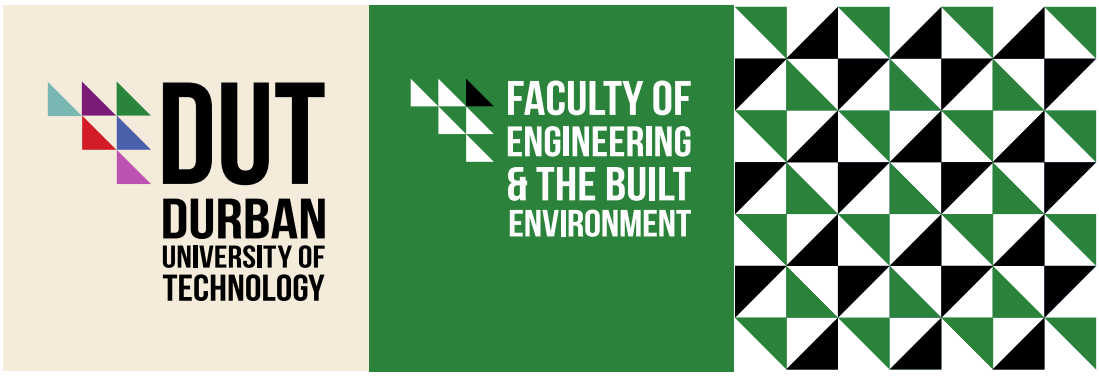

AEROBIC SEQUENCING BATCH REACTOR FOR THE TREATMENT OF INDUSTRIAL WASTEWATER FROM THE BREWERY

Submitted in fulfilment of the requirements of the degree of Master of Engineering in the Department of Chemical Engineering in the Faculty of Engineering and the Built Environment at Durban University of Technology, KwaZulu-Natal, South Africa

Khaya Pearlman Shabangu

December 2016

Dr M Chetty

Dr BF Bakare

DECLARATION

I, **Khaya Pearlman Shabangu**, hereby declare that

i. The research reported in this thesis, except where otherwise indicated, is my original work.

ii. This thesis has not been submitted for any degree or examinations at any other university.

iii. This thesis does not contain data, pictures, graphs or other information belonging to other people, unless specially acknowledge as being sourced from other persons.

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_____

Khaya Pearlman Shabangu

As the candidate's supervisors we have approved this dissertation for submission.

_____	_____
Dr B.F. Bakare	Dr M. Chetty
Date:	
_____	_____

DEDICATIONS

To

My mother: “Mrs Glenrose S. Shabangu”,

And

My children whose presence and thought inspires me to attain the best of my abilities:

“Ongeziwe”, “Ovayo” and “Akhile Shabangu”.

ACKNOWLEDGEMENTS

I would like to concede the credit most of all to the **Lord Almighty** for inspiring this project and strengthening me to triumph. “I can do all things through Christ who strengthens me” **(Philippians 4:13)**. I would also like to express my profound gratitude to the following individuals for constant support, continued dedication and advice for the whole duration of this research study:

i. The Directorate of Research and Development at MUT for making it possible to proceed with this study and for the financial support provided to me through the staff study grant.

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vii. Most of all, my thanks to my daughter, Akhile Shabangu, whose faith in me never faded, no matter how many trials I underwent. Her astuteness, zealous support and personal encouragement critically improved my sense of perceptive. Because of her: “I always aim for the moon; even if I miss, I'll land among the stars”. She has taught me to be a better father to her and her siblings and a better son to my mother, who has never lost faith in all my work and personal drive, attributes and vision.

ABSTRACT

One of the major effects of socio-economic change due to industrialisation is the generation of industrial wastewater, which requires treatment before being released into the environment. Laboratory-scale aerobic sequencing batch reactors under suspended-growth heterotrophic activated sludge were operated in different aeration configurations to study their effect on the treatment of wastewater generated by a local brewery. The main purpose of this study was to evaluate the performance of the two laboratory-scale aerobic sequencing batch reactors treating brewery wastewater under continuous low-oxygen dosing concentration and cyclic aeration schemes on SBR operation. The characterisation of brewery wastewater was undertaken to assess the physicochemical composition of the wastewater produced from one of the breweries in South Africa (SAB).

The data showed distinctive characteristics of brewery wastewater, which coincided with studies previously carried out on characterisation of brewery wastewater. The COD average concentration of the brewery influent was 7100 mg/L, with average pH values of 7. The BOD and the total solids content of the brewery wastewater influent from the facility were both high, implying that the influent was very rich in organic content and its discharge into water-receiving bodies or the municipal treatment plant could have adverse effects.

From these results, a need for a competitive treatment technology was clearly highlighted so as to carry out a feasible treatment of the influent for the brewery industry. The aerobic sequencing batch reactors were designed, fabricated and set up for laboratory-scale treatment of wastewater from the brewery for 15 weeks. The performance of the two SBR configurations was determined with reference to COD, BOD, TS, VS and TSS. The experimental results demonstrated that wastewater generated from the breweries can be treated successfully using both aeration configurations. The results obtained indicated that treatment efficiencies in terms of COD and BOD were 94 % and 85 % respectively, for the reactor operated under continuous aeration configuration, while 81 % and 65 % was achieved for the reactor operated in the cyclic aeration scheme. The findings from this study demonstrate that the performance of the reactor operated under the continuous aeration scheme was successful, and showed statistically significant differences from the performance of the reactor operated under cyclic aeration schemes. These findings imply that there is a

potential for the equipment, including financial benefit as a result of operating aerobic sequencing batch reactors for treating brewery wastewater under continuous low-oxygen concentration dosing schemes.

In this study, it was also established that the maximum COD removal could be reached at an optimum hydraulic retention times of 5 days for both reactors. This was based upon viewing the experimental data; it appeared that the most significant difference in percentage COD removal was for HRTs 3 days and 4 days. Although, due to less percentage COD removal observed from HRTs 5 days till 7 days, it was hence established that the optimum removal of high strength organics in the brewery wastewater could be achieved within 5 days of treatment time. The pH adapted at an average of 7 for all batch experimentations of the study. The temperature maintained an average of 23 ^{o}C ambient, throughout the experimental period. These physical parameters ensured that the microbial population was kept healthy, without inhibiting its biological degradation activity. Although, sludge build up was observed in both aerobic SBRs on completion of each batch operation due to solids retention and organic pollutants biodegradation from the brewery wastewater. It was perceived that frequently reseeding both aerobic SBRs, as an alternative to 28 days sludge retention time would enhance the recovery of biomass, thus improving the overall removal of TSS consequently minimising sludge bulking in both reactors.

PREFACE

This project was carried out at the Mangosuthu University of Technology (MUT), Department of Chemical Engineering. The pilot scale experiments and laboratory analyses were conducted at MUT Wastewater Management Research Laboratory. This project was supervised by Dr M Chetty (Durban University of Technology) and Dr BF Bakare (Mangosuthu University of Technology).

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LIST OF ABBREVIATIONS

BOD	Biological oxygen demand
SAB	South African Breweries
COD	Chemical oxygen demand
CORR	Correlation analysis
DO	Dissolved oxygen
LSD	Least significant difference
MLSS	Mixed liquor suspended solids
HRT	Hydraulic retention time
SBR	Sequencing batch reactor
SS	Suspended solids
TKN	Total Kjedahl nitrogen
TOC	Total organic carbon
VSS	Volatile suspended solids
SRT	Solids Retention Time
CON	Continuous low-oxygen concentration
CYC	Cyclic high oxygen concentration
AFBR	Aerobic fluidised bed reactors
SOUR	Specific oxygen uptake rate
JLR	Jet-Loop-Reactor
NTUs	Nephelometric turbidity units
pH	Potential of hydrogen
SBBR	Sequencing batch biofilm reactor
ASBBR	Anaerobic sequencing batch biofilm reactor
SND	Simultaneous nitrification and denitrification
TAD	Thermophilic aerobic digestion
OLR	Organic loading rate
BWW	Brewery wastewater
UASB	Up-flow anaerobic sludge blanket
DGGE	Denaturing gradient gel electrophoresis

VSS	Volatile suspended solids
AGS	Aerobic granular sludge
GCFMBR	Granular continuous flow membrane bioreactor
DWA	Department of Water Affairs
CI	Confidence interval level
COV	Coefficient of variation
PCR	Profiles of quantitative results
VS	Volatile solids
TS	Total solids
SPSS	Statistical packages for social sciences
ANOVA	Analysis of variation
VFA	Volatile fatty acids
PVC	Polyvinyl chloride
PO_4	Phosphates
CO_2	Carbon dioxide
H_2O	Water
NH_3	Ammonia
TDS	Total dissolved solids
TSS	Total suspended solids

NOMENCLATURE

RE	Removal Efficiency
$C_{influent}$	Concentration of substrate stream
$C_{effluent}$	Concentration of output stream
T	Time
V	Volume of wastewater
^{o}C	Degree centigrade
m^3	Cubic metres
kg	Kilograms
g	Grams
cm	Centimetres
m	Metres
W	Watts
rpm	Revolutions per minute
min	Minutes
MPa	Mega Pascals
V	Voltage
kW	Kilowatts
x_i	Value of the data analysed
n	Number of observations or analysis (n = 2)
x	Average of analysis data
µS	Micro Siemens
h	hour
R	Pearson correlation factor
p	Statistical significance level (SPSS, Student t-test, ANOVA test)
σ	Standard deviation
µ	Mean value

CHAPTER: 1
INTRODUCTION

In South Africa and many other parts of the world, there has been a rise in environmental pollution caused by the discharge of industrial effluents into the environment. Wastewater generated from breweries is among the major industrial effluents contributing to such pollution, due to its high strength in terms of chemical oxygen demand (COD) and biological oxygen demand (BOD). Also, parameters such as total organic carbon (TOC), alkalinity, acidity, and volatile fatty acids contribute enormously to the pollution of the environment, especially when they are found in high concentrations in brewery wastewater.

Historically, sequencing batch reactors (SBRs) have been used in many cases for wastewater treatment, especially for domestic wastewater, because of its simple configuration and high treatment efficiency in terms of organic compound removal (Simate *et al*., 2011). In this study, two laboratory-scale sequencing batch reactors were constructed and used for the treatment of wastewater generated from the brewery. The overall objective of this study was first of all to evaluate the performance of two laboratory-scale aerobic sequencing batch reactors in suspended-growth treatment of brewery wastewater and to determine the effects of continuous low-oxygen versus cyclic aeration schemes. Physicochemical parameters such as pH, conductivity, chemical oxygen demand (COD), biological oxygen demand (BOD), and solids are used as performance-monitoring parameters.

The brewery industry produces large quantities of polluted wastewater, heavily loaded with organic substances. There is usually a wide variation in the pollutant strength in wastewater discharged during brewery process, and as such, wastewater generated tends to be heavily polluted (Simate *et al*., 2011). As the scale of production of the brewing process increases, the amount of wastewater increases substantially, resulting in potential increases in levels of environmental pollution if discharged to the environment. Wastewater discharged from the breweries is usually a combined effluent, comprising discharges from various sources within the plant. Although wastewater varies in composition depending on the nature of brewery processes, it is mostly characterised by high-strength organic pollutants in the form of COD.

Brewery wastewater analyses is usually based on physicochemical parameters, including total organic carbon (TOC), biological oxygen demand (BOD) and chemical oxygen demand (COD), are very important when assessing the level of pollutant from the effluent generated by the process plant (Sinbuathong *et al*., 2007; Xu *et al*., 2013; Nel, 2014). Therefore, brewery wastewater requires substantial removal of organic pollutants prior to discharge into receiving bodies to minimise environmental pollution.

1.1 AIM

The aim of this study was to evaluate the performance of two laboratory-scales aerobic sequencing batch reactors in suspended-growth treatment of brewery wastewater and determine the effects of continuous low-oxygen concentration dosing scheme versus cyclic aeration scheme.

1.2 SPECIFIC OBJECTIVES

In order to achieve the aim of this research study, the following specific objectives were investigated and considered:

i. To investigate the characteristics of wastewater generated from the brewery.
ii. To determine the variation of COD removal efficiency with hydraulic retention time (HRT) on the two laboratory-scales aerobic sequencing batch reactors treating brewery wastewater, under different aeration configurations.
iii. To set-up, operate and evaluate the performance of the two laboratory-scale sequencing batch reactors treating brewery wastewater based on different aeration schemes.

1.3 JUSTIFICATION

Due to the high organic content and biodegradability of brewery wastewater, biological treatments are usually an appropriate treatment method. Biological treatment involves the removal and stabilisation of organic matter present in wastewater using microorganisms. Most of the previous studies conducted on brewery wastewater involve the use of anaerobic treatment for brewery wastewater because of its energy saving cost, occasioned by the release of methane gas which is in turn used as a source of fuel for this process. In this study, the performance of two laboratory-scale aerobic sequencing batch reactors for the treatment of brewery wastewater was investigated. SBRs are versatile and time sequence based treatment

processes, as opposed to space sequence based conventional activated sludge process (this is an activated sludge process with all the treatment occurring in a single reactor). Since treatment is based on a time schedule, there are four basic phases undergone during treatment: filling, mixing/reacting, settling and effluent discharge. The configuration of the SBR can always be adjusted to suit the content of the treated wastewater achieved after characterisation. The basic operating factors that influence the performance of a typical SBR include: reactor volume, hydraulic retention times (HRT), solids retention times (SRT), influent or effluent volumes, mixing rates, aeration methods and cycles, microbiological growth-support media and operating temperature.

1.3 OUTLINE

The general approach used to accomplish the objectives, the structure of this study and findings are presented in the following five chapters of the dissertation.

Chapter One presents an overview introduction stating the background and motivation in the management and treatment of industrial wastewater for this study. The aims, specific objectives and a clear problem statement have been included.

Chapter Two presents the review of the literature related to the study and discusses some aspects of work carried out earlier in other studies on sequencing batch reactors. A review of key aspects related to the general characteristics of wastewater generated from the brewery, anaerobic, aerobic and other treatment processes for brewery wastewater was undertaken. This chapter also covered aspects related to the use of sequencing batch reactors for wastewater treatment, operations, applications and advantages of SBR for wastewater treatment. A summary of literature reviewed is presented at the end of the chapter.

Chapter Three focuses on the methodological approach undertaken in this study, which was built upon information presented in the literature review. This chapter covers aspects related to the design, construction and operation of the sequencing batch reactor, as well as sampling methods conducted. Statistical methods used for the data analysis are included in this chapter.

Chapter Four presents and discusses the results of the study.

Chapter Five presents the conclusions of this study. Recommendations for future work are also presented in this chapter. The schematic representation of the dissertation is provided in **Figure 1.1**.

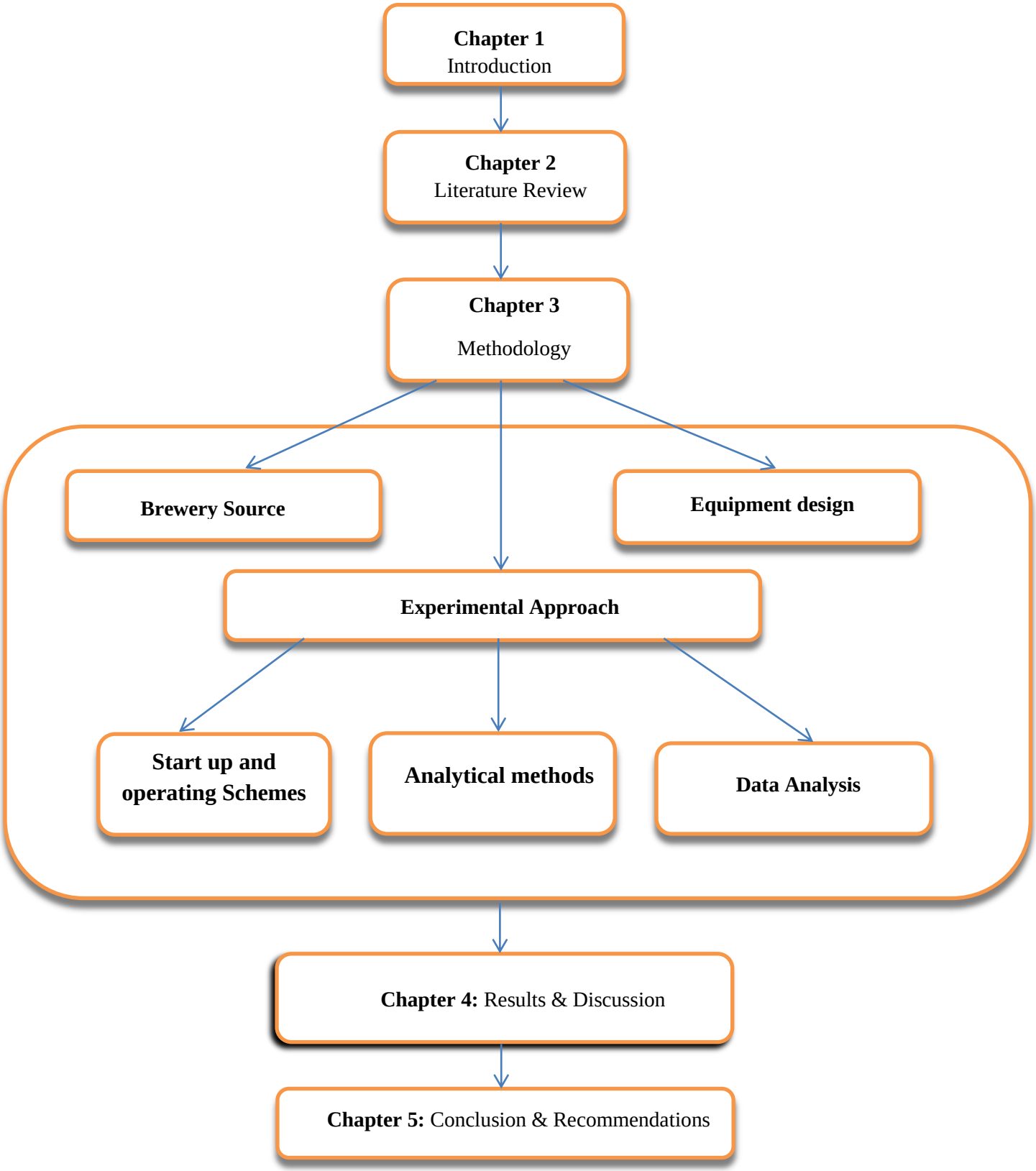


Figure 1.1: Schematic layout of the dissertation.

CHAPTER: 2
LITERATURE REVIEW

This chapter provides a review of relevant literature related to the seminal aspects of this study. The chapter is divided into four basic sections, which are covered as follows: the first section presents literature related to the general characteristics of wastewater generated from the brewery. The second section briefly outlines literature on previous studies conducted in brewery wastewater treatment. The third section presents review of anaerobic processes for the treatment of brewery wastewater as well as depicting the different studies and methods already envisaged for the aerobic treatment of brewery wastewater. A summary of the literature reviewed is presented at the end of this chapter.

2.1 GENERAL CHARACTERISTICS OF BREWERY WASTEWATER

Brewery wastewater contains high levels of biodegradable and complex organic matter characterised by-high biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total solids (TS), coupled with a wide range of other organic pollutants, which will be covered at a later stage of this study (Tam, 2002). Fluctuations in these levels are primarily dependent on the nature of the effluent generated from the brewing section and the packaging plants, mostly believed to have production rates varying independently of each other (Tam, 2002). Typical brewing stages produced wastewater low in pH and high in alcohol, proteins and carbohydrates (Tam, 2002). Packaging sections in the breweries normally generates a high volume of wastewater, with high pH and low organic matter content, since it is comprised primarily of residual beer and caustic bottle cleaning compositions (Le Clair, 1984). The high variability in BOD and flow quality forms the crux of the problem of treating brewery wastewater through a biological treatment method (Tam, 2002). Brewing processes are reportedly capable of generating large amounts of wastewater substrate and high organic sludge content that must be disposed or treated in the least costly and safest way so as to meet the stringent environmental standards applicable under the South African context (Braeken *et al*., 2004; Simate *et al*., 2011). It has also been determined that millions of cubic meters of industrial wastewater effluent has to be released into the surrounding water bodies, treated on-site or processed at municipal treatment plants (Enitan *et al*., 2015). Determining the levels of organic matter present in the wastewater generated are therefore very important, to avoid the problem created by the discharge of untreated or inappropriately treated wastewater into the environment.

It is estimated that for every one litre of beer that is brewed almost ten litres of water is used *(*Simate *et al*., 2011). Generally water in the brewing process is used for brewing, rinsing and cooling processes. Thereafter, the wastewater generated must be either discharged or treated. Brewery wastewater has a very high chemical oxygen demand (COD), ranging from 80-6000 mg/L and more, depending on the nature of the processes occurring in the production plant on the day. This COD level is a result of the total levels of all organics e.g. sugars, soluble starch, ethanol, volatile fatty acids etc. Goldammer (1999). Naturally, brewery wastewater has a relatively high temperature, ranging between 25 ^{o}C to 38 ^{o}C (mesophilic conditions) and possibly rising even higher (Briggs *et al*., 2004). The nitrogen and phosphorus content has been reported at levels between 28-343 mg/L, believed to rely on the maintenance of raw material and the amount of yeast contained in the discharged brewery wastewater (Ling, 1998). Most wastewater is generated from the separation of spent grain and yeast from the fermentation processes, but can also be made up, to a greater or lesser extent by water used in the packaging process, due to product spillages and from the washing processes.

Previous studies conducted on brewery wastewater indicated that a continuous monitoring of effluent from a brewery plant presented considerable variation in wastewater characteristics in the form of BOD, COD and total solids concentrations (Enitan *et al*., 2015). As summarised in Table 2.1, the chemical oxygen demand ranged from 2000-6000 mg/L, the biological oxygen demand in 5 days varied from 1200-3600 mg/L. The concentration of suspended solids ranged from 2901-3000 mg/L. The ratio of COD to BOD ranged from 1.53-1.67, which displayed the magnitude of biodegradability of soluble material in the wastewater. It was observed that different studies presented in Table 2.1 showed that brewery wastewater has the characteristic of fluctuating volume and quality in terms of organic and physical parameters. This fluctuating quality is illustrated by the range of concentrations of each pollutant (presented in **Table 2.1** formulated on the basis of previous work conducted by various authors). Temperature of brewery wastewater ranged between 18-40 ^{o}C, as presented in **Table 2.1** (Ling, 1998; Rao et *al*., 2007; Enitan *et al*., 2015; Dai, 2002). This might have been due to effects of environmental conditions or the general change of seasons.

Table 2.1: Characteristics of brewery wastewater (Rao *et al*., 2007; Dai, 2002; Ling *et al*., Enitan *et al*., 2015).

Constituent	**Range (Rao *et al*., 2007)**	**Range (Dai, 2002)**	**Range (Enitan *et al*., 2015)**	**Range (Ling, 1998)**
pH	3-12	7.9-8.7	4.6-7.3	6.1-9.5
Temperature ^{o}C	18-40	18-35	24-30.5	18-40
COD (Chemical Oxygen Demand) mg/L	2000-6000	454-673	1096-8926	87-6550
BOD (Biological Oxygen Demand) mg/L	1200-3600	650-1000	-	41-4260
COD / BOD ratio	1.667	1.53	-	1.53
VFA (Volatile Fatty Acids) mg/L	1000-2500	800-1500	-	11-1230
PO_4 (Phosphates) mg/L	10-50	10-50	-	10-50
TKN (Total Kjedahl Nitrogen) mg/L	25-80	25-80	-	28-343
TS (Total Solids) mg/L	5100-8750	5000-6000	1289-12248	16-1360
TSS (Total Suspended Solids) mg/L	2901-3000	None	530-3728	None
TDS (Total Dissolved Solids) mg/L	2020-5940	2000-4000	-	2010-4000

Direct discharge of brewery wastewater into the water-receiving bodies, municipal treatment plants or the aquatic environment has been reported as a significant contributing factor to eutrophication of these bodies. The high concentrations of organic pollutants consume the water of oxygen as they decompose, increasing noxious odours (Tam, 2002). Excess nitrogen and phosphorus in the effluent also give rise to plant growth and result in an explosive growth of algae (Tam, 2002). The death of algae in turn produces nutrients for other microorganisms, hence the net respiration rate exceeds the rate of photosynthesis and the concentration of oxygen in the water is depleted, resulting in the death of aquatic organisms (Tam, 2002).Treatment processes, whether anaerobic or aerobic, must concentrate on reducing the level of polluting organic matter in wastewater to a permissible level by the time it is discharged (Tam, 2002). Normally the level of BOD reduction depends on whether the

wastewater is to be further treated or to be disposed of directly into water-receiving bodies (Enitan *et al*., 2015).

2.2 STUDIES CONDUCTED ON BREWERY WASTEWATER TREATMENT

Because of the high organic content and biodegradability, brewery wastewater is an ideal candidate for biological treatment (Simate *et al*., 2011). There has been extensive research carried out on physical, chemical, biological approaches, as well as combinations of the three, to the treatment of brewery wastewater (Ling, 1998). Biological treatment has since been the preferred method for the treatment of brewery wastewater, specifically those processes utilising aerobic treatment and anaerobic treatment processes (Ling, 1998). The main objective of biological treatment is to reduce biodegradable constituents; BOD, the coagulation of non-settleable colloidal particles, and the stabilisation of organic matter present in wastewater (Simate *et al*., 2011). Historically, the treatment of brewery wastewater mainly used anaerobic treatment systems, which showed significantly better treatment efficiencies when it came to chemical oxygen reduction and had greater economic viability due to the production of biogas (methane) which can be a source of energy (Tam, 2002). The following sections discuss previous studies conducted on anaerobic, aerobic and other treatment processes for brewery wastewater treatment. Each process has both advantages and disadvantages, which are demonstrated, in addition to a review of treatment systems described in the literature. Commonly, the anaerobic processes involve the anaerobic fluidised bed (AFB) reactor processes, the up-flow anaerobic sludge blanket system (UASB) and anaerobic digestion in a granular biomass reactor. The jet loop reactor and the attached growth and suspended growth in a sequencing batch reactor have also been reviewed under aerobic treatment processes.

2.2.1 ANAEROBIC PROCESSES FOR BREWERY WASTEWATER TREATMENT

Anaerobic treatment processes consist simply of the conversion or breakdown of organic matter by microbes in an environment free of molecular oxygen. The anaerobic digestion treatment process is also well recommended and favoured, because it typically produces biogas. It is has been indicated that anaerobic treatment of high-strength industrial effluent can be superior to conventional aerobic treatment processes. Anaerobic processes have also been recommended as a more economical process for brewery wastewater treatment (Strohwald and Ross, 1992, Yongming *et al*., 1993, Cronin and Lo, 1998). In breweries, direct utilisation of biogas in a boiler is usually the preferred solution. The reason for this is that investment costs for a combined heat and power unit are higher and more extensive biogas treatment is required (Simate *et al*., 2011). The findings of these studies by Simate *et al*. (2011) and Strohwald and Ross (1992) presented over 90 % COD removal efficiencies on brewery wastewater treatment.

Brewery wastewater treatment using an anaerobic inverse fluidised bed reactor (AFBR) was assessed by (Alvarado-Lassman *et al*., 2008). In this study, two reactors were employed to evaluate organic matter removal from brewery wastewater. These reactors were ultimately operated continuously, with stepwise adjustments in organic loading rates, until limiting conditions were achieved. The findings of this study showed that the process is capable of achieving about 90 % removal of COD in the treatment of brewery wastewater. This efficacy was achieved at an optimum organic level of around 10 000 mg COD/L in a day. Based on the feasibility of the results assessed by Alvarado-Lassman *et al*. (2008), this method can be confidently applied at commercial scale. This study presented interesting COD removal efficiencies of more than 90 % at optimum organic loading rates. These results were coupled with reliable support selection and stability of the process operation when overloaded. It was also noted that, under tested conditions, extended sphere support presented a better behaviour of the fluidisation, colonisation and biofilm attached growth mechanism. The only setback observed in this study was during backwashing of excess biofilm. Time intensity control was therefore imperative for this process to avoid temporal loss of active biofilm, which would affect COD removal efficiency. Based on the study conducted by Alvarrado-Lassman *et al*. (2008), this process can be implemented and attain high COD removals.

Efficient COD removal efficiencies were recorded in the use of anaerobic fluidised bed reactor (AFBR), which was also assessed by Tanemura *et al*. (1992). This study was conducted at a laboratory-scale level. Fresh brewery wastewater had a concentration of 4700 mg COD/L and an organic loading rate (OLR) of 100 mg COD/L, at a reactor temperature of about 37 ^{o}C with a specified treatment time or hydraulic retention time of 25 hours. At this temperature, Tenemura *et al*. (1992) attained an average COD removal efficiency of about 96 %. It is believed that AFBR requires lengthy retention times for the microbial population to adapt to the support material. Elevated temperatures are required to enhance this process. The reactor used in this study required three months for the acclimation and proper attachment of the sludge to a support material used in the fluidised bed reactor at 37 ^{o}C. It was determined that the crucial benefit of this method is that little organic waste is consumed for the production of new cells. This process has an average sludge production rate of 70-130 mg of suspended solids per gram of BOD removed. This stage rendered the sludge suitable to be used for landfill applications (Metcalf and Eddy, 1991). This process is environmentally efficient, with crucial sludge by-products and has the ability to achieve very high COD removal efficiencies. It can therefore be adapted for commercial applications.

The major differences between the UASB and the AFBR, which have been covered in some literature, are that biologically-formed granules and particles are used in the UASB, while the

AFBR setup utilises a biofilm-covered support medium (Tam, 2002). The operating conditions in this study (UASB) adapted by Liu and Sun. (2011) were; an effluent from the brewery with COD levels of 2030 mg/L; OLR of about 510 mg/L within a hydraulic retention time of 4 hours and a working reactor pH around 7.1. This study attained an effective COD removal efficiency of 89 %. However, the formation of full-grown sludge granules with high activity and good settleabilty in wastewater treatment required about 6 months for start-up. This lengthy start-up time caused a setback in production rates.

A study of industrial anaerobic treatment of opaque beer brewery wastewater in a tropical climate using a full-scale UASB reactor seeded with activated sludge was demonstrated by Srivastava *et al*. (2004) and Parawira *et al*. (2005). The overall reactor volume was 500m^3 and employed a hydraulic retention time of approximately 24 hours. An average COD removal efficiency of 57 % was achieved. The total settleable solids were also reduced by 50 % and 90 %. It was observed that this study fulfilled the theoretical treatment expectations of reducing the organic pollutants to an allowable assay suitable for disposal and in compliance with local Zimbabwean wastewater discharge authorities, as stated. This opaque beer brewery effluent initial had high solids content, coupled with very high levels of organic matter, and therefore required efficient reduction before disposal. Based on the achieved COD removal efficiency, a need to optimise this process was imperative to match the overall COD removal reported as 96 % on anaerobic full-scale up-flow sludge blanket processes in previous studies by Tam (2002). Although there were disadvantages demonstrated by Parawira *et al*. (2005) specifically of low COD removal efficiency, this process showed less energy consumption in terms of heating costs since it had the ability to maintain the mesophilic operating temperature conditions. Also, methane yield was high, and the gas itself could easily be a reliable source of energy for operating the boiler and hence generation of electricity to power this process operation. Further study on improving the efficiency of COD removal is needed. Based on the findings of this study, which are partially not in congruence with literature with regard to COD removal, Parawira *et al*. (2005) needs to conduct more work before the commercial application of this study is feasible. It does, however, have the potential to serve as a critical energy alternative to remedy the recurrent power shortages and can also minimise energy cost incurred during production.

The use of identical full-scale airlift reactors with anaerobic granular sludge and residential activated sludge for brewery wastewater treatment and kinetic modelling was investigated by Xu *et al*. (2013). In this study, two identical full-scale biogas lift reactors used for treating brewery wastewater were inoculated with different types of microbial population sludge to evaluate their

feasibility constraints, activated sludge characteristics and kinetic models at a mesophilic temperature. Reactor one was operated with anaerobic granular sludge for 12 weeks and managed continuously at average organic loading rate of 7.4 kg COD/m^3 day, a COD removal efficiency of 80 % and effluent COD of 450 mg/L. Reactor two managed an average of 8.3 kg COD/m^3 day, a COD removal efficiency of 90 % and effluent COD of 240 mg/L within a hydraulic retention time of 30 weeks. It was determined that sludge characteristics, biogas compositions and biogas lift processes could be responsible for the greater effectiveness of the treatment of brewery wastewater by reactor two when compared with reactor one. This method seems to be efficient and can be adapted for commercial-scale applications for the treatment of brewery wastewater for reuse.

The anaerobic process has many advantages. Recognized notable effect of the anaerobic process is the production of biogas in the form of methane. This gas is normally used to run the whole process as a reliable recycled source of energy, commonly referred to as 'clean' energy. This gas production is an outcome of the biodegradation process in the absence of oxygen. The anaerobic process also produces significantly less sludge when compared with aerobic processes. Its wider use has been limited by ambient temperatures and the inability to adequately control the fermentation process which produces the methane. Since methane has unpleasant side-effects when breathed, and is also combustible, overflow problems are more serious than with other gases, making regulation of the process producing the gas essential.

Generally, the anaerobic treatment process is considered as a preliminary treatment stage in most wastewater treatment plants (Ling, 1998). The product of this stage ultimately requires post-treatment or further polishing in order to conform to local wastewater standards. Most anaerobic treatment processes for brewery wastewater encounter pH fluctuations, sludge bulking and longer reaction residence times as fundamental issues affecting the magnitude of treatment and reliable efficacies in this process.

2.2.2 Aerobic processes for brewery wastewater treatment

Aerobic treatment is a basic biological treatment processes in which microorganisms convert non-settle-able solids to settle-able solids (Zvauya *et al*., 1994). If the organic content of a wastewater is sufficiently low, conventional aerobic biological treatments are commonly employed, since they are cost-effective in terms of treatment and maintenance cost (Ling, 1998). Aerobic treatment of brewery wastewater has previously demonstrated viability on an industrial-scale treatment platform. This biological treatment process normally occurs in an air-abundant environment utilising aerobic micro-organisms (principally bacteria or biomass) that biologically digest and convert organic

material into more microorganisms and inorganic end-products (principally CO_2, NH_3 and H_2O) (Chan *et al*., 2009).

The high rate aerobic treatment of brewery wastewater using the jet loop reactor has been studied by Bloor *et al*. (1995). The use of a jet aeration system for the biological treatment of brewery wastewater has since become more of a research commonplace. This process transpired through the use of combining oxygen transfer with high turbulent mixing. In their studies, a loading rate of 50 kg COD/m^3day was attained with 97 % COD reduction within a period of 5 weeks. Although the settleability was found to be acceptable, non-flocculating motile bacteria caused the effluent to be cloudy and to have high suspended solids concentration around 200-350 mg/L. Based on the above mentioned operating conditions and removal efficacies, it can be concluded that this process is viable and shows proficient treatment of brewery wastewater up to 97 %. Long treatment times were observed in terms of hydraulic retentions time of about five weeks. Based on poor settling of suspended solids one can conclude that not all the organics can be feasible treated since its encountering settleabilty issue. On an experimental point of view, seemingly more work has to be done to modify the reliability of this method.

Ling (1998) commended the application of laboratory-scale aerobic sequencing batch reactors, in both suspended and of attached growth on brewery wastewater treatment. Experimental runs were carried out through a wide range of hydraulic retention times, from 0.56 to 6.06 days of treatment time. The experimental result showed that brewery wastewater could be successfully treated with both microbial configuration schemes entailing the suspended growth type and the attached growth of microbial community. The attained treatment efficacies in terms of total organic carbon (TOC), five days biological oxygen demand (BOD), chemical oxygen demand (COD) and suspended-growth reactors were achieved at a constant value more 90 % with the suspended-growth reactors performing significantly better than the attached-growth reactors. The results of this study showed that the performance of the suspended growth SBRs was more efficient compared to the of attached growth type. Therefore only the suspended growth-operation was selected for the study regarding the effect of hydraulic retention time versus loading rate. Results obtained in terms of TOC and SS were corresponding to optimum hydraulic retentions times. This system provided direct correlation between increased treatment efficiencies and increased treatment time.

The key strengths of this study were its ability to relatively maintain the level of pH at almost constant values throughout the aeration stage of this study. It was noted that the dissolved oxygen concentration varied as the aeration sequence was carried out through the reaction and mixing

phase. This was believed to be linked to TOC degradation and the microbial mass activity rate during experimentation. Most of all the strongest key strength was the ability of this system to maintain very low sludge production rates mostly observed in the aerobic suspended-growth SBRs. One can confidently advise employing this treatment method since it bears more financial convenience in the main aspects that normally impact negatively on the overall operation and maintenance of aerobic SBRs. A high level of treatment significance was demonstrated in this method; therefore it can be commercially applicable for the proficient treatment of brewery wastewater.

Aerobic sequencing batch reactor systems were much-admired for the treatment of brewery wastewater, industrial wastewater and municipal wastewater coupled with agricultural waste (Irvin *et al*., 1997). The overall achievement of this biological technology when executed in conventional operation and as SBR envisaging other operation modes referred to as contact stabilisation mode were taken into comparison to evaluate its treatment performances (Yu *et al*., 1997). The findings that were reported indicated that the BOD reduction was about 85 %. Since this SBR technology was operated in a two tank system, the almost purified substrate effluent flows gravitational into second tank for further treatment. In this vessel it was deemed to have achieved 98 % BOD reduction. This method has also been recommended for temporary operation as two high loaded one stage systems whereby a treatment efficiency based on BOD reduction was maintained at 85 %. The method was also recommended for its economic viability and reasonable operating costs in overall and easy mechanical maintenance sequence. Furthermore, Zaiat *et al*. (2001) reported that the SBR uni-tank systems ability to achieve a biological Nitrogen and Phosphorus removal efficiency of 90 % to 99 % and 97 % respectively, which proves to be a most commercial viable biological treatment technology ready to uptake at a bigger scale. Based on the above mentioned aspects of the study by Irvin *et al*. (1997) it can be advised for commercial implementation due to its ability of delivering high removal efficiencies at affordable operational costs and its simplicity of the operational procedure. This method also has the advantage of demanding a very small footprint in terms of construction space since most of the fundamental phases all take place in one vessel hence they refer to it as a typical fill-and-draw conventional sludge tank. This could be a viable method to remove high organic strength brewery wastewater pollutants.

A granular continuous membrane bioreactor with a novel hydrodynamics configuration was developed to evaluate the stability of aerobic granular sludge (AGS) (Corsino *et al*., 2016). Under continuous flow operation (Period I), AGS rapidly lost their structural integrity resulting in loose and fluffy microbial community aggregates where by filamentous bacteria were dominant. This

type of bacteria is well known for tempering with the settleability rate of the suspended solids in any biological reactor, and therefore lessens the solids retention inside the reactor (Ling, 1998; Matsumoto *et al*., 2012). Thereafter the intermittent feeding (Period II) permitted attaining the succession of feast and famine operating conditions that favoured the increase in aerobics granular sludge stability. It was gathered that non-fluctuating of this AGS transpired. According to Corsino *et al*. (2016), the preliminary study demonstrated the proposed configuration could meet the first aspect in distinction, biomass mixture prerequisite to be developed. The operating conditions of this study were on this Continuous flow rector entailed a working volume of 7.5 L and operating with a flow rate of 0.7 L/h was implementing for the duration of this work. An overview or schematic diagram is being present in **Figure 2.1** presenting the different views of the granular continuous flow membrane bioreactor (GCFMBR). It was also gathered that just like previous studied membrane bioreactors the recurrent clogging of the granules poised a treatment efficiency treat if clogged through the membrane, therefore backwashing was done to remedy this issue and project feasible high strength organic pollutants of about 90 % on COD removals. This cleaning and maintenance sequence was done every 45 minutes to assure that no clogging issues will be encountered. As aforementioned initially this reactor seeded with stabilised aerobic granules sometimes experienced rapid loss of their structural integrity ending up in loose and unstable aggregates. During this deformation of structure phase both the removal of TSS and VSS showed slight increase in trend. A number of authors noted a number of imperativeness regarding the proteins maintaining the structural strength of the aerobic granules (Sun *et al*., 2016). It was also gathered that the performance of the system in this study did not focus on the manipulation of hydraulics as they were not part of this study, therefore physical cleanings were frequently carried out to ensure constant flow of the effluent permeate. This process once well mastered and thoroughly investigated shows the ability of achieving feasible results on organic strength pollutants and therefore could be adapted with appropriate operational expertise.

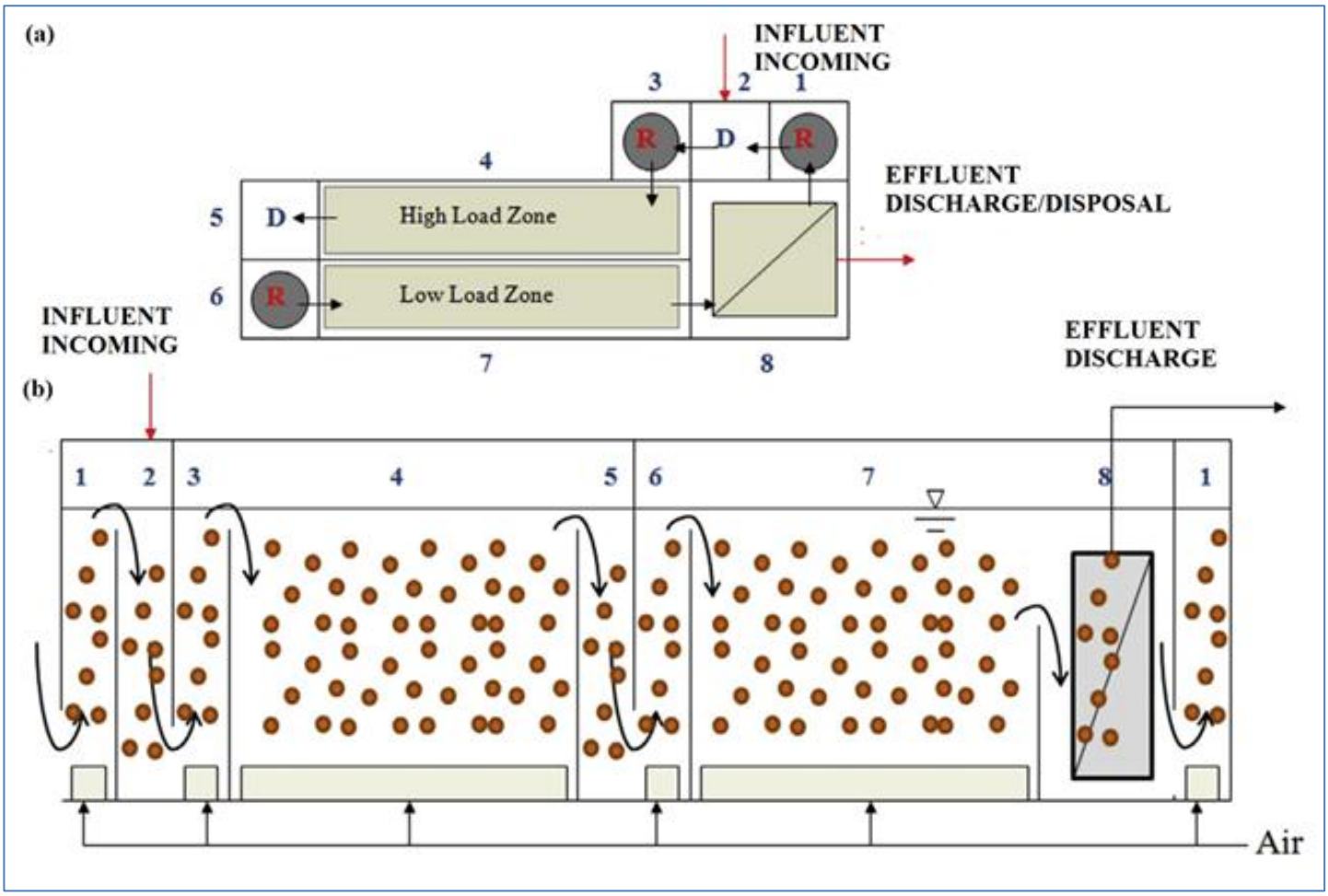


Figure 2.1: Schematic diagram of an aerobic granular continuous flow bioreactor (Corsino *et al*., 2016), (a) Ariel views projection of aerobic MBR. (b) Membrane Bioreactor longitudinal flow view.

According to Petruccioli *et al*. (2002), the aerobic jet loop reactor (JLR) activated sludge process reported its appropriateness for the treatment of industrial wastewaters, specifically brewery wastewater was investigated. A loading rate of 50 kg COD/m^3 was achieved with 97 % COD removal for a period of 5 weeks although the settleability was found to be acceptable non-flocculating motile bacteria caused the effluent to be cloudy and have a high suspended solids concentration in the order of 200 - 350 mg/L. Investigations into how this loading rate was achievable and its consequences included measurements of oxygen transfer rate, Specific Oxygen Uptake Rate (SOUR), determination of Monod kinetic coefficients and microscopic examination. Oxygen transfer rates were found to be high, with a low energy efficiency possibly due to the small scale of the rig, Although the jet loop reactor was found to be a suitable method for pre-treating brewery wastewater, an effluent polishing stage before final discharge to a watercourse was still necessary, and it was concluded that further investigations into jet design may increase the oxygen transfer efficiency and the resulting quality of effluent.

Bennett *et al*. (2007) presented a study on an evaluation of bench-scale sequencing batch reactor swine waste treatment under continuous and cyclic aeration. The findings indicated a COD mass removal efficiency of 52 % continuous low-oxygen sequencing batch reactors. It showed better performance than cyclic sequencing batch reactors systems. The suspended solids removal efficiency on the continuous aeration sequencing batch reactors was 82 %, an improvement over cyclic aeration on the sequencing batch reactors with $P < 0.004$. A total phosphorus average removal efficiency of 91 % was achieved in continuous low-oxygen sequencing batch reactors showing a better significance compared to the cyclic sequencing batch reactors with $P < 0.007$. Total Kjedahl Nitrogen (TKN) average removal efficiency of 86 % was attained with continuous low-oxygen aeration, again showing greater efficiency versus the cyclic aeration sequencing bath reactors with $P < 0.0092$. It was indicated that the performance of the two reactor configurations did not meet expectations, due to excessive loading and source inconsistency; hence operational changes were adopted to improve the reactors' performances. This study showed strong viability for the treatment of wastewater for reuse and safe disposal to municipal drains and water-receiving bodies. Based on the findings of this study, this method can be confidently adopted.

2.2.3 Current brewery wastewater treatment technologies

Generally, wastewater from the biological pre-treatment processes can be further treated even more efficiently. This section of this dissertation presents various methods that can be used for the treatment of brewery wastewater for either reuse or safe discharge in compliance with environmental standards. Some methods are used as polishing steps, especially when the discharge requirements are very stringent.

It must be stated that recycling of regenerated water as brewing water is considered inappropriate and would require that drinking water standards are complied with Braeken *et al*. (2004). The most important parameter to be considered when water is intended treated and reused is the COD (Braeken *et al*., 2004). The COD value precisely represents both the biodegradable and non-biodegradable organic components in the brewery wastewater (Ince *et al*., 2000). Brewery effluents are easily biodegradable, with BOD to COD ratio in the range 0.6 - 0.7 (Driessen and Vereijken, 2003). The organic content in the brewery wastewater expressed as COD usually consist of sugars, soluble starch, ethanol, volatile fatty acids etc., with levels varying dependent on the various sections within the brewery plant discharging the effluent (Braeken *et al*., 2004).

According to Madaeni and Mansourpanah, (2006), a review of literature has shown that reverse osmosis (RO) is a highly feasible brewery wastewater treatment based on membrane technology,

particularly suitable as a result of its greenhouse-gas friendliness, as well as flexibility in terms of mechanical sequence service and maintenance (Madaeni and Mansourpanah, 2006). Furthermore, it requires no regenerating chemical, which means no additional salts have to be added for wastewater neutralisation. (Madaeni and Mansourpanah, 2006) indicated that the efficiency of the Nanofiltration and reverse osmosis methods for the feasible treatment of brewery wastewater was 99 % COD reduction, given an influent COD concentration of around 10 500 mg/L. Nanofiltration and reverse osmosis can also be used when the final product is needed as potable water. The quality of treated effluent is very high as a result of the high removal efficiencies. However, these membrane processes are energy-consuming and require regular maintenance to avoid fouling.

Doubla *et al*. (2007) suggested the use of humid air plasma created by an electric gliding arc discharge in humid air to lower organic pollutants in brewery wastewater. The gliding arc discharge in humid air generates NO and OH radicals, which have strong oxidising characteristics. In this study Doubla *et al*. (2007), reported that the BOD removal efficiency of the process with brewery industrial waters of BOD values of 385 and 1018 mg/L were 74 % and 98 %, respectively. The alkaline wastewaters were also rapidly neutralised, due to the pH-lowering effect of the plasma treatment emanating from the production of nitrite ions (Benstaali *et al*., 1998). This process can be coupled with biological processes for further treatment to lower the organic concentration more easily and rapidly to an acceptable level for reuse (Doubla *et al*., 2007). Furthermore, it can be deduced that the flexibility of this treatment technique is promising for commercial-scale application, since it can be combined with other methods to achieve higher treatment efficiencies and thus improve the cost-effectiveness of the system as a whole. Doubla *et al*. (2007) has alluded to the suitability of this method for the treatment of brewery wastewater. Therefore, based on the above factors, combined with the easy operational conditions mentioned above, one would strongly recommend its use.

The acidification during anaerobic treatment of brewery wastewater was studied by Suzuki *et al*. (1997), in a number of laboratory tests to evaluate acidification during the anaerobic treatment of brewery wastewater. The test results indicated that pH 5-6 and a water temperature of 40 °C were optimal conditions for acidification. The findings of this process were that continuous-flow test had a tendency for the carbohydrate reduction percentage to become higher with longer retention time in the acidification reactor. A high specific methanogenic activity of about 1.4 kg COD/kg mother liquor on volatile suspended solids was observed, during which the carbohydrate reduction percentage exceeded 75 %. However, there was a tendency for the specific methanogenic activity to reduce, due to residues of highly concentrated carbohydrates. Generally,

the carbohydrate reduction was under 60 % in the acidification treated water when the retention time in the acidification reactor was short.

Anaerobic and aerobic treatments are often combined in brewery wastewater treatment, according to Driessen *et al*. (2000) and Ware and Pescod (1989). The attributes of the integration of the anaerobic and aerobic bioreactors were reported as follows: firstly, in the anaerobic reactor bulk of the COD, approximately 70-80 % was converted into biogas over a small surface area. Secondly, in an aerobic/anoxic post-treatment step, up to 98 % of the COD and nutrients were removed. Furthermore, some of the important advantages of combined aerobic and anaerobic treatment of brewery effluent over complete aerobic treatment systems showed in this study included a significant positive energy balance, reduced bio-sludge production and minimal space requirements. The recent development of tall and slender anaerobic and aerobic reactors allows for extremely compact effluent treatment plant design and stringent requirements of surface water quality (Driessen *et al*., 2000 and Ware and Pescod, 1989). **Figure 2.2** illustrates the on-site setup for the combined anaerobic and aerobic treatment system for industrial wastewater (Driessen *et al*., 2000). This process emerged as one of the most commonly applied methods in most wastewater treatment plants. It's viable in terms of high wastewater organic pollutants, removing more than 2000 mg/L and with high nitrogen assays, which strongly supports the use of aerobic biological treatment.

In the case where there is a need for very high COD removal efficiencies of more than 82 %, the anaerobic digester stage performs an immaculate removal, with very low energy consumption and highly perplexed methane gas production, which can also be recycled to fuel the very same process. This combined aerobic and anaerobic method stands out above all other reviewed technologies, due to the possibility of integrating two operations into one process, plant hence remedying of the disadvantages presented by individual stages and therefore resulting in high organic removal in compliance with wastewater disposal standards. This process has proven more effective than other methods and can thus be confidently applied. This method also demonstrates more economical viability in terms of overall operational costs, due to its simple configuration, which facilitates high reliability in compliance with stringent disposal standards.

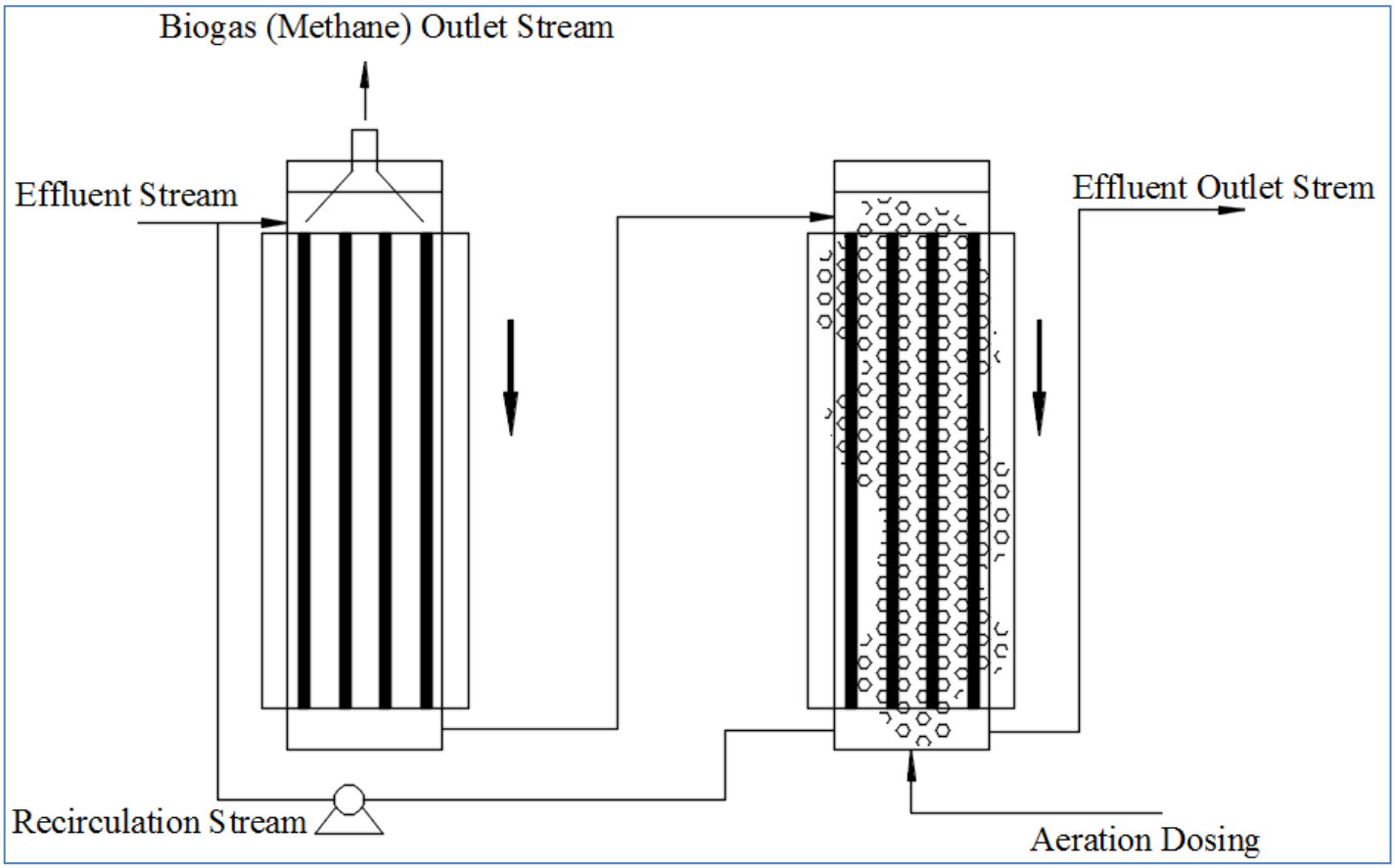


Figure 2.2: Schematic diagram of a combined anaerobic and aerobic unit (Driessen *et al*., 2000).

According to Jang *et al*. (2013), an evaluation of the applicability of single-stage thermophilic aerobic digestion (TAD) process in treating high strength brewery wastewater (BWW) was conducted. This process was undertaken under the following conditions; four organic loading rates (OLRs) from 9.2 to 37.2 kg COD/m^3 cycles. The effects of Organic Loading Rates on microbial community changes were also examined. The highest volumetric removal rate (13.3 kg COD/m^3) and the highest thermo-stable protease activity (0.95 unit/ml) were detected at OLR of 18.6 kg COD/m^3. Denaturing gradient gel electrophoresis (DGGE) profiles and quantitative results (PCR) showed significant microbial community shifts in response to changes in OLR. In particular, DGGE and phylogenetic analysis demonstrated that the presence of Bacillus sp. (phylum of Firmicutes) was strongly correlated with efficient removal of organic particulates from high-strength food wastewater. From a theoretical point of view, this process showed the ability of feasible microbial shits positively responding to the different tested organic loading rates without any setbacks. Hence, this process can be applicable to attaining proficient removal of COD, BOD and high levels of solid materials. However, it should be highlighted that the black box concept of the optimum use of microbial mass population still needs to be assessed to achieve optimum operating removal efficiencies. This process also seems to be a bit pricey for consideration as a commercial application.

2.3 SEQUENCING BATCH REACTOR FOR WASTEWATER TREATMENT SYSTEM

Sequencing batch reactors have been in use since the 1920s in most part of the world as a biological treatment for wastewater (Braeken *et al*., 2004; Irvine and Busch, 1979). The heavy contaminants in industrial wastewater from the brewery are believed to generally vary in space and time as well. The strength of organic pollutants in wastewater normally changes from time to time naturally, or is sometimes linked to variable processes within the brewing industry which in turn result in variations in overall levels of organic pollutants. These variations in compositions or organic contents are believed to be unsteady; hence steady-state treatment systems are normally designed to treat brewery wastewater discharged into receiving bodies (Braeken *et al*., 2004; Irvine and Busch, 1979; Morgenroth *et al*., 1997).

2.3.1 Operation of the sequencing batch reactor

Sequencing batch reactors (SBRs) are a type of activated-sludge process. They differ from standard activated sludge plants, since they pool all treatment steps and processes into a single basin, or tank, whereas conventional facilities rely on multiple basins (Tomei *et al*., 2003). According to Ris. (2007) and Irvine *et al*. (1989) a sequencing batch reactor is no more than an activated sludge plant that operates in time rather than space. In its simplest form, the SBR system is a set of tanks that operate on a fill-and-draw basis. Each tank in the SBR system is filled during a discrete period of time and then operated as a batch reactor. The cycle of each tank in a typical SBR is divided into four: fill, react, settle, draw and idle. **Figure 2.3** presents the basic operation of the sequencing batch reactor for each tank for one cycle in four discrete time periods (Irvine *et al*., 1989; Ketchum Jr *et al*., 1979).

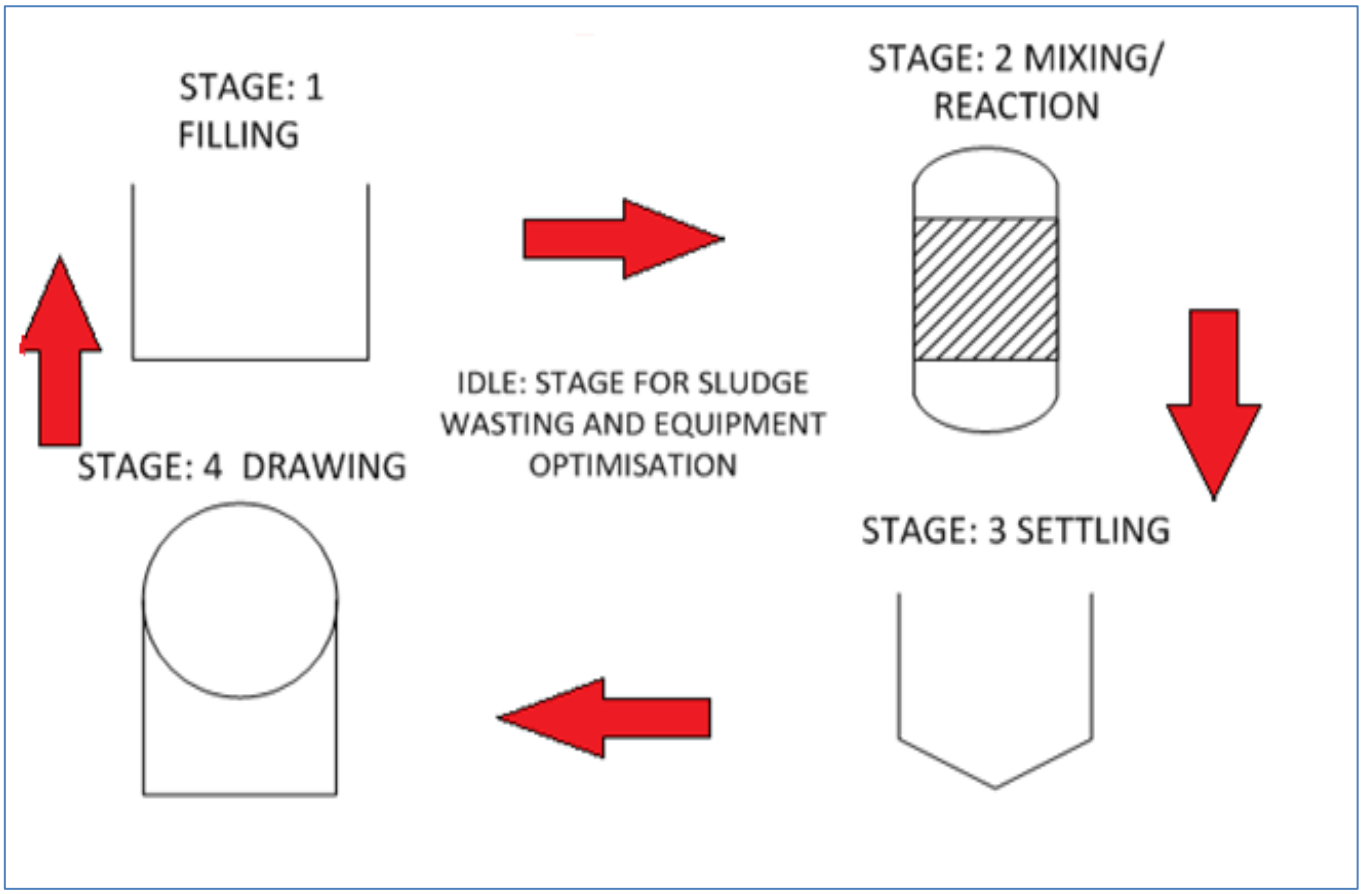


Figure 2.3: Schematic diagram of the SBR operations time periods of fill, react, settle, draw and idle (Ling, 1998).

Each tank is filled during a discrete period and then operated as a batch reactor. After desired treatment, the mixed liquor is allowed to settle and the clarified supernatant will be drawn from the tank. This illustrates the essential difference between the SBR technology and the continuous-flow conventional activated sludge system. In the SBRs, functions such as equalisation, aeration and sedimentation are carried out in a sequence dictated by time, not the space that is occupied (Bennett, 2007). A detailed description of the anticipated phases for the aerobic SBR sequence is as follows:

The fill phase provides for the addition of influent to the reactor. During this sequence, the influent wastewater will be added to the biomass. Depending upon treatment objectives set forth, the fill may be static, mixed or aerated. Static fill, meaning no mixing or aeration, results in minimum energy input and high substrate concentration at the end of this phase. Static fill has been recommended with neither aeration nor mechanical mixing, as this will enhance high fermentation rates, which will in turn allow flocculants bacteria to outcompete filamentous species, hence preventing sludge bulking (Irvine and Busch, 1979; Irvine *et al*., 1989).

The reaction phase follows once the reactor is filled. In general, vigorous aeration characterises this phase. Depending on requirements, this stage can be carried out in high dissolved oxygen concentrations (aerated react) or in low dissolved oxygen concentrations (mixed react). The time to be allocated here should suit the desired level of effluent quality. Usually, more than 50 % of overall cycle time is allocated. Review of the literature established that longer aeration periods in the order of 4 hours or more are normally required for long-term stability of the aeration during the react phase is interrupted (Irvine *et al*., 1989). Anoxic conditions will also be provided to enhance the stripping away of nitrogen gas bubbles and aid in sedimentation (Irvine & Busch, 1997).

The settling phase normally allows for separation of bio-solids from the treated effluent without any inflow or outflow, in the SBR reactor, that may have a volume more than ten times that of a secondary clarifier used for conventional continuous-flow activated sludge plant (Irvine *et al*., 1989). The crucial advantage of the SBR will be its use as a clarifier, which allows for truly quiescent sedimentation conditions (Irvine *et al*., 1989). Normally, all the biomass remains in the tank until some fraction must be wasted, hence no needed for underflow hardware commonly found in the conventional systems (Irvine & Busch, 1997; Irvine *et al*., 1997).

Finally, the draw or decant phase follows. Basically, this is a withdrawal phase to discharge the clarified effluent from the reactor (Morgenroth *et al*., 1997). Literature has mentioned several withdrawal mechanisms available (Irvine *et al*., 1989). Such mechanisms could include a simple pipe fixed at some depth, with the flow regulated by a pump. Alternatively adjustable with regulated weir at or just beneath the liquid surface can be used. The design criteria for withdrawal mechanisms will be based on the fact that floating matter must be prevented. This draw phase normally occupies about 5 % to more than 30 % of the total cycle time. This period should not be overly extended, as this would result in a rise in sludge problems. Typically, one hour will be employed (Braeken *et al*., 2004). The idle mechanism is envisaged as a maintenance sequence to fine-tune the biological treatment efficacy of the microorganisms. It can be determined by the net solids increase in the reactor for each cycle and the mixing and aeration equipment capacity (Braeken *et al*., 2004).

2.3.2 Applications of aerobic sequencing batch reactors in wastewater treatment

The sequencing batch reactor (SBR) is an activated sludge process designed to operate under non steady-state conditions (Irvine *et al*., 1989). A sequencing batch reactor operates in a true batch mode whereby aeration and sludge settlement both occur in the same tank (Ling, 1998). The essential variance between SBR and conventional, continuous flow activated sludge systems is that

the sequencing batch reactor vessel executes the purposes of equalisation aeration and sedimentation in a time sequence process, rather than in the conventional space sequence of continuous flow systems (Ling, 1998). Moreover, the sequencing batch reactor tank can be fabricated with the potential to treat a broad spectrum of effluent volumes, but the continuous system is based upon a fixed influent flow rate. Thus there is a degree of flexibility associated with operating in a sequence based on time, rather than in a space sequence (Ling, 1998).

It has been reported by Fernandes (1994) that the sequencing batch reactor technology system, operated in a fill-and-draw mode under sequential anoxic or aerobic conditions in a single tank, yielded a high combined rate of organic carbon and nitrogen compounds removal. An anoxic fill sequence, rich in exogenous organic carbon, favoured denitrification and, as a result, oxidised nitrogen levels dropped. In the aerated react phase the ammonia accumulated during the fill sequence is oxidised to NO_2 - NO_3 - NO. The nitrifiers were not inhibited by the anoxic operation (Feng *et al*., 2008; Ling, 1998).

Some studies have also described SBR processes consisting of two or more tanks. One tank receives the incoming wastewater substrate while the others are in reaction, settling, draw-down or idle phases. When the first tank is full, the incoming wastewater stream is diverted to a second tank which has been drawn and is in a standby phase, ready to accept wastewater (Irvine and Busch, 1979; Ketchum Jr *et al*., 1979). It was observed that a highly variable oxygen demand was exerted on an SBR system. Irvine *et al.* (1989) stated that the required aeration rate increased from a level needed for endogenous respiration in the standby phase, when the substrate concentration and liquid volume were both low, to a peak at the end of the filling cycle (Irvine *et al*., 1989). During the reaction phase, the required aeration rate will be dropped to a level needed for endogenous respiration and then shut off completely to allow settling and draw-down to the minimum level needed to contain the settled solids.

Novel approaches have also been developed based on sequencing batch reactor concepts. One was the sequencing batch biofilm reactor (SBBR) technology. Irvine and Busch (1979) used an anaerobic SBBR (or ASBBR) to reductively dechlorinate PCE (perchloroethylene). The ASBBR was a periodically-operated up-flow packed column reactor. It operated on a cycle consisting of three periods: fill, react and draw, and was constructed from glass columns filled with acid-washed pea gravel as a support matrix. The consortium of microbes which can dechlorinate was enriched by this ASBBR, and the reductive dechlorination always occurred in the presence of methanogenesis (Ling, 1998). The efficiency of an SBR operation is also affected by factors such as nutrient levels,

temperature, and fill strategies (Irvine and Busch, 1979). It has been proven that higher temperatures exert a positive influence on the overall performance of the SBR in the range (5 – 21) ^{o}C, and the process performance seriously deteriorated at 5 ^{o}C (Fernandes, 1994). The effects of anoxic and oxic fill strategies on SBR performance under nitrogen (NH_4Cl as the nitrogen source)-deficient and nitrogen-rich conditions were evaluated using glucose as the sole substrate (Sheker *et al*., 1993). The performance was evaluated on the basis of substrate removal, sludge settling ability, supernatant suspended solids, and reactor biomass concentration. Substrate removal efficiencies were found to be independent of the fill strategies adopted, under all conditions tested. The incorporation of the anoxic selector environment failed to prevent the development of bulking sludge under conditions of nitrogen deficiency, thereby resulting in a gradual depletion of reactor biomass (Sheker *et al*., 1993). Under nitrogen rich conditions, the sludge settleability improved significantly when an anoxic fill strategy was adopted. Furthermore, suspended solids readings taken at the end of the settling period were higher with anoxic fill than oxic fill, indicating that the latter discourages the growth of dispersed bacteria (Sheker *et al*., 1993).

2.3.3 Advantages of aerobic batch sequencing reactors

Comparing the sequencing batch reactor with the continuous system, the former is more dynamic and flexible in terms of operation and has more advantages kinetically (Irvine and Busch, 1979; Irvine *et al*., 1989; Zvauya *et al*., 1994). The SBR process covers a range from feast to famine during the reaction cycle and the different aerobic/anoxic/aerobic conditions imposed (Ling, 1998; Tam, 2002). Since SBRs impose a diverse array of operating conditions and selectivity pressures, they can be used as a versatile tool for the enrichment of specific pressures and the induction of desired metabolic pathways. By adding the systems own periodicity of forcing function, the potentially negative impact on those forcing functions associated with variations in contamination concentration, and other environmental uncertainties, can be mitigated (Irvine *et al*., 1989). Studies of sequencing batch operations indicated that the sequencing batch reactor concept is a viable and economically attractive alternative to the conventional continuous flow activated-sludge process in BOD, SS and nitrogen removal, as well as in the chemical precipitation of phosphorus (Chan *et al*., 2009). The dynamic and flexible nature of SBR systems allows ample room for expansion and operational adjustments at minimal costs.

According to Ling (1998), the potential advantages of sequencing batch reactors for wastewater treatment are as follows:

1. A smaller reaction volume, because both aeration and settling are in the same tank;

2. Batch discharge of only treated wastes meeting effluent limitations (this is possible by monitoring the wastes and proving additional treatment if its quality is poor);
3. Great oxygen transfer efficiency;
4. Facilitated design of a series of specific operating states;
5. Anoxic periods enhance denitrification and nitrogen removal, control for filamentous organisms and reduce power consumption;
6. Cost operational;
7. Operating flexibility and control;
8. Minimal footprint;
9. Potential capital cost savings by eliminating clarifiers and other equipment; and
10. Equalisation, primary clarification (in most cases), biological treatment, and secondary clarifiers can be achieved in a single reactor vessel.

However, it was documented by Ris (2007) that there are also potential disadvantages to the application of aerobic sequencing batch reactors in wastewater treatment. These include:

1. A greater level of sophistication is required, especially for larger systems, for control units and panels;
2. Higher levels of maintenance (related to conventional systems) as a result of more sophisticated controls, automated switches, and automated valves;
3. Potential of discharge floating or settled sludge during the draw or decant phase, with some SBR configurations;
4. Possible plugging of aeration devices throughout designated operating cycles, liable on the aeration systems used by the manufacturer; and
5. Probable condition for equalisation after the SBR, depending on the downstream processes.

2.4 SUMMARY OF LITERATURE REVIEW

A summary of the literature reviewed highlighted that the application of a sequencing batch reactor treatment of wastewater process has the ability to significantly reduce the organic pollutants in the wastewater. This research is driven by the need to reduce the pollutant concentration typical of wastewater generated from the brewery process.

Generally aerobic treatment has been applied for the treatment of brewery wastewater and recently, anaerobic systems have become an attractive option because of their high COD content removal, among other advantages. Though these biological methods have found widespread application for the treatment of the characteristically high organic content of brewery wastewater, further treatment is typically required for water reuse.

This literature review highpoints the necessity of the treatment of brewery wastewater. Emphasis was made on various methods that may be used to securely and cost-effectively treat brewery wastewater for reuse and safe discharge into receiving bodies, in compliance with environmental legislation. It should be noted and emphasised herein that the treatment of brewery wastewater effluent is a costly and relatively complex activity; particularly with the need to meet stringent governmental regulations and requirements of environmental friendliness (Kanagachandran and Jayaratne, 2006).

Wastewater treatment has been a challenge throughout the years due to varying influent chemical and physical characteristics and stringent effluent regulations (Irvine *et al*., 1989). Treatment systems using activated sludge have been able to handle many of these difficulties. This coupled with the flexibility of a SBR in the treatment of variable flows, minimum operator interaction required, option of anoxic or anaerobic conditions in the same tank, good contact with microorganisms and substrate, small floor space, and good removal efficiency (Irvine *et al*., 1989), makes an SBR a live option. From the literature review, it was evident that the gap that needs to be addressed regarding brewery wastewater treatment both globally and otherwise entails the following relevant key aspects. A survey conducted by the American Brewers Association found that not many breweries have a dedicated onsite wastewater treatment system (Association, 2013). Most discharge their effluent to a municipal treatment centre, due to shortage of existing efficient treatment methods. This normally incurs extra cost, resulting in additional municipal treatment work in order to meet discharge standards set by local water and wastewater authorities. Some operations have on-site collection of high strength waste material and therefore require some pre-

treatment processes installed at their facility to treat the effluent prior to disposal into water-receiving bodies and municipal discharge sewers. Most commonly, pre-treatment mainly entails adjusting of the pH and settling out of solids. As stated above, stringent regulations on the high strength organic pollutants (BOD and TSS concentrations) results in unnecessarily high cost to the brewery industry during disposal, therefore highlighting a need for viable treatment technologies to reduce this organic matter cost. This cost have been approximated to a third paid on extra surcharge based on the effluent strength in terms of Association (2013).

It has been established that anaerobic systems are efficient at treating high strength organic pollutants contained in brewery wastewater, often comprising high COD assays of more than 2000 mg/L and consistent average COD removal efficiencies above 82 %. Anaerobic systems also have lower energy consumption demands, especially during the operation duration, low sludge generation and a fuel product in the form of methane, which is normally efficient for sourcing the very same process. This anaerobic system typically requires high COD concentrations in the brewery wastewater substrate for treatment (Fao, 2004). Deviation from the operational conditions range for an anaerobic system produces destabilisation of the system. It was gathered once again that the prolonged start-up periods coupled with the possibility of destabilisation and the potential lengthy restart durations, make anaerobic systems unsuitable for the brewery wastewater treatment scope.

In conclusion, the aerobic systems studied in this literature review presented the primary advantage of being more robust than anaerobic processes. The major downfall observed in most of the aerobic processes was with restart sequences, which would be in the order of hours and days, not months. The optimum operation temperature of aerobic processes, according to the above studies, ranged between 25 and 35 ^{o}C (Fao, 2004). This implied that the energy requirement for heating would be substantially minimised, compared to the anaerobic processes, which must operate mostly above 30 ^{o}C (mesophilic conditions) in order to attain optimal organic pollutants removal. Even though this process has the tendency to produce sludge that is generally more effusive than in the anaerobic process, recycling of a portion of the settled cells back into the reactor maintains the desirable treatment efficiency in the reactor, and the remainder of the settled solids is normally pumped to a digester for further processing (Metcalf and Eddy, 1991).

It was established that the aerobic system presented treatment efficiencies above 82 % of COD removal efficiencies at given optimum operating conditions, even though this aforementioned removal efficiency, was significantly less than the average of 90 % normally attained in anaerobic

processes. This present study focuses on the use of aerobic sequencing batch reactors due to the variable nature of brewery wastewater. It should be noted at this stage that no feedback control system on the proposed method will be implemented. No additional chemicals for boosting the C:N:P ratios were used. A purely biological aerated system with mixed-culture heterotrophic microorganisms was evaluated on its ability to efficiently treat brewery wastewater and, finally, compare its performance with the reviewed studies in the above literature review.

CHAPTER: 3
METHODOLOGY

This chapter presents the methodological approach undertaken to achieve the objectives of this study. The chapter is divided into four main sections. The first section presents the methods for sample collection and preparation; the second section incorporates the description of the reactor design and construction and the operation of the two sequencing batch reactors. The analytical methods considered in this study are presented in the third section. A description of the statistical analysis conducted to analyse the data collected is presented in the last section of this chapter.

3.1 SAMPLE COLLECTION AND PREPARATION

The brewery wastewater used for this study was collected from a local brewery, South African Breweries (SAB) in Durban, South Africa. Brewery wastewater samples were collected for two main purposes; initially to characterise the wastewater generated from the brewery in order to identify the pollutant strength of the wastewater and secondly, samples were collected for the operation of the two constructed laboratory-scale SBR for treatment purposes, to investigate the performance of the SBR in reducing the organic pollutant strength in the wastewater generated from the brewery. **Figures 3.1** and **Figure 3.2** shows the sampling site at the SAB Breweries plant.

Figure 3.1: Image of the sampling point, SAB (Durban) wastewater treatment plant.

Figure 3.2: Image of brewery wastewater sampling in-progress, SAB (Durban) wastewater treatment plant.

For the purpose of characterisation of the wastewater generated from the brewery, samples were collected on a daily basis from the brewery for a month to allow for the evaluation of the extent of variation in the wastewater generated from the brewery, which widely depends on the processes taking place within the plant. Samples collected were transported to the university laboratory immediately in a cooler box full of ice and analyses were conducted immediately, where possible. However, if it was not possible to conduct the analysis immediately, samples were kept in the cold room of the laboratory at 4 ^{o}C and analysis was conducted within 48 hours of sample collection. A brief description of analyses conducted on collected samples is presented in Section 3.3. Samples collected for the operation of the SBR were carried out once a week, fed into the SBRs and treatment proceeded immediately. Influent and effluent samples were taken for each run and subsequently analysed. A grab sampling approach was implemented to collect brewery wastewater substrate. This was done to obtain the parameters used to determine the performance of the two SBRs: COD, BOD, total solids (TS), volatile solids (VS) and total suspended solids (TSS), according to the standard methods (APHA, 1998). A detailed description of the standard procedure that was carried out for analysing all performance monitoring parameters is presented in **Appendix A**.

The acclimation or adaptation of microorganisms to organic chemicals is an important factor influencing both the rate and the extent of biodegradation. In this study the acclimation procedures were conducted within the laboratory under continuous aeration at high-oxygen dosing concentrations of about 7.5 L/min. The inoculum was harvested from the activated sludge digester plant of the SAB wastewater treatment works section of the mill. This procedure is theoretically referred to as the 'single-bucket' procedure; microorganisms were acclimated over a 21-day period in a 5 L bucket. Due to the nature of the brewery wastewater, often characterised by high pollutant concentration, causing difficulties in biodegradation and thus contributing to environmental pollution, an adequate acclimation was completed in order to achieve the adequate degradation of some recalcitrant compounds, such as total solids contained in the brewery wastewater. Acclimated microorganisms were used as the source of inoculum for subsequent biodegradation of batch runs, in which carbon dioxide evolution was measured in the form of organic carbon as chemical oxygen demand (COD) and biological oxygen demand (BOD). Based on findings from the literature, the acclimation period was maintained at about a month, as stated. Almost importantly, no chemical additions to enhance total nitrogen and phosphorus were employed. Therefore, a dark brown to blackish colour change of these microorganisms was noticed once acclimation was stopped after a month, proving its efficient activity and readiness for seeding into the reactors. This procedure was necessary as part of the start-up for the aerobic SBRs in treating brewery wastewater.

3.2 EQUIPMENT DESIGN

This section of the chapter presents the detailed reactor design features and specifications that were used in the fabrication of the two sequencing batch reactors for the treatment of brewery wastewater. There were two reactors operating in two different aeration schemes: one with cyclic aeration and the other with constant low-level aeration. Other than the aeration schemes, the reactors were identical. The reactor tanks were calibrated to18 L; clear PVC, mix-and-fill tanks, with the bottom of each tank having a slope of 60 ^{o}. Each reactor had a diameter of 35 cm and a height of 45 cm, therefore yielding a theoretical reactor volume of 21 L. Based on the selected HRT, the daily batch volume was set at 12 L working volume to 2.5 L of microbial mass population. The slope at the bottom of each tank made it easier to drain the bio-solids from the system. Both reactor tanks were none baffled. This was perceived to avoid proper sludge mixing with the treated brewery waste water during operation. Also, the lab scale capacity and conical design of these SBRs seemed non compatible with extending baffles on its bed. A more quiescent and easy gravitational settling mechanism was perceived in a more open batch reactor as compared to a baffled one at laboratory scale dimensions.

In order to drain the treated water after solids settling, two spigots were added to the side of each tank. The use of this spigot is intended to minimise the occurrence of scouring during the removal of the supernatant. Tank drainage occurred manually by opening the spigot valve and collecting the desired volume of sample. **Figure 3.3** illustrates the theoretical configuration of the mix-and-fill tanks with the utilisation of a detailed piping and instrumentation diagram that was used to optimise the design of these mix-and-fill SBR tanks. **Figures 3.4** presents the isometric design view for the two SBRs employed on the treatment of brewery wastewater in this study. **Figure 3.5** shows the cross-sectional view for the laboratory-scale SBR employed in this study (see **Appendix H**).

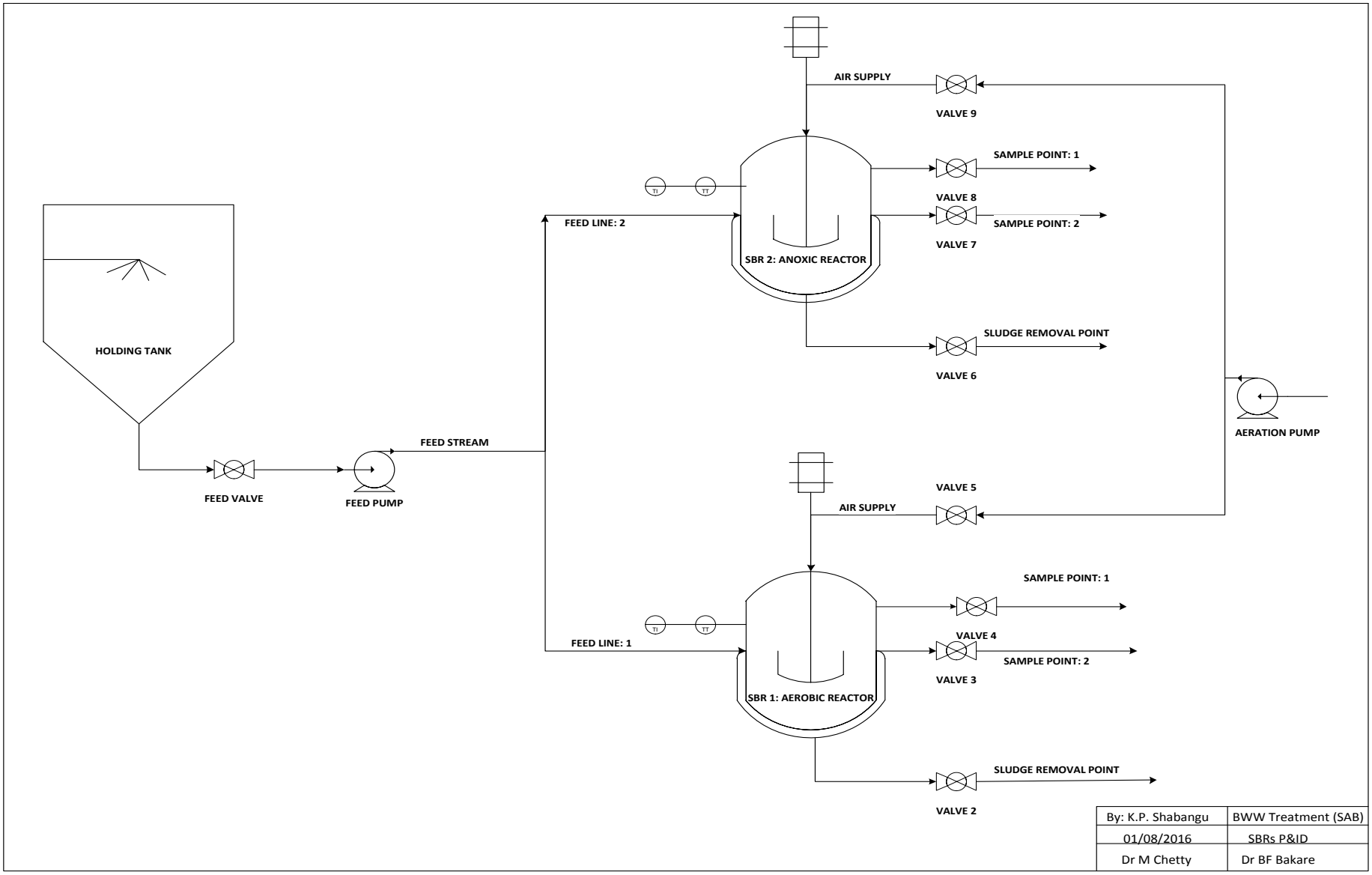
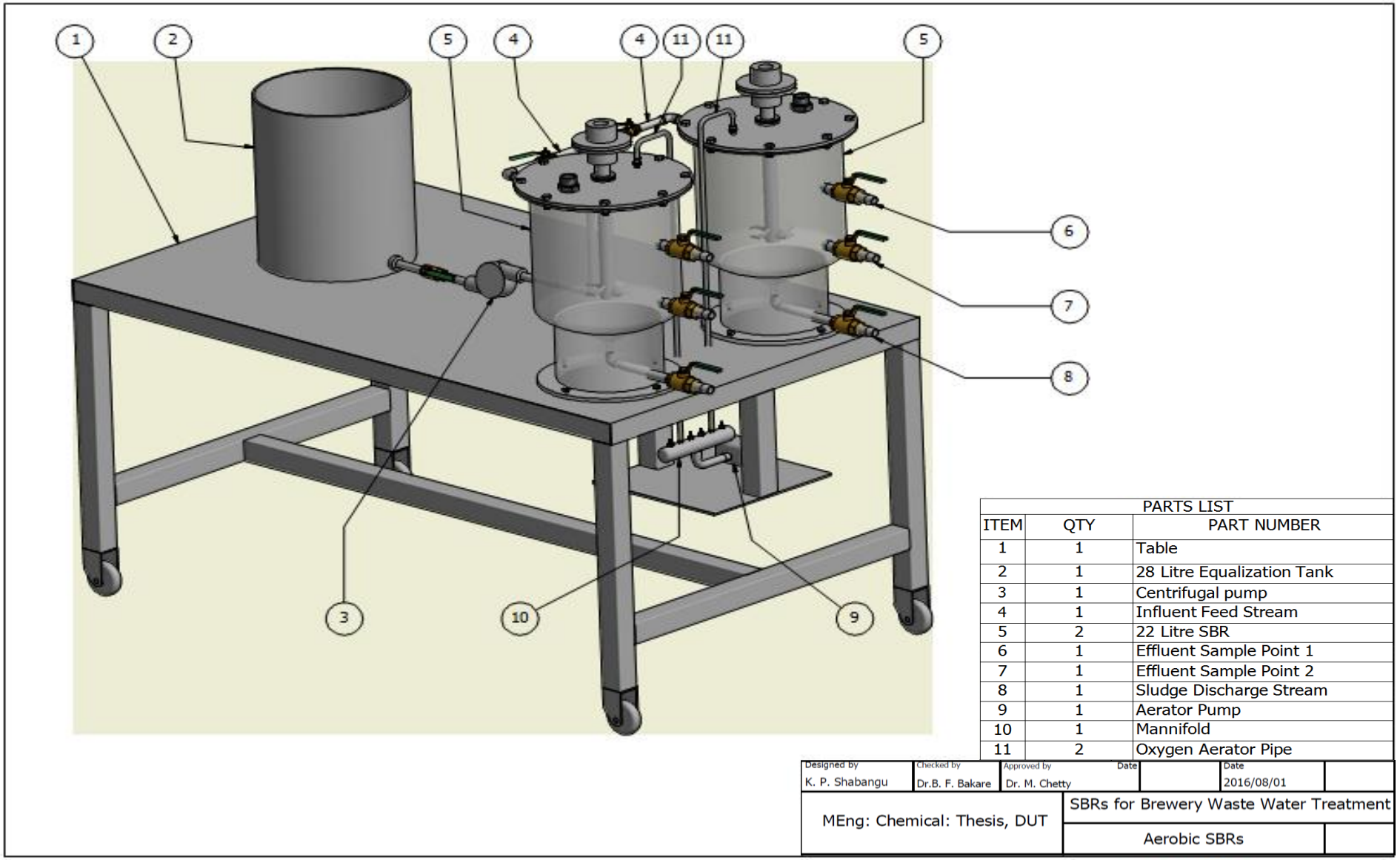


Figure 3.3: P&ID for SBR in Treating Brewery Wastewater.



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Table
2	1	28 Litre Equalization Tank
3	1	Centrifugal pump
4	1	Influent Feed Stream
5	2	22 Litre SBR
6	1	Effluent Sample Point 1
7	1	Effluent Sample Point 2
8	1	Sludge Discharge Stream
9	1	Aerator Pump
10	1	Mannifold
11	2	Oxygen Aerator Pipe

Designed by	Checked by	Approved by	Date	Date	
K. P. Shabangu	Dr.B. F. Bakare	Dr. M. Chetty		2016/08/01	

MEng: Chemical: Thesis, DUT	SBRs for Brewery Waste Water Treatment
	Aerobic SBRs

Figure 3.4: Isometric view for the SBRs.

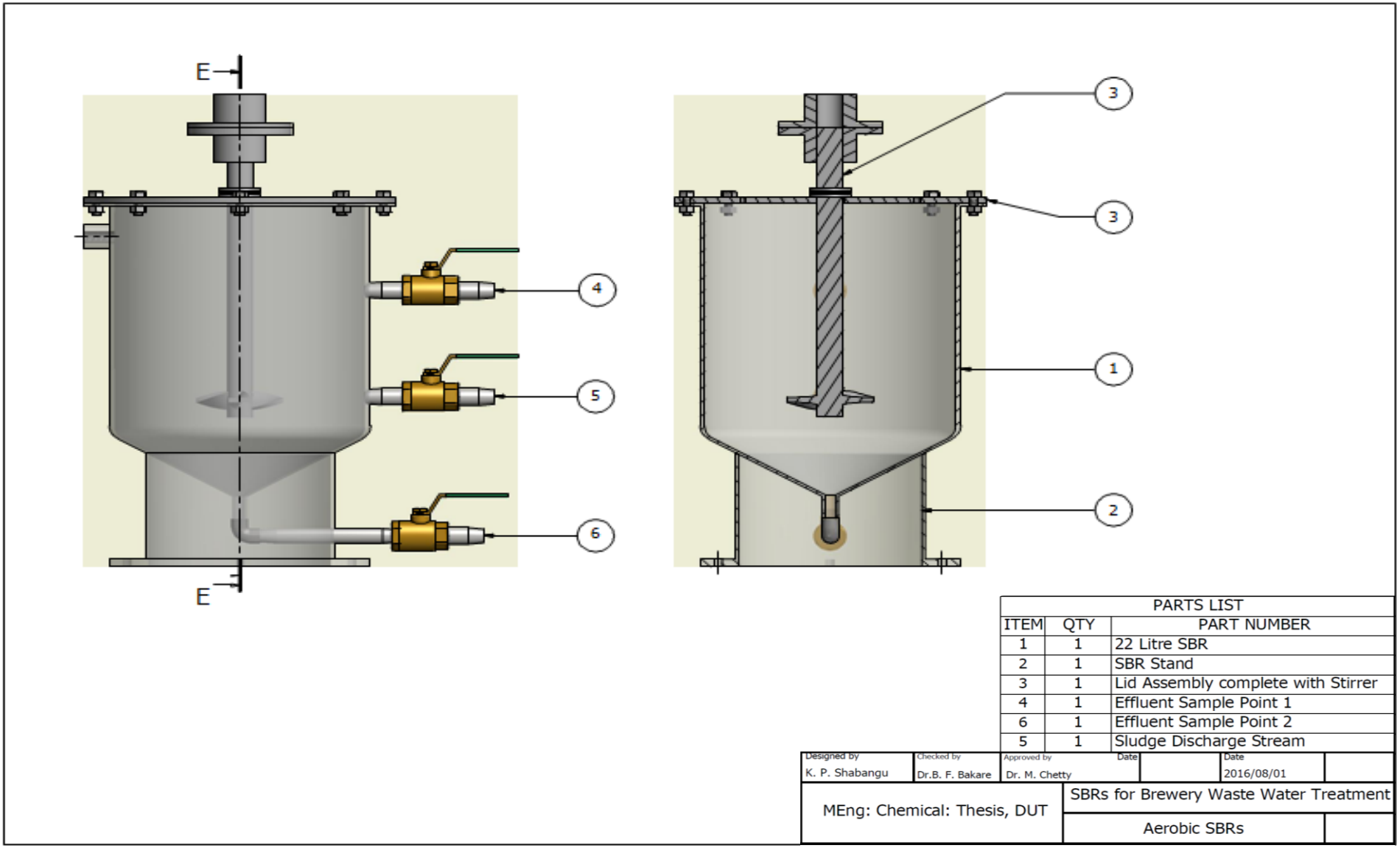


Figure 3.5: Cross-Sectional view for the SBR.

Figure 3.6: Full front view image for the two aerobic sequencing batch reactors after construction.

Portable shaft mixers kept the solids suspended in the reactors. The motors were mounted on rubber gaskets and the shafts entered the reactors via 7.62 cm diameter holes in each reactor lid. The mixer shafts descended vertically into the tanks. The impeller blades were made of stainless steel, with a diameter of 6.35 cm. These mixers operated continuously, except during the short time allowed for settling and supernatant draining. The low or mid solidity hydrofoils impellers were selected for both SBRs. This impeller uses the Bernoulli's principle in the design of its blade. The camber of the blade increases the efficiency of the impeller, reducing its power and pumping ratio. A more technical benefit perceived to be the laminar flow created by the camber of this impeller. This camber reduces turbulence or shear mechanism substantially during mixing which is imperative to avoid sludge bulking of microbial mass. That is why it was selected in this study due to the shear-sensitive nature of microorganisms. The mixer switches were operated manually. The rubber gaskets were modified rubber end-caps for 7.62 cm PVC piping. The modifications consisted of removing the thinner portion of the cap, leaving a 1.27 cm thick disk, and then cutting a hole to allow passage of the mixer blade through the newly-formed rubber ring. These rubber gaskets acted as seals to minimise leakage of odorous gases and absorb noisy vibrations from the motors during

mixing. Each mixer blade was positioned a few centimetres above the bottom outlet, allowing for the dispersion of the larger solids. The motor operated at 10.0 W and 600 rpm. The shaft was stainless steel with a length of 45.7 cm and a diameter of 0.79 cm. Two thin copper lines fitted into each SBR from top-down half way must of the reactor to enhance even dosing and aeration of oxygen during the mix-react and aeration phase were used in this study. The 2.5 cm diameters of these dosing lines were perceived to maintain the aeration pump oxygen dosing capacity efficiently. Less pumping power and at higher efficiencies will be achieved as well. A detailed apparatus sheet for the aerobic sequencing batch reactors and instruments used during designing and fabrication is presented in **Table 3.1**.

Table 3.1: Instrumentation used for the fabrication of the SBRs **mix-and-fill tanks.**

Apparatus	**Quantity**	**Description**
Reactor	2	Clear PVC plastic column Working volume: 21 L
Frequency inverter	1	CFW-08 with motor –WEG-IP55 Frequency: 60Hz
Input /Output control card	None	None
Centrifugal pump	1	**Waterfall garden pump** Flow: 700 L/hr. Power: 10 W Head $_{(min)}$: 0 Head $_{(max)}$: 1.2 m Temperature $_{(max)}$: 35 ^{o}C
Air pump	1	**Waterfall Garden pump** Air Flow: 22 L/min. Power: 10 W Pressure$_{(max)}$: 0.028 MPa Temperature $_{(max)}$: 35 ^{o}C
Temperature probe	2	**Min/ Max** Temp$_{(min)}$: 20 ^{o}C Temp$_{(Max)}$: 70 ^{o}C
Mixer	2:1	**Mixtec Stirrers** 1 x 1.25 kW WEG motors x 220V 1 x 0.37 kW variable speed controllers 2 x stainless steel shaft / impellor 1 x mild steel mounting brackets 1 x switch gear

3.3 EXPERIMENTAL

The experimental operation of each sequencing batch reactor was covered within 15 consecutive weeks of investigating and studying of the operating parameters in the two SBRs that determined the efficiency of brewery wastewater treatment, in terms of stabilising organic pollutants and solids removal. A comprehensive operation sequence is described in the following sections.

3.3.1 Aerobic Sequencing Batch Reactors operation

Sequencing batch reactors are characterised by a series of steps or phases, each lasting for a specific period of time, in sequential manner as below:

1. Filling: the purpose is to add substrate or wastewater into SBRs.

2. Reaction: the purpose is to complete the reactions that were initiated during filling.

3. Settling: separation of the biomass from the treated waters.

4. Drawing: withdrawal of treated effluent, which is the supernatant that forms during the settling.

And idling process was also carried out, which basically reflects the excess capacity of the system being wasted at specific times, normally referred to as ‘sludge age’.

In its simplest form, the sequencing batch reactor system is a set of tanks that operate on a fill-and-draw basis. Therefore, each reactor had to be filled for a discreet period and then operated as a batch reactor. After the optimum treatment time, the mixed liquor was allowed to settle and the clarified supernatant was drawn from the tank. Prior to full experimentation, the hydraulic retention time had been experimentally determined. This was done as per the following descriptive procedure:

Experimental runs were conducted for determining the HRT, and precise data was obtained in terms of COD biodegradation, which presented a hydraulic retention time of 5 days. This period was selected as an optimum treatment time for proper biodegradation of high strengths pollutants and optimum solids removal in this study. According to the reviewed literature, theoretical hydraulic retention time (HRT) for any batch process has to be modelled based on sequencing reactor volume with regards to the filling volumetric flow rate. A fixed sludge retention time (SRT) of about 28 days was implemented and a standard operating pH value of 6.0-9.0 was maintained though, the variation caused by fluctuating due to the alkalinity of the microbial mass.

Figure 3.7: The operation image of the two SBRs.

The full descriptive approach of the experimental approach and operation was done as per the following:

1. Filling phase

The fill phase was carried out first. This provided for the addition of influent into the reactors. Based on the objectives of this study as set forth, the static fill sequence was adopted. No mixing or aeration was concurrently carried out with mixing.

The static fill method has been recommended requiring neither aeration nor mechanical mixing, as this enhances high fermentation rates which allow flocculent bacteria to outcompete filamentous species, hence preventing and minimising chances of sludge bulking (Irvine and Busch, 1979; Irvine *et al*., 1989). This sequence was carried out within 3 minutes of the treatment time in every batch.

2. Aeration phase

The reaction phase was carried out once the aerobic sequencing batch reactors were completely filled to desired reactor working volume. In general, intensive aeration is the outstanding feature of the continuous aeration configuration in this treatment phase. An adequate amount of dissolved oxygen (DO) was supplied during the cyclic aeration configuration "on" phases to meet the supply level of the COD while allowing the reactor environment to return to anoxic conditions during the aeration "off" phases. The following sections provide details of the two aeration configuration's that were carried out considered and in principle the overall aim of the study.

The aeration sequence was carried out by means of a diaphragm air pump connected to the air diffusing copper pipes. To keep the small diffusers from floating freely in the tank, they were fitted to the end of a solid, copper pipe tube, which descended vertically into the reactor through a hole in the lid. The flow rate for the continuous aeration reactors was at 2.5 L/min. The room temperature was averaged around 23 ^{o}C. The continuous reactor needed a supply of oxygen to meet the COD oxygen demands while maintaining a constant, low-oxygen concentration in the reactor environments. The objective of establishing low oxygen level within the continuous aeration reactors was to provide the opportunity for low-oxygen nitrification and simultaneous denitrification to occur, by means of microbial adaptation over time. Agitation was started and set at 600 rpm throughout the treatment period of each and every batch. It was observed that higher agitation speeds tended to result in sludge bulking which resulted from un-settleable solids, and the microorganisms which made settling and sampling of the effluent difficult.

The principle of this aeration configuration was to supply the air within the reactor as evenly and quickly as possible, providing sudden changes from aerobic to anoxic conditions. The aeration cycle for the cyclic aerobic sequencing batch reactor was conducted for 9 hours daily over the 5 days of treatment time in every batch. The airflow rate during the "9 hour on" phase was selected, which is equal to three times the continuous aeration rate of 7.5 L/min.

3. Settling phase

According to literature, the settle phase normally allows for separation of bio-solids from the treated effluent without any inflow or outflow in the SBR reactor. This sequence is the paramount final stage for solids removal, enhancing the biodegradation of the high concentrations of organic pollutants contained with the settled solids. It was done within a 3 hour period, to allow for adequate settling. The crucial advantage of the SBR is its use as a clarifier, which allows for truly quiescent sedimentation conditions, and for this study a conical bottom reactor design structure was

envisaged to even further enhance gravity-driven sedimentation of the biomass according to particle size.

Figure 3.8: Settling- phase image for the SBRs.

4. Drawing Phase

Finally, the draw or decant phase followed. The design criteria for withdrawal were based on a desire to prevent the presence of floating matter. This phase normally occupies about 5-30% of the total cycle time. Three minutes per batch was the chosen duration for this sequence in all experiments. Sampling of the treated brewery wastewater was done by means of tapping the well-settled substrates as per desired volumes from the bottom spigot into a sample bottle of 2 L. This was done to provide enough volume for analysis of all the desired performance monitoring parameters.

The idle mechanism was carried out as a maintenance sequence to improve the biological treatment activity of the microorganisms. This sequence lasted for one hour and was performed using a lab-

scale peristaltic pump. This process is referred to as ‘sludge wasting’. At the beginning of each experimental run, each SBR was inoculated with an inoculum of 2.5 L; in accordance with the operation strategy was employed in this research work. Hence, the reactors were seeded to a specific mark with the already-acclimated microbial mass. An observation would be made after each run to ensure that the specific maximum growth rate of the microbial mass had increased with regards to the operating hydraulic retention time. Idling of accumulated sludge was done at the end of each run to enhance the treatment efficacy and maintain smooth running of both reactors. The idling sequence also served to prevent unnecessary sludge bulking, which seemed possible on observation of a complete run, given that the retention time allowed for massive growth of excess microbial mass. A laboratory-scale syringe pump was adapted to enhance idling of the excess growth of microbial mass.

The physical operation of the two SBRs, continuous low oxygen concentration dosing Sequencing Batch Reactor 1 (CON SBR1) and cyclic aeration Sequencing Batch Reactor 2 (CYC SBR2) consisted of several steps. The first of these required analysing the influent stream or sample collected from the brewery wastewater plant before treatment with microbial mass in the two different SBRs. The next step was sampling from the collection tank, thorough characterisation of the performance monitoring parameters that was carried out to benchmark the performance of the two different configured SBRS in terms of aeration sequences. **Table 3.4** shows the overall process monitoring parameters, on-line and after treatment.

Table 3.4: Process monitoring parameters and sample points.

PROCESS	SAMPLING POINT	PARAMETERS TESTED	FREQUENCY
Brewery Waste Water	Offline and Online	PH	Beginning 5 day HRT and 3 hourly
Influent Stream	Offline and Online	EC	Beginning 5 day HRT and 3 hourly
(Feed tank)	Offline	COD	Beginning 5 day HRT
	Offline	BOD	Beginning 5 day HRT
	Offline	TS	Beginning 5 day HRT
	Offline	VS	Beginning 5 day HRT
	Offline	TSS	Beginning 5 day HRT
	Offline	TDS	Beginning 5 day HRT
	Offline	Turbidity	Beginning 5 day HRT
	Offline and Online	Temperature	Beginning 5 day HRT and 3 hourly
Brewery Wastewater	Offline and Online	PH	Every 3 hourly and After 5 days HRT
Effluent stream	Offline and Online	Temperature	Every 3 hourly and After 5 days HRT
(CON SBR1 and CYC SBR2)	Offline and Online	EC	Every 3 hourly and After 5 days HRT
	Offline	COD	After 5 days HRT
	Offline	BOD	After 5 days HRT
	Offline	TS	After 5 days HRT
	Offline	VS	After 5 days HRT
	Offline	TSS	After 5 days HRT
	Offline	Turbidity	After 5 days HRT

Parameter trending was carried out due to ever-changing daily conditions, which sometimes were due to natural conditions, which ultimately affected the overall treatment efficacies of the SBRs. Recurrent power cuts were one contributing factor to fluctuating and inconsistent treatment efficiencies of the reactors. The mixing processes would therefore be stopped, along with aeration pumps, for an average of two hours or more. This analytical data will all be shown and discussed in the results and discussion section.

3.4 ANALYTICAL METHODS

A series of laboratory analyses were carried out. According to the first objective of this research study, this was characterising the brewery wastewater in order to determine its actual organic and physicochemical strength and capacity, was naturally tackled first. This would make it easy to determine viable treatment options and re-uses. Samples were characterised using APHA (1998) which include the following physicochemical parameters; pH, conductivity (CD), total dissolved solids (TDS), ammonium nitrogen (NH_4-N), biological oxygen demand (BOD), chemical oxygen demand (COD), turbidity, total solids (TS), and volatile solids (VS). This characterisation is normally performed after all the physical and chemical pre-treatment stages have been thoroughly undergone. The following physicochemical treatment parameters were analysed during characterisation and the treatment sequence of the brewery wastewater is explained in the following subsections.

pH

This is a physicochemical parameter used in various treatment methods. The aim of the measurement is to determine the acidity or alkalinity of the influents and effluents. Low pH normally indicates increasing acidity while a high pH indicates increasing alkalinity, whereby a pH of 7 is commonly considered neutral. The pH of brewery wastewater was kept between 6 and 8 to protect the existence of the microbial organisms. Alkalis and acids can alter pH thus inactivating wastewater treatment processes. pH measurement was used to monitor the performance and pre-treatment parameters in this study, enhancing the removal of toxic materials and colloidal impurities. The acidity or alkalinity of wastewater affects both wastewater treatment itself, as well as the environment, specifically during disposal. In this study, pH was monitored and analysed during characterisation of the brewery wastewater using the APHA (1998) standard method, as mentioned earlier. As also mentioned earlier, close pH monitoring during treatment of brewery wastewater was done on a daily basis and finally recorded on completion of each batch weekly. This was done by direct measurement of samples in triplicate, using a calibrated Thermo Scientific Orion Star A215 pH/conductivity meter. The samples were analysed in triplicate to ensure the credibility of the obtained data.

CONDUCTIVITY

Conductivity was considered for the characterisation of brewery wastewater. Conductivity in general is a measurement of the amount of dissolved solids in brewery wastewater. This parameter is used to determine the concentration of dissolved molecules or ions in the brewery wastewater. In this study, a conductivity test was completed during characterisation of the brewery wastewater for both the influent and effluent streams. This was done by the direct measurement of samples in triplicate, using a calibrated Thermo Scientific Orion Star A215 pH/conductivity meter. The samples were also analysed in triplicate (APHA, 1998).

TOTAL SOLIDS

The term 'total dissolved solids' refers to the material residue that will be left in the porcelain crucible after evaporation has been provided by means of an oven which provides adequate drying at a specific temperature, as per standard operating methods set. As per norm, the following items of apparatus are used: porcelain crucibles, drying oven, analytical balance and a desiccator. This total dissolved solids parameter was used in this study to assess the concentration of solids present in the brewery wastewater from SABMiller being used for the experiment. The samples were analysed in triplicates. APHA (1998) method was applied to attain the analysis results in this study. A detailed description of the standard methods used for analysing this parameter is presented in **Appendix A2**.

TURBIDITY

Turbidity measurement was also performed to characterise the brewery wastewater. In its simplest form, turbidity of the brewery wastewater is a result of the suspended and colloidal material, such as starch, spent grain and any other finely-divided organic and inorganic matter and microscopic organisms. Turbidity is expressed in NTUs (known as number of turbidity unit). It is an indication of the tangible material that causes light to be scattered and absorbed, rather than transmitted with no change in direction through the sample. Turbidity was recorded immediately after sampling of brewery wastewater. For accuracy purposes, and adequate examination, the sample has to be smoothly shaken to achieve one homogenous sample and hence ensure a perfect representation of measurement. The sample was also kept in a cold storage facility at about 4 ^{o}C, to lessen the microbial decomposition of solids. The turbidity was actually taken by using a calibrated turbidity meter (TB300 IR Orbeco Hellige). The samples were analysed in triplicate to ensure credibility of the data.

TOTAL DISSOLVED SOLIDS

These are the solids that manage to pass through the filter paper during the filtration process. Hence the nature and quality of the filter paper determines the efficiency of the separation process of these suspended solids from the dissolved solids. Normally, the principal apparatus include: porcelain crucibles, drying oven, analytical balance, desiccator and the vacuum filtration apparatus. This procedure was carried out at 180 ^{o}C for an hour in an oven situated in the research laboratory. The samples were analysed in triplicate to ensure credibility of the data. The APHA (1998) method was applied to attain the analysis results in this study. A detailed description of the standard methods used for analysing this parameter is presented in **Appendix A2**.

VOLATILE SOLIDS

Volatile solids were also analysed as part of the characterisation parameters of the brewery wastewater. Volatile solids are normally referred to as the fraction of the total solids lost during furnace ignition at high temperatures ranging around 550 ^{o}C. They represent a measure of the organic solids present in every sample analysed. The apparatus that were used included: porcelain crucibles, drying oven, analytical balance and a muffle furnace. The samples were analysed in triplicate to ensure credibility of the data. The APHA (1998) method was applied to attain the analysis results in this study. A detailed description of the standard methods used for analysing this parameter is presented in **Appendix A3**.

CHEMICAL OXYGEN DEMAND (COD)

Chemical oxygen demand is the measure of the amount of organic compounds in water. Most applications of COD determine the amount of organic pollutants found in water (e.g. lakes and rivers) or wastewater, making COD a useful measure of water quality, especially in industrial wastewater from the brewery. It is expressed in milligrams per litre (mg/L) also referred to as ppm (parts per million), which indicates the mass of oxygen consumed per litre of solution. This parameter was considered the major performance-monitoring parameter to evaluate the overall performances of both SBRs and was initially monitored to determine the optimum hydraulic retention time for the SBRs. It was monitored on a weekly basis upon completion of each batch. The brewery wastewater sample was collected into an Erlenmeyer digestion flask with all necessary reagents and set to digest over a period of 2 hours at 150 ^{o}C. The end product, normally containing excess dichromate, had to be titrated with ammonium iron sulphate and the COD value was calculated from the amount of dichromate used. The apparatus that were used for this analysis included the following: digester unit, Erlenmeyer flask, pipettes, automatic bottle dispenser and a digital auto titrator. The samples were analysed in triplicate to ensure credibility of the data. The

APHA (1998) method was again used to determine COD in this study. A detailed description of the standard methods used for analysing this parameter is presented in **Appendix A6**.

BIOLOGICAL OXYGEN DEMAND (BOD)

In this study, the BOD was measured by the principle of pressure difference within a closed system, referred to as a respirometric BOD, within five days after treatment and sampling were carried out. This operation was set to run over a period of five days hence we referred to this parameter as BOD. The BOD is an expression for the amount of oxygen consumed by the decomposition of organic matter in a biochemical process. The BOD of wastewater and industrial effluents (which in this study is brewery wastewater) normally ranges between high concentrations of about 1500-3000 mg/L depending on the nature of the wastewater source from the brewery process. This system was used during the characterisation of the brewery wastewater influent and effluent. This system consisted of 6 sample bottles and the BOD sensor, representing a closed system. In the bottle, above the sample, was a defined volume of air. During the BOD measurement, the bacteria in the sample consumed the dissolved oxygen in the sample. This was replaced by the oxygen in the bottle above the sample. The carbon dioxide released at the same time reacted with the potassium hydroxide that was added as drops into the seal gasket. This generated a decrease in pressure within the system. This was measured by the BOD sensor and displayed as a BOD value in mg/L basis. The samples were analysed in triplicate to ensure credibility of the data (Association, 1998). A detailed description of the standard methods used for analysing this parameter is presented in **Appendix A5**.

3.5 DATA ANALYSIS

Statistical Analysis

Data was entered into SPSS version 23 (Statistical Packages for the Social Sciences) for analysis. A value $P < 0.05$ was considered as statistically significant. Data analysis was initiated with a check of the data for outliers, missing data, and normality through skewness and kurtosis values that could affect relations between variables. A descriptive statistical analysis of the data such as means, standard deviations, ranges, frequencies, percentages and confidence intervals was initially conducted prior to conducting the multivariate analysis. The choice of these statistical parameters was undertaken with the aim of attaining an efficient comparison of the aeration configuration schemes on both SBRs, which is in line with the main objective of this study.

Correlation analysis was applied to determine the significance of relationships between the performance monitoring parameters. Statistical analysis of the data from the continuous low-oxygen

dosing aeration scheme and the cyclic aeration schemes was conducted by using the t-test (Student's t-test with unequal variances) method, with 95% confidence interval level. This was applied to detect the significance of differences between compared mean averages of sample results. Comparison of treatment efficiency was based on the percentage removal of the performance monitoring parameters for both SBRs. Relevant statistical models were implemented for data analysis and efficiency calculations are presented in **Appendix G**. As stated above, unless specified in that instance, the level of significance used throughout these studies was maintained at $P < 0.05$, whereby the results of data analysis of means were presented as Mean ± standard deviation and average efficiency removal percentages.

Replicability Analysis

With every analysis that was carried out, the necessary precautions were followed. The standard methods for examination of water and wastewater and the American Public Health Association APHA (1998) methods were used for all analyses. Each performance monitoring parameter analysis was carried out in triplicate and in some cases, duplicate, and the average of each analysis was calculated for the final results. **Table 3.5** presents the replicability accuracy check carried out on the TDS removal data analysis of aerobic SBR1 on the treatment of brewery wastewater. This analysis was carried for all performance monitoring parameters in all experimental batch runs.

Table 3.5: Demonstrations of replicability check done on effluent stream data for TDS (mg/L) analysis.

Sample Date:	Sample ID:	A	B	Sample Vol. mL	mg TDS /L
04-Jul-15	BWW 1	43.55	43.35	150	1.32
	BWW 2	44.19	43.99	150	1.32
	BWW 3	42.87	42.64	150	1.54
	AVERAGE				1.39
	STDEV				0.12
08-Jul-15	BWW 1	44.23	43.68	150	3.72
	BWW 2	43.14	42.93	150	1.37
	BWW 3	44.89	44.12	150	5.10
	AVERAGE				3.40
	STDEV				1.88
13-Jul-15	BWW 1	44.75	44.62	150	0.83
	BWW 2	44.11	43.98	150	0.87
	BWW 3	40.45	40.32	150	0.87
	AVERAGE				0.86
	STDEV				0.02

CHAPTER 4
RESULTS AND DISCUSSION

The research findings are presented in this chapter. The results from the characterisation of collected wastewater samples from the brewery and the results obtained from the operation of the two sequencing batch reactors which were used to evaluate the performance and ability of the SBRs to reduce the pollutant concentrations of the wastewater collected from the brewery under two different aeration schemes, are presented in this chapter. **Appendix B, C, D**, **E**, **F, G** and **H** presents the raw data and sample calculations of all performance-monitoring parameters discussed in the following sections.

4.1 RESULTS OF BREWERY WASTEWATER CHARACTERISATION

The results from the characterisation of collected wastewater samples from the brewery over a period of 4 weeks are summarised in **Table 4.1** (see **Appendix E**).

Table 4.1: Characteristics of brewery wastewater from the studied brewery plant **(SAB).**

Parameters	Mean	COV	95 %CI
Total Dissolved Solids (mg/L)	9.15 ± 7.16	0.04	4.97-16.34
pH	6.74 ± 0.62	0.05	6.16-7.17
Conductivity (µs/cm)	1968 ± 1347	0.41	702-2847
Turbidity(NTU)	341 ± 44	0.13	304-378
Ammonical Nitrogen(mg/L)	6.10 ± 9.11	0.18	0.84-15.31
Biological Oxygen Demand (mg/L)	2746 ± 394	0.03	2388-3015
Chemical Oxygen Demand(mg/L)	11214 ± 1965	0.07	9549-12878
Total Solids (mg/L)	1866 ± 2067	0.17	66.6-3666
Volatile-Solids(mg/L)	0.005 ± 0.01	0.01	6.66-66.6

As shown in **Table 4.1**, the characterisation of the brewery wastewater fluctuated considerably and this could have been attributed to the fact that the composition of the effluent from the brewery depended on the various processes that were taking place within the brewery itself. The findings of this study mainly focused on the physicochemical and organic pollutant strength parameters, as shown in **Table 4.1**. Phosphorus and Nitrogen analyses were not characterised as part of this study. However, the characteristics of the collected wastewater from the brewery in this present study demonstrated similar characteristics of brewery wastewater from previous studies, as presented in **Table 4.2**.

Table 4.2: Summary of characteristics of brewery wastewater for this study and literature.

Parameter	Range Present Study	Range (Rao *et al*., 2007)	Range (Dai, 2002)	Range (Enitan *et al*., 2015)	Range (Ling, 1998)
pH	5 - 11	3-12	7.9-8.7	4.6-7.3	6.1-9.5
Temperature ^{o}C	19-25	18-40	18-35	24-30.5	18-40
COD (Chemical Oxygen Demand) mg/L	2280 - 10210	2000-6000	454-673	1096 - 8926	87-6550
BOD (Biological Oxygen Demand) mg/L	2180 - 3018	1200-3600	650-1000	-	41-4260
COD to BOD ratio	1.04	1.667	1.53	-	1.53
VFA (Volatile Fatty Acids) mg/L	-	1000-2500	800-1500	-	11-1230
PO_4 (Phosphates)	-	10-50	10-50	-	10-50
TKN (Total Kjedahl Nitrogen) mg/L	-	25-80	25-80	-	28-343
TS (Total Solids) mg/L	2000-9200	5100-8750	5000-6000	1289-12248	16-1360
TSS (Total Suspended Solids) mg/L	-	2901-3000	None	530-3728	None
TDS (Total Dissolved Solids) mg/L	-	2020-5940	2000-4000	-	2010-4000

The characterisation results as presented in **Table 4.2** clearly demonstrate that the collected wastewater samples from the brewery were high in organic components, which are generally easily biodegradable, with a BOD to COD ratio of 0.6. Thus a high observed ratio of BOD to COD is an indication that the wastewater generated from the brewery used for this study can be sufficiently treated using biological treatment technologies. These findings confirm previous studies that have been conducted on brewery wastewater by Dai, (2002), Enitan *et al*. (2015) and Rao *et al*. (2007).

4.2.1 VARIATION OF COD REMOVAL EFFICIENCY WITH HYDRAULIC RETENTION TIME (HRT)

The effect of hydraulic retention time on the performance of the SBRs under different aeration scheme in-terms of COD removal is presented in **Figure 4.1** (see **Appendix F**).

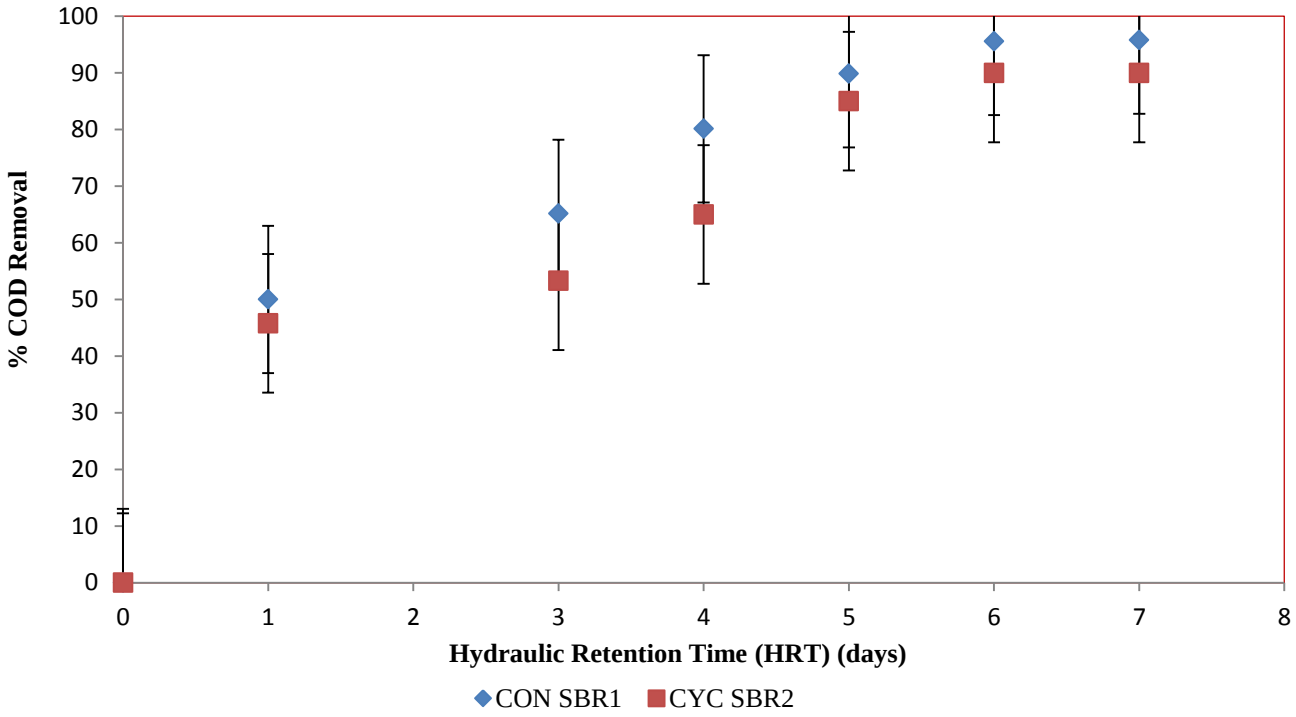


Figure 4.1: Variation of COD removal efficiency with HRT.

As can be seen, the COD removal in terms of the hydraulic retention time in the continuous low aeration scheme was significantly different from the cyclic aeration scheme. A polynomial fit correlation constant $R^2 = 0.9281$ for the continuous low aeration as compared to $R^2 = 0.9026$ for the cyclic aeration schemes. The R^2 values proved significant percentage COD removal fit in relation to the HRT between the two aeration configurations and the second order polynomial approximation. However, a similar trend in COD removal was accomplished for both aeration configuration schemes as a function of the hydraulic retention time, as is shown in **Figure 4.1**. Upon viewing the experimental data; it appeared that the most significant difference in percentage COD removal was for HRTs 3 days and 4 days as is in **Figure 4.1**. Although, due to less percentage COD removal observed from HRT 5 days till 7 days, it was established that optimum high strength organic removal was accomplished after 5 days was reached.

The COD measurements carried out during all batch experiments were conducted in triplicate for accuracy check purposes. This was used to estimate the uncertainty and through standard error

propagation rules. Hence as shown in **Figure 4.1,** at higher HRTs, there was more percentage COD removal. It was perceived from the standard error bars that higher HRTs resulted to higher errors as well. It was hypothesised that this could be due to the sampling technique that was employed during experimentation even though the accuracy check was conducted in all measurements. The experimental mode of operation as batch mode, and the aeration configuration could also contribute to the magnitude of error that increased with higher HRTs as presented in **Figure 4.1**. Therefore all batch experiments for both aerobic SBRs were conducted over 5 days HRT. This was perceived to avoid the magnitude of uncertainty levels in percentage COD removal with increased HRTs.

Table 4.2: Comparison of HRT with COD removal in CON SBR1**.**

		Time	**COD**	**Removal**
Time	Pearson Correlation	1	-0.948**	0.949**
	Sig. (2-tailed)		0.001	0.001
COD	Pearson Correlation	-0.948**	1	-1.000**
	Sig. (2-tailed)	0.001		0.000
Removal	Pearson Correlation	0.949**	-1.000**	1
	Sig. (2-tailed)	0.001	0.000	
**. Correlation is significant at the 0.01 level (2-tailed).				

A Pearson product-moment correlation was ran to determine the relationship between time and COD as well as time and percentage removal in CON SBR1 **Table 4.2**. The data showed no violation of normality, linearity or homoscedasticity. There was a strong, positive correlation between time and removal, which was statistically significant ($R = 0.949$; $P < 0.05$). Also, there was a strong, negative correlation between time and COD, which was statistically significant ($R = - 0.948$; $P < 0.05$). As is shown in **Table 4.3**, for cyclic aeration configuration, a Pearson product-moment correlation which was run to determine the relationship between time and COD as well as time and percentage removal in CYC SBR2, showed no violation of normality, linearity or homoscedasticity. There was a strong, positive correlation between time and percentage removal, which was statistically significant ($R = 0.899$; $P < 0.05$). Also, there was a strong, negative correlation between Time and COD, which was statistically significant ($R = - 0.901$; $P < 0.05$).

Table 4.3: Comparison of HRT with COD removal in CYC SBR2.

		Time	COD	Removal
Time	Pearson Correlation	1	-0.901**	0.899**
	Sig. (2-tailed)		0.006	0.006
COD	Pearson Correlation	-0.901**	1	-1.000**
	Sig. (2-tailed)	0.006		0.000
Removal	Pearson Correlation	0.899**	-1.000**	1
	Sig. (2-tailed)	0.006	0.000	
**. Correlation is significant at the 0.01 level (2-tailed).				

As seen in both **Table 4.2** and **Table 4.3** above, as the hydraulic retention time increases, the COD removal for both aeration schemes increased, meaning that the COD content in the brewery wastewater is reduced as time increases, which is being shown by the strong negative correlation in both reactors. This could be attributed to the fact that microbial activities degrade the available nutrients present as the hydraulic retention time is increased. Sludge bulking and poor sludge settling was observed at increased COD removal. This observation is an indication that available nutrients present in the wastewater from the brewery fed into the SBRs have been depleted. This could also be due to recurrent sludge bulking, which was observed in a couple of runs during experimentation mostly in CON SBR1. It can be gathered that, sludge bulking can be controlled by alternating between anoxic and oxic conditions.

4.2.2 RESULTS OF THE EFFECTS OF THE DIFFERENT AERATION CONFIGURATION SCHEMES ON THE PERFOMANCE OF THE TWO SEQUENCING BATCH REACTORS

Temperature, pH, conductivity, COD, BOD, total solids, volatile solids and total suspended solids were the selected parameters used to evaluate the effect of the different aeration scheme or performance of the SBRs. Mass balances were done for selected pollutant parameters, specifically: COD, BOD and total solids. A total of 15 different batch runs were conducted in each SBR, respectively continuously low-oxygen dosing aeration Sequencing Batch Reactor (CON SBR1) and cyclic aeration configuration Sequencing Batch Reactor (CYC SBR2). All the 15 batch experimental runs were conducted over the experimentally attained 5 days Hydraulic Retention Time (HRT) as presented in Section 4.2.1 above. This HRT was maintained the same for both SBRs throughout the experimental operation.

4.2.2.1 Reactor Temperature

Measurement of the temperature within the reactors was performed to ensure that microbial activity was not impacted as a result of temperature fluctuations. **Figure 4.2** presents the average measured temperature within the two SBRs for the experimental batches (see **Appendix F**). As it can be seen in **Figure 4.2**, the average temperature was within the range of 21-22 ^{o}C for the entire duration of the experimental set-up. This temperature was found to be within the mesophilic temperature appropriate temperature to effective biological treatment that supports microbial activities under aerobic conditions. Thus it could be said that temperatures in which the reactors were operated enhanced microbial activities within the reactors.

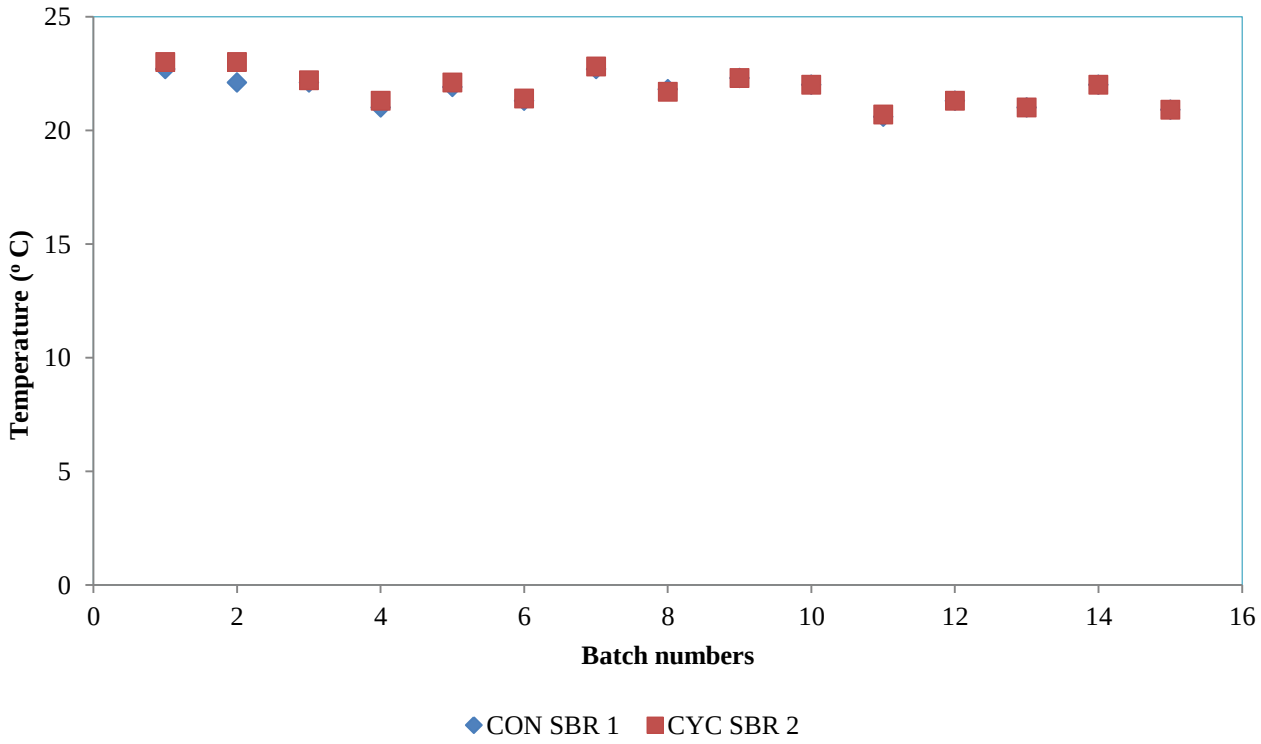


Figure 4.2: Temperature profile for CON SBR 1 and CYC SBR 2.

4.2.2.2 Reactor pH

The average pH measured for the influent wastewater within the reactors for each of the batches conducted is presented in **Figure 4.3** (see **Appendix F**). The results attained show that the pH was kept within 6-8 for most of the experimental batches. This range is crucial for COD removal, solids removal and the existence of microorganisms. Instances like week 14 displaying very low pH values were controlled through adjusting pH with NaOH and HCl. During the experimentation period the effluent pH was maintained between: 6-8. This was to instigate feasible organic material removal in both reactors. The average pH values for the influent into CON SBR1 and CYC SBR2 was 6.5 for all the batch runs. While during operation, the average pH of both CON SBR1 and CYC

SBR2 was 8.05 and 7.45 respectively. The adaptation of the reactor bed pH implied a good buffering capacity was maintained in the aerobic sequencing batch reactors. This pH level clearly showed it was not inhibiting the efficient operation of these aerobic SBRs. This in turn implied that there was good level of biological activity occurring within the reactors' sludge beds in both SBRs. The pH values observed during the operation of the SBRs were imperative for good COD removal and efficient solids settleabilty within the reactor cell bed (biomass). It was also noted that the effluent pH met the brewery wastewater disposal standard (pH range of 6.5-8.5) (Meyers, 1998) and (Metcalf and Eddy, 1991) and pH values of 5.0-9.5 according to South African standards (DWAF and Ractliffe, 2007; DWAF, 2004).

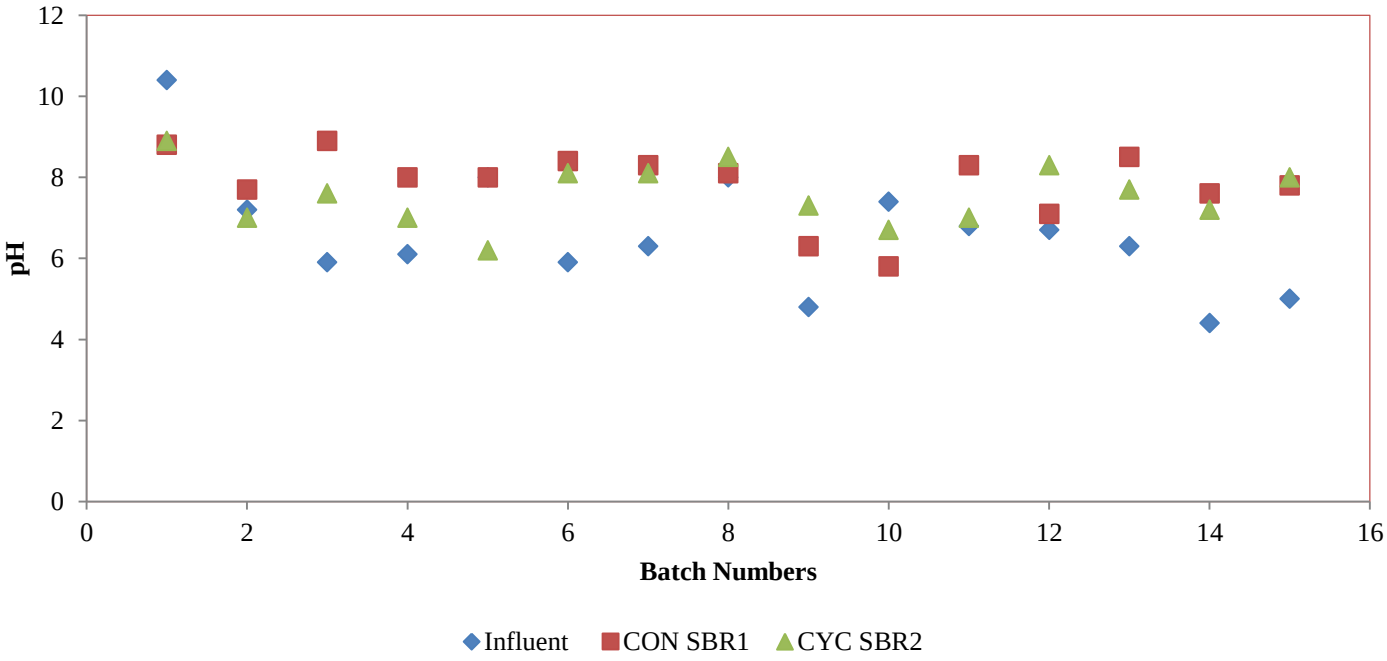


Figure 4.3: pH results for Influent, CON SBR 1 and CYC SBR 2.

4.2.2.3 Conductivity

Figure 4.4 presents the conductivity results obtained from the analysis of the influent brewery wastewater into the SBRs (see **Appendix F**). The conductivity exhibited a great degree of variability due to the nature of the brewery wastewater sources, with fluctuating compositions based on different production processes differing on a weekly basis from various sources within the plant. The increasing amount of dissolved molecules during the biodegradation process taking place in the biological reactors had a direct influence on the conductivity values recorded from fresh brewery wastewater as well as the collected wastewater from the reactors' effluent. It was observed that a slight decrease of conductivity from influent to effluent occurred in both aerobic SBRS. The influent brewery wastewater feed had an average level of 525 µS/cm, as shown in **Figure 4.4**.

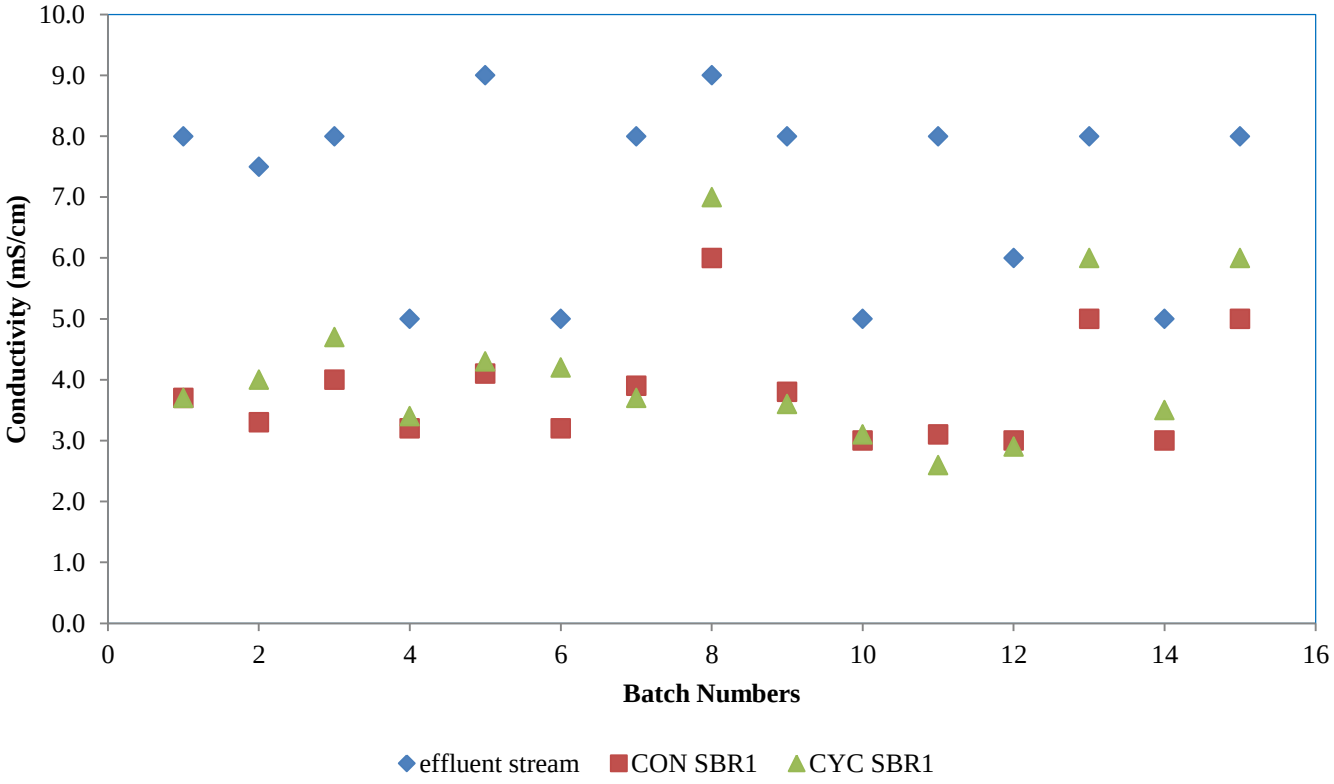


Figure 4.4: Conductivity results.

CON SBR1 attained an effluent system showing a slight decrease on average of 473 µS/cm. CYC SBR2 showed a further decrease of an average of 449 µS/cm in terms of conductivity. It was observed in CYC SBR2, which was operated in a cyclic aeration scheme, that there was a high reduction in conductivity compared to CON SBR1, which was operated under continuous low-oxygen concentration dosing. This was attributed to the fact that SBR2 was more of an anoxic process, which favoured a high level of biological nitrogen removal, therefore enhancing the reduction of dissolved molecules. These conductivity results meet neither the South African wastewater disposal standards or the European wastewater effluent disposal standards allowable level of 70 -150 µS/cm by Enitan *et al.* (2015) and DWAF (2004).

4.2.2.4 Chemical oxygen demand (COD)

The data for all the 15 batch runs for the reduction of COD in brewery wastewater within the two aerobic SBRs is presented in **Table 4.4** (See **Appendix F**).

Table 4.4: COD results for all batch runs.

Batch	Influent (mgCOD/L)	OLR (kg COD/day)	Effluent CON SBR1 (mgCOD/L)	Effluent CYC SBR2 (mgCOD/L)	CON SBR 1 %COD Removal	CYC SBR 2 %COD Removal
1	8031	0.0080	556	1195	93	85
2	9826	0.0098	242	339	98	97
3	14860	0.0149	113	1195	99	92
4	14806	0.0148	805	6836	95	54
5	18151	0.0182	1386	1255	92	93
6	10384	0.0104	368	2528	96	76
7	10576	0.0106	784	3662	93	65
8	9104	0.0091	224	1264	98	86
9	13296	0.0133	2496	544	81	96
10	9152	0.0092	432	2080	95	77
11	6560	0.0066	472	1008	93	85
12	9824	0.0098	128	2784	99	72
13	9168	0.0092	400	2000	96	78
14	2976	0.0030	232	964	92	68
15	4752	0.0048	272	624	94	87

As shown, the average organic loading rate (OLR) for all the batch runs was 0.0101 kg COD/day. It was observed that in all the batches, there was a direct correlation between the organic loading rate and the influent brewery wastewater concentrations. An increase in the influent concentration in terms of COD resulted in an increased OLR. The OLR, in turn had an effect on the organic pollutant removal efficiency in terms of COD. It was generally observed that at high OLR there was high removal efficiency in both SBRs, although SBR1 performed better at high OLR. The better performance of SBR1 compared to SBR2 can be attributed to the different aeration configuration scheme. The aerobic SBR treatment of brewery wastewater with COD influent concentrations between 9000-18 000 mg/L showed removal efficiencies of 80-99 %, corresponding to OLR of between 0.0080-0.0182 kg COD/day. For influent with lower concentrations between 2000-4000 mg/L, the efficiency decreased to about 68 % for OLR of 0.0030 kg COD/day, especially in CYC SBR2. The average influent COD into both reactors was found to be 10098 mg/L, while the average COD obtained after treatment from CON SBR1 and CYC SBR2 was 594 mg/L and 5865 mg/L respectively. It was observed from the result obtained that there was a statistically significant COD

reduction in both SBRs as compared to the influent to the reactors ($P < 0.05$). **Figure 4.5** presents the average results for all batches in terms of percentage COD removal for the two SBRs.

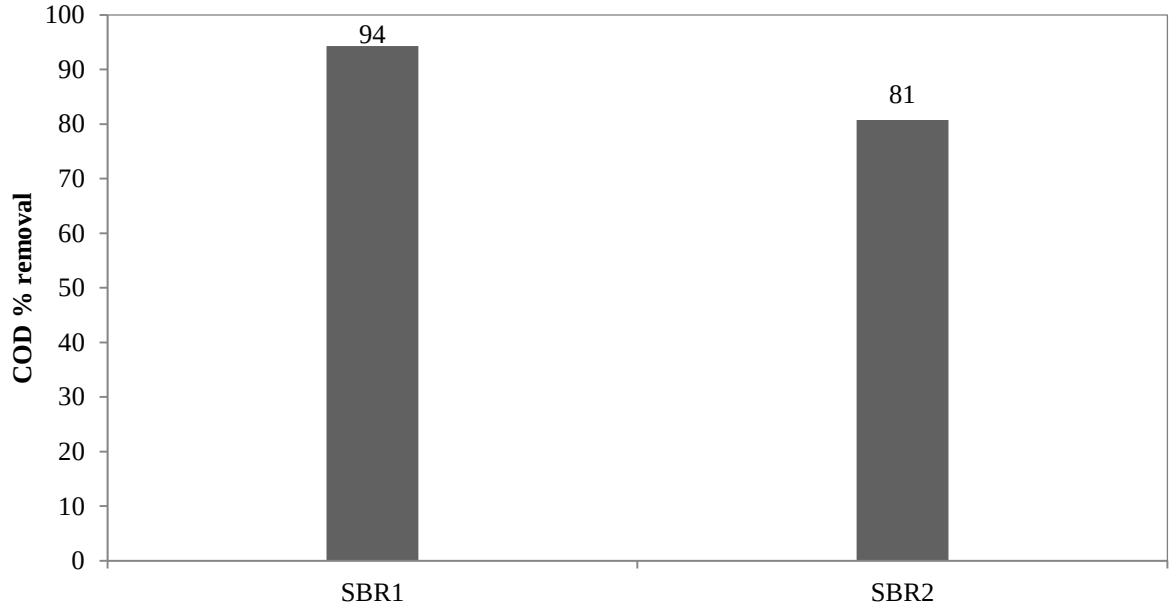


Figure 4.5: Comparison between both SBRs based on their COD removal efficiency.

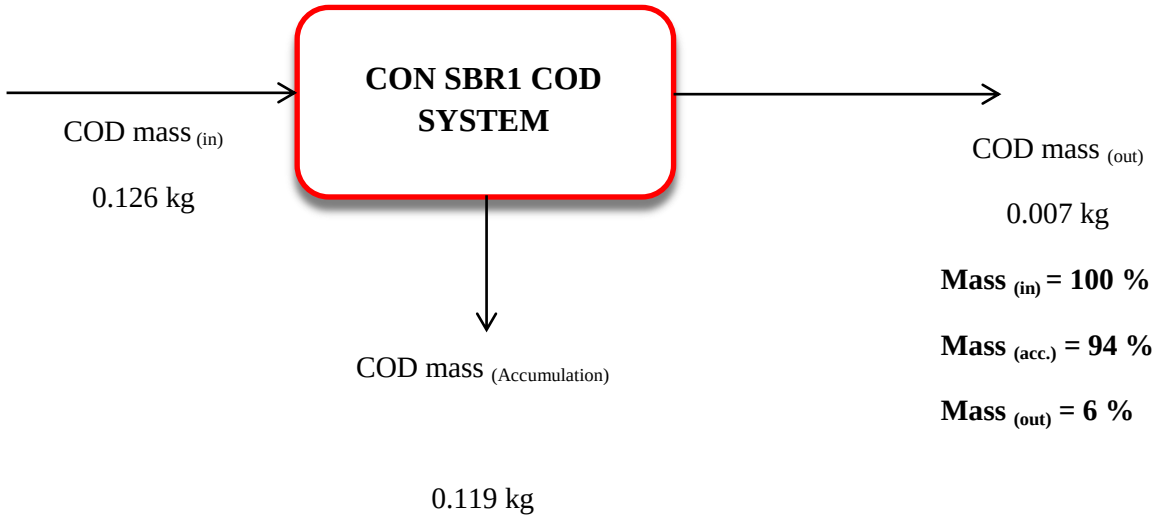
As is shown, the percentage COD removal in CON SBR1 was found to be 94 %, while that of CYC SBR2 was found to be 81 %. The high performance of CON SBR1 when compared to CYC SBR2 in terms of COD could be attributed to the type of aeration configuration. This is because CON SBR1 was continuously supplied with low oxygen concentration, which enhances biological activities within the reactor. CON SBR1 in this study had effectively presented a great ability to achieve optimum treatment of COD within a 5 day of HRT cycle. The average COD removal efficiencies that were attained in this study showed congruency to previously done work by Ling (1998), Bennett *et al*. (2007) and Irvine *et al*. (1997). A statistical t–test analysis with unequal variances was performed to determine if there existed a significant difference between CON SBR1 and CYC SBR2 in terms of percentage COD removal. This was conducted using SPSS version 23 (Statistical Packages for the Social Sciences) to investigate if the was any correlation in COD removal in both SBRs. A Pearson correlation was conducted and the output is presented in **Table 4.5**.

Table 4.5: Pearson correlation analysis for CON SBR1 and CYC SBR2 on the removal of COD.

		SBR1	SBR2	COD
SBR1	Pearson Correlation	1	-0.021	0.492
	Sig. (2-tailed)		0.040	0.063
SBR2	Pearson Correlation	-0.021	1	0.329
	Sig. (2-tailed)	0.040		0.032
COD	Pearson Correlation	0.492	0.329	1
	Sig. (2-tailed)	0.053	0.032	

As shown in **Table 4.5**, a Pearson product-moment correlation was run to determine the relationship between CON SBR1 and CYC SBR2 as well as CON SBR1 and COD removal in both CON SBR1 and CYC SBR2 was carried out. The data showed no violation of normality, linearity or homoscedasticity. There was a weak, negative correlation between CON SBR1 and CYC SBR2, which was statistically significant ($R = -0.021$; $P < 0.05$). Also, there was a strong correlation between SBR1 and COD removal, which was statistically significant ($R = 0.492$; $P < 0.05$). There was a weak negative correlation between CYC SBR2 and CON SBR1, which was statistically significant ($R = -0.021$; $P < 0.05$). Also, there was a strong correlation between CYC SBR2 and COD, which was statistically significant ($R = 0.329$; $P < 0.05$). These results indicated that CON SBR1 was more efficient for the optimum removal of COD in brewery wastewater. The comparison between CON SBR1 and CYC SBR2 indicated a strong significant difference with a value of ($P < 0.05$). CON SBR1 Showed a higher positive Pearson correlation factor, which indicated a higher COD removal efficiency compared to CYC SBR2. **Figure 4.6** presents the COD mass balance for CON SBR1 and CYC SBR2 based on the averages of all batch experiments.

(i)



(ii)

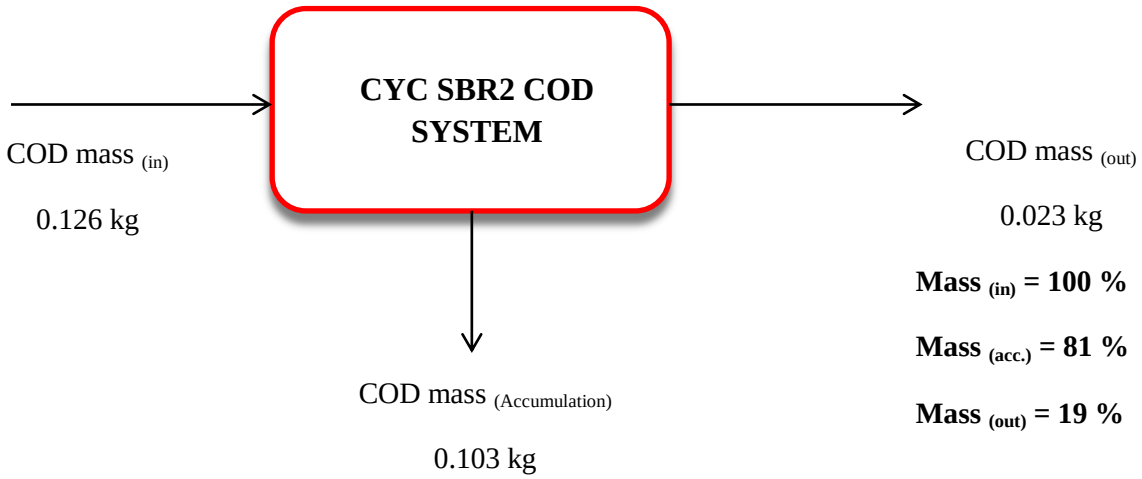


Figure 4.6: (i) and (ii) presents the COD mass balances for CON SBR1 and CYC SBR2.

As is shown, the total input COD with 100 % basis before treatment in SBRs was an average of 0.126 kg. It was observed that after treatment in CON SBR1, an output of 0.007 kg, representing 6 % was achieved. This result prompts the inference that a total COD mass of 0.119 kg representing 94 % was accumulated in CON SBR1. This total biological organic pollutant in terms of COD accumulation was due to solids retention and biological degradation activity in CON SBR1. CYC SBR2 showed a total mass output of 0.023 kg, representing 19 %. An accumulation of 0.103 kg, representing 81 %, was achieved in this reactor, proving that most of the organic pollutants in terms of COD were removed through solids retention and a high level of biological degradation within the reactor. This outcome also implied that COD removal was achieved through solids retention and biological degradation within CYC SBR2, as achieved in CON SBR1.

4.2.2.5 Biological oxygen demand (BOD)

The data for all of the 15 batch runs for the reduction of biological oxygen demand in brewery wastewater within the two aerobic SBRs are presented in **Table 4.6** (see **Appendix F**).

Table 4.6: BOD results for all batch runs.

Batch	Influent (mgBOD/L)	OLR (kgBOD/day)	Con SBR1 (mgBOD/L)	Cyclic SBR2 (mgBOD/L)	CON SBR1 BOD %Removal	CYC SBR2 BOD %Removal
1	2622	0.0026	372	453	86	83
2	3764	0.0038	1264	2159	66	43
3	2741	0.0027	372	334	86	88
4	2743	0.0027	353	234	87	91
5	3206	0.0032	128	1424	96	56
6	3207	0.0032	388	1782	88	44
7	2383	0.0024	140	567	94	76
8	3086	0.0031	222	839	93	73
9	3032	0.0030	1177	1069	61	65
10	3726	0.0037	1330	2485	64	33
11	3257	0.0033	301	395	91	88
12	3137	0.0031	389	789	88	75
13	2815	0.0028	959	293	66	90
14	2648	0.0026	942	2294	64	13
15	2291	0.0023	795	890	65	61

It was observed from the data obtained that the effects of OLR on biological oxygen demand removal efficiency were similar to those observed for the chemical oxygen demand. Applying the aerobic SBR treatment to brewery wastewater, biological oxygen demand influent concentrations between 2600-3200 mg/L showed significant removal efficiencies of 80-90 %, corresponding to OLR of between 0.0026-0.0031 kg BOD/day. For influent with lower concentrations, between 2000-2800 mg/L, the efficiency decreased to about 65 % for OLR of 0.0028 kg BOD/day. Therefore, the aerobic SBRs' removal efficiency on biological pollutants appeared to be dependent on the OLR. As OLR increased, the occurrence of solids and microorganism populations did so, too. This had no significant negative impact on the solids settleabilty, but resulted in the formation of more flocculating motile bacteria, which resulted in very low suspended solids removal. **Figure 4.7** presents the average results for all batches in terms of percentage BOD removal from CON SBR1 and CYC SBR2. It was observed that there was significant BOD removal in both SBRs. The average percentage COD removals from CON SBR1 and CYC SBR2 were 80 % and 65 % respectively.

Figure 4.7: Comparison between both SBRs based on their BOD removal efficiency.

Brewery effluents are easily biodegradable in the range between 0.6-0.7. This range clearly shows easy biodegradation of the brewery wastewater effluent. An efficient biodegradation process was displayed in both reactors, based on the experimental findings. There was significant treatment of organic matter in both reactors. The average BOD obtained after treatment from CON SBR1and CYC SBR2 was 609 mg/L and 1067 mg/L respectively.

It should be noted that the accumulation of microbial compounds and non-biodegradable matter probable lessen the BOD parallel to the COD in terms of ratios. It should be noted that from an experimental point of view, the degree of treatment of the brewery wastewater varies with the ratios of the influent BOD to COD compositions. The average BOD removal efficiencies attained in this study were congruent to previously done work by Ling (1998), Zaiat *et al*. (2001), Irvine *et al*. (1997) and Yu *et al*. (1997).

The Student's t-test with unequal variance method was conducted to distinguish the level of significance between the two reactors with different aeration schemes. The microbial conditions in these two reactors were supposed to have been kept at balance, though the pH was fluctuating between 6-8. The t-test analysis between influent and effluent streams demonstrated strong significance in the removal of organic pollutants in the form of BOD with a value of ($P < 0.05$) in both reactors. A value of ($P < 0.05$) was attained when comparing both effluent systems from CON SBR1 and CYC SBR2. The general hypothesis was that there were very strong significant removal differences between the performances of the two reactors in terms of BOD removal. Statistical

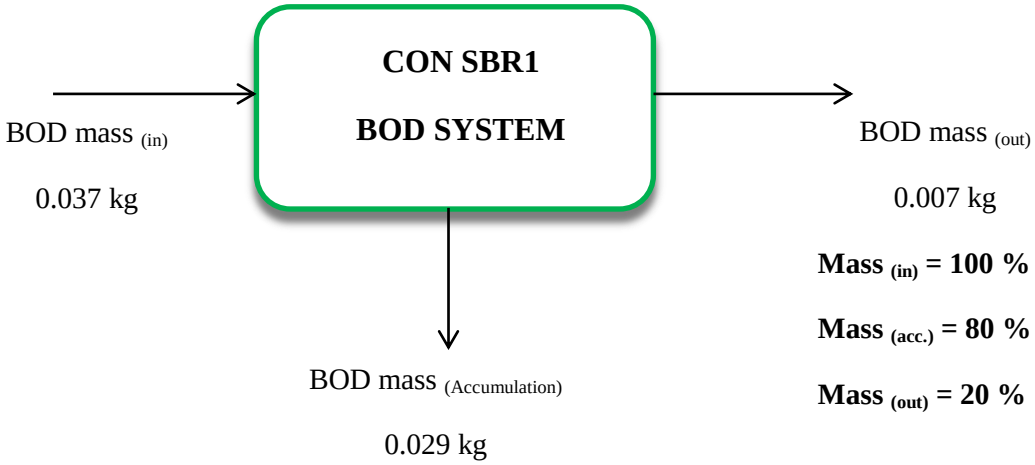
analysis was conducted using SPSS version 23 (Statistical Packages for the Social Sciences) to investigate if the was any correlation in BOD removal in both SBRs. A Pearson correlation was conducted ant the output is presented in **Table 4.7**.

Table 4.7: Pearson correlation analysis for CON SBR1 and CYC SBR2 on the removal of BOD.

		SBR1	**SBR2**	**BOD**
SBR1	Pearson Correlation	1	0.574*	0.671
	Sig. (2-tailed)		0.025	0.004
SBR2	Pearson Correlation	0.574*	1	0.564*
	Sig. (2-tailed)	0.025		0.029
BOD	Pearson Correlation	0.671	0.564*	1
	Sig. (2-tailed)	0.004	0.029	

The data showed no violation of normality, linearity or homoscedasticity. There was a positive correlation between CON SBR1 and CYC SBR2, which was statistically significant ($R = 0.574$; $P < 0$ .05). Also, there was a positive correlation between CON SBR1 and BOD, which was statistically significant ($R = 0.671$; $P < 0.05$). There was an average positive correlation between CON SBR2 and CY SBR1, which was statistically significant ($R = 0.574$; $P < 0$ .05). Also, there was a strong correlation between CYC SBR2 and BOD, which was statistically significant ($R = 0.564$; $P < 0.05$). These results implied that the effect of continuous low aeration in CON SBR1 on the removal of BOD was significant when compared to CYC SBR2. **Figure 4.8** presents the BOD mass balance for CON SBR1 and CYC SBR2 based on overall batch averages. As mentioned in the previous chapter, both SBRs showed great significance in BOD removal.

(i)



(ii)

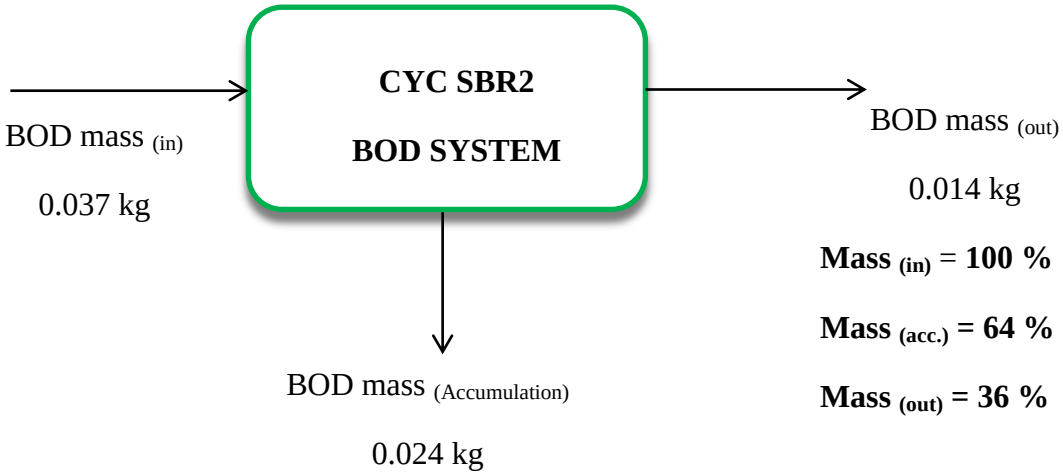


Figure 4.8: (i) and (ii) presents the BOD mass balances for CON SBR1 and CYC SBR2.

As is shown, a total of 100 % BOD input before treatment in SBRs was 0.037 kg on mass basis. It was observed that after treatment in the CON SBR1, an output of 0.007 kg was achieved representing 20 %. It was thus inferred that a total mass of 0.029 kg, representing 80 % was accumulated in CON SBR1. This total biological organic pollutant accumulation was due to solids retention and the biological degradation activity in CON SBR1. CYC SBR2 showed a total mass output of 0.014 kg, representing 36 %. An accumulation of 0.023 kg, representing 64 %, was achieved in this reactor, proving that most of the organic pollutants in terms of BOD were removed through solids retention and biological degradation within the reactor.

4.2.2.6 Total Solids (TS) and Volatile Solids (VS)

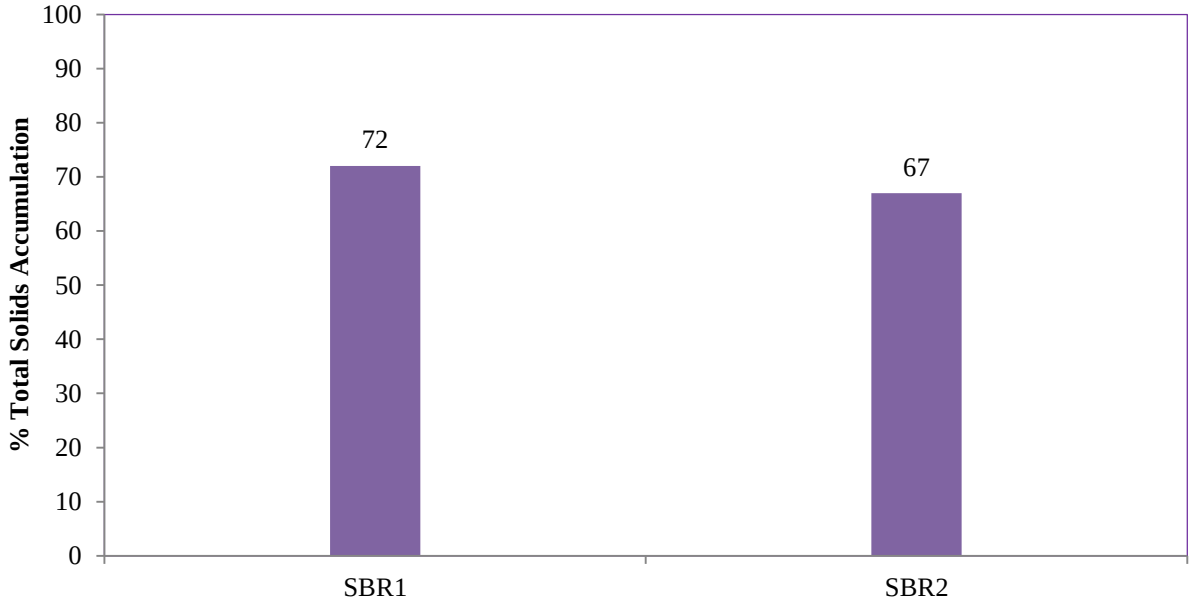
The data for all 15 batch runs for the total solids and volatile solids analyses in brewery wastewater within the aerobic SBRs are presented in **Table 4.8** (see **Appendix F**).

Table 4.8: Total solids and volatile solids results for all batch runs.

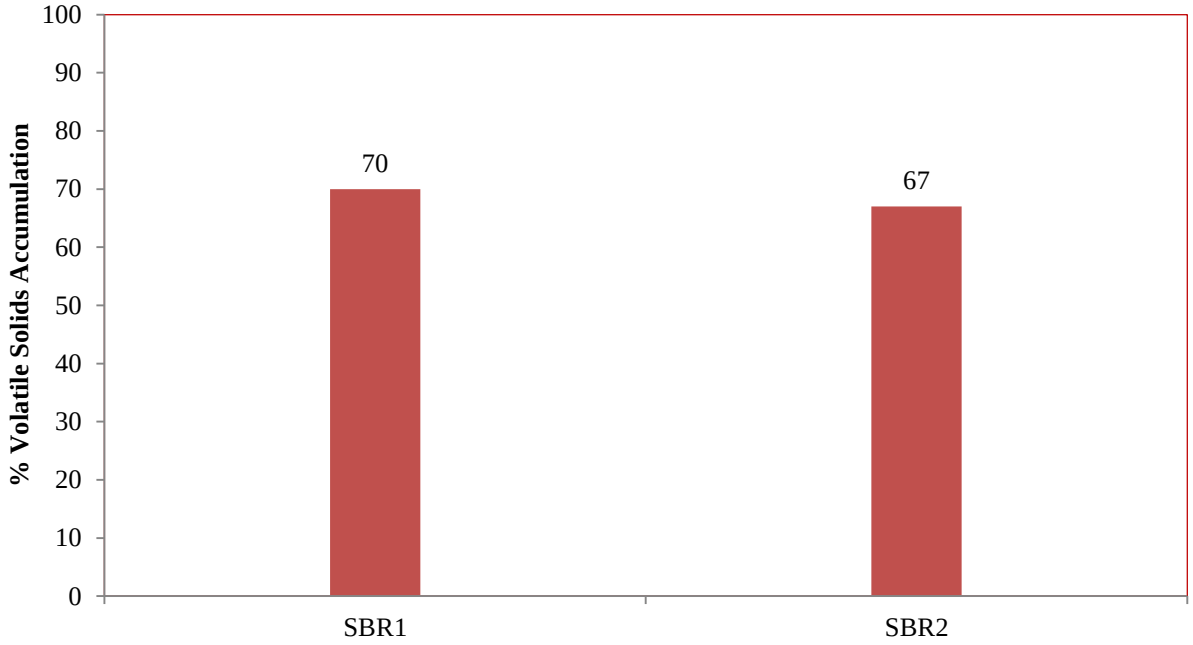
Batch	INFLUENT STREAM		CON SBR 1		CYC SBR 2		% TS Accumulation		% VS Accumulation	
	g/gsample		g/gsample		g/gsample					
	TS	VS	TS	VS	TS	VS	CON SBR1	CYC SBR2	CON SBR1	CYC SBR2
1	0.0451	0.0090	0.0043	0.0029	0.0038	0.0060	91	92	68	33
2	0.0060	0.0100	0.0043	0.0023	0.0040	0.0060	58	63	77	40
3	0.0060	0.0080	0.0043	0.0023	0.0038	0.0009	49	57	71	89
4	0.0050	0.0090	0.0043	0.0023	0.0038	0.0060	73	43	74	33
5	0.0200	0.0075	0.0043	0.0023	0.0200	0.0009	78	56	69	88
7	0.0169	0.0090	0.0053	0.0020	0.0034	0.0008	69	80	77	41
8	0.0056	0.0032	0.0025	0.0011	0.0030	0.0003	56	47	65	51
9	0.0099	0.0019	0.0023	0.0003	0.0022	0.0002	76	77	83	88
10	0.0090	0.0060	0.0013	0.0006	0.0014	0.0040	86	84	89	33
11	0.0060	0.0040	0.0045	0.0020	0.0114	0.0001	55	75	80	98
13	0.0109	0.0100	0.0011	0.0011	0.0038	0.0015	70	65	89	85
14	0.0186	0.0060	0.0035	0.0012	0.0032	0.0036	81	83	80	40
15	0.0093	0.1200	0.0049	0.0039	0.0061	0.0030	48	34	97	88

As shown, the average solids (TS and VS) values for all the batch runs were observed to have a direct relationship with the organic pollutant strength in the brewery wastewater, with respect to the influent brewery wastewater concentrations. These fluctuations were observed over the different batches and were due to unsteady production activities within the brewery plant on a daily basis.

The average influent total solids into both reactors was found to be 184 mg/L, while the average total solids obtained after treatment from CON SBR1and CYC SBR2 was 164 mg/L and 174 mg/L respectively. It was observed from the result obtained that there was a statistically significant total solids reduction in both SBRs, as compared to the influent into the reactors ($P < 0.05$). **Figure 4.9 (a)** and **(b)** presents the overall average percentage solids accumulation in terms of TS and VS conducted for all experimental batch runs.



(a)



(b)

Figure 4.9: (a) and (b) presents the percentage solid accumulation in terms of TS and VS.

As is shown, the percentage total solids removal in CON SBR1 was found to be 72 %, while that of CYC SBR2 was found to be 67 %. The almost same performance of CON SBR1 when compared with CYC SBR2 in terms of total solids removal could be attributed to the fact that a more balanced C:N:P (100:5:1) ratio is needed. This would improve the biodegradation activity of the heterotrophs in both reactors, and therefore enhance easy solids settleability and efficient removal in the biological reaction bed. It was also established that settling of solids within the aerobic sequencing batch reactors was the primary factor affecting the solids concentrations for the effluent. Moreover,

the data showed reasonable differences between the influent and effluent concentrations for both aerobic reactors. This, it may be hypothesised, could be due to the treatment efficiencies attained in the aerobic SBRs. A Student's t-test with unequal variances was performed to determine if there existed a significant difference between CON SBR1 and CYC SBR2 in terms of percentage total solids accumulated.

The average influent volatile solids into both reactors was found to be 136 mg/L, while the average volatile solids obtained after treatment from CON SBR1and CYC SBR2 was 332 mg/L and 210 mg/L respectively. It was observed from the result obtained that there was a statistically significant volatile solids reduction in both SBRs as compared to the influent into the reactors ($P < 0.05$). As is shown, the percentage volatile reduction in CON SBR1 was found to be 70 % while that of SBR2 was found to be 67 %.

In evaluating the performance the two laboratory-scales sequencing batch reactors treating brewery wastewater based on TS and VS. A correlation of the continuous and cyclic aeration schemes with TS and VS removal was carried out. The findings of this study on TS and VS are shown in **Table 4.9** and **Table 4.10**.

Table 4.9: Pearson correlation analysis for CON SBR1 and CYC SBR2 on the removal of total solids.

		SBR1	**SBR2**	**TS**
SBR1	Pearson Correlation	1	0.357	0.168
	Sig. (2-tailed)		0.021	0.054
SBR2	Pearson Correlation	0.357	1	0.098
	Sig. (2-tailed)	0.021		0.039
TS	Pearson Correlation	0.168	0.098	1
	Sig. (2-tailed)	0.056	0.039	

As is shown in **Table 4.9** for cyclic aeration configuration, a Pearson product-moment correlation was run to determine the relationship between CON SBR1 and CYC SBR2, as well as SBR1 and TS in both CON SBR1 and CYC SBR2. The data showed no violation of normality, linearity or homoscedasticity. There was a positive correlation between SBR1 and SBR2, which was statistically significant, with a weak correlation between the two reactors ($R = 0.357$; $P < 0 .05$). Also, there was a weak positive correlation between SBR1 and TS, which was statistically

significant (R = 0.168; P < 0.05). There was a weak positive correlation between CYC SBR2 and CON SBR1, which was statistically significant (R = 0.357; P < 0 .05). Also, there was a weak positive correlation between SBR1 and TS, which was statistically significant (R = 0.098; P < 0.05). The comparison between CON SBR1 and CYC SBR2 indicated a significant difference with a value of (P < 0.05). These results suggested that the effect of continuous low aeration in CON SBR1 on the accumulation of total solids was significant when compared to SBR2.

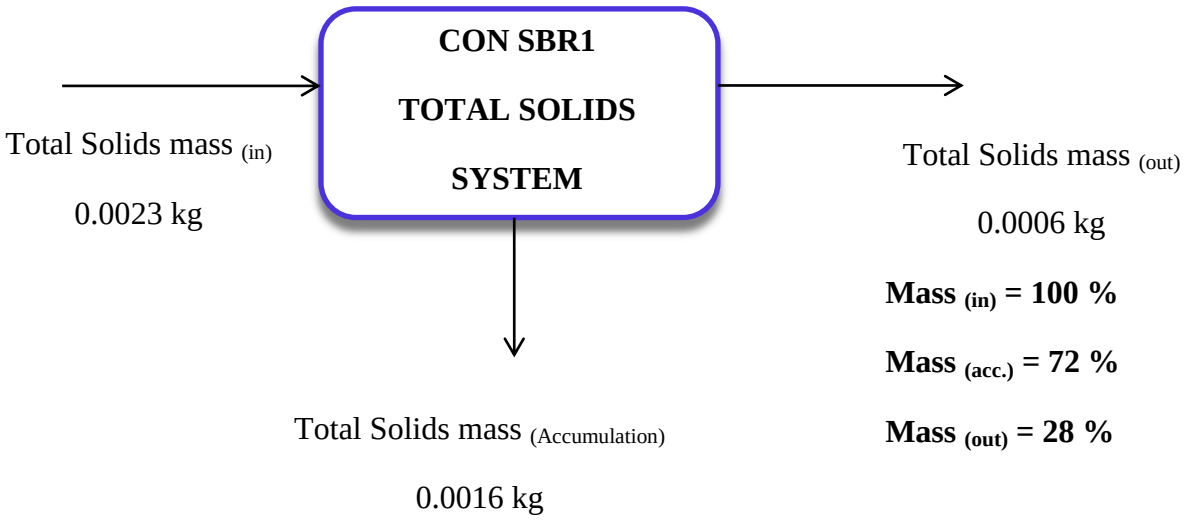
Table 4.10: Pearson correlation analysis for CON SBR1 and CYC SBR2 on volatile solids.

		SBR1	**SBR2**	**VS**
SBR1	Pearson Correlation	1	0.439	0.578*
	Sig. (2-tailed)		0.016	0.030
SBR2	Pearson Correlation	0.439	1	0.057
	Sig. (2-tailed)	0.016		0.046
VS	Pearson Correlation	0.578*	0.057	1
	Sig. (2-tailed)	0.030	0.846	

As is shown in **Table 4.10** for cyclic aeration configuration, a Pearson product-moment correlation was run to determine the relationship between SBR1 and SBR2 as well as SBR1 and VS, in both CON SBR1 and CYC SBR2. The data showed no violation of normality, linearity or homoscedasticity. There was a positive correlation between SBR1 and SBR2, which was statistically significant (R = 0.439; P < 0.05). Also, there was a stronger, positive correlation between SBR1 and TS, which was statistically significant (R = 0.578; P < 0.05). There was a weak positive correlation between SBR2 and SBR1, which was statistically significant (R = 0.439; P < 0 .05). Also, there was a weaker positive correlation between SBR1 and TS, which was statistically significant (R = 0.056; P < 0.05). The findings of this study show that there was a difference in terms of volatile solids reduction in both SBRs, and that this difference was statistically significant. CON SBR1 Showed a higher positive Pearson correlation factor, which indicated higher solids removal efficiency when compared to CYC SBR2.

Figure 5.0 presents the total solids mass balances for overall batch averages in both CON SBR1 and CYC SBR2. As is seen, both SBRs showed a significant total solids removal in the treatment of brewery wastewater.

(i)



(ii)

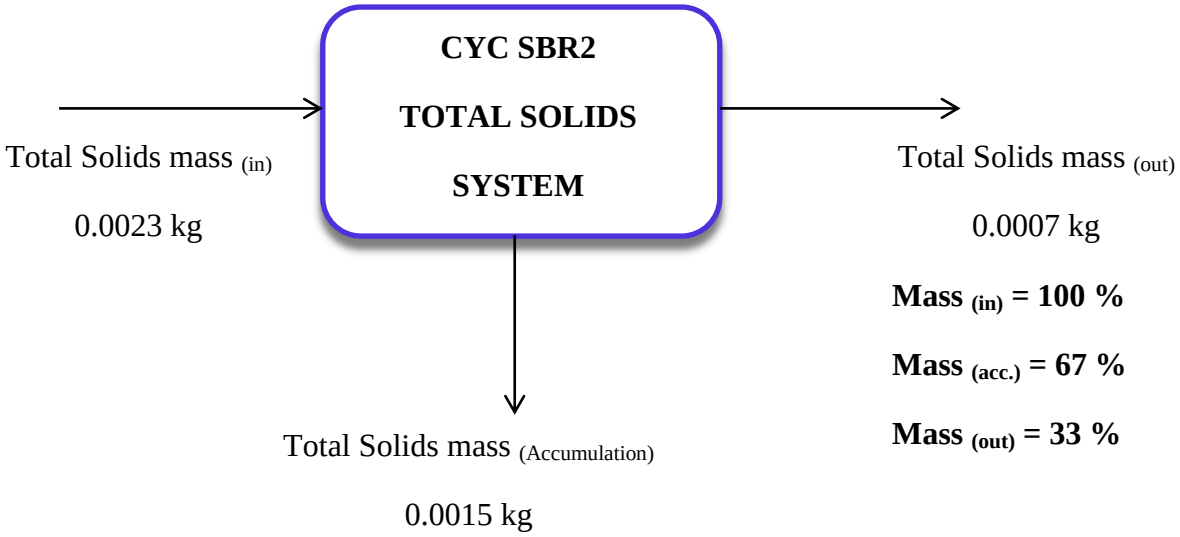


Figure 5.0: (i) and (ii) present the total solids mass balances for CON SBR1 and CYC SBR2.

As is shown, the total solids mass before treatment in the SBRs was 0.002 kg, representing 100 %. It was observed that after effective treatment in CON SBR1, an output of 0.0006 kg, representing 28 %, was attainable. This result implied that a total mass of 0.0016 kg, representing 72 %, was accumulated in CON SBR1. This solids accumulation was due to retention and biological degradation activity by heterotrophic organisms in CON SBR1. CYC SBR2 also indicated a total mass output of 0.0007 kg, representing 33 %. An accumulation of 0.0015 kg, representing 67 %, was found in this reactor, indicating that most of the organic solids were removed through biological degradation, therefore enhancing the settleabilty rate of the solids within the reactor.

4.2.2.7 Total suspended solids (TSS)

The data for all 15 batch runs for the total suspended solids and analyses in brewery wastewater within the aerobic SBRs are presented in **Table 4.11** (see **Appendix F**).

Table 4.11: Total suspended solids results for all batch runs.

Batch	Influent mg TSS /L	CON SBR 1 mg TSS /L	CYC SBR 2 mg TSS /L	% Accumulation CON SBR1	% Accumulation CYC SBR2
1	0.2000	0.0153	0.0500	92	75
2	0.3410	0.0500	0.1000	85	71
3	0.4561	0.2350	0.1030	48	77
4	0.2000	0.0990	0.0135	51	93
5	0.3001	0.1200	0.1111	60	63
6	0.2000	0.0153	0.0135	92	93
7	0.2698	0.2436	0.09	10	67
8	0.1333	0.0551	0.0313	59	77
9	0.1318	0.0113	0.0527	91	60
10	0.0869	0.0151	0.0198	83	77
11	0.1358	0.0862	0.0531	37	61
12	0.0609	0.0051	0.0033	92	95
13	0.5638	0.4182	0.4091	26	27
14	0.4096	0.2131	0.1864	48	54
15	0.0571	0.0244	0.0087	57	85

The average influent total suspended solids into both reactors was found to be 0.1532 mg/L, while the average total suspended solids obtained after treatment from SBR1and SBR2 was 0.1330 mg/L and 0.1586 mg/L respectively. It was observed from the result obtained that there was strong statistically significant total suspended solids reduction in both SBRs, when compared to levels in the influent entering the reactors ($P < 0.05$). **Figure 5.1** presents the average performances of all batch runs conducted in the two SBRs in terms of percentage total suspended solids removal.

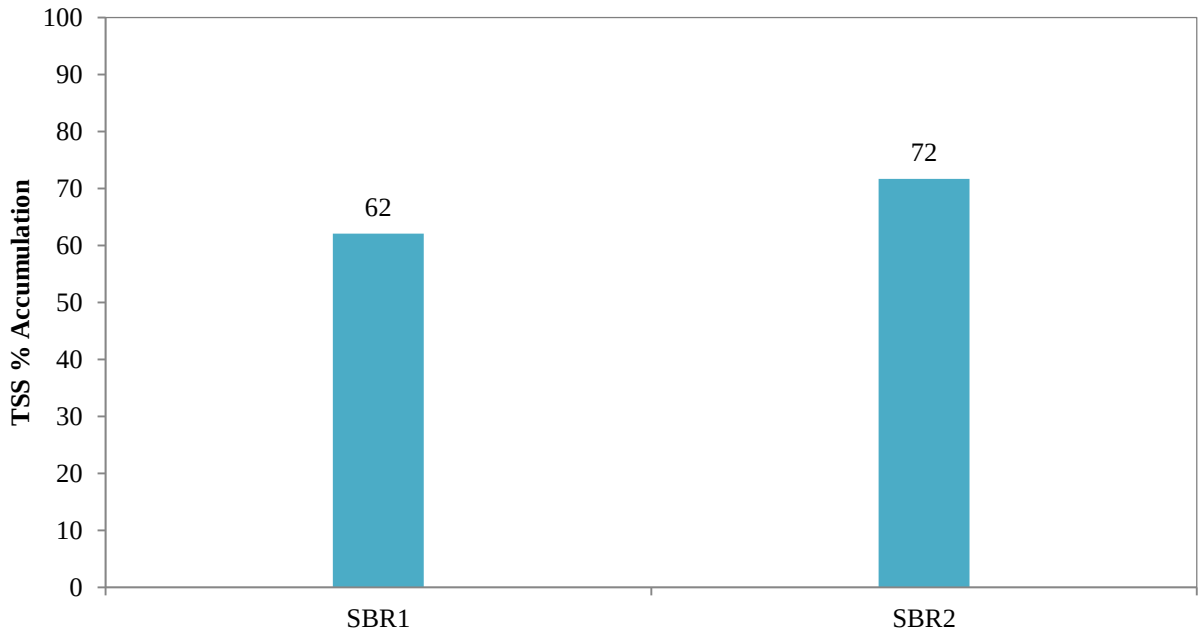


Figure 5.1: Comparison between both SBRs based on their TSS removal efficiency.

As is shown, the percentage of total suspended solids removal in CON SBR1 was found to be 62 %, while that of SBR2 was found to be 72 %. The low performance of CON SBR1 compared to CYC SBR2 in terms of total suspended solids removal could be attributed to the fact that nutrient removal in a sequencing batch reactor takes place through alternating aerobic or anoxic aeration periods, nitrification and denitrification, all of which happens during the reaction periods of the sequencing batch reactor within the on or off cycles of air mixers. Biological nutrient removal is one of the methods that can reduce waste solids production in the form of TSS. It was deduced that nitrogen removal by autotrophic nitrifiers and heterotrophic denitrifier bacteria is superior under anoxic conditions.

From an experimental point of view, it was also noted that there was poor settling of the sludge in CON SBR1 after a complete run of 5 days hydraulic retention time. This led to poor TSS removal in this reactor. This could be due to recurrent sludge bulking, which was observed in some of the batches during experimentation, but primarily in CON SBR1. It was perceived that reseeding both aerobic SBRs more frequently than the set operation sludge retention time of 28 days would enhance the recovery of biomass, thereby improving the overall removal of TSS in both reactors. Therefore, the higher removal efficiency of TSS in CYC SBR2 supported this hypothesis. A Student's t-test with unequal variances was performed to determine if there existed a significant difference between CON SBR1 and CYC SBR2 in terms of percentage total solids removal.

In evaluating the performance of the two laboratory-scales sequencing batch reactors treating brewery wastewater based on TSS removal, a correlation between the continuous and cyclic aeration schemes was done. As is shown in **Table 4.13,** a Pearson correlation analysis on TSS removal was performed, obtaining the following findings.

Table 4.12: Pearson correlation on TSS removal for both CON SBR1 and CYC SBR2.

		SBR1	**SBR2**	**TSS**
SBR1	Pearson Correlation	1	0.873**	0.853**
	Sig. (2-tailed)		0.000	0.000
SBR2	Pearson Correlation	0.873**	1	0.858**
	Sig. (2-tailed)	0.000		0.000
TSS	Pearson Correlation	0.853**	0.858**	1
	Sig. (2-tailed)	0.000	0.000	

The data showed no violation of normality, linearity or homoscedasticity. There was a strong positive correlation between SBR1 and SBR2, which was statistically significant ($R = 0.873$; $P < 0\ .05$). Also, there was a strong positive correlation between SBR1 and TSS, which was statistically significant ($R = 0.853$; $P < 0.05$). There was a positive correlation between CYC SBR2 and CON SBR1, which was statistically significant ($R = 0.873$; $P < 0\ .05$). Also, there was a strong positive correlation between CON SBR1 and TSS, which was statistically significant ($R = 0.858$; $P < 0.05$). The comparison between CON SBR1 and CYC SBR2 indicated a significant difference, with a value of ($P < 0.05$). These results implied that the effect of cyclic or anoxic aeration in CYC SBR2 on the removal of total suspended solids was a more feasible configuration.

4.2.2.8 SUMMARY OF INDEPENDENT SAMPLES T-TEST PERFORMED ON SPSS

Table 4.13: Summary of independent samples of both CON SBR1 and CYC SBR2.

CHARACTERISTIC	CON SBR1	CYC SBR2	P-VALUE
TSS (mg/L)	0.141 ± 0.227	0.122 ± 0.132	0.049
COD (mg/L)	594 ± 621	1885 ± 1649	0.011
BOD (mg/L)	609 ± 424	1067 ± 775	0.050
TS (mg/L)	26.7 ± 0.667	40 ± 30	0.049
VS (mg/L)	26.6 ± 6.67	20 ± 19	0.021

Interpretation of the T-Test from Table 4.14

In evaluating the performance of the two laboratory-scales sequencing batch reactors treating brewery wastewater, an independent sample t-test to compare parameter levels between the two laboratory-scales was also carried out. We correlated the continuous and cyclic aeration schemes with COD, BOD, TS, VS and TSS. CON SBR1 and CYC SBR2 indicated positive correlations, as shown in Section 4.2.2. This study found that CON SBR1 had statistically significantly higher COD Removal (594 ± 624.1 mg/L) when compared to CYC SBR2 (1885.2 ± 1649.1 mg/L), $P < 0.011$. A higher BOD removal on CON SBR1 of (608.8 ± 423.5 mg/L) compared (1067.7± 1649.1 mg/L), $P < 0.057$ was statically attained. A higher statistical TS removal was observed on CON SBR1 with (26.7 ± 0.667 mg/L) compared to (40 ± 30 mg/L), $P < 0.049$. A higher statistical VS removal was observed on CON SBR1 with (26.6 ± 6.67 mg/L) compared to (20 ± 19 mg/L), $P < 0.021$. A higher statistical TSS removal was observed on CON SBR1 with (0.122 0.132 mg/L) compared to (0.141 0.227 mg/L), $P < 0.049$. Based on the above statistical analysis performed on SPSS, CON SBR1 showed better organic pollutant removal ability when compared to CYC SBR2.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

The performance of two laboratory-scale aerobic sequencing batch reactors treating wastewater collected from the brewery under different aeration configurations, namely; continuous aeration scheme and cyclic aeration scheme, was investigated. Treatment of industrial wastewaters such as those generated from the brewery has been a challenge throughout the years, due to varying chemical and physical characteristics in the quality of the generated wastewater from such industrial processes, as well as stringent regulations regarding their release. The findings of this study demonstrated that the use of an aerobic sequencing batch reactor, either by use of a continuous aeration scheme or a cyclic aeration scheme, is capable of significantly reducing the organic pollutants contained in the brewery wastewater used in this study, without any need to enhance the activity of microorganisms in both sequencing batch reactors by providing supplementary nitrogen and phosphorus nutrients. This research study was undertaken to achieve the objectives laid out in **Chapter 1**, and this chapter thus presents the conclusions and recommendations that have arisen from this research.

5.1 CONCLUSIONS

5.1.1 Characteristics of wastewater generated from the brewery

The results of this investigation showed that the quality of wastewater generated from the brewery used for this study was high in organic materials and did not meet the required regulatory standards. Therefore, there is a need to treat the wastewater generated from the brewery in order to protect the environment. As is shown in **Chapter 4**: **Table 4.2**, the results obtained from the investigation conducted to determine the characteristics of wastewater generated from the brewery showed similar characteristics of brewery wastewater presented in various studies. The characterisation of results obtained in this study clearly demonstrated a wastewater quality that is high in organic material, which is highly biodegradable, and will require treatment prior to discharge into the environment.

5.1.2 Effect of hydraulic retention time on the performance of the two SBRs under different aeration schemes

The results of this investigation, conducted to study the effect of hydraulic retention time on the performance of the two aerobic sequencing batch reactors, demonstrated that, for both SBRs operated under different aeration schemes, hydraulic retention time has a direct effect on the treatment efficiency. It was found that as the hydraulic retention time increases, the treatment efficiency also increases. This was determined based on the chemical oxygen demand removal. This implies that, at longer hydraulic retention times, the effluent produced, in terms of chemical oxygen demand, had a higher quality. It was observed that, as the hydraulic retention time increases, there was an increased amount of solids retained in both sequencing batch reactors. However, the amount of solid retained in the SBR that was operated under continuous aeration scheme was significantly higher compared than the SBR operated under a cyclic aeration scheme. This observation can be attributed to enhanced microbial activity as a result of continuous supply of oxygen to the microorganisms, enabling higher biodegradation of organic material present, thereby resulting in an increased biomass production.

5.1.3 Performance of the two laboratory-scale sequencing batch reactors treating brewery wastewater based on different aeration scheme

In this study, the removal performance of two aerobic sequencing batch reactors with regard to organic pollutants and solids was investigated. The experimental work took place over 15 batches for each reactor effluent stream. The feed was brewery wastewater from a local brewery, with varying organic pollutant strength, as shown in **Table 4.2** in **Chapter 4**. The same operation conditions in terms of pH, temperature and the microbial population, acclimated for a month with no biological nutrient additions, was employed on both aerobic reactors. The difference was the aeration configuration schemes, namely continuous low-oxygen concentration vs. cyclic aeration schemes. The performance of the aerobic sequencing batch reactor under the effect of continuous low-concentration oxygen demonstrated superior removal efficiency and a more significant organic pollutant removal in the form of COD, BOD, TS, VS and TSS for CON SBR1 compared to the CYC SBR2. The results obtained indicated that average of all batch experiments treatment efficiencies in terms of COD and BOD were 94 % and 85 % respectively for the reactor operated under continuous aeration configuration, while the overall average treatment efficiencies of 81 % and 65 % were achieved for the cyclic aeration scheme. The Pearson Correlations performed on SPSS and the Student’s t-test analysis done on the abovementioned parameters showed a strong significance difference between the two reactors, based on the attained results with a value of

$P < 0.05$, indicating that the continuous aeration reactor had better removal ability compared to the anoxic or cyclic aeration configuration. These aforementioned results indicated that the continuously aerated reactor had more capable biodegradation activity of the microbial mass due to oxygen abundance. It was also discovered that total suspended solids removal efficiencies were a function of the aeration configuration scheme. Higher TSS removal efficiencies were observed under anoxic conditions, as opposed to continuous low-oxygen dosing. The aforementioned concept was not part of this study. The aerobic SBRs, removal efficiency on biological pollutants appeared dependent of the OLR. The more OLR increased, the greater the occurrence of solids and microorganism population within the reactor systems.

Based on the mass balances, as shown in Section 4.2.2, it can be hypothesised that the high strength organics were accumulated in the sludge bed within the SBRs. The accumulated sludge is therefore of possible concern in terms of environmental considerations and it is likely that care will have to be taken in its disposal. This is an indication that there would be a need for sludge treatment before disposal from the treated brewery wastewater in the SBRs. This would be done to avoid unnecessary environmental and aquatic pollution during wasting the sludge after the biological degradation process within the aerobic SBRs had taken place.

5.2 RECOMMENDATIONS

The research work presented in this study came up with various findings on possibilities of brewery wastewater treated effluent reuse in the production environment and safe disposal into municipal sewers, provided it the resultant effluent adheres to the disposal standards.

1. An investigation on the influence of mixing through bubbling with oxygen, as opposed to stirring with reactor mixers to facilitate homogeneity of the reaction contents in the aerobic reactors for the treatment of brewery wastewater was carried out. It is suggested that minimal sludge bulking could occur. This would improve the overall total suspended solids removal and enhance the settleability of the motile bacteria in the reactors.

2. Based on the on the findings of this study, it is recommended that a well-acclimated and balanced microbial community in terms of nutrient ratios, C: N: P is required to improve the biodegradation activity of the heterotrophs and therefore improve the removal of organic pollutants and solids in both reactors.

3. Biological nutrient removal in terms of nitrogen and phosphorus using an aerobic sequencing batch reactor system.

4. The impact of OLR on the removal of organic pollutants in the form of COD, BOD and TOC should be examined.

5. Continuously develop mass balances and correlation coefficients with empirical models based on the optimum overall treatment efficiency of both the aerobic SBRs. This would theoretically predict the overall performance of the aerobic reactors before operation is commenced.

6. A need for further sludge treatment techniques before disposal into receiving bodies. Incineration may also present a workable alternative.

7. This work could be developed for further future studies. Testing the reactors at abnormal operating conditions (temperature and pH etc.); to better understand their effect on the SBRs treatment efficiency. A detailed qualitative modelling analysis would then be carried out to theoretical predict the performance SBRs.

8 It was recommended that the relationships between HRT and COD removal may be even more established through more experimentations and relevant theoretical studies.

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APPENDIX A

STANDARD METHODS THAT WERE CARRIED OUT FOR THE PERFOMANCE MONITORING PARAMETERS

A1. DETERMINATION OF TOTAL SUSPENDED SOLID IN SAMPLE

Apparatus

i. Measuring cylinder
ii. Analytical balance, capable of weighing to 0.1mg
iii. Glass fibre filter
iv. Desiccator - containing desiccants used for preventing moisture build-up
v. Drying oven equipped with thermostatic control, capable of maintaining the temperature within a 2 °C tolerance
vi. Buchner funnels to accommodate the filter paper

Method

i. Dry a glass filter paper for 10min at 105 °C to 110 °C in an oven.
ii. Remove from oven, cool in a desiccator for 5 minutes and weigh (name it weight A).
iii. Place the filter paper into the Buchner funnel, which has been placed on suction flask.
iv. Measure out 100ml of the well-mixed sample and add slowly to Buchner funnel, while applying suction through a vacuum pump. Continue adding sample until the whole of the liquid has passed through the filter paper.
v. Rinse remains of sample in measuring cylinder with distilled water and pour into Buchner funnel.
vi. Allow solution to continue filtering until the excess water has been removed from filter paper.
vii. Careful remove filter paper. Place the filter paper in an oven at 105°C and 110°C for 2 hours.
viii. Thereafter cool in desiccator for 5 minute and weigh (name it weight B).

Calculation for total suspended solid

Total Suspended Solids, mg/L = $(A - B) \times \left[\frac{100}{C}\right]$……..1

Where: A = weight of filter and dish + residue in mg

B = weight of filter and dish in mg and C = volume of sample filtered in Ml

A2. TOTAL SOLIDS

Apparatus required

i. Porcelain Crucibles
ii. Drying Oven
iii. Analytical Balance
iv. Desiccator

Procedure

i. Heat clean dish to 103 to 105°C for 1 hour. Store and cool dish in desiccator until needed. Weigh immediately before use.
ii. Pipette 50 ml of well mixed sample to the pre-weighed crucible.
iii. Weigh crucible containing sample and place in an oven at 103 - 105°C for 24 hours.
iv. Remove crucible from oven and place in desiccator to cool.
v. Weigh the crucible.

The total solids are therefore calculated as follows:

Mg Total Solids /L = $\frac{(A-B)\times 1000}{Sample\ volume,mL}$…….2

A= weight of dried residue + dish, (mg)

B= weight of dish (mg)

A3. VOLATILE SOLIDS

Aim was to determine the amount of volatile suspended solid in sample, after determining the final weight in the total solids analysis.

Apparatus

i. Muffle furnace
ii. Dish for TS
iii. Furnace tongs
iv. Insulated gloves

Method

i. Place the filter and dish in the muffle furnace.
ii. Ignite at 550 °C ± 50 °C for 30 minutes.
iii. Allow to partially air cool, desiccate and weigh.(name it weight B).

Calculation of Volatile Suspended Solids

Volatile Suspended Solids, mg/L = (A-B) x 1,000/C

Where: A = weight of residue + filter and crucible in mg from Total Suspended Solids test
B = weight of residue + filter and crucible in mg after ignition
C = volume of sample filtered in mL

A4. TOTAL DISSOLVED SOLIDS

Apparatus Required

i. Porcelain Crucibles
ii. Drying Oven
iii. Analytic Balance
iv. Desiccator
v. Vacuum filtration apparatus(glass filter attached)

Procedure

i. Heat clean dish to 180 °C for 1 hour. Store and cool dish in desiccator until needed. Weigh immediately before use.
ii. Assemble filtering apparatus and filter and begin suction. Filter about 150 ml of well-mixed sample using the vacuum filtration apparatus. If volume filtered fails to meet minimum yield, increase sample volume up to 1 L. If complete filtration takes more than 10 min, increase filter diameter or decrease sample volume. Continue suction for about 3 min after filtration is complete.
iii. Evaporate the portion that passes through the filter for 24 hours at 180 °C in an oven, cool in a desiccator to balance temperature, and weigh.

The total dissolved solid is therefore calculated as follows:

mg Total dissolved solid/L= $\frac{(A-B)\times 1000}{\text{Sample Volume,mL}}$……..3

A= weight of dried residue+dish, (mg)

B= weight of dish (mg)

A5. BIOCHEMICAL OXYGEN DEMAND (BOD)

Apparatus and Reagents Required

i. BOD System
ii. 300ml incubation bottles
iii. A nitrifying inhibitor (ATH) (N-Allythiourea)

Procedure

i. Add a sample volume into the incubation bottles; this depends on the range of BOD estimated in the collected sample.
ii. Add drops of ATH based on the sample size, then place in the BOD system for 5 days. (A table presenting the relationship between sample volume and drops of ATH required was attached with this BOD system).
iii. For all BOD analysis for brewery wastewater; this range was considered in this study:
iv. Sample volume: 21.7; Measuring range (mg/L) 0-4000; ATH drops – 1

A6. CHEMICAL OXYGEN DEMAND (COD)

Apparatus Required

i. Digester unit
ii. Erlenmeyer flasks
iii. Pipettes
iv. 10 ml and 5ml automatic bottle top dispensers
v. Digital titrator

Reagents

i. Standard Potassium Dichromate (K_2 CrO_7) Digestion Solutions: 0.0167M
ii. Sulphuric Acid H2SO4/ or Silver Sulphate reagent Ag_2SO_4 (COD reagent)
iii. Ferroin Indicator 2 drops
iv. Ferrous Ammonium Sulphate Fe $(NH_4)_2$ $(SO_4)_{6.}H_2O$: 0.1M

Weekly Standard Preparation

Add 3ml standard K_2 CrO_7 digestion solution to 5ml distilled water. Add 7ml COD reagent and cool it down. Prepare a standard K_2 CrO_7 solution daily to correct any variations in the concentration of the ferrous ammonium sulphate. Titrate with FAS titrate using 2 drops of ferroin indicator.

Procedure

i. Add 5ml sample to each digestion tube.
ii. Add 5ml distilled water to another vessel (blank).
iii. Add 3ml potassium dichromate digestion solution into each vessel.
iv. Add 7ml sulphuric acid reagent (with silver sulphate) in each vessel.
v. The acid must be poured down the wall of the flask while flask is tilted. If sample is too concentrated, it will turn green, and higher dilution of sample must be used.
vi. Prepare a blank with each set of samples consisting of 5ml distilled water in place of sample together with all reagents and digest together with samples.
vii. Digest for 2 Hours at 150 °C.
viii. Transfer contents from tube into 100 ml flasks for titrating.
ix. Transfer the excess dichromate in the digest mixture with standard ferrous ammonium sulphate.
x. Titrate from sharp green/orange to brown end point.
xi. Take reading.

APPENDIX B

RAW DATA FOR INFLUENT BREWERY WASTEWATER

TABLE B1: SUMMARY OF RAW DATA RESULTS TABLE FOR BREWERY WASTEWATER TREATMENT

Batch	pH	Cond. (mS/cm)	(mg COD/L)	(mgBOD/L)	mg TSS /L	TS (g/gsample)	VS (g/gsample)
1	10	8	8031	2622	0.2000	0.1195	0.1166
2	7	8	9826	3764	0.3410	0.0080	0.0042
3	6	8	14860	2741	0.4561	0.0079	0.0046
4	6	5	14806	2743	0.2000	0.0451	0.0090
5	8	9	18151	3206	0.3001	0.0203	0.0059
6	6	5	10384	3207	0.2000	0.0244	0.0065
7	6	8	10576	2383	0.2698	0.0299	0.0072
8	8	9	9104	3086	0.1333	0.0249	0.0065
9	5	8	13296	3032	0.1318	0.0264	0.0067
10	7	5	9152	3726	0.0869	0.0271	0.0068
11	7	8	6560	3257	0.1358	0.0261	0.0067
12	7	6	9824	3137	0.0609	0.0265	0.0067
13	6	8	9168	2815	0.5638	0.0266	0.0068
14	6	5	2976	2648	0.4096	0.0264	0.0067
15	4	8	4752	2291	0.0571	0.0265	0.0067

APPENDIX C

RAW DATA FOR EFFLUENT CON SBR1 BREWERY WASTEWATER

Table C1: SUMMARY OF RAW DATA RESULTS TABLE FOR BREWERY WASTEWATER TREATMENT

Batch	Temp ^{o}C	pH	Cond. (mS/cm)	(mg COD/L)	mgBOD/L	mg TSS /L	TS (g/gsample)	VS (g/gsample)
1	23	9	4	556	372	0.0153	0.0043	0.0029
2	22	8	3	242	1264	0.0500	0.0043	0.0023
3	22	9	4	113	372	0.2350	0.0043	0.0023
4	21	8	3	805	353	0.0990	0.0043	0.0023
5	22	8	4	1386	128	0.1200	0.0043	0.0023
6	21	8	3	368	388	0.0153	0.0053	0.002
7	23	8	4	784	140	0.2436	0.0025	0.0011
8	22	8	6	224	222	0.0551	0.0023	0.0003
9	22	6	4	2496	1177	0.0113	0.0013	0.0006
10	22	6	3	432	1330	0.0151	0.0045	0.002
11	21	8	3	472	301	0.0862	0.0011	0.0011
12	21	7	3	128	389	0.0051	0.0035	0.0012
13	21	9	5	400	959	0.4182	0.0049	0.0039
14	22	8	3	232	942	0.2131	0.0049	0.0033
15	21	8	5	272	795	0.0244	0.0043	0.0023

APPENDIX D

RAW DATA FOR EFFLUENT CYC SBR2 BREWERY WASTEWATER

Table D1: SUMMARY OF RAW DATA RESULTS TABLE FOR BREWERY WASTEWATER TREATMENT

Batch No:	Temp ^{o} C	pH	Cond. (mS/cm)	mg COD/L	mgBOD/L	mg TSS /L	TS (g/gsample)	VS (g/gsample)
1	23	9	4	1195	453	0.0500	0.0038	0.0060
2	23	7	4	339	2159	0.1000	0.0040	0.0060
3	22	8	5	1195	334	0.1030	0.0038	0.0009
4	21	7	3	6836	234	0.0135	0.0038	0.0060
5	22	6	4	1255	1424	0.1111	0.0200	0.0009
6	21	8	4	2528	1782	0.0135	0.0034	0.0008
7	23	8	4	3662	567	0.0900	0.0030	0.0003
8	22	9	7	1264	839	0.0313	0.0022	0.0002
9	22	7	4	544	1069	0.0527	0.0014	0.0040
10	22	7	3	2080	2485	0.0198	0.0114	0.0001
11	21	7	3	1008	395	0.0531	0.0038	0.0015
12	21	8	3	2784	789	0.0033	0.0032	0.0036
13	21	8	6	2000	293	0.4091	0.0061	0.0030
14	22	8	4	964	2294	0.1864	0.0065	0.0060
15	21	7	6	624	890	0.0087	0.0056	0.0060

APPENDIX E

BREWERY WASTEWATER CHARACTERISATION RAW DATA AND SAMPLE CALCULATION SHEETS

TABLE E1: SUMMARY OF ALL PARAMETERS RAW CHARACTERISATION DATA

Time(days)	TDS(mg/L)	pH	EC (us/cm)	Turbidity(NTU)	NH3N (mg/L)	BOD (mg/L)	COD(mg/L)	Total solids g/gsample	Volatile solids g/gsample
1	4.50	7.23	5.47	300.33	2.13	2773.33	12546.06	0.6076	0.0010
2	6.37	7.10	2174.00	390.67	19.70	2180.33	13209.71	0.4882	0.0014
3	19.82	5.85	2793.00	306.67	2.16	3017.67	9174.72	0.0062	0.0021
4	5.91	6.77	2900.33	365.00	0.40	3012.67	9923.50	0.0198	0.0170
5	7.97	6.69	3.27	84.10		2734.33	9485.86	0.1342	0.1219
6	6.49	6.09	2570.00	122.00		2713.67	8319.20	0.0080	0.0041
7	5.08	6.06	3.52	189.33			6583.79	0.0065	0.0028
8	7.97	5.53	1898.00	203.67			12557.47	0.0051	0.0025
9	8.49	6.45	3.22				9147.23	0.0080	0.0044
10	9.00	5.42	2412.00				7241.46	0.0267	0.0178
11	8.07	11.23	5.33				9818.90	0.0090	0.0048
12	5.27	6.93	3.28				2279.89	0.0081	0.0050
13	7.47	6.01	2329.00					0.0053	0.0030
14		6.39	3.21					0.0075	0.0046
AVARAGES:	**7.88**	**7**	**1222**	**245**	**6**	**2739**	**9191**	**0.0957**	**0.0138**

TABLE E2: pH RAW DATA

Sample ID:	**pH**
BWW 1	6.87
BWW 2	7.94
BWW 3	6.87
AVERAGE	7.23
STDEV	0.62
BWW 1	7.10
BWW 2	7.08
BWW 3	7.13
AVERAGE	7.10
STDEV	0.03
BWW 1	5.89
BWW 2	5.83
BWW 3	5.83
AVERAGE	5.85
STDEV	0.03
BWW 1	6.79
BWW 2	6.77
BWW 3	6.76
AVERAGE	6.77
STDEV	0.02
BWW 1	6.69
BWW 2	6.70
BWW 3	6.69
AVERAGE	6.69
STDEV	0.01
BWW 1	6.10
BWW 2	6.08
BWW 3	6.08
AVERAGE	6.09
STDEV	0.01
BWW 1	6.05
BWW 2	6.06
BWW 3	6.07
AVERAGE	6.06
STDEV	0.01
BWW 1	5.52
BWW 2	5.53
BWW 3	5.55
AVERAGE	5.53
STDEV	0.02
BWW 1	6.4
BWW 2	6.48
BWW 3	6.48
AVERAGE	6.45

STDEV	0.05
BWW 1	5.42
BWW 2	5.42
BWW 3	5.43
AVERAGE	5.42
STDEV	0.01
BWW 1	11.23
BWW 2	11.23
BWW 3	11.23
AVERAGE	11.23
STDEV	0.00
BWW 1	6.94
BWW 2	6.92
BWW 3	6.92
AVERAGE	6.93
STDEV	0.01
BWW 1	6.02
BWW 2	6.00
BWW 3	6.00
AVERAGE	6.01
STDEV	0.01
BWW 1	6.36
BWW 2	6.40
BWW 3	6.41
AVERAGE	6.39
STDEV	0.03

TABLE E3: CONDUCTIVITY RAW DATA

Sample ID:	Turbidity (NTU):
BWW 1	5.51
BWW 2	5.42
BWW 3	5.48
AVERAGE	5.47
STDEV	0.05
BWW 1	2143.00
BWW 2	2192.00
BWW 3	2187.00
AVERAGE	2174.00
STDEV	26.96
BWW 1	2788.00
BWW 2	2783.00
BWW 3	2808.00
AVERAGE	2793.00
STDEV	13.23
BWW 1	2870.00
BWW 2	2901.00
BWW 3	2930.00
AVERAGE	2900.33
STDEV	30.01
BWW 1	3.27
BWW 2	3.29
BWW 3	3.25
AVERAGE	3.27
STDEV	0.02
BWW 1	2600.00
BWW 2	2598.00
BWW 3	2512.00
AVERAGE	2570.00
STDEV	50.24
BWW 1	3.52
BWW 2	3.53
BWW 3	3.50
AVERAGE	3.52
STDEV	0.02
BWW 1	1933.00
BWW 2	1893.00
BWW 3	1868.00
AVERAGE	1898.00
STDEV	32.79
BWW 1	3.22
BWW 2	3.19

BWW 3	3.25
AVERAGE	3.22
STDEV	0.03
BWW 1	2434
BWW 2	2423
BWW 3	2379
AVERAGE	2412
STDEV	29.10
BWW 1	5.27
BWW 2	5.34
BWW 3	5.37
AVERAGE	5.33
STDEV	0.05
BWW 1	3.27
BWW 2	3.27
BWW 3	3.31
AVERAGE	3.28
STDEV	0.02
BWW 1	2313
BWW 2	2331
BWW 3	2343
AVERAGE	2329
STDEV	15.10
BWW 1	3.18
BWW 2	3.25
BWW 3	3.21
AVERAGE	3.21
STDEV	0.04

TABLE E4: TURBIDITY RAW DATA

Sample ID:	Turbidity (NTU):
BWW 1	184.00
BWW 2	349.00
BWW 3	368.00
AVERAGE	300.33
STDEV	101.19
BWW 1	360.00
BWW 2	369.00
BWW 3	443.00
AVERAGE	390.67
STDEV	45.54
BWW 1	265.00
BWW 2	327.00
BWW 3	328.00
AVERAGE	306.67
STDEV	36.09
BWW 1	449.00
BWW 2	398.00
BWW 3	248.00
AVERAGE	365.00
STDEV	104.48
BWW 1	74.60
BWW 2	77.70
BWW 3	100.00
AVERAGE	84.10
STDEV	13.86

BWW 1	111.00
BWW 2	115.00
BWW 3	140.00
AVERAGE	122.00
STDEV	15.72
BWW 1	220.00
BWW 2	154.00
BWW 3	194.00
AVERAGE	189.33
STDEV	33.25
BWW 1	270.00
BWW 2	157.00
BWW 3	184.00
AVERAGE	203.67
STDEV	59.01

TABLE E5: TDS RAW DATA CALCULATION SHEET

Sample ID:	A	B	Sample Vol. mL	mg TDS /L	
BWW 1	65.4643	65.3291	23.5471	5.7417	88.8762
BWW 2	69.0631	68.9512	20.3396	5.5016	89.2908
BWW 3	68.6457	68.5540	15.3888	5.9589	83.9428
AVERAGE				5.7340	
STDEV				0.2287	
BWW 1	57.3949	57.2952	20.0645	4.9690	77.3597
BWW 2	57.4037	57.3158	22.9202	3.8350	80.2360
BWW 3	63.5811	63.5104	15.0412	4.7004	78.5516
AVERAGE				4.5015	
STDEV				0.5926	
BWW 1	35.8001	35.6010	38.7327	5.1404	74.3337
BWW 2	35.9200	35.6662	36.5011	6.9532	72.1673
BWW 3	37.7211	37.4190	43.0266	7.0212	80.4456
AVERAGE				6.3716	
STDEV				1.0668	
BWW 1	39.9376	39.6507	47.9086	5.9885	87.5593
BWW 2	47.308	47.0898	42.9333	5.0823	90.0231
BWW 3	47.7848	45.5315	46.5549	48.4009	92.0864
AVERAGE				19.8239	
STDEV				24.7526	
BWW 1	39.9619	39.8376	39.0341	3.1844	78.8717
BWW 2	47.9366	47.6080	31.8059	10.3314	79.4139
BWW 3	35.7560	35.5848	40.7544	4.2008	76.3392
AVERAGE				5.9055	
STDEV				3.8665	
BWW 1	37.7758	37.4188	44.1991	8.0771	81.6179
BWW 2	47.4096	47.089	40.8764	7.8432	87.9654
BWW 3	35.9504	35.5998	43.8274	7.9996	79.4272
AVERAGE				7.9733	
STDEV				0.1192	
BWW 1	35.9361	35.6645	41.6383	6.5228	77.3028
BWW 2	45.7869	45.5257	40.5007	6.4493	86.0264
BWW 3	39.9232	39.6473	42.3821	6.5098	82.0294
AVERAGE				6.4940	
STDEV				0.0393	
BWW 1	37.6168	37.4097	41.1244	5.0359	78.5341
BWW 2	47.2766	47.0843	37.9504	5.0671	85.0347
BWW 3	35.8117	35.5885	43.4298	5.1393	79.0183
AVERAGE				5.0808	
STDEV				0.0530	
BWW 1	45.8208	45.5221	38.9852	7.6619	84.5073
BWW 2	35.9849	35.6539	38.8358	8.5231	74.4897

BWW 3	39.9534	39.6452	39.9288	7.7187	79.5740
AVERAGE				7.9679	
STDEV				0.4816	
BWW 1	37.6547	37.4092	37.6828	6.5149	75.0920
BWW 2	47.3191	47.0839	35.1352	6.6941	82.2191
BWW 3	37.8475	37.4095	35.6803	12.2757	73.0898
AVERAGE				8.4949	
STDEV				3.2755	
BWW 1	40.0309	39.6468	39.3839	9.7527	79.0307
BWW 2	35.9904	35.6553	38.8656	8.6220	74.5209
BWW 3	45.8127	45.5219	33.7308	8.6212	79.2527
AVERAGE				8.9986	
STDEV				0.6530	
BWW 1	37.6972	37.4026	36.7282	8.0211	74.1308
BWW 2	47.3614	47.0785	34.8177	8.1252	81.8962
BWW 3	35.9229	35.5873	41.6598	8.0557	77.2471
AVERAGE				8.0673	
STDEV				0.0530	
BWW 1	39.8328	39.6317	38.2679	5.2551	77.8996
BWW 2	35.8632	35.6464	41.3723	5.2402	77.0187
BWW 3	45.716	45.5107	38.6360	5.3137	84.1467
AVERAGE				5.2697	
STDEV				0.0389	
BWW 1	37.6780	37.3973	37.4176	7.5018	74.8149
BWW 2	47.3309	47.0748	34.2738	7.4722	81.3486
BWW 3	35.8605	35.5801	37.6587	7.4458	73.2388
AVERAGE				7.4733	
STDEV				0.0280	

TABLE E6: BOD RAW DATA CALCULATION SHEET

Sample ID:	Sample Volume	Measurement Value (mg/L)
BWW 1	21.10	2762
BWW 2	21.10	2754
BWW 3	21.10	2804
AVERAGE		2773.33
STDEV		26.86
BWW 1	21.10	2041
BWW 2	21.10	1500
BWW 3	21.10	3000
AVERAGE		2180.33
STDEV		759.64
BWW 1	21.10	3111
BWW 2	21.10	3000
BWW 3	21.10	2942
AVERAGE		3017.67
STDEV		85.87
BWW 1	21.1	3060
BWW 2	21.1	3050
BWW 3	21.1	2928
AVERAGE		3012.67
STDEV		73.49
BWW 1	21.10	3084
BWW 2	21.10	2098
BWW 3	21.10	3021
AVERAGE		2734.33
STDEV		551.98
BWW 1	21.10	3018
BWW 2	21.10	2201
BWW 3	21.10	2922
AVERAGE		2713.67
STDEV		446.57

TABLE E7: TOTAL SOLIDS AND VOLITILE SOLIDS RAW DATA CALCULATION SHEET

Crucible No	Sample ID	dish weight(g)	Sample Mass(g)	Sample mass+ dish(g)	dry mass + dish(g)	mass of residue+dish after ignition(g)	Total solids	Volatile solids
1A	BWW 1	35.2341	53.6421	88.8762	65.4643	65.4081	0.5636	0.0010
1B	BWW 2	40.2016	49.0892	89.2908	69.0631	69.0179	0.5879	0.0009
1C	BWW 3	37.4182	46.5246	83.9428	68.6457	68.6038	0.6712	0.0009
AVERAGE							0.6076	0.0010
STDEV							0.0564	0.0001
2A	BWW 1	35.6010	41.7587	77.3597	57.3949	57.3327	0.5219	0.0015
2B	BWW 2	47.3090	32.9260	80.2350	57.4037	57.3486	0.3066	0.0017
2C	BWW 3	37.4180	41.1336	78.5516	63.5811	63.5341	0.6361	0.0011
AVERAGE							0.4882	0.0014
STDEV							0.1673	0.0003
3A	BWW 1	35.6010	38.7327	74.3337	35.8001	35.7575	0.0051	0.0011
3B	BWW 2	35.6662	38.5449	74.2111	35.9200	35.8151	0.0066	0.0027
3C	BWW 3	37.4190	43.0266	80.4456	37.7211	37.6081	0.0070	0.0026
AVERAGE							0.0062	0.0021
STDEV							0.0010	0.0009
4A	BWW 1	39.6507	47.9086	87.5593	39.9376	39.7940	0.0060	0.0030
4B	BWW 2	47.0898	42.9333	90.0231	47.3080	47.2016	0.0051	0.0025
4C	BWW 3	45.5315	46.5549	92.0864	47.7848	45.6589	0.0484	0.0457
AVERAGE							0.0198	0.0170
STDEV							0.0248	0.0248
5A	BWW1	35.8619	43.0098	78.8717	39.9376	35.7266	0.0948	0.0979
5B	BWW 2	35.9366	43.4773	79.4139	47.3080	35.7946	0.2615	0.2648
5C	BWW3	35.7848	40.5544	76.3392	37.6560	37.5304	0.0461	0.0031
AVERAGE							0.1342	0.0170
STDEV							0.1130	0.1325
7A	BWW 1	37.4188	44.1991	81.6179	37.7758	37.5923	0.0081	0.0042
7B	BWW 2	47.0890	40.8764	87.9654	47.4096	47.2477	0.0078	0.0040

7C	BWW 3	35.5998	43.8274	79.4272	35.9504	35.7725	0.0080	0.0041
AVERAGE							0.0080	0.0041
STDEV							0.0001	0.0001
8A	BWW 1	35.6645	41.6383	77.3028	35.9361	35.8214	0.0065	0.0028
8B	BWW 2	45.5257	40.5007	86.0264	45.7869	45.6741	0.0064	0.0028
8C	BWW 3	39.6473	42.3821	82.0294	39.9232	39.8029	0.0065	0.0028
AVERAGE							0.0065	0.0028
STDEV							0.0000	0.0000
9A	BWW 1	37.4097	41.1244	78.5341	37.6168	37.5158	0.0050	0.0025
9B	BWW 2	47.0843	37.9504	85.0347	47.2766	47.1833	0.0051	0.0025
9C	BWW 3	35.5885	43.4298	79.0183	35.8117	35.7011	0.0051	0.0025
AVERAGE							0.0051	0.0025
STDEV							0.0001	0.0001
10A	BWW 1	45.5221	38.9852	84.5073	45.8208	45.6581	0.0077	0.0042
10B	BWW 2	35.6539	38.8358	74.4897	35.9849	35.7910	0.0085	0.0050
10C	BWW 3	39.6452	39.9288	79.5740	39.9534	39.7865	0.0077	0.0042
AVERAGE							0.0080	0.0044
STDEV							0.0005	0.0005
11A	BWW 1	37.4092	37.6828	75.0920	37.6547	37.4983	0.0065	0.0042
11B	BWW 2	47.0839	35.1352	82.2191	47.3191	47.1712	0.0067	0.0042
11C	BWW 3	34.8475	38.2423	73.0898	37.4095	35.6863	0.0670	0.0451
AVERAGE							0.0267	0.0178
STDEV							0.0349	0.0236
12A	BWW 1	39.6468	39.3839	79.0307	40.0309	39.8067	0.0098	0.0057
12B	BWW 2	35.6553	38.8656	74.5209	35.9904	35.8215	0.0086	0.0043
12C	BWW 3	45.5219	33.7308	79.2527	45.8127	45.6625	0.0086	0.0045
AVERAGE							0.0090	0.0048
STDEV							0.0007	0.0007
13A	BWW 1	37.4026	36.7282	74.1308	37.6972	37.5138	0.0080	0.0050
13B	BWW 2	47.0785	34.8177	81.8962	47.3614	47.1854	0.0081	0.0051

13C	BWW 3	35.5873	41.6598	77.2471	35.9229	35.7135	0.0081	0.0050
AVERAGE							0.0081	0.0050
STDEV							0.0001	0.0000
14A	BWW 1	39.6317	38.2679	77.8996	39.8328	39.7204	0.0053	0.0029
14B	BWW 2	35.6464	41.3723	77.0187	35.8632	35.7382	0.0052	0.0030
14C	BWW 3	45.5107	38.6360	84.1467	45.7160	45.5993	0.0053	0.0030
AVERAGE							0.0053	0.0030
STDEV							0.0000	0.0000
15A	BWW 1	37.3973	37.4176	74.8149	37.6780	37.5037	0.0075	0.0047
15B	BWW 2	47.0748	34.2738	81.3486	47.3309	47.1727	0.0075	0.0046
15C	BWW 3	35.5801	37.6587	73.2388	35.8605	35.6862	0.0074	0.0046
AVERAGE							0.0075	0.0046
STDEV							0.0000	0.0000

TABLE E8: COD RAW DATA CALCULATION SHEETS

Run #1

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.98	0.15	4.13	1.54	12481.93
		2	4.96	0.15	4.13	1.54	12532.26
		3	5	0.15	4.35	1.72	12624.00
		AVERAGE	4.98	0.15	4.20	1.60	12546.06
		STDEV	0.02	0.00	0.13	0.10	72.04

Run #2

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5	0.15	4.45	1.69	13248.00
		2	4.98	0.15	4.42	1.69	13156.63
		3	4.9	0.15	4.45	1.75	13224.49
		AVERAGE	4.96	0.15	4.44	1.71	13209.71
		STDEV	0.05	0.00	0.02	0.03	47.45

Run #3

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5	0.15	4.00	2.32	8064.00
		2	4.98	0.15	4.05	2.00	9879.52
		3	4.96	0.15	3.98	2.00	9580.65
		AVERAGE	4.98	0.15	4.01	2.11	9174.72
		STDEV	0.02	0.00	0.04	0.18	973.45

Run #4

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.98	0.15	4.05	1.86	10554.22
		2	4.96	0.15	3.79	1.96	8854.84
		3	4.98	0.15	4.04	1.89	10361.45
		AVERAGE	4.97	0.15	3.96	1.90	9923.50
		STDEV	0.01	0.00	0.15	0.05	930.49

Run #5

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5.00	0.15	3.79	1.83	9408.00
		2	4.95	0.15	4.04	1.93	10230.30
		3	4.98	0.15	3.83	2.00	8819.28
		AVERAGE	4.98	0.15	3.89	1.92	9485.86
		STDEV	0.03	0.00	0.13	0.09	708.73

Run #6

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5.00	0.15	4.00	2.40	7680.00
		2	4.98	0.15	4.00	2.60	6746.99
		3	4.90	0.15	4.00	1.85	10530.61
		AVERAGE	4.96	0.15	4.00	2.28	8319.20
		STDEV	0.05	0.00	0.00	0.39	1971.14

Run #7

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.95	0.15	4.55	3.23	6400.00
		2	4.98	0.15	4.55	3.05	7228.92
		3	4.90	0.15	4.53	3.28	6122.45
		AVERAGE	4.94	0.15	4.54	3.19	6583.79
		STDEV	0.04	0.00	0.01	0.12	575.67

Run #8

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.92	0.15	4.63	2.00	12829.27
		2	4.98	0.15	4.60	1.96	12722.89
		3	4.99	0.15	4.60	2.08	12120.24
		AVERAGE	4.96	0.15	4.61	2.01	12557.47
		STDEV	0.04	0.00	0.02	0.06	382.37

Run #9

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.95	0.15	4.33	2.20	10327.27
		2	5.00	0.15	4.32	2.13	10512.00
		3	4.98	0.15	4.35	2.98	6602.41
		AVERAGE	4.98	0.15	4.33	2.44	9147.23
		STDEV	0.03	0.00	0.02	0.47	2205.81

Run #10

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.98	0.15	4.33	2.90	6891.57
		2	4.92	0.15	4.47	2.95	7414.63
		3	4.95	0.15	4.36	2.83	7418.18
		AVERAGE	4.95	0.15	4.39	2.89	7241.46
		STDEV	0.03	0.00	0.07	0.06	303.02

APPENDIX F

RAW DATA AND SAMPLE CALCULATION SHEETS FOR ALL BATCH RUNS

TABLE: F1: TSS RAW DATA

Batch	Influent stream mg TSS /L	CON SBR 1 mg TSS /L	CYC SBR 2 mg TSS /L	% REMOVAL CON SBR1	% REMOVAL CYC SBR2
1	0.2000	0.0153	0.0500	92	75
2	0.3410	0.0500	0.1000	85	71
3	0.4561	0.2350	0.1030	48	77
4	0.2000	0.0990	0.0135	51	93
5	0.3001	0.1200	0.1111	60	63
6	0.2000	0.0153	0.0135	92	93
7	0.2698	0.2436	0.09	10	67
8	0.1333	0.0551	0.0313	59	77
9	0.1318	0.0113	0.0527	91	60
10	0.0869	0.0151	0.0198	83	77
11	0.1358	0.0862	0.0531	37	61
12	0.0609	0.0051	0.0033	92	95
13	0.5638	0.4182	0.4091	26	27
14	0.4096	0.2131	0.1864	48	54
15	0.0571	0.0244	0.0087	57	85

TABLE F2: TOTAL SOLIDS AND VOLIATLE SOLIDS RAW DATA

	INFLUENT STREAM		CON SBR 1		CYCLIC SBR 2		% TS REMOVAL		% VS REMOVAL	
	g/gsample	g/gsample	g/gsample	g/gsample	g/gsample	g/gsample				
Time (Wks.)	Total solids	Volatile solids	Total solids	Volatile solids	Total solids	Volatile solids	CON SBR1	CYC SBR2	CON SBR1	CYC SBR2
1	0.0451	0.0090	0.0043	0.0029	0.0038	0.0060	91	92	68	33
2	0.0060	0.0100	0.0043	0.0023	0.0040	0.0060	28	33	77	40
3	0.0060	0.0080	0.0043	0.0023	0.0038	0.0009	28	37	71	89
4	0.0050	0.0090	0.0043	0.0023	0.0038	0.0060	13	23	74	33
5	0.0200	0.0075	0.0043	0.0023	0.0200	0.0009	78	20	69	88
7	0.0169	0.0090	0.0053	0.0020	0.0034	0.0008	69	80	77	91
8	0.0056	0.0032	0.0025	0.0011	0.0030	0.0003	56	47	65	91
9	0.0099	0.0019	0.0023	0.0003	0.0022	0.0002	76	77	83	88
10	0.0090	0.0060	0.0013	0.0006	0.0014	0.0040	86	84	89	33
11	0.0060	0.0040	0.0045	0.0020	0.0050	0.0001	25	17	50	98
13	0.0109	0.0100	0.0011	0.0011	0.0038	0.0015	90	65	89	85
14	0.0186	0.0060	0.0035	0.0012	0.0032	0.0036	81	83	80	40
15	0.0093	0.1200	0.0049	0.0039	0.0061	0.0030	48	34	97	98

TABLE F3: (A) AND (B) HRT RAW DATA CALCULATION SHEETS

(a) CYCLIC AERARTION SBR2

TIME (Days)	mg COD/L	% REMOVAL
0	11300	0
1	6128	46
3	5280	53
4	904	92
5	1168	90
6	996	91
7	964	91

(b) CONTINOUS AERATION SBR1

TIME (Days)	mg COD/L	% REMOVAL
0	11300	0
1	6923	39
3	3936	65
4	2246	80
5	1144	90
6	500	96
7	475	96

(%) Removal efficiency = $\frac{C_{influent} - C_{effluent}}{C_{influent}} \times 100$ … … … … … … … … … … … … … .4

Where:

$C_{influent}$ = Initial parameter concentration.

$C_{effluent}$ = Final parameter concentration.

TABLE F4: COD RAW DATA SHEET AND SAMPLE CALCULATION SHEETS

Batches	Influent (mgCOD/L)	OLR (kg COD/day)	EFFLUENT CON SBR1 (mgCOD/L)	EFFLUENT CYC SBR2 (mgCOD/L)	CON SBR 1 %COD REMOVAL	CYC SBR 2 %COD REMOVAL
1	8031	0.0080	556	1195	93	85
2	9826	0.0098	242	339	98	97
3	14860	0.0149	113	1195	99	92
4	14806	0.0148	805	6836	95	54
5	18151	0.0182	1386	1255	92	93
6	10384	0.0104	368	2528	96	76
7	10576	0.0106	784	3662	93	65
8	9104	0.0091	224	1264	98	86
9	13296	0.0133	2496	544	81	96
10	9152	0.0092	432	2080	95	77
11	6560	0.0066	472	1008	93	85
12	9824	0.0098	128	2784	99	72
13	9168	0.0092	400	2000	96	78
14	2976	0.0030	232	964	92	68
15	4752	0.0048	272	624	94	87
AVA.	**10098**	**0.0101**	**594**	**1885**	**94**	**81**

DILUTION FACTOR SAMPLE CALCULATION

Dilution	Y introduced		in X mL phial		Dilution factor
	Y (unit)	quantities	Quantities		
1	$V_{pipetted}$ (mL)	50	1000		0.0500
Total dilution:					20.0000

SAMPLE CALCULATION SHEETS- CON SBR1

(SBR INFLUENT STREAM 29 June 2015) DATA FOR EXPERIMENTAL HRT OVER SEVEN DAYS								
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5	3	1	4.98	0.15	4.23	2.08	10361.45	
		2	4.96	0.15	4.23	1.77	11903.23	
		3	5.00	0.15	4.23	1.44	13392.00	
		AVERAGE	4.98	0.15	4.23	1.76	11885.56	
		STDEV	0.02	0.00	0.00	0.32	1515.35	
		VAR	0.00	0.00	0.00	0.10	2296298.85	
SBR#1 EFFLUENT :DAY#1								
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5	3	1	5.00	0.15	3.95	2.67	6144.00	
		2	4.98	0.15	3.95	2.47	7132.53	
		3	4.90	0.15	3.95	2.42	7493.88	
		AVERAGE	4.96	0.15	3.95	2.52	6923.47	

		STDEV	0.05	0.00	0.00	0.13	698.80
		VAR	0.00	0.00	0.00	0.02	488322.19
DAY#2: EXPERIMENTAL HRT							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5.00	0.15	3.15	1.35	8640.00
		2	4.98	0.15	3.15	1.22	9301.20
		3	4.96	0.15	3.15	1.74	6822.58
		AVERAGE	4.98	0.15	3.15	1.44	8254.60
		STDEV	0.02	0.00	0.00	0.27	1283.47
		VAR	0.00	0.00	0.00	0.07	1647297.12
DAY#3: EXPERIMENTAL HRT							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	3.15	0.15	3.83	2.19	7872.00
		2	3.15	0.15	3.83	3.20	3024.00
		3	3.15	0.15	3.83	3.64	912.00
		AVERAGE	3.15	0.15	3.83	3.01	3936.00
		STDEV	0.00	0.00	0.00	0.74	3568.50
		VAR	0.00	0.00	0.00	0.55	12734208.00
DAY#4: EXPERIMENTAL HRT							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5.00	0.15	4.40	3.58	3936.00

		2	4.95	0.15	4.40	4.08	1551.52
		3	4.98	0.15	4.40	4.14	1253.01
		AVERAGE	4.98	0.15	4.40	3.93	2246.84
		STDEV	0.03	0.00	0.00	0.31	1470.45
		VAR	0.00	0.00	0.00	0.09	2162216.07
DAY#5: EXPERIMENTAL HRT							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	5.00	0.15	4.40	4.19	1008.00
		2	4.98	0.15	4.40	4.10	1445.78
		3	4.90	0.15	4.40	4.20	979.59
		AVERAGE	4.96	0.15	4.40	4.16	1144.46
		STDEV	0.05	0.00	0.00	0.06	261.34
		VAR	0.00	0.00	0.00	0.00	68299.24
DAY#6: EXPERIMENTAL HRT							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5	3	1	4.95	0.15	4.40	4.18	1066.67
		2	4.98	0.15	4.40	4.36	192.77
		3	4.90	0.15	4.40	4.26	685.71
		AVERAGE	4.94	0.15	0.00	0.00	648.38
		STDEV	0.04	0.00	0.00	0.09	438.14
		VAR	0.00	0.00	0.00	0.01	191968.53
DAY#7: EXPERIMENTAL HRT							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total

V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5	3	1	4.92	0.15	4.41	4.18	1121.95	
		2	4.98	0.15	4.41	4.16	1204.82	
		3	4.99	0.15	4.41	4.41	0.00	
		AVERAGE	4.96	0.15	4.41	0.00	775.59	
		STDEV	0.04	0.00	0.00	0.14	672.96	
		VAR	0.00	0.00	0.00	0.02	452871.86	
(SBRs INFFLUENT) - BATCH#1								
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5	3	1	4.95	0.15	4.41	1.92	12072.73	
		3	4.98	0.15	4.41	3.32	5253.01	
		AVERAGE	4.98	0.15	4.41	2.75	8031.25	
		STDEV	0.03	0.00	0.00	0.73	3581.06	
		VAR	0.00	0.00	0.00	0.54	12823972.61	
(SBR#1 EFFLUENT) - BATCH#1								
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
V_{sample} (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5	3	1	4.98	0.15	4.38	3.25	5445.78	
		2	4.92	0.15	4.38	3.22	5658.54	
		3	4.95	0.15	4.38	3.22	5624.24	
		AVERAGE	4.95	0.15	4.38	3.23	5576.19	
		STDEV	0.03	0.00	0.00	0.02	114.23	
		VAR	0.00	0.00	0.00	0.00	13047.97	
(SBRs INFFLUENT) - BATCH#2								

			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
V_{sample} (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5.00	3.00	1.00	4.98	0.15	5.00	2.88	10216.87	
		2.00	4.92	0.15	5.00	2.95	10000.00	
		3.00	4.95	0.15	5.00	3.09	9260.61	
		AVERAGE	4.95	0.15	5.00	2.97	9825.82	
		STDEV	0.03	0.00	0.00	0.11	501.36	
		VAR	0.00	0.00	0.00	0.01	251361.80	
(SBR#1 EFFLUENT) - BATCH#2								
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
Vsample (mL)	$V_{K2Cr2O7}$ (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5.00	3	1.00	5.00	0.15	4.30	4.30	0.00	
		2.00	4.98	0.15	4.30	4.20	481.93	
		3.00	4.96	0.15	4.30	4.25	241.94	
		AVERAGE	4.98	0.15	4.30	4.25	241.29	
		STDEV	0.02	0.00	0.00	0.05	240.96	
		VAR	0.00	0.00	0.00	0.00	58063.89	
(SBRs INFFLUENT) - BATCH 3								
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total	
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)	
5.00	3.00	1.00	4.92	0.15	4.41	1.44	14487.80	
		2.00	4.98	0.15	4.41	1.23	15325.30	
		3.00	4.99	0.15	4.41	1.34	14765.53	
		AVERAGE	4.96	0.15	4.41	1.34	14859.55	
		STDEV	0.04	0.00	0.00	0.11	426.59	

		VAR	0.00	0.00	0.00	0.01	181979.09
(SBR#1 EFFLUENT) - BATCH #3							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.92	0.15	4.22	4.20	97.56
		2.00	4.98	0.15	4.22	4.18	192.77
		3.00	4.99	0.15	4.22	4.21	48.10
		AVERAGE	4.96	0.15	0.00	4.20	112.81
		STDEV	0.04	0.00	0.00	0.02	73.53
		VAR	0.00	0.00	0.00	0.00	5407.09
(SBRs INFFLUENT) - BATCH 4							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.92	0.15	4.22	1.49	13317.07
		2.00	4.98	0.15	4.22	1.02	15421.69
		3.00	4.99	0.15	4.22	0.96	15679.36
		AVERAGE	4.96	0.15	4.22	1.16	14806.04
		STDEV	0.04	0.00	0.00	0.29	1295.90
		VAR	0.00	0.00	0.00	0.08	1679364.36
(SBR#1 EFFLUENT) - BATCH #4							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.95	0.15	4.45	4.18	1309.09
		2.00	5.00	0.15	4.45	4.33	576.00
		3.00	4.98	0.15	4.45	4.34	530.12

		AVERAGE	4.98	0.15	4.45	4.28	805.07
		STDEV	0.03	0.00	0.00	0.09	437.10
		VAR	0.00	0.00	0.00	0.01	191053.69
(SBRs INFFLUENT) - BATCH 5							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.98	0.15	4.45	0.86	17301.20
		2.00	4.92	0.15	4.45	0.75	18048.78
		3.00	4.95	0.15	4.45	0.51	19103.03
		AVERAGE	4.95	0.15	4.45	0.71	18151.01
		STDEV	0.03	0.00	0.00	0.18	905.25
(SBR#1 EFFLUENT) - BATCH #5							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	5.02	0.15	4.20	3.90	1434.26
		2.00	5.02	0.15	4.20	3.92	1338.65
		3.00	5.02	0.15	4.20	3.91	1386.45
		AVERAGE	5.02	0.15	4.20	3.91	1386.45
		STDEV	0.00	0.00	0.00	0.01	47.81
(SBRs INFFLUENT) - BATCH 6							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.62	0.15	4.20	1.54	12768.00
		2.00	4.62	0.15	4.20	2.50	8160.00
		3.00	4.62	0.15	4.20	2.07	10224.00

		AVERAGE	4.62	0.15	4.20	2.04	10384.00
		STDEV	0.00	0.00	0.00	0.48	2308.16
(SBR#1 EFFLUENT) - BATCH #6							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	3.39	0.15	4.34	4.27	336.00
		2.00	3.39	0.15	4.34	4.23	528.00
		3.00	3.39	0.15	4.34	4.29	240.00
		AVERAGE	3.39	0.15	4.34	4.26	368.00
		STDEV	0.00	0.00	0.00	0.03	146.64
(SBRs INFFLUENT) - BATCH 7							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	3.39	0.15	4.34	2.03	11088.00
		2.00	3.39	0.15	4.34	2.01	11184.00
		3.00	3.39	0.15	4.34	2.37	9456.00
		AVERAGE	3.39	0.15	4.34	2.14	10576.00
		STDEV	0.00	0.00	0.00	0.20	971.14
(SBR#1 EFFLUENT) - BATCH #7							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.62	0.15	4.22	4.10	576.00
		2.00	4.61	0.15	4.22	4.05	816.00
		3.00	4.61	0.15	4.22	4.02	960.00
		AVERAGE	4.61	0.15	4.22	4.06	784.00

		STDEV	0.01	0.00	0.00	0.04	193.99
		VAR	0.00	0.00	0.00	0.00	37632.00
(SBR#1 INFLUENT) - BATCH #8							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.61	0.15	4.22	2.43	8592.00
		2.00	4.61	0.15	4.22	2.36	8928.00
		3.00	4.10	0.15	4.22	2.18	9792.00
		AVERAGE	4.44	0.15	4.22	2.32	9104.00
		STDEV	0.29	0.00	0.00	0.13	619.06
(SBR#1 EFFLUENT) - BATCH #8							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.61	0.15	4.38	4.34	192.00
		2.00	4.61	0.15	4.38	4.36	96.00
		3.00	4.61	0.15	4.38	4.30	384.00
		AVERAGE	4.61	0.15	4.38	4.33	224.00
		STDEV	0.00	0.00	0.00	0.03	146.64
(SBR#1 INFLUENT) - BATCH #9							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.61	0.15	4.38	1.82	12288.00
		2.00	4.61	0.15	4.38	1.69	12912.00

		3.00	4.61	0.15	4.38	1.32	14688.00
		AVERAGE	4.61	0.15	4.38	1.61	13296.00
		STDEV	0.00	0.00	0.00	0.26	1245.23
(SBR#1 EFFLUENT) - BATCH #9							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.61	0.15	2.18	1.54	3072.00
		2.00	4.61	0.15	2.18	1.60	2784.00
		3.00	4.61	0.15	2.18	1.84	1632.00
		AVERAGE	4.61	0.15	2.18	1.66	2496.00
		STDEV	0.00	0.00	0.00	0.16	761.98
(SBR#1 INFLUENT) - BATCH #10							
			VFAS for K2Cr2O7	NFAS	VFAS for blank	VFAS for sample	COD Total
Vsample (mL)	VK2Cr2O7 (mL)	Replicates	(mL)	(M)	(mL)	(mL)	(mg/L)
5.00	3.00	1.00	4.61	0.15	2.18	0.24	9312.00
		2.00	4.61	0.15	2.18	0.28	9120.00
		3.00	4.61	0.15	2.18	0.30	9024.00
		AVERAGE	4.61	0.15	2.18	0.27	9152.00
		STDEV	0.00	0.00	0.00	0.03	146.64

TABLE F5: BOD RAW DATA SHEET

Batch	INFLUENT (mgBOD/L)	OLR (kgBOD/day)	CON SBR1 (mgBOD/L)	CYCLIC SBR2 (mgBOD/L)	CON SBR1 BOD5 %Removal	CYC SBR2 BOD5 %Removal
1	2622	0.0026	372	453	86	83
2	3764	0.0038	1264	2159	66	43
3	2741	0.0027	372	334	86	88
4	2743	0.0027	353	234	87	91
5	3206	0.0032	128	1424	96	56
6	3207	0.0032	388	1782	88	44
7	2383	0.0024	140	567	94	76
8	3086	0.0031	222	839	93	73
9	3032	0.0030	1177	1069	61	65
10	3726	0.0037	1330	2485	64	33
11	3257	0.0033	301	395	91	88
12	3137	0.0031	389	789	88	75
13	2815	0.0028	959	293	66	90
14	2648	0.0026	942	2294	64	13
15	2291	0.0023	795	890	65	61
AVA	**2977**	**0**	**609**	**1067**	**80**	**65**

TABLE F6: BOD SAMPLE CALCULATION SHEETS

Time (Wks.)	Sample ID:	Sample Volume	Influent Measurement (mg/L)	Con SBR1 Measurement (mg/L)	Cyclic SBR2 Measurement(mg/L)
	BWW 1	21.1	2686	357	449
	BWW 2	21.1	2581	360	460
5-Jul-15	BWW 3	21.1	2600	400	451
1	AVERAGE	21.1	2622	372	453
	STDEV	0.0	56	24	6
	BWW 1	21.1	4000	3293	2137
	BWW 2	21.1	3293	3210	2200
10-Jul-15	BWW 3	21.1	4000	3290	2140
2	AVERAGE	21.1	3764	3264	2159
	STDEV	0.0	408	47	36
	BWW 1	21.1	2713	371	330
	BWW 2	21.1	2700	370	340
15-Jul-15	BWW 3	21.1	2810	375	333
3	AVERAGE	21.1	2741	372	334
	STDEV	0.0	60	3	5
	BWW 1	21.1	2713	352	230
	BWW 2	21.1	2715	351	233
20-Jul-15	BWW 3	21.1	2800	356	240
4	AVERAGE	21.1	2743	353	234
	STDEV	0.0	50	3	5
	BWW 1	21.1	3300	127	2461
	BWW 2	21.1	3100	128	2400
25-Jul-15	BWW 3	21.1	3217	128	2410
5	AVERAGE	21.1	3206	128	2424

	STDEV	0.0	100	1	33
	BWW 1	21.1	3261	388	1776
	BWW 2	21.1	3160	387	1770
30-Jul-15	BWW 3	21.1	3200	388	1800
6	AVERAGE	21.1	3207	388	1782
	STDEV	0.0	51	1	16
	BWW 1	21.1	2400	140	560
	BWW 2	21.1	2300	138	580
5-Aug-15	BWW 3	21.1	2450	141	562
7	AVERAGE	21.1	2383	140	567
	STDEV	0.0	76	2	11
	BWW 1	21.1	3108	222	839
	BWW 2	21.1	2950	221	841
10-Aug-15	BWW 3	21.1	3200	224	836
8	AVERAGE	21.1	3086	222	839
	STDEV	0.0	126	2	3
	BWW 1	21.1	3097	2165	1063
	BWW 2	21.1	3100	2200	1065
20-Aug-15	BWW 3	21.1	2900	2166	1080
9	AVERAGE	21.1	3032	2177	1069
	STDEV	0.0	115	20	9
	BWW 1	21.1	3629	3671	2185
	BWW 2	21.1	3800	3468	2796
25-Aug-15	BWW 3	21.1	3750	2851	2475
10	AVERAGE	21.1	3726	3330	2485
	STDEV	0.0	88	427	306
	BWW 1	21.1	3185	300	360
30-Aug-15	BWW 2	21.1	3375	302	460

	BWW 3	21.1	3211	300	366
11	AVERAGE	21.1	3257	301	395
	STDEV	0.0	103	1	56
	BWW 1	21.1	3213	393	756
	BWW 2	21.1	2931	437	810
4-Sep-15	BWW 3	21.1	3268	336	800
12	AVERAGE	21.1	3137	389	789
	STDEV	0.0	181	51	29
	BWW 1	21.1	2705	1904	287
	BWW 2	21.1	2775	2205	262
9-Sep-15	BWW 3	21.1	2966	2069	331
13	AVERAGE	21.1	2815	2059	293
	STDEV	0.0	135	151	35
	BWW 1	21.1	2595	2165	2247
	BWW 2	21.1	2620	2160	2359
14-Sep-15	BWW 3	21.1	2730	2100	2275
14	AVERAGE	21.1	2648	2142	2294
	STDEV	0.0	72	36	58
	BWW 1	21.1	2239	725	837
	BWW 2	21.1	2365	655	949
17-Sep-15	BWW 3	21.1	2270	1006	884
15	AVERAGE	21.1	2291	795	890

TABLE F7: TEMPERATURE AND PH SUMMARYAND RAW DATA SHEETS

pH AND TEMPERAUTE SUMMARY SHEET

Batch No:	Temperature ^{o}C		pH			CONDUCTIVITY (mS/cm)		
	SBR1	SBR2	Infl	SBR1	SBR2	Infl	SBR1	SBR2
1	23	23	10	9	9	8	4	4
2	22	23	7	8	7	8	3	4
3	22	22	6	9	8	8	4	5
4	21	21	6	8	7	5	3	3
5	22	22	8	8	6	9	4	4
6	21	21	6	8	8	5	3	4
7	23	23	6	8	8	8	4	4
8	22	22	8	8	9	9	6	7
9	22	22	5	6	7	8	4	4
10	22	22	7	6	7	5	3	3
11	21	21	7	8	7	8	3	3
12	21	21	7	7	8	6	3	3
13	21	21	6	9	8	8	5	6
14	22	22	6	8	8	5	3	4
15	21	21	4	8	7	8	5	6
AVARAGES:	**22**	**22**	**7**	**8**	**8**	**7**	**4**	**4**

TABLE F8: pH AND TEMPERATURE SAMPLE RAW DATA SHEETS

Date	Sample ID	pH		Average	Standard Dev.	TEMPERATURE °C		Average	Standard Dev.
4-Jul-15	Con SBR1	8.8	8.70	8.8	0.1	22.60	22.7	22.7	0.1
	Cyclic SBR	8.86	8.87	8.9	0.0	22.90	23	23.0	0.1
8-Jul-15	Con SBR1	7.37	8.00	7.7	0.4	21.30	22.8	22.1	1.1
	Cyclic SBR	7	6.92	7.0	0.1	25.40	22.9	24.2	1.8
13-Jul-15	Con SBR1	8.93	8.92	8.9	0.0	21.60	22.6	22.1	0.7
	Cyclic SBR	7.55	7.56	7.6	0.0	21.70	22.6	22.2	0.6
18-Jul-15	Con SBR1	8.05	8.00	8.0	0.0	20.70	21.7	21.2	0.7
	Cyclic SBR	7	7.03	7.0	0.0	20.80	21.8	21.3	0.7
28-Jul-15	Con SBR1	7.98	8	8.0	0.0	22.6	21.2	21.9	1.0
	Cyclic SBR	6.2	6.14	6.2	0.0	22.9	21.2	22.1	1.2
2-Aug-15	Con SBR1	8.4	8.49	8.4	0.1	21.1	21.5	21.3	0.3
	Cyclic SBR	8.1	8.07	8.1	0.0	21.2	21.5	21.4	0.2
13-Aug-15	Con SBR1	8.26	8.3	8.3	0.0	22.7	22.7	22.7	0.0
	Cyclic SBR	8.1	8.11	8.1	0.0	22.8	22.7	22.8	0.1
18-Aug-15	Influent	4.85	4.8	4.8	0.0				
	Con SBR1	6.32	6.33	6.3	0.0	21.4	23.2	22.3	0.6
	Effluent2	7.36	7.32	7.3	0.0	21.3	23.3	22.3	0.6
	Con SBR1	5.66	6	5.8	0.2	22.2	21.7	22.0	1.3

	Cyclic SBR	6.69	6.73	6.7	0.0	22.3	21.6	22.0	1.4
23-Aug-15									
	Con SBR1	8.35	8.34	8.3	0.0	21.2	20	20.6	0.4
	Cyclic SBR	7	7	7.0	0.0	21.2	20.2	20.7	0.5
28-Aug-15									
	Con SBR1	7.1	7	7.1	0.1	21.5	21	21.3	0.8
	Cyclic SBR	8.3	8.25	8.3	0.0	21.4	21.1	21.3	0.7
2-Sep-15									
	Con SBR1	8.6	8.36	8.5	0.2	20.8	21.1	21.0	0.4
	Cyclic SBR	7.7	7.67	7.7	0.0	20.8	21.1	21.0	0.2
7-Sep-15									
	Con SBR1	7.63	7.63	7.6	0.0	20.9	20.8	20.9	0.2
	Cyclic SBR	7.07	7.08	7.1	0.0	20.9	20.8	20.9	0.2
12-Sep-15									
	Con SBR1	7	7.70	7.4	0.5	21.70	19.4	20.6	0.1
	Cyclic SBR	8	8.02	8.0	0.0	21.20	19.4	20.3	0.1

TABLE F9: SUMMARY STUDENT T-TEST CALCULATION SHEETS

COD

t-Test: Two-Sample Assuming Unequal Variances		
	Influent	*SBR1*
Mean	10229.0224	1577.0324
Variance	15689342	324172
Observations	44.0000	44.0000
Hypothesized Mean Difference	1.0000	
df	60.0000	
t Stat	13.1888	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6706	
P(T<=t) two-tail	0.0000	
t Critical two-tail	2.0003	

t-Test: Two-Sample Assuming Unequal Variances		
	SBR1	*SBR2*
Mean	1637.2721	3194.0607
Variance	3314675	851431
Observations	42.0000	42.0000
Hypothesized Mean Difference	0.0000	
Df	69.0000	
t Stat	-2.9335	
P(T<=t) one-tail	0.0023	
t Critical one-tail	1.6672	
P(T<=t) two-tail	0.0045	
t Critical two-tail	1.9949	

t-Test: Two-Sample Assuming Unequal Variances		
	Influent	*SBR2*
Mean	10479.5472	3194.0607
Variance	1501973	851431
Observations	42.0000	42.0000
Hypothesized Mean Difference	0.0000	
df	76.0000	
t Stat	9.7327	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6652	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9917	

BOD

t-Test: Two-Sample Assuming Unequal Variances

	Influent	*SBR1*
Mean	2977.3556	1095.4444
Variance	190925	1294592
Observations	45.0000	45.0000
Hypothesized Mean Difference	0.0000	
df	57.0000	
t Stat	10.3578	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6720	
P(T<=t) two-tail	0.0000	
t Critical two-tail	2.0025	

t-Test: Two-Sample Assuming Unequal Variances

	Influent	*SBR2*
Mean	2977.3556	1133.8889
Variance	190925	690856
Observations	45.0000	45.0000
Hypothesized Mean Difference	0.0000	
Df	67.0000	
t Stat	13.1692	
P(T<=t) one-tail	0.0000	
t Critical one-tail	1.6679	
P(T<=t) two-tail	0.0000	
t Critical two-tail	1.9960	

t-Test: Two-Sample Assuming Unequal Variances

	SBR1	*SBR2*
Mean	1095.4444	1133.8889
Variance	1294592	690856
Observations	45.0000	45.0000
Hypothesized Mean Difference	0.0000	
df	81.0000	
t Stat	-0.1830	
P(T<=t) one-tail	0.4276	
t Critical one-tail	1.6639	
P(T<=t) two-tail	0.8552	
t Critical two-tail	1.9897	

TOTAL SOLIDS

t-Test: Two-Sample Assuming Unequal Variances

	influent	*SBR1*
Mean	0.0092	0.0080
Variance	0.0003	0.0002
Observations	48.0000	48.0000
Hypothesized Mean Difference	0.0000	
df	87.0000	
t Stat	0.3940	
P(T<=t) one-tail	0.3473	
t Critical one-tail	1.6626	
P(T<=t) two-tail	0.6945	
t Critical two-tail	1.9876	

t-Test: Two-Sample Assuming Unequal Variances

	influent	*SBR2*
Mean	0.0092	0.0086
Variance	0.0003	0.0002
Observations	48.0000	48.0000
Hypothesized Mean Difference	0.0000	
Df	86.0000	
t Stat	0.2096	
P(T<=t) one-tail	0.4172	
t Critical one-tail	1.6628	
P(T<=t) two-tail	0.8345	
t Critical two-tail	1.9879	

t-Test: Two-Sample Assuming Unequal Variances

	SBR1	*SBR2*
Mean	0.0080	0.0086
Variance	0.0002	0.0002
Observations	48.0000	48.0000
Hypothesized Mean Difference	0.0000	
df	94.0000	
t Stat	-0.2218	
P(T<=t) one-tail	0.4125	
t Critical one-tail	1.6612	
P(T<=t) two-tail	0.8250	
t Critical two-tail	1.9855	

VOLITILE SOLIDS

t-Test: Two-Sample Assuming Unequal Variances

	influent	*SBR1*
Mean	0.0068	0.0064
Variance	0.0003	0.0003
Observations	48.0000	48.0000
Hypothesized Mean Difference	0.0000	
df	94.0000	
t Stat	0.1104	
P(T<=t) one-tail	0.4562	
t Critical one-tail	1.6612	
P(T<=t) two-tail	0.9123	
t Critical two-tail	1.9855	

t-Test: Two-Sample Assuming Unequal Variances

	influent	*SBR2*
Mean	0.0068	0.0052
Variance	0.0003	0.0001
Observations	48.0000	48.0000
Hypothesized Mean Difference	0.0000	
Df	79.0000	
t Stat	0.5573	
P(T<=t) one-tail	0.2895	
t Critical one-tail	1.6644	
P(T<=t) two-tail	0.5789	
t Critical two-tail	1.9905	

t-Test: Two-Sample Assuming Unequal Variances

	SBR1	*SBR2*
Mean	0.0064	0.0052
Variance	0.0003	0.0001
Observations	48.0000	48.0000
Hypothesized Mean Difference	0.0000	
df	78.0000	
t Stat	0.4166	
P(T<=t) one-tail	0.3391	
t Critical one-tail	1.6646	
P(T<=t) two-tail	0.6781	
t Critical two-tail	1.9908	

TSS

t-Test: Two-Sample Assuming Unequal Variances

	Influent	*SBR1*
Mean	0.1532	0.1330
Variance	0.0310	0.0252
Observations	42.0000	42.0000
Hypothesized Mean Difference	0.0000	
df	81.0000	
t Stat	0.5532	
P(T<=t) one-tail	0.2908	
t Critical one-tail	1.6639	
P(T<=t) two-tail	0.5817	
t Critical two-tail	1.9897	

t-Test: Two-Sample Assuming Unequal Variances

	Influent	*SBR2*
Mean	0.1532	0.1410
Variance	0.0310	0.0675
Observations	42.0000	42.0000
Hypothesized Mean Difference	0.0000	
Df	72.0000	
t Stat	0.2523	
P(T<=t) one-tail	0.4008	
t Critical one-tail	1.6663	
P(T<=t) two-tail	0.8015	
t Critical two-tail	1.9935	

t-Test: Two-Sample Assuming Unequal Variances

	SBR1	*SBR2*
Mean	0.1330	0.1410
Variance	0.0252	0.0675
Observations	42.0000	42.0000
Hypothesized Mean Difference	0.0000	
df	68.0000	
t Stat	-0.1705	
P(T<=t) one-tail	0.4326	
t Critical one-tail	1.6676	
P(T<=t) two-tail	0.8651	
t Critical two-tail	1.9955	

TURBIDITY

t-Test: Two-Sample Assuming Unequal Variances

	Infl	*SBR1*
Mean	168.8214	90.3000
Variance	10735	5252
Observations	14.0000	14.0000
Hypothesized Mean Difference	0.0000	
df	23.0000	
t Stat	2.3236	
P(T<=t) one-tail	0.0147	
t Critical one-tail	1.7139	
P(T<=t) two-tail	0.0293	
t Critical two-tail	2.0687	

t-Test: Two-Sample Assuming Unequal Variances

	Infl	*SBR2*
Mean	168.8214	106.7786
Variance	10735	5709
Observations	14.0000	14.0000
Hypothesized Mean Difference	0.0000	
Df	24.0000	
t Stat	1.8103	
P(T<=t) one-tail	0.0414	
t Critical one-tail	1.7109	
P(T<=t) two-tail	0.0828	
t Critical two-tail	2.0639	

t-Test: Two-Sample Assuming Unequal Variances

	SBR1	*SBR2*
Mean	90.3000	106.7786
Variance	5252	5709
Observations	14.0000	14.0000
Hypothesized Mean Difference	0.0000	
df	26.0000	
t Stat	-0.5889	
P(T<=t) one-tail	0.2805	
t Critical one-tail	1.7056	
P(T<=t) two-tail	0.5610	
t Critical two-tail	2.0555	

CONDUCTIVITY

t-Test: Two-Sample Assuming Unequal Variances

	Infl	*SBR1*
Mean	525.5286	473.8286
Variance	944839	875464
Observations	14.0000	14.0000
Hypothesized Mean Difference	0.0000	
df	26.0000	
t Stat	0.1434	
P(T<=t) one-tail	0.4435	
t Critical one-tail	1.7056	
P(T<=t) two-tail	0.8871	
t Critical two-tail	2.0555	

t-Test: Two-Sample Assuming Unequal Variances

	Infl	*SBR2*
Mean	525.5286	449.2286
Variance	944839	794008
Observations	14.0000	14.0000
Hypothesized Mean Difference	0.0000	
Df	26.0000	
t Stat	0.2165	
P(T<=t) one-tail	0.4151	
t Critical one-tail	1.7056	
P(T<=t) two-tail	0.8303	
t Critical two-tail	2.0555	

t-Test: Two-Sample Assuming Unequal Variances

	SBR1	*SBR2*
Mean	473.8286	449.2286
Variance	875464	794008
Observations	14.0000	14.0000
Hypothesized Mean Difference	0.0000	
df	26.0000	
t Stat	0.0712	
P(T<=t) one-tail	0.4719	
t Critical one-tail	1.7056	
P(T<=t) two-tail	0.9438	
t Critical two-tail	2.0555	

APPENDIX G

STATISTICAL ANALYSIS TOOLS USED FOR DATA ANALYSIS ON ALL RESEARCH PARAMETERS

G1. STANDARD DEVIATION

This function is reported to estimate the standard deviation based on sample. According to statistical theory, the standard deviation (SD) is a measure that is to quantify the amount to be very close to the mean, normally referred to as accepted value of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values. Moreover, as previously mentioned, with regard to expressing the variability of a population, the standard deviation is commonly used to measure confidence in statistical conclusions (Mankiewicz, 2000).

$$\text{Standard deviation} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - x)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Where:

x_i is a value of the analysis data

n is the number of observations of data (n = 2)

x is the average of the analysis data

G2. MEAN VALUES

According to descriptive statistics, the mean of a set of observation is the arithmetic average of the values. However, for skewed distribution, the mean is not the same as the middle value. For example, mean income is typically skewed upwards by a small number of people with very large incomes, so that the majority has an income lower than the mean. In general, it is used synonymously to refer to one measure of the central tendency either of probability distributions or of the random variable characterised by that distribution (Mankiewicz, 2000).

$$\text{Average} = \frac{1}{n}\sum_{i=1}^{n} x_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

G3. VARIANCE

In statistics, the variance measures how far a set of numbers is spread out. A variance of zero indicates that all the values are identical. Variance is always non-negative. A small variance indicates that the data points tend to be very close to the mean (expected value). While a higher variance indicates the data points are very sparsely spread apart out around the mean and from each other (Mankiewicz, 2000).

$$\text{Variance} = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - x)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

G4. COEFFICIENT OF VARIATION

According to statistical terms, the coefficient of variation (CV), also known as a relative standard deviation (RSD), is a standardised measure of dispersion of probability distribution of frequency. It is often expressed as a percentage and is defined as the ratio of the standard deviation on the mean value. The CV or RSD is widely used in analytical chemistry to express the precision and repeatability of the assay. It is commonly used in fields such as engineering when doing quality assurance on research and development (Mankiewicz, 2000).

$$\text{CV} = \frac{\text{standard deviation}}{\text{Mean}} = \left[\sigma/\mu\right] = \text{Coeffieicnt of variation} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

CV does not have a meaning for data on an interval scale, like temperature values, which tend to be negative at some readings. CV is basically relevant as a measure of relative variability.

G5. STUDENT'S T-TEST ANALYSIS WITH UNEQUAL VARIANCES

The t-test was first established by William Sealy Gosset in 1908. This analysis has been widely reported for its many uses. In this present study, it has been adapted in a number of significance analyses to determine the effect of aeration configuration on the removal of high-strength organic pollutants from the brewery wastewater substrate. A test of the null hypothesis that is the difference

between two responses on the same statistical unit has a mean of zero. For example, the measure of size of a cancer patient's tumour before and after a treatment is effective; we expect the tumour size for many of the patients to be smaller following the treatment. This is often referred to as the 'paired' or 'repeated measure' t-test. Explicit expressions that can be used to carry out various t-tests are given below in the next sections. The standard t-test formulas follow exciting or closely approximately a distribution under the null hypothesis is given. Each statistic can be used to carry out one-tailed or two-tailed tests. Once a t-test value is determined, a p-value can be found using a table of values for started t-distribution. If the calculated p-value is below the threshold chosen for statistical significance (usually 0.1 ; 0.05 or 0.01), the null hypothesis is rejected in favour of the alternative hypothesis (Mankiewicz, 2000).

G6. SPSS (STATISTICAL PACKAGE FOR SOCIAL SCIENCES) FOR CORRELATION ANALYSIS

SPSS Statistics is a software package used for statistical analysis. Long produced by SPSS Inc., it was acquired by IBM in 2009. The 2015 version is named IBM SPSS Statistics. It was originally named Statistical Package for the Social Sciences (SPSS), reflecting the original market, although the software is now popular in other fields as well, including the health sciences and marketing. The statistics included in the base software are as follows:

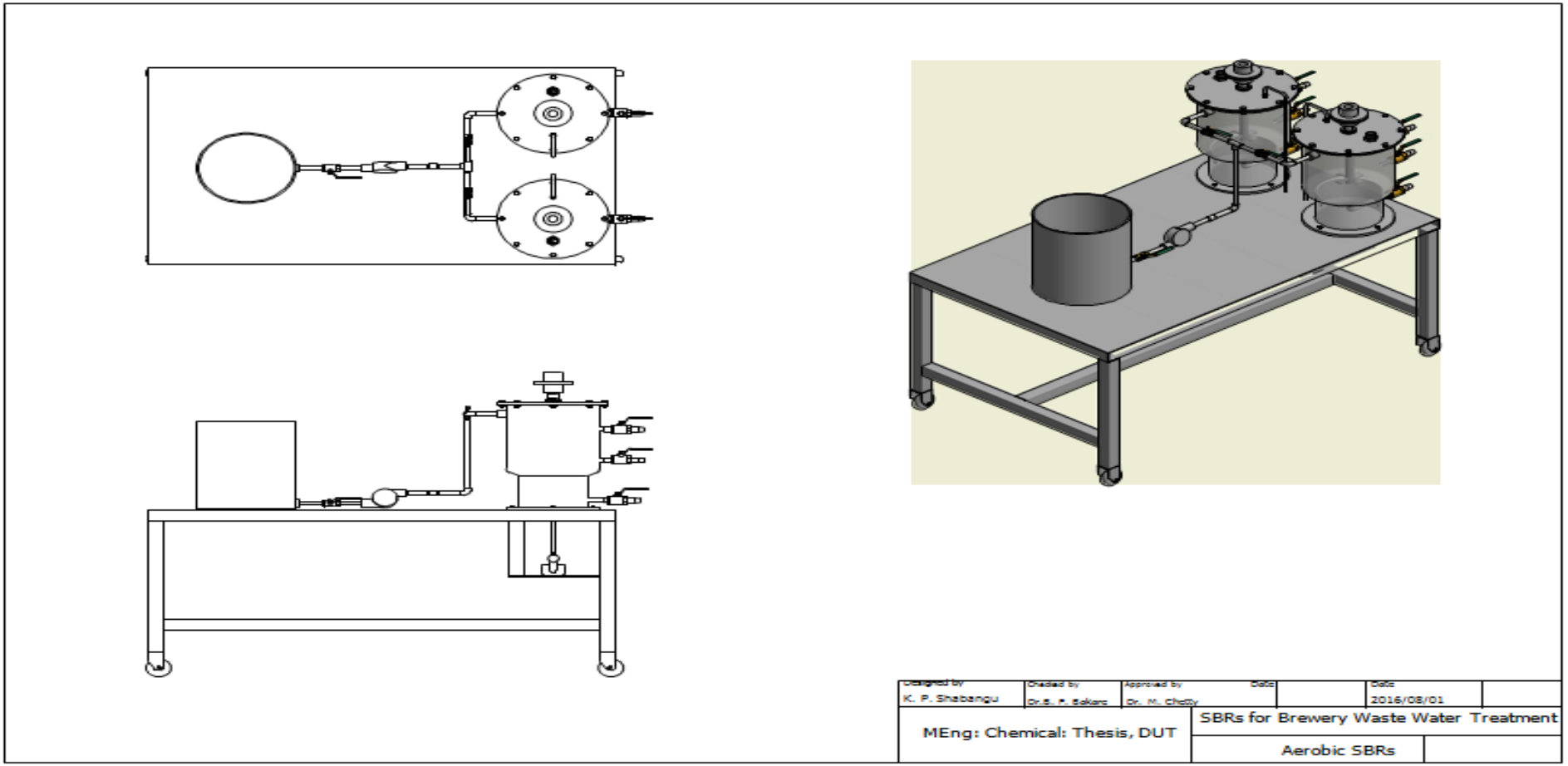
i. Descriptive statistics: Cross tabulation, Frequencies, Descriptive, Explore, Descriptive ratio Statistics.
ii. Bivariate statistics: Means, t-test, ANOVA, Correlation (bivariate, partial, distances), nonparametric tests.
iii. Prediction for numerical outcomes: Linear regression.
iv. Prediction for identifying groups: Factor analysis, cluster analysis (two-step, K-means, hierarchical), discriminants.

The many features of SPSS statistics are accessible via pull-down menus. Command syntax programming has the benefits of reproducibility, simplifying repetitive tasks, and handling complex data manipulations and analyses. Additionally, a micro language can be used to command language subroutines. A Python programmability extension can access the information in the data dictionary and dynamically build command syntax programs. The graphical user interface has two views: the data view and the variable view. The data view displays a spread sheet view of cases and variables. The variable view shows the metadata dictionary, where each row represents a variable and shows the variable name. SPSS can read and write data from ASCII text files, other statistics packages,

and spread sheets and databases. This statistics tool was implemented in this research study to predict the correlation coefficients attained from the removal of the high-strength biological organics in the form of stream removal efficiencies. This data was also interpreted in the form of relevant scatter plots and linear regression and relevant empirical models generated from the correlation coefficients for each performance monitoring parameter.

APPENDIX H

SBR DESIGN ORTHOGRAPHIC PICTURES AND OPERATIONAL VIEWS DURING EXPERIMENTATION



FigureH1: SBRs isometric view.

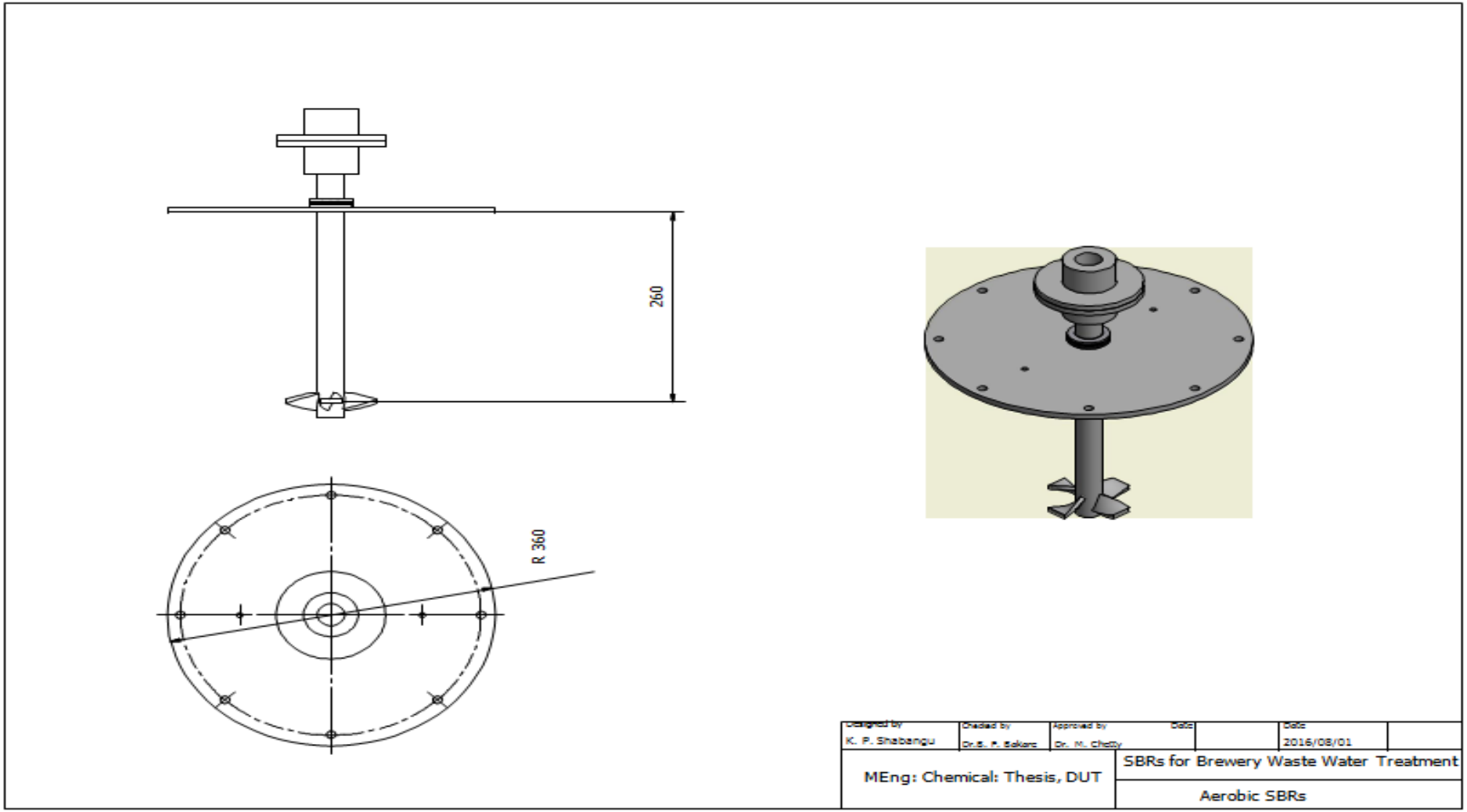


Figure H2: Stirrer isometric view.

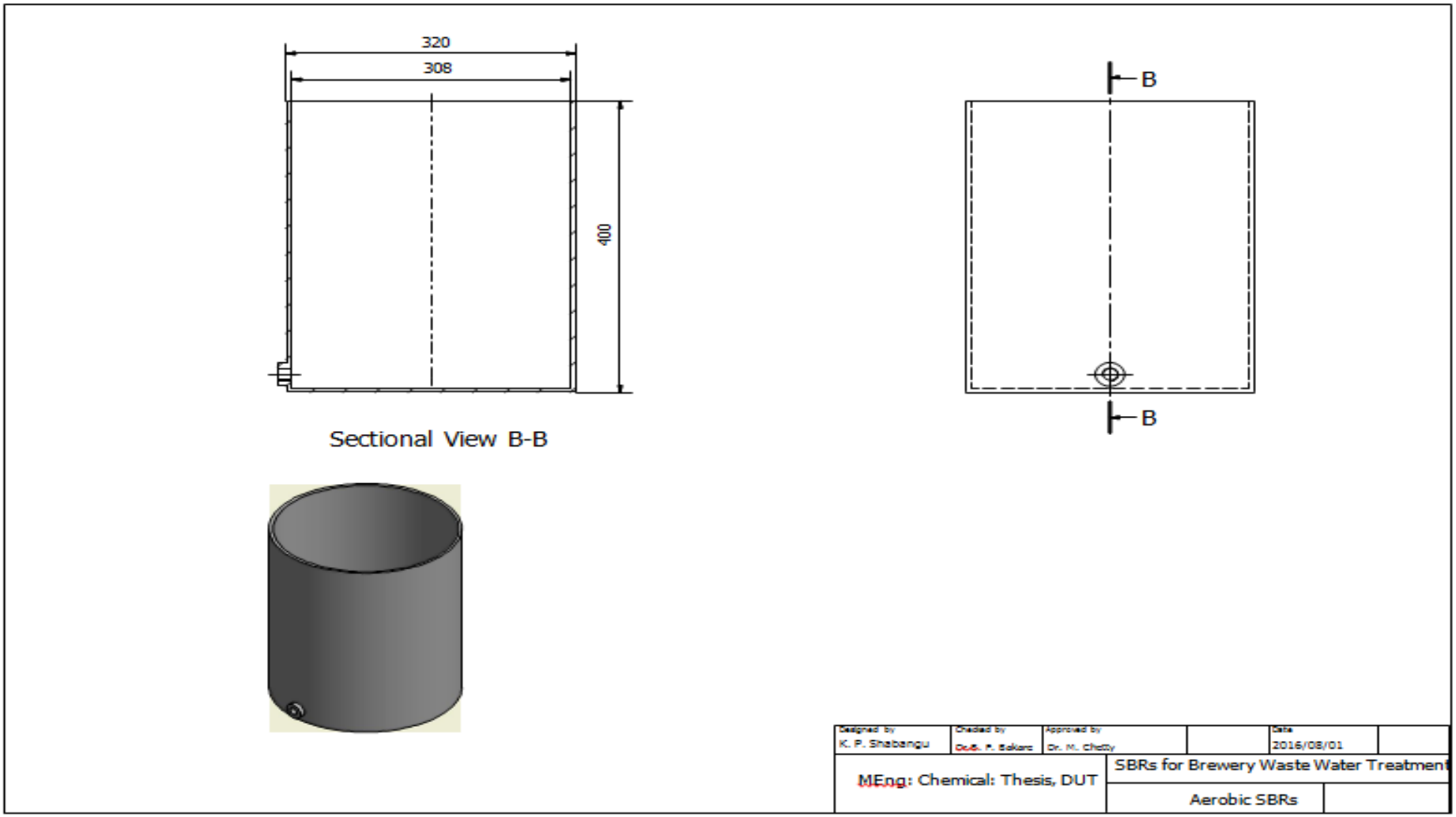


Figure H3: Equalization Tank cross-sectional and isometric view.

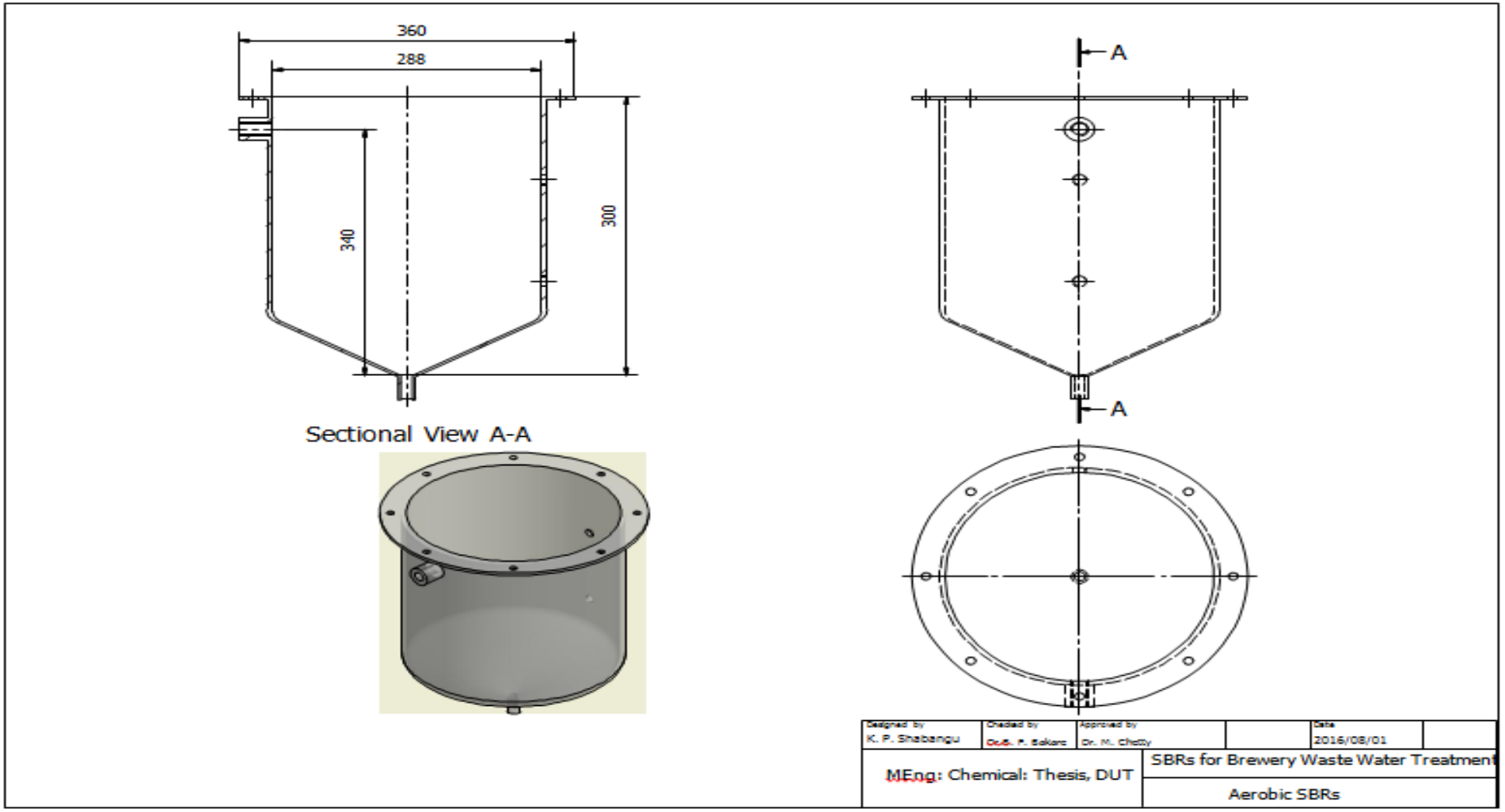


Figure H4: SBRs cross-sectional and isometric view.

Figure H5: Sectional views of the aerobic sequencing batch reactors.

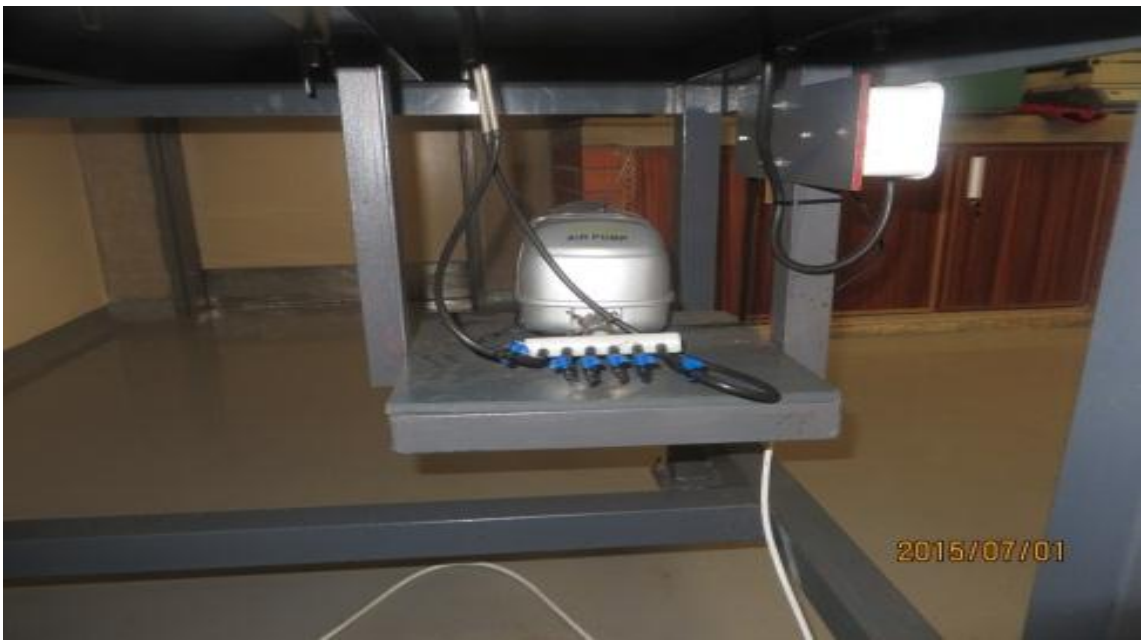


Figure H6: Air pump for continuous and cyclic aeration schemes.

Figure H7: COD FoodALYT Digester experimental apparatus.

Figure H8: SBR operational phases; (i) filling (ii) mix and react (iii) settling (iv) sampling or draw (v) idling phase and (vi) acclamatization process