liters of Water Annually with GE Technology. *Benzinga Newswires*, 05/30/2014 May 30.
- SWARTZ, C. D., GENTHE, B., MENGE, J. G., COOMANS, C. J. & OFFRINGA, G. 2015. Direct reclamation of municipal wastewater for drinking purposes. Pretoria: Water Research Commission.
- THE ASSOCIATED PRESS. 2017. Arizona breweries to make beer with treated wastewater. *AP English Language News (includes AP 50 State Report)*, 07/08/2017 Jul 08.

- TOCZYŁOWSKA-MAMIŃSKA, R. 2017. Limits and perspectives of pulp and paper industry wastewater treatment – A review. *Renewable and Sustainable Energy Reviews*, 78, 764-772.
- TRADING ECONOMICS. 2018. *China interest rate* [Online]. China. Available: <https://tradingeconomics.com/china/interest-rate> [Accessed 18 August 2018 2018].
- UNITED NATIONS WORLD WATER ASSESSMENT PROGRAMME 2017. Wastewater - The untapped resource. Paris.
- UNITED STATES ENVIRONMENTAL PROTECTION AGENCY 2000. Using Water Efficiently: Ideas for Industry. In: WATER, E. O. O. (ed.). USA.
- VAN DER BERG, E. 2016. Screening of WCWDM options for Richards Bay. Cape Town: Aurecon.
- VAN DER BRUGGEN, B. & BRAEKEN, L. 2006. The challenge of zero discharge: from water balance to regeneration. *Desalination*, 188, 177-183.
- VAN DER MERWE, A. I. & FRIEND, J. F. C. 2002. Water management at a malted barley brewery. *WRC Knowledge Hub: Water SA*, 28, 6.
- VIJAYARAGHAVAN, K., AHMAD, P. & LESA, R. 2006. Electrolytic treatment of beer brewery wastewater. *Industrial and Engineering Chemistry Research*, 45, 6854-6859.
- VYMAZAL, J. 2014. Constructed wetlands for treatment of industrial wastewaters: A review. *Ecological Engineering*, 73, 724-751.
- WADA, Y., FLÖRKE, M., HANASAKI, N., EISNER, S., FISCHER, G., TRAMBEREND, S., SATOH, Y., VAN VLIET, M. T. H., YILLIA, P., RINGLER, C., BUREK, P. & WIBERG, D. 2016. Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. *Geoscientific Model Development*, 9, 175-222.
- WATANABE, T., MASAKI, K., IWASHITA, K., FUJII, T. & IEFUJI, H. 2009. Treatment and phosphorus removal from high-concentration organic wastewater by the yeast *Hansenula anomala* J224 PAWA. *Bioresource Technology*, 100, 1781-1785.
- WEHN, U. & MONTALVO, C. 2018. Exploring the dynamics of water innovation: Foundations for water innovation studies. *Journal of Cleaner Production*, 171, S1-S19.
- WEN, Q., WU, Y., ZHAO, L. X., SUN, Q. & KONG, F. Y. 2010. Electricity generation and brewery wastewater treatment from sequential anode-cathode microbial fuel cell. *Journal of Zhejiang University-SCIENCE B*, 11, 87-93.
- WOLZ K.D., DU TOIT A. & VAN DER WALT C. 1998. Goreangab water reclamation plant - Process train report. Stuttgart: FMG Goreangab JV.
- WORLD HEALTH ORGANIZATION 2011. Guidelines for Drinking-water Quality - 4th ed. Fourth ed. Geneva: World Health Organization,.
- WORLD HEALTH ORGANIZATION 2017a. *Guidelines for drinking-water quality: Fourth edition incorporating the first addendum.*, Geneva, World Health Organization 2017
- WORLD HEALTH ORGANIZATION 2017b. Potable reuse: Guidance for producing safe drinking-water. Geneva: World Health Organization.
- ZHANG, H., YEE, R. A., ZHOU, Q. & LIU, Y. 2017. Water Reclamation and Reuse. *Water Environ Res*, 89, 1281-1298.
- ZHOU, H. & SMITH, D. W. 2001. Advanced technologies in water and wastewater treatment. *Canadian Journal of Civil Engineering*, 28, 49-66.
- ZINADINI, S., ZINATIZADEH, A. A., RAHIMI, M., VATANPOUR, V. & BAHRAMI, K. 2017. Energy recovery and hygienic water production from wastewater using an innovative integrated microbial fuel cell–membrane separation process. *Energy*, 141, 1350-1362.
- ZUMSTEG, J. M., COOPER, J. S. & NOON, M. S. 2012. Systematic Review Checklist. *Journal of Industrial Ecology*, 16, S12-S21.

Appendix A

Literature search results

Table 27 Full list of studies scored 'High'

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	3	Author: Simate, Geoffrey S.	2015	Title: The treatment of brewery wastewater for reuse by integration of coagulation/flocculation and sedimentation with carbon nanotubes 'sandwiched' in a granular filter bed	Journal: Journal of Industrial and Engineering Chemistry	Notes: A20 TT5Re5QP3CC1OC1Sk1Li1O 3
Reference Type: Journal Article	4	Author: Simate, Geoffrey S., Cluett, John, Iyuke, Sunny E., Musapatika, Evans T., Ndlovu, Sehliselo, Walubita, Lubinda F. and Alvarez, Alex E.	2011	Title: The treatment of brewery wastewater for reuse: State of the art	Journal: Desalination	Notes: A20 TT5Re5QP3CC1OC1Sk1Li1O 3
Reference Type: Report	5	Author: Ramukhwatho, F., Seetal, A. and Pienaar, H.	2016	Title: Natsurv 1: Water and wastewater management in the malt brewing industry	Place Published: Water Research Commission	Notes: A18 TT3Re3QP2CC2OC2Sk2Li1O 3
Reference Type: Journal Article	6	Author: Jaiyeola, A.T. and Bwapwa, J.K.	2016	Title: Treatment technology for brewery wastewater in a water-scarce country: A review	Journal: South African Journal of Science	Notes: A18 TT5Re3QP3CC1OC1Sk1Li1O 3
Reference Type: Journal Article	7	Author: Janhom, T., Pavasant, P. and Wattanachira, S.	2011	Title: Profiling and monitoring of DOM in brewery wastewater and treated wastewater	Journal: Environmental Monitoring and Assessment	Notes: A14 TT2Re5QP5CC0OC0Sk0Li0O 2
Reference Type: Journal Article	9	Author: Shao, X., Peng, D., Teng, Z. and Ju, X.	2008	Title: Treatment of brewery wastewater using anaerobic sequencing batch reactor (ASBR)	Journal: Bioresource Technology	Notes: A10 TT2Re2QP5CC1OC0Sk0Li0O 0
Reference Type: Report	10	Author: Edwards, W., Sheldon, M.S., Zeelie, P.J., de Jager, D., Dekker, L.G. and Bezuidenhout, C.C	2013	Title: Water Reuse using a dual-stage membrane bioreactor for industrial effluent treatment	Place Published: Water Research Commission	Notes: A23 TT3Re3QP3CC4OC4Sk1Li2O 3
Reference Type: Journal Article	11	Author: van der Merwe, A.I. and Friend, J.F.C.	2002	Title: Water management at a malted barley brewery	Journal: WRC Knowledge Hub: Water SA	Notes: A6 TT0Re3QP1CC0OC0Sk0Li0O 2
Reference Type: Journal Article	13	Author: Salipira, K.L., Mamba, B.B., Krause, R.W., Malefetse, T.J. and Durbach, S.H.	2007	Title: Cyclodextrin polyurethanes polymerised with carbon nanotubes for the removal of organic pollutants in water	Journal: WRC Knowledge Hub: Water SA	Notes: A16 TT4Re3QP3CC1OC1Sk1Li1O 2
Reference Type: Report	14	Author: Cowan, J.A.C., Little, J.C., Skivington, P. and Elphinston, A.J.	1986	Title: Water and wastewater management in the malt brewing industry		Notes: A14 TT2Re3QP3CC1OC1Sk1Li1O 2
Reference Type: Journal Article	15	Author: Kilani, J.S.	1993	Title: A compatibility study of the effects of dairy and brewery effluents on the treatability of domestic sewage	Journal: WRC Knowledge Hub: Water SA	Notes: A10 TT2Re3QP3CC0OC0Sk0Li0O 2
Reference Type: Report	17	Author: World Health Organisation	2017	Title: Potable reuse: Guidance for producing safe drinking-water	Place Published: Geneva	Notes: AB14 TT3Re3QP3CC0OC0Sk1Li0O 4
Reference Type: Thesis	18	Author: Simate, G.S.	2012	Title: The treatment of brewery wastewater using carbon nanotubes synthesized from carbon dioxide carbon source	Academic Department: Faculty of Engineering and the Built Environment	Notes: A21 TT5Re5QP5CC1OC1Sk1Li1O 2
Reference Type: Journal Article	23	Author: Olajire, Abass A.	2012	Title: The brewing industry and environmental challenges	Journal: Journal of Cleaner Production	Notes: A16 TT1Re2QP5CC1OC1Sk1Li0O 5
Reference Type: Journal Article	24	Author: Götz, Gesine, Geißen, Sven-Uwe, Ahrens, Alfons and Reimann, Stefan	2014	Title: Adjustment of the wastewater matrix for optimization of membrane systems applied for water reuse in breweries	Journal: Journal of Membrane Science	Notes: A22 TT5Re5QP3CC2OC2Sk1Li1O 3

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	25	Author: Fillaudeau, Luc, Blanpain-Avet, Pascal and Daufin, Georges	2006	Title: Water, wastewater and waste management in brewing industries	Journal: Journal of Cleaner Production	Notes: A21 TT4Re3QP3CC3OC3Sk1Li1O 3
Reference Type: Report	26	Author: Beekman, H.G., Kloper, D.N., Fawcett, K.S. and Novella, P.H.	1990	Title: Construction and operation of the Cape Flats water reclamation plant and the surveillance of the reclaimed water quality	Place Published: Cape Town	Notes: A20 TT4Re4QP4CC1OC1Sk3Li1O 2
Reference Type: Report	29	Author: Barnard, J.L. and Law, I.B.	1982	Title: A guide for the planning, design and implementation of a water reclamation scheme	Institution: Water Research Commission	Notes: A23 TT4Re4QP4CC2OC2Sk3Li1O 3
Reference Type: Thesis	30	Author: Buntner, D.	2013	Title: Combined UASB-MBR system for the treatment of low-strength wastewater at ambient temperatures	Academic Department: Department of Chemical Engineering	Notes: A20 TT3Re4QP4CC2OC2Sk1Li1O 3
Reference Type: Journal Article	32	Author: Lin, Hongjun, Chen, Jianrong, Wang, Fangyuan, Ding, Linxian and Hong, Huachang	2011	Title: Feasibility evaluation of submerged anaerobic membrane bioreactor for municipal secondary wastewater treatment	Journal: Desalination	Notes: A19 TT2Re2QP2CC4OC4Sk1Li2O 2
Reference Type: Book	33	Author: Arslan-Alaton, I., Bertanza, G., Esplugas, S., De Feo, G., Galasso, M., Garcia-Molina, V., De Gisi, S., Lofrano, G., Nikolaou, A., Olmez-Hanci, T. and Pedrazzani, R.	2012	Title: Green Technologies for Wastewater Treatment. Energy Recovery and EmergingbCompounds Removal	Series Editor: Sanjay, K.S.	Notes: A18 TT4Re3QP3CC1OC1Sk1Li2O 3
Reference Type: Report	43	Author: Team, Sustainable Development	2014	Title: A Practical water efficiency guide for buisnesses in Northern Ireland	Publisher: Ireland, Invest Northern	Notes: A15 TT1Re3QP2CC3OC3Sk0Li0O 3
Reference Type: Report	45	Author: Pietschke, B.I., Warburg, L., Khan, N., Terblanche, G., Clarke, M.D., Bhattacharya, A., Weels, S., Morake, S.T., Rose, S., Le Roes-Hill, M. and Van Zyl, W.H.	2016	Title: INTEGRATED BIOREMEDIATION AND BENEFICIATION OF BIO-BASED WASTE STREAMS		Notes: A14 TT2Re4QP2CC1OC1Sk0Li1O 3
Reference Type: Conference Proceedings	46	Author: Metcalf, G.	2015	Title: Wastewater Reclamation for Potable Reuse	Date Accessed: 1 August 2017	Notes: A26 TT5Re5QP2CC4OC4Sk1Li1O 4
Reference Type: Electronic Book	47	Author: Group, 2030 Water Resources	2015	Title: Maximising water reuse at a brewery. Vialonga, Portugal		Notes: A12 TT3Re4QP1CC1OC1Sk0Li0O 2
Reference Type: Book	50	Author: Metcalf & Eddy, Inc. an AECOM Company, Asano, Takashi, Burton, Franklin and Leverenz, Harold	2007	Title: Water Reuse: Issues, Technologies and Applications		Notes: A
Reference Type: Journal Article	58	Author: Herman, Jason G., Scruggs, Caroline E. and Thomson, Bruce M.	2017	Title: The costs of direct and indirect potable water reuse in a medium-sized arid inland community	Journal: Journal of Water Process Engineering	Notes: A22 TT2Re2QP2CC5OC5Sk2Li2O 2
Reference Type: Thesis	59	Author: Adewumi, James Rotimi	2011	Title: A decision support system for assessing the feasibility of implementing wastewater reuse in South Africa	Academic Department: Faculaty of Engineering and the Built Environment	Notes: A19 TT2Re2QP2CC3OC3Sk1Li1O 5
	60	Author: 3, Part		Title: Examples of food processing wastewater treatment		Notes: A
Reference Type: Electronic Book	61	Author: Ranade, Vivek V. and Bhandari, Vinay M.	2014	Title: Industrial wastewater treatment, recycling and reuse	Place Published: Oxford	Notes: A22 TT4Re4QP4CC2OC2Sk2Li1O 3

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	62	Author: Hafez, Azza, Khedr, Maaly and Gadallah, Hanaa	2007	Title: Wastewater treatment and water reuse of food processing industries. Part II: Techno-economic study of a membrane separation technique	Journal: Desalination	Notes: AD23 TT4Re5QP4CC3OC2Sk1Li1O 3
Reference Type: Journal Article	63	Author: Qasim, Wael and Mane, A. V.	2013	Title: Characterization and treatment of selected food industrial effluents by coagulation and adsorption techniques	Journal: Water Resources and Industry	Notes: AD23 TT4Re5QP4CC3OC2Sk1Li1O 3
Reference Type: Report	67	Author: Metcalf, G., Pillay, L., Murutu, C., Chiburi, S., Gumede, N. and Gaydon, P	2014	Title: Wastewater reclamation for potable reuse. Volume 2: Integration of MBR technology with advanced treatment processes	Place Published: Pretoria	Notes: A26 TT5Re5QP2CC4OC4Sk1Li1O 4
Reference Type: Report	68	Author: Swartz, C.D., Genthe, B., Menge, J.G., Coomans, C.J. and Offringa, G.	2015	Title: Direct reclamation of municipal wastewater for drinking purposes	Place Published: Pretoria	Notes: A15 TT1Re3QP5CC1OC1Sk0Li1O 3
Reference Type: Report	69	Author: Jones, C.L.W., Britz, P.J., Scheepers, R., Power, S., Cilliers, A. and Laubscher, R.	2014	Title: Environmentally Sustainable Beneficiation of Brewery Effluent: Algal ponding, Constructed Wetland, Hydroponic Vegetables and Aquaculture	Place Published: Pretoria	Notes: A22 TT5Re3QP3CC2OC2Sk3Li2O 2
Reference Type: Journal Article	75	Author: Capar, G., Yilmaz, L. and Yetis, U.	2008	Title: A membrane-based co-treatment strategy for the recovery of print- and beck-dyeing textile effluents	Journal: Journal of Hazardous Materials	Notes: H16 Re4QP4CC1OC1Sk2Li1O 3
Reference Type: Journal Article	77	Author: Liu, Ranbin, Zhao, Yaqian, Doherty, Liam, Hu, Yuansheng and Hao, Xiaodi	2015	Title: A review of incorporation of constructed wetland with other treatment processes	Journal: Chemical Engineering Journal	Notes: H19 Re5QP3CC2OC4Sk1Li1O 3
Reference Type: Journal Article	78	Author: Statyukha, Gennadiy, Kvitka, Olexandr, Dzhygyrey, Iryna and Jeżowski, Jacek	2008	Title: A simple sequential approach for designing industrial wastewater treatment networks	Journal: Journal of Cleaner Production	Notes: H19 Re4QP4CC2OC2Sk2Li1O 4
Reference Type: Journal Article	79	Author: Alnouri, Sabla Y., Linke, Patrick and El-Halwagi, Mahmoud M.	2018	Title: Accounting for central and distributed zero liquid discharge options in interplant water network design	Journal: Journal of Cleaner Production	Notes: H21 Re5QP3CC3OC3Sk2Li1O 4
Reference Type: Journal Article	80	Author: Hamza, Rania Ahmed, Iorhemen, Oliver Terna and Tay, Joo Hwa	2016	Title: Advances in biological systems for the treatment of high-strength wastewater	Journal: Journal of Water Process Engineering	Notes: HM15 Re4QP3CC2OC1Sk1Li1O 3
Reference Type: Journal Article	81	Author: He, Li, Du, Peng, Chen, Yizhong, Lu, Hongwei, Cheng, Xi, Chang, Bei and Wang, Zheng	2017	Title: Advances in microbial fuel cells for wastewater treatment	Journal: Renewable and Sustainable Energy Reviews	Notes: H19 Re5QP4CC2OC2Sk2Li1O 3
Reference Type: Journal Article	86	Author: Bello, Mustapha Mohammed, Abdul Raman, Abdul Aziz and Purushothaman, Monash	2017	Title: Applications of fluidized bed reactors in wastewater treatment – A review of the major design and operational parameters	Journal: Journal of Cleaner Production	Notes: H20 Re5QP3CC3OC3Sk2Li1O 3
Reference Type: Journal Article	87	Author: Shahadat, Mohammad, Teng, Tjoon Tow, Rafatullah, Mohd, Shaikh, Z. A., Sreekrishnan, T. R. and Ali, S. Wazed	2017	Title: Bacterial bioflocclulants: A review of recent advances and perspectives	Journal: Chemical Engineering Journal	Notes: HM20 Re3QP4CC3OC2Sk2Li1O 5
Reference Type: Journal Article	88	Author: Kahoush, May, Behary, Nemeshwaree, Cayla, Aurélie and Nierstras, Vincent	2018	Title: Bio-Fenton and Bio-electro-Fenton as sustainable methods for degrading organic pollutants in wastewater	Journal: Process Biochemistry	Notes: H22 Re4QP3CC3OC3Sk2Li3O 4
Reference Type: Book Section	93	Author: Seneviratne, M.	2006	Title: Industrial Water Reuse Technologies	Book Title: A Practical Approach to Water Conservation for	Notes: H23 Re5QP4CC3OC3Sk3Li2O 3

Ref Type	#	Author	Year	Title	Journal	Notes
					Commercial and Industrial Facilities	
Reference Type: Journal Article	96	Author: Vymazal, Jan	2014	Title: Constructed wetlands for treatment of industrial wastewaters: A review	Journal: Ecological Engineering	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	102	Author: Bennett, Anthony	2014	Title: Food & drink: New technologies in feed water and effluent treatment	Journal: Filtration + Separation	Notes: H22 TT5Re5QP4CC1OC2Sk1Li1O 3
Reference Type: Journal Article	103	Author: Klemeš, Jiří Jaromír	2012	Title: Industrial water recycle/reuse	Journal: Current Opinion in Chemical Engineering	Notes: H18 ReQP3 CC3OC3Sk2Li3O 4QP3CC3OC3Sk2Li3O 4
Reference Type: Journal Article	105	Author: Toczyłowska-Mamińska, Renata	2017	Title: Limits and perspectives of pulp and paper industry wastewater treatment – A review	Journal: Renewable and Sustainable Energy Reviews	Notes: H19 Re4QP4CC2OC2Sk2Li1O 4
Reference Type: Journal Article	108	Author: Arimi, Milton M.	2017	Title: Modified natural zeolite as heterogeneous Fenton catalyst in treatment of recalcitrants in industrial effluent	Journal: Progress in Natural Science: Materials International	Notes: HM15 Re4QP3CC3OC3Sk0Li0O 2
Reference Type: Journal Article	111	Author: Ji, Jing, Liu, Fu, Hashim, N. Awanis, Abed, M. R. Moghareh and Li, Kang	2015	Title: Poly(vinylidene fluoride) (PVDF) membranes for fluid separation	Journal: Reactive and Functional Polymers	Notes: H22 Re5QP3CC3OC3Sk2Li2O 4
Reference Type: Journal Article	112	Author: Liu, Ranbin, Wei, Ting, Zhao, Yaqian and Wang, Ya'e	2017	Title: Presentation and perspective of appealing Green Facilities for eco-cyclic water management	Journal: Chemical Engineering Journal	Notes: H17 Re5QP2CC2OC2Sk2Li1O 3
Reference Type: Journal Article	118	Author: Xu, Xing, Gao, Baoyu, Jin, Bo and Yue, Qinyan	2016	Title: Removal of anionic pollutants from liquids by biomass materials: A review	Journal: Journal of Molecular Liquids	Notes: HM18 Re4QP3CC3OC3Sk0Li0O 5
Reference Type: Journal Article	119	Author: Gude, Veera Ghaneswar, Nirmalakhandan, Nagamany and Deng, Shuguang	2010	Title: Renewable and sustainable approaches for desalination	Journal: Renewable and Sustainable Energy Reviews	Notes: H20 Re4QP3CC2OC2Sk2Li3O 4
Reference Type: Journal Article	120	Author: Dizge, Nadir, Akarsu, Ceyhun, Ozay, Yasin, Gulsen, H. Elif, Adiguzel, Serpil Konen and Mazmanci, M. Ali	2018	Title: Sono-assisted electrocoagulation and cross-flow membrane processes for brewery wastewater treatment	Journal: Journal of Water Process Engineering	Notes: H25 Re5QP4CC4OC4Sk2Li3O 3
Reference Type: Journal Article	125	Author: Oladoja, N. A., Ademoroti, C. M. A. and Asia, I. O.	2006	Title: Treatment of industrial effluents using fortified soil-clay	Journal: Desalination	Notes: H19 Re5QP4CC1OC1Sk2Li3O 3
Reference Type: Journal Article	126	Author: de Sena, Rênio F., Tambosi, José L., Genena, Aziza K., Moreira, Regina de F. P. M., Schröder, Horst Fr and José, Humberto J.	2009	Title: Treatment of meat industry wastewater using dissolved air flotation and advanced oxidation processes monitored by GC–MS and LC–MS	Journal: Chemical Engineering Journal	Notes: H20 Re4QP3CC2OC2Sk2Li3O 4
Reference Type: Journal Article	127	Author: Gebreyohannes, Abaynesh Yihdego, Mazzei, Rosalinda and Giorno, Lidietta	2016	Title: Trends and current practices of olive mill wastewater treatment: Application of integrated membrane process and its future perspective	Journal: Separation and Purification Technology	Notes: H11 Re1QP1CC1OC5Sk0Li1O 2
Reference Type: Journal Article	131	Author: Feng, Xiao, Huang, Long, Zhang, Xun and Liu, Yang	2009	Title: Water system integration of a brewhouse	Journal: Energy Conversion and Management	Notes: H21 Re4QP3CC2OC2Sk2Li3O 5

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	137	Author: de Andrade, Bárbara de A. S., de Lacerda, Paulo S. B. and Oliveira, Jaime L. M.	2017	Title: Technical feasibility of reuse of effluent generated from reverse osmosis system in a pharmaceutical plant	Journal: Revista Ambiente & Água	Notes: H22 Re4QP4CC2OC5Sk2Li1O 4
Reference Type: Newspaper Article	139	Reporter: The Associated Press	2017	Title: Arizona breweries to make beer with treated wastewater	Newspaper: AP English Language News (includes AP 50 State Report)	Notes: H7 Re5QP0CC0OC0Sk0Li0O 2
Reference Type: Newspaper Article	140	Reporter: Bansal, Devika G.	2017	Title: TOILET TO TAP? SOME SAY IT'S TIME	Newspaper: East Bay Times	Notes: H17 Re3QP3CC3OC3Sk0Li0O 5
Reference Type: Journal Article	141	Author: Hultberg, M. and Bodin, H.	2017	Title: Fungi-based treatment of brewery wastewater--biomass production and nutrient reduction	Journal: Applied Microbiology and Biotechnology	Notes: HM15 Re3QP2CC2OC2Sk2Li1O 3
Reference Type: Journal Article	149	Author: Pasterczyk, J. P.	2016	Title: Advantages Gained in Automating Industrial Wastewater Treatment Plants	Journal: Chemical Engineering Journal	Notes: H15 Re5QP3CC1OC1Sk1Li1O 3
Reference Type: Newspaper Article	161		2015	Title: Cambrian Innovation; Northern United Brewing Company Installs Cambrian Innovation's EcoVolt Mini	Newspaper: Journal of Engineering	Notes: H9 Re4QP1CC1OC1Sk0Li0O 2
Reference Type: Newspaper Article	163		2015	Title: Northern United Brewing Company Installs Cambrian Innovation's EcoVolt Mini	Newspaper: Business Wire	Notes: H9 Re4QP1CC1OC1Sk0Li0O 2
Reference Type: Journal Article	164	Author: van Lier, J. B., van der Zee, F. P., Frijters, C. T. and Ersahin, M. E.	2015	Title: Celebrating 40 years anaerobic sludge bed reactors for industrial wastewater treatment	Journal: Reviews in Environmental Science and Biotechnology	Notes: HM16 Re3QP3CC2OC2Sk1Li1O 4
Reference Type: Journal Article	167	Author: Labs, Wayne	2015	Title: Weighing all the options in wastewater treatment	Journal: Food Engineering	Notes: H22 Re4QP4CC3OC3Sk2Li2O 4
Reference Type: Newspaper Article	180	Reporter: Staley, Eddie	2014	Title: Portuguese Brewery Saves 72 Million Liters of Water Annually with GE Technology	Newspaper: Benzinga Newswires	Notes: H16 Re4QP2CC2OC2Sk1Li1O 4
Reference Type: Newspaper Article	183		2014	Title: Bear Republic Brewing Company and Cambrian Innovation Unveil Pioneering Wastewater Reuse System	Newspaper: Business Wire	Notes: H10 Re5QP1CC1OC1Sk0Li0O 2
Reference Type: Journal Article	191	Author: Higgins, Kevin T.	2012	Title: Toward zero liquid discharge	Journal: Food Engineering	Notes: H19 Re4QP2CC2OC2Sk2Li3O 4
Reference Type: Journal Article	193	Author: Gomez, Kevin	2012	Title: Anaerobic pre-treatment technology delivers water and energy gains for brewer	Journal: Manufacturers' Monthly	Notes: H9 Re4QP3CC0OC0Sk0Li0O 2
Reference Type: Thesis	194	Author: Mo, Weiwei	2012	Title: Water's Dependence on Energy: Analysis of Embodied Energy in Water and Wastewater Systems	Place Published: Ann Arbor	Notes: H21 Re4QP3CC2OC2Sk2Li3O 5
Reference Type: Thesis	197	Author: Massen, Scott James	2011	Title: Progressive Brewery Wastewater Management Strategies ©	Place Published: Ann Arbor	Notes: H23 Re5QP4CC2OC2Sk2Li3O 5
Reference Type: Journal Article	202	Author: Chiavola, Agostina	2009	Title: Textiles	Journal: Water Environment Research	Notes: H16 Re4QP2CC1OC1Sk2Li3O 3
Reference Type: Newspaper Article	206	Reporter: Anonymous	2008	Title: Ronser Bio-Tech takes over Shanghai company	Newspaper: New Straits Times	Notes: H - voorbeeld plant

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	212	Author: Chiavola, Agostina	2005	Title: TEXTILES	Journal: Water Environment Research	Notes: H16 Re4QP2CC1OC1Sk2Li3O 3
Reference Type: Newspaper Article	216	Reporter: Avery, Roberta	2004	Title: Clear solution for wastewater; A small Ontario municipality one of the first in Canada to use new sewage treatment technology ZeeWeed system filters water through microscopic pores in a membrane, writes Roberta Avery	Newspaper: Toronto Star	Notes: H12 Re0QP3CC3OC1Sk1Li1O 3
Reference Type: Thesis	323	Author: Zhang, Bo	2013	Title: Using bioelectrochemical systems for sustainable desalination	Place Published: Ann Arbor	Notes: H20 Re4QP4CC3OC3Sk1Li1O 4
Reference Type: Thesis	421	Author: Daborn, Lia Astrid	1997	Title: Choosing the appropriate technology for sewage treatment in small Nova Scotia communities	Place Published: Ann Arbor	Notes: HB11 Re0QP1CC1OC1Sk2Li1O 5 Intro - hoe kies jy technologie?
Reference Type: Thesis	1086	Author: Bahrami, Shirin	2002	Title: Heavy metal removal using modified sol -gels derived powder matrices containing crude metallothionein extracts from Schizosaccharomyces pombe	Place Published: Ann Arbor	Notes: H12 Re2QP5CC1OC1Sk1Li1O 1
Reference Type: Thesis	1176	Author: Bisesi, Michael Salvatore	1987	Title: VERMIMICROBEDAPHIC BIOTECHNOLOGY: A HOLISTIC APPROACH FOR MANAGEMENT OF RESIDUALS DERIVED FROM USED-WATER TREATMENT	Place Published: Ann Arbor	Notes: H14 Re1QP3CC1OC2Sk1Li1O 5 Sludge
Reference Type: Journal Article	1418	Author: Binz, Christian, Harris-Lovett, Sasha, Kiparsky, Michael, Sedlak, David L. and Truffer, Bernhard	2016	Title: The thorny road to technology legitimation — Institutional work for potable water reuse in California	Journal: Technological Forecasting and Social Change	Notes: H17 Re3QP3CC2OC2Sk1Li1O 5
Reference Type: Journal Article	1422	Author: Chen, H., Chang, S., Guo, Q. B., Hong, Y. S. and Wu, P.	2016	Title: Brewery wastewater treatment using an anaerobic membrane bioreactor	Journal: Biochemical Engineering Journal	Notes: H17 Re5QP3CC1OC3Sk1Li1O 3
Reference Type: Journal Article	1428	Author: Burakov, A. E., Galunin, E. V., Burakova, I. V., Kucheroval, A. E., Agarwal, S., Tkachev, A. G. and Gupta, V. K.	2018	Title: Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review	Journal: Ecotoxicology and Environmental Safety	Notes: H18 Re5QP3CC2OC2Sk2Li3O 1
Reference Type: Journal Article	1430	Author: Tejedor-Sanz, S., Ortiz, J. M. and Esteve-Núñez, A.	2017	Title: Merging microbial electrochemical systems with electrocoagulation pretreatment for achieving a complete treatment of brewery wastewater	Journal: Chemical Engineering Journal	Notes: H19 Re3QP4CC2OC2Sk2Li1O 5
Reference Type: Journal Article	1431	Author: Zinadini, S., Zinatizadeh, A. A., Rahimi, M., Vatanpour, V. and Bahrami, K.	2017	Title: Energy recovery and hygienic water production from wastewater using an innovative integrated microbial fuel cell–membrane separation process	Journal: Energy	Notes: H20 Re5QP4CC2OC2Sk2Li1O 4
Reference Type: Journal Article	1437	Author: Massara, T. M., Komesli, O. T., Sozudogru, O., Komesli, S. and Katsou, E.	2017	Title: A Mini Review of the Techno-environmental Sustainability of Biological Processes for the Treatment of High Organic Content Industrial Wastewater Streams	Journal: Waste and Biomass Valorization	Notes: H20 Re5QP4CC3OC2Sk2Li1O 3

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	1438	Author: Zubair, M., Daud, M., McKay, G., Shehzad, F. and Al-Harhi, M. A.	2017	Title: Recent progress in layered double hydroxides (LDH)-containing hybrids as adsorbents for water remediation	Journal: Applied Clay Science	Notes: HM21 Re4QP4CC3OC3Sk2Li1O 4
Reference Type: Journal Article	1462	Author: Eyvaz, M.	2016	Title: Treatment of brewery wastewater with electrocoagulation: Improving the process performance by using alternating pulse current	Journal: International Journal of Electrochemical Science	Notes: H17 Re4QP4CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1469	Author: Heim, C., Rajab, M., Letzel, T., Drewes, J. E. and Helmreich, B.	2016	Title: Ozone III: Application of boron-doped diamond electrodes for inactivation of microbial contaminants in different water matrices	Journal: BrewingScience	Notes: H17 TT4Re3QP4CC1OC1Sk0Li1O 3
Reference Type: Journal Article	1472	Author: Ihsanullah, Abbas, A., Al-Amer, A. M., Laoui, T., Al-Marri, M. J., Nasser, M. S., Khraisheh, M. and Atieh, M. A.	2016	Title: Heavy metal removal from aqueous solution by advanced carbon nanotubes: Critical review of adsorption applications	Journal: Separation and Purification Technology	Notes: H15 Re4QP3CC1OC1Sk1Li1O 4
Reference Type: Conference Proceedings	1474	Author: Sultana, S., Rahaman, Md S. and Baltodano, A.	2016	Title: Highly effective electro-fenton oxidation treatment for concentrated brewery wastewater	Conference Name: Proceedings, Annual Conference - Canadian Society for Civil Engineering	Notes: HM16 Re2QP3CC3OC3Sk0Li0O 5
Reference Type: Journal Article	1476	Author: Hua, B., Xiong, H., Zhu, G., Wang, L., Yan, S., Yang, J. and Deng, B.	2016	Title: Physico-chemical processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1479	Author: Pellegrin, M. L., Burbano, M. S., Sadler, M. E., Diamond, J., Baker, S., Greiner, A. D., Arabi, S., Wong, J., Doody, A., Padhye, L. P., Sears, K., Kistenmacher, P., Kent, F., Tootchi, L., Aguinaldo, J., Saddredini, S., Schilling, B., Min, K., McCandless, R., Danker, B., Gamage, N. P., Wang, S. and Aerts, P.	2016	Title: Membrane processes	Journal: Water Environment Research	Notes: H18 Re5QP3CC3OC3Sk1Li1O 2
Reference Type: Journal Article	1486	Author: Choi, H. J.	2015	Title: Effect of Mg-sericite flocculant for treatment of brewery wastewater	Journal: Applied Clay Science	Notes: H22 Re3QP3CC3OC4Sk2Li2O 5
Reference Type: Journal Article	1497	Author: Prajapati, A. K. and Chaudhari, P. K.	2015	Title: Physicochemical Treatment of Distillery Wastewater—A Review	Journal: Chemical Engineering Communications	Notes: H17 Re4QP3CC2OC2Sk1Li1O 4
Reference Type: Journal Article	1499	Author: Li, L., Hu, C., Dai, X., Jin, W., Hu, C. and Ma, F.	2015	Title: The performance of a biological aerated filter loaded with a novel non-sintered fly-ash ceramsite as pretreatment for dual membrane processes	Journal: Environmental Technology (United Kingdom)	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1501	Author: Pellegrin, M. L., Sadler, M. E., Greiner, A. D., Aguinaldo, J., Min, K., Zhang, K., Arabi, S., Burbano, M. S., Kent, F. and Shoaf, R.	2015	Title: Membrane processes	Journal: Water Environment Research	Notes: H18 Re5QP3CC3OC3Sk1Li1O 2
Reference Type: Journal Article	1509	Author: Piadeh, F., Moghaddam, M. R. A. and Mardan, S.	2014	Title: Present situation of wastewater treatment in the Iranian industrial estates: Recycle and reuse as a solution for achieving goals of eco-industrial parks	Journal: Resources, Conservation and Recycling	Notes: H20 Re4QP2CC4OC4Sk1Li1O 4

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	1517	Author: Pellegrin, M. L., Min, K., Diamond, J., Sadler, M. E., Greiner, A. D., Zhang, K., Aguinaldo, J., Arabi, S., Liu, M., Burbano, M. S., Padhye, L. P., Kent, F. and McCandless, R.	2014	Title: Membrane processes	Journal: Water Environment Research	Notes: H18 Re5QP3CC3OC3Sk1Li1O 2
Reference Type: Journal Article	1527	Author: Safari, G. H., Yetilmezsoy, K., Mavi, A. H. and Zarrabi, M.	2013	Title: Post-treatment of secondary wastewater treatment plant effluent using a two-stage fluidized bed bioreactor system	Journal: Journal of Environmental Health Science and Engineering	Notes: H21 Re4QP5CC3OC3Sk1Li1O 4
Reference Type: Journal Article	1530	Author: Hua, B., Yang, J., Lester, J. and Deng, B.	2013	Title: Physico-chemical processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1533	Author: Pellegrin, M. L., Aguinaldo, J., Arabi, S., Sadler, M. E., Min, K., Liu, M., Salamon, C., Greiner, A. D., Diamond, J., McCandless, R., Owerdieck, C., Wert, J. and Padhye, L. P.	2013	Title: Membrane processes	Journal: Water Environment Research	Notes: H18 Re5QP3CC3OC3Sk1Li1O 2
Reference Type: Journal Article	1539	Author: Lin, H., Gao, W., Meng, F., Liao, B. Q., Leung, K. T., Zhao, L., Chen, J. and Hong, H.	2012	Title: Membrane bioreactors for industrial wastewater treatment: A critical review	Journal: Critical Reviews in Environmental Science and Technology	Notes: H23 Re4QP3CC4OC4Sk2Li3O 3
Reference Type: Journal Article	1541	Author: Simate, G. S., Iyuke, S. E., Ndlovu, S. and Heydenrych, M.	2012	Title: The heterogeneous coagulation and flocculation of brewery wastewater using carbon nanotubes	Journal: Water Research - IWA	Notes: H15 Re3QP3CC1OC1Sk2Li1O 4
Reference Type: Journal Article	1542	Author: Meng, F., Chae, S. R., Shin, H. S., Yang, F. and Zhou, Z.	2012	Title: Recent advances in membrane bioreactors: Configuration development, pollutant elimination, and Sludge Reduction	Journal: Environmental Engineering Science	Notes: H22 Re4QP3CC3OC2Sk2Li3O 5
Reference Type: Journal Article	1544	Author: Simate, G. S., Iyuke, S. E., Ndlovu, S., Heydenrych, M. and Walubita, L. F.	2012	Title: Human health effects of residual carbon nanotubes and traditional water treatment chemicals in drinking water	Journal: Environment International	Notes: H14 Re2QP3CC1OC1Sk1Li1O 5
Reference Type: Journal Article	1546	Author: Pellegrin, M. L., Greiner, A. D., Aguinaldo, J., Diamond, J., Gluck, S., Burbano, M. S., Arabi, S., Wert, J., McCandless, R., Padhye, L. P. and Shoaf, R.	2012	Title: Membrane processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1553	Author: Fu, F. and Wang, Q.	2011	Title: Removal of heavy metal ions from wastewaters: A review	Journal: Journal of Environmental Management	Notes: H7 Re0QP0CC0OC0Sk0Li2O 5
Reference Type: Journal Article	1568	Author: Moawad, A., Mahmoud, U. F., El-Khateeb, M. A. and El-Molla, E.	2009	Title: Coupling of sequencing batch reactor and UASB reactor for domestic wastewater treatment	Journal: Desalination	Notes: H20 Re3QP4CC3OC3Sk2Li2O 3
Reference Type: Journal Article	1570	Author: Watanabe, T., Masaki, K., Iwashita, K., Fujii, T. and Iefuji, H.	2009	Title: Treatment and phosphorus removal from high-concentration organic wastewater by the yeast <i>Hansenula anomala</i> J224 PAWA	Journal: Bioresource Technology	Notes: H20 Re4QP3CC2OC2Sk2Li3O 4
Reference Type: Journal Article	1579	Author: Madaeni, S. S. and Mansourpanah, Y.	2006	Title: Screening membranes for COD removal from dilute wastewater	Journal: Desalination	Notes: H18 Re4QP4CC1OC1Sk2Li3O 3
Reference Type: Journal Article	1581	Author: Vijayaraghavan, K., Ahmad, P. and Lesa, R.	2006	Title: Electrolytic treatment of beer brewery wastewater	Journal: Industrial and Engineering Chemistry Research	Notes: HL 21 Re4QP4CC4OC1Sk2Li3O 3

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	1582	Author: Anjaneyulu, Y., Sreedhara Chary, N. and Samuel Suman Raj, D.	2005	Title: Decolourization of industrial effluents - Available methods and emerging technologies - A review	Journal: Reviews in Environmental Science and Biotechnology	Notes: H22 Re5QP4CC3OC2Sk2Li3O 3
Reference Type: Journal Article	1587	Author: Zhou, H. and Smith, D. W.	2001	Title: Advanced technologies in water and wastewater treatment	Journal: Canadian Journal of Civil Engineering	Notes: H21 Re5QP2CC3OC3Sk2Li3O 3
Reference Type: Journal Article	1596	Author: Adapa, Sujana, Bhullar, Navjot and de Souza, Simone Valle	2016	Title: A systematic review and agenda for using alternative water sources for consumer markets in Australia	Journal: Journal of Cleaner Production	Notes: H17 Re3QP3CC2OC2Sk1Li1O 5
Reference Type: Web Page	1606	Author: BrewersAssociation	2011	Title: Water Conservation and Wastewater Reduction for Breweries	Series Editor: Stier, J.	Notes: H
Reference Type: Journal Article	1609	Author: Nelson, Dennis and Smith, Rick	2013	Title: THE RIGHT COMBINATION	Journal: Civil Engineering	Notes: H13 Re5QP1CC1OC2Sk1Li1O 2
Reference Type: Journal Article	1610	Author: Munoz, I., Rodriguez, A., Rosal, R. and Fernandez-Alba, A. R.	2009	Title: Life Cycle Assessment of urban wastewater reuse with ozonation as tertiary treatment: a focus on toxicity-related impacts	Journal: Science of the Total Environment	Notes: H20 Re5QP3CC2OC2Sk2Li2O 4
Reference Type: Thesis	1611	Author: Nel, H.	2004	Title: A research project proposal submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfillment of the requirements for the degree of Master of Science in Engineering	Academic Department: Faculty of Engineering	Notes: H19 Re2QP3CC2OC2Sk2Li3O 5
Reference Type: Journal Article	1616	Author: Kothiyal, Mahesh	2018	Title: Performance Evaluation of Brewery Biological Wastewater Treatment Plant	Journal: MOJ Ecology & Environmental Sciences	Notes: H17 Re4QP3CC2OC2Sk1Li1O 4
Reference Type: Journal Article	1617	Author: Pellegrin, M. L., Arabi, S., Aguinaldo, J., Sadler, M. E., Greiner, A. D., Padhye, L. P., Burbano, M. S., Wong, J., Kent, F., Dow, A., Danker, B., Diamond, J., Sadreddini, S., McCandless, R., Tootchi, L., Schilling, B. and Kinser, K.	2017	Title: Membrane Processes	Journal: Water Environment Research	Notes: H18 Re5QP3CC3OC3Sk1Li1O 2
Reference Type: Journal Article	1618	Author: Frenkel, Val S., Cummings, Gregg, Scannell, Dennis E., Tang, Walter Z., Maillacheruvu, Krishnanand Y. and Treanor, Patrick	2011	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1619	Author: Frenkel, Val S., Cummings, Gregg, Tang, Walter Z. and Maillacheruvu, Krishnanand Y.	2012	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1620	Author: Frenkel, Val S., Cummings, Gregg, Maillacheruvu, K. Y. and Tang, Walter Z.	2013	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1621	Author: Frenkel, Val S., Cummings, Gregg A., Maillacheruvu, K. Y. and Tang, Walter Z.	2014	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1622	Author: Frenkel, V. S., Cummings, G. A., Maillacheruvu, K. Y. and Tang, W. Z.	2015	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1623	Author: Frenkel, V. S., Cummings, G. A., Maillacheruvu, K. Y. and Tang, W. Z.	2016	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	1624	Author: Frenkel, V. S., Cummings, G. A., Maillacheruvu, K. Y. and Tang, W. Z.	2017	Title: Food-Processing Wastes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1625	Author: Pellegrin, Marie-Laure, Greiner, Anthony D., Diamond, Jason, Aguinaldo, Jorge, Padhye, Lokesh, Arabi, Sara, Min, Kyungnan, Burbano, Marie Sedran, McCandless, Robert and Shoaf, Robert	2011	Title: Membrane Processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1626	Author: Chelme-Ayala, Pamela, Afzal, Atefeh, Ding, Ning, Moustafa, Ahmed M. A., Pourrezaei, Parastoo, Alpatova, Alla, Drzewicz, Przemysław, Hwang, Geelsu, Kim, Eun-Sik, Liu, Yang and El-Din, Mohamed Gamal	2012	Title: Physico-Chemical Processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1627	Author: Pellegrin, Marie-Laure, Min, Kyungnan, Diamond, Jason, Sadler, Mary E., Greiner, Anthony D., Zhang, Kai, Aguinaldo, Jorge, Arabi, Sara, Liu, Minggang, Burbano, Marie S., Padhye, Lokesh P., Kent, Fraser and McCandless, Robert	2014	Title: Membrane Processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1629	Author: Hua, Bin, Xiong, Huixin, Wang, Zhengyang, Yang, John, Zhang, Shichen, Wang, Zhongzhen and Deng, Baolin	2014	Title: Physico-Chemical Processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1631	Author: Hua, B., Xiong, H., Kadhon, M., Wang, L., Zhu, G., Yang, J., Cunningham, G. and Deng, B.	2017	Title: Physico-Chemical Processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1632	Author: Bickerton, Ben, Camara, Eliman, Mclwain, Brad, Walsh, M. E. and Gagnon, G. A.	2011	Title: Water Reclamation and Reuse	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1633	Author: McVicar, Monica, Anderson, Lindsay, Zevenhuizen, Emily, Mackie, A. L., Walsh, M. E. and Gagnon, G. A.	2012	Title: Water Reclamation and Reuse	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1634	Author: Pei, Wen Wen, Xie, Xuesong, Ong, Phuong, Trueman, Benjamin F., McVicar, Monica A., Walsh, Margaret E. and Gagnon, Graham A.	2013	Title: Water Reclamation and Reuse	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1635	Author: Anderson, Lindsay, DiCicco, Julie, Sampson, Holly, Wesley, Daniel, Walsh, Margaret E. and Gagnon, Graham A.	2014	Title: Water Reclamation and Reuse	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1636	Author: Huang, C., Zeng, P., Yang, S., Shao, Y. and Liu, Y.	2016	Title: Water Reclamation and Reuse	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1637	Author: Zhang, H., Yee, R. A., Zhou, Q. and Liu, Y.	2017	Title: Water Reclamation and Reuse	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Journal Article	1638	Author: Hua, B., Xiong, H., Wang, Z., Hill, J., Buckler, S., Gao, S., Yang, J. and Deng, B.	2015	Title: Physico-Chemical Processes	Journal: Water Environment Research	Notes: H16 Re4QP3CC2OC2Sk1Li1O 3
Reference Type: Web Page	1639	Author: Lenntech		Title: Water treatment: Phosphorous removal from wastewater		Notes: H11 Re1QP3CC1OC1Sk0Li0O 5

Ref Type	#	Author	Year	Title	Journal	Notes
Reference Type: Journal Article	1640	Author: Ioannou, L. A., Li Puma, G. and Fatta-Kassinos, D.	2015	Title: Treatment of winery wastewater by physicochemical, biological and advanced processes: a review	Journal: Journal of Hazardous Materials	Notes: H19 Re4QP3CC2OC2Sk2Li1O 5
Reference Type: Journal Article	1641	Author: Michael-Kordatou, I., Michael, C., Duan, X., He, X., Dionysiou, D. D., Mills, M. A. and Fatta-Kassinos, D.	2015	Title: Dissolved effluent organic matter: Characteristics and potential implications in wastewater treatment and reuse applications	Journal: Water Research - IWA	Notes: H16 Re4QP3CC1OC1Sk1Li3O 3

