



Evaluation of a data-driven primary sedimentation tank model using settleometer data

By

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ABSTRACT

Data-driven primary sedimentation (or settling) tank (DDPST) model was recently developed to improve the existing primary sedimentation (or settling) tank (PST) models which are largely total suspended solids (TSS) based. The purpose of the DDPST model is to realistically simulate the full-scale PST (FS-PST) underflow and overflow outputs in terms of biodegradable particulate organics (BPO), unbiodegradable particulate organics (UPO), and inorganic suspended solids (ISS) compositions. This characterization is fundamental to the planning of the downstream resource recovery systems such as anaerobic digestion (AD) and activated sludge (AS) systems through accurate process predictions.

The DDPST model was previously subjected to rigorous mass balance verifications and has undergone a general sensitivity analysis (GSA) to identify the most important parameters required to allow the accurate predictions. The settling velocities and settling proportions of the five particle settling velocity groups (SVGs) were identified as significant. These five SVGs are characterized by different proportions of settleable BPO (BPOset), settleable UPO (UPOset) and settleable ISS (ISetS). Due to variability in wastewater (WW) characteristics from plant to plant, the DDPST model requires settleability data that is specific to a plant to make correct predictions. A five-column settleometer (5C-settleometer) has been proposed as a tool that can provide this necessary data. Essentially, the 5C-settleometer is regarded a lab-scale PST that allows detailed study of the FS-PST critical parameters through segregation of settleable TSS into five different SVGs. Along with the Augment Biomethane Potential (AugBMP) test procedure and parameter estimation tools, the particles from the SVGs can be fractionated into BPOset, UPOset, and ISetS. To this date, however, the accurateness of the 5C-settleometer to provide accurate FS-PST settleability characteristics has not been confirmed. This implies that the 5C-settleometer, as a suggested tool to provide the necessary data, cannot be used with confidence, and so is the DDPST model.

The purpose of this study was to evaluate the DDPST model through comprehensive characterization of the primary sewage sludge (PSS). To achieve this, the ability of the 5C-settleometer to accurately characterize the PSS in terms of settling velocities and settling proportions was verified. This was done by collecting the FS-PST influent, underflow, and overflow diurnal data in parallel with the 5C-settleometer test runs at the Bellville Wastewater Treatment Works (WWTWs). Using the FS-PST diurnal data, the related percentage removals for settleable solids (in terms of BPOset, UPOset, and ISetS) were determined. Using the 5C-settleometer characterized PSS outputs, the parameters required to run the DDPST model (i.e., five settling

velocity groups and their corresponding BPOset, UPOset, and ISetS settling proportions) were determined to allow the PST underflow and overflow model predictions. Following this, the PST percentage removals (underflow) and overflow characteristics from (i) the DDPST model, and (ii) the FS-PST, were compared to confirm whether the model predictions fully replicate the FS-PST. Important to note is that both the FS-PST and the 5C-settleometer received the same influent characteristics to ensure that the settleometer overflow and underflow are reasonably compared with the FS-PST to check the representativeness.

While the 5C-settleometer has proven (i) the ability to segregate the particles into distinguishable particle sizes, and (ii) the ability to somewhat account for the overall removal proportions that are comparable to the FS-PST at a flow rate fluctuating between 0.6 and 0.8 l/min, its relationship with the DDPST model needs to be reassessed. The settleometer upflow velocities appeared to be too high to allow accurate model predictions. Unfortunately, it is impossible to achieve very low velocities to fulfil the DDPST model requirements with the current settleometer design. This shortfall on the model to represent the 5C-settleometer makes it impossible to yield reasonable predictions. This gap requires to be addressed to ensure that the 5C-settleometer, as a lab-scale version of the FS-PST, is correctly translated into the DDPST model, not only in terms of the upflow velocities which govern the particle settling, but also, the accompanying settleometer features which affects the particle or flow movements, i.e., (i) the occurrence of sharp bends or curvatures in a 5C-settleometer, or (ii) the increased probability of inter-particle forces especially when operating the settleometer at low flow rates. While it may be a challenge to model these interfering instances, it is essential that they are accounted for in the model to ensure accurate DDPST model predictions.

It is further recommended to explore ways to improve the operation of the current settleometer. For instance, investing in a higher capacity pump and a settleometer flow meter will, with no doubt, add a benefit to the quality of the settleometer output data. In addition, the use of multiple settleometer runs with a combination of high and low flow rates can be explored, to achieve exceptionally representative FS-PST data.

In terms of the elemental compositions (EMs), the five SVGs showed a marginally varied BPOset and UPOset compositions. This could be the result of particulate material differences between the SVGs. Nonetheless, the average BPO and UPO compositions recorded in terms of $C_xH_yO_zN_aP_b$ are $C_{1.5}H_{5.99}O_{1.13}N_{0.05}P_{0.00}$ and $C_{1.79}H_{1.79}O_{0.45}N_{0.22}P_{0.02}$, respectively. The subscript “Y” (i.e., 5.99) of the BPO composition marginally differs from what has already been reported on literature. This

difference could be linked to (i) the discrepancies related to the carbon measurements experimentally (carbon is calculated from biogas measurement and alkalinity), and (ii) the source of Bellville WW, i.e., Bellville WWTWs receives both domestic and industrial WW. Overall, the ISetS (76.7%) and UPOset (78.1%) were found to be removed in greater proportions than BPOset (37.7%) in the FS-PST.

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LIST OF ABBREVIATIONS AND ACRONYMS

5C-Settleometer	Five-column settleometer
A/B chemistry	Acid/base chemistry
AD	Anaerobic digestion
A_{pvcn}	Internal area for any of the PVC columns (m^2)
ASS	Activated sludge system
AugBMP test	Augmented biomethane potential test
BMP test	Biomethane potential test
BO	Biodegradable organics
BPO	Biodegradable particulate organics
BPO_{biomass}	BPO conserved in biomass
BPOCOD	Biodegradable particulate organics COD (denoted as S_{bpi})
BPOset	Settleable BPO
BPOVSS	Biodegradable particulate organics VSS (denoted as VSS_{bpi})
BR	Batch reactor
BSO	Biodegradable soluble organics
BSR	Biological sulphate reduction
CO₂	Carbon dioxide
COD	Chemical oxygen demand
COD_{end}	COD concentrations at the end of AugBMP test experiment
CODset	Settleable particulate COD
COD_{start}	COD concentrations at the start of AugBMP test experiment
DDPST	Data-driven PST model
DPS	Discrete particle settling
EC	Electric conductivity
FAS	Ferrous ammonium sulphate
FBSO	Fermentable biodegradable soluble organics
FSA	Free and saline ammonia
FS-PST	Full-scale primary sedimentation tank
g	Grams
GSA	Global sensitivity analysis
H₂CO₃* alkalinity	Hydrogen carbonate alkalinity (carbonic acid)
HRT	Hydraulic retention time
ISetS	Inorganic settleable solids
ISovS	Inorganic settled solids (Overflow solids)
ISS	Inorganic suspended solids
IWA ADM1	International Water Association Anaerobic Digestion Model 1
l/min	Litre per minute
m/hr	meter per hour

m³/min	Cubic meter per minute
mg	Milligrams
mg/l	Milligrams per litre
MLISS	Mixed liquor inorganic suspended solids
MLSS	Mixed liquor suspended solids
MLTSS	Mixed liquor total suspended solids
MLVSS	Mixed liquor volatile suspended solids
mm	Millimeter
N	Nitrogen
ND	Nitrification-denitrification
NDEBPR	Nitrification-denitrification Excess Biological Phosphorus Removal
OFM	Open flux method
OP	Orthophosphate
P	Phosphorus
PAD	Parent anaerobic digestion
PAO	Polyphosphate Accumulating Organisms
PE	Parameter estimation
pH	Hydrogen power
PP	Polyphosphate
PS BPO	primary sludge biodegradable particulate organics
PSS	Primary sewage sludge
PST	Primary sedimentation tank
PSVD	Particle settling velocity distribution
PVC	Polyvinyl chloride
PVCn	n th Polyvinyl chloride column
PWM_SA	Plant-wide model of South Africa
Q_{5SET}	5-column settleometer flow rate
Q_{5SET,eff}	Effluent flow from the 5C-settleometer
Q_{5SET,inf}	5-column settleometer influent flow rate
Q_{inf} or Q_I	Influent flow rate in l/min
Q_{PST,inf}	Primary settling tank influent flow rate
Q_{PST,R}	Primary settling tank recycle flow rate
R_{hn,5SET}	Hydraulic retention time in a 5-column settleometer
R_{hn,pst}	Hydraulic retention time in a primary settling tank
R_s	Sludge age
SD (σ)	Standard deviation
SOP	Standard Operating Procedure
SS	Steady state
SST	Secondary sedimentary solids
S-SVG	Substrate settling velocity group
SVG	Settling velocity group

SVG_n	n^{th} Settling velocity group
SVG_n	n^{th} Settling velocity group
Temp	Temperature
TeR	Test run
TeR1	Test run 1
TeR2	Test run 2
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphate
TPOCOD	Total particulate organics COD (denoted as S_{upi})
TrR	Trial run
TrR1	Trial run 1
TrR2	Trial run 2
TSetS	Total settleable solids
TSovS	Total settled solids (Overflow solids)
TSS	Total suspended solids
T-SVG	Settling velocity group AugBMP test reactor
UASB	Upflow anaerobic sludge blanket
UCT	University of Cape Town
UCT WQL	University of Cape Town Water Quality Laboratory
UCTADM1	University of Cape Town Anaerobic Digestion Model no 1
UCTADM-3P	Three-phase University of Cape Town Anaerobic Digestion Model no 1
UCTPSU	University of Cape Town Primary Sedimentation Unit
UO	Unbiodegradable organics
UPO	Unbiodegradable particulate organics
UPOCOD	Unbiodegradable particulate organics COD (denoted as S_{upi})
UPOset	Settleable UPO
UPOVSS	Unbiodegradable particulate organics VSS (denoted as VSS_{upi})
USO	Unbiodegradable soluble organic
USO	Unbiodegradable soluble organics
V_{5SET}	5-column settleometer total volume
VFA	Volatile fatty acids
ViCAs	Vittesses de Chute en Assainissement solid settling protocol
V_{PST}	Primary settling tank volume
VSetS	Volatile settleable solids
VSovS	Volatile settled solids (Overflow solids)
VSS	Volatile suspended solids
V_{UP}	Upflow velocity
WAS	Wastes Activated Sludge
WQL	Water Quality Laboratory
WRRF	Water resource recovery facility
WW	Wastewater

WWTP	Wastewater treatment plant
WWTWs	Wastewater treatment works

CHAPTER 1:

INTRODUCTION

Chapter 1: Introduction

1.1. Background to the problem

Some of the world's common issues, including climate change (Scovronick *et al.*, 2017), energy demands (Imasiku & Ntagwirumugara, 2020), water scarcity (Okello *et al.*, 2015), and depletion of phosphate rock reservoirs (fertilizer for agriculture) (Samreen & Kausar, 2019: 90), emanate from the continuous population growth, which enhances (i) the increase in waste production, and (ii) the over-utilisation of natural resource reserves. In the context of wastewater treatment plants (WWTPs), these issues call for advancement towards water resource recovery facilities (WRRFs). The effectiveness of the WRRFs is dependent on the level of sophistication of the governing technologies. Studies conducted by Kehrein *et al.* (2020) and Jafarinejad (2020) on WWTP existing technologies revealed that more work still needs to be done to ensure the successful shift towards WRRFs. The gap between the existing technologies and need to shift towards more sustainable systems make the subject of the present study not only interesting, but highly imperative.

The benefits associated with WRRFs are greatly improved when treating the municipal wastewater (WW) as settled WW rather than raw WW. The settled WW system configuration differs from that of the raw WW system given that it includes a primary sedimentation tank (PST). As illustrated in **Figure 1.1**, the PST marks the first treatment stage in a WWTP, after the preliminary treatment stage, and represent the primary focus for the present study. The PST is primarily designed to physically separate the settleable solids from the raw WW via gravitational settling processes. Jover-Smet *et al.* (2017: 5) affirm that the settleability patterns within PSTs are governed by particulate' size and density relationships with the liquid medium. Solid particles denser than the liquid accumulates at the bottom of the PST forming the primary sewage sludge (PSS), while the remaining supernatant, also referred to as settled WW (with no settleable solids), progresses to the secondary treatment stage. Ikumi (2011: 16) citing Marais and Ekama (1976), suggests that the PSTs have a potential to remove approximately 80% of the settleable matter present in raw WW, which usually comprises approximately 40% of the total chemical oxygen demand (COD) and 45% of the total solids of the influent. The author further mentions that removing the settleable organics from the PST yields benefits, namely the decrease in the required bioreactor size and WWTP's energy demand. These appreciable benefits are reasons to rather treat municipal WW in a settled WW configuration.

The primary sewage sludge, defined as the PST underflow output, is usually fed into an anaerobic digestion (AD) system to recover energy (in the form of biogas) and nutrients (specifically nitrogen and phosphorus) (Flores-Alsina *et al.*, 2019). The effectiveness of an AD system is dependent on the feed compositional characteristics. Using PSS as a feed, the principal compositional characteristics are those of the total settleable solids (TSetS), namely, the inorganic settleable solids (ISetS), settleable biodegradable particulate organics (BPOset) and settleable unbiodegradable particulate organics (UPOset), where the sum of the BPOset and UPOset equals the volatile settleable solids (VSetS). Duan *et al.* (2016) studied the impact of the volatile suspended solids (VSS) to total suspended solids (TSS) ratio (VSS/TSS) on the performance of an AD system and discovered that the changes in the ratio have potential effects on the system's internal processes. For instance, the anaerobic digestion of the PSS containing a high ISetS concentration results in a low VSetS/TSetS ratio, and consequently; reduces the biogas yield. The lack of knowledge on the PST underflow characteristics implies the lack knowledge of the PST overflow (also known as settled wastewater) characteristics. The settled wastewater flows into the activated sludge system (ASS) for the biological treatment towards generating a safe effluent quality; therefore, a poor knowledge of the PST overflow characteristics can result in inaccurate predictions of the overall WWTP performance and final effluent quality. Hence, the need to accurately characterize the PST components as a source of input into the proceeding WRRF units.

The current PST models, being fundamental to predicting the full-scale PST (FS-PST) outcomes, lack the ability to fully characterize the PSS, and they have received minimal attention to date. In response, Polorigni *et al.* (2021) expanded the University of Cape Town Primary Sedimentation Unit (UCTPSU) model by implementing a discrete particle settling (DPS) model, which adopts the particle settling velocity distribution (PSVD) concept by Bachis *et al.* (2015). The expanded UCTPSU model, also referred to as the data-driven PST (DDPST) model, aims to virtually replicate a given FS-PST in terms of BPO, UPO, and ISS removals and overflow. To make predictions, the model requires plant specific settling data. This is due to raw wastewater characteristics varying from plant to plant depending on several factors, including wastewater such as source, geographic location, and population dietary considerations. A settleometer, initially developed by Poinapen (2008) to measure the settleability of particulates in an upflow anaerobic sludge bed (UASB), has been identified as an effective tool to provide the DDPST model with the required solids' settleability data. Essentially, the settleometer acts as a tool between the FS-PST and DDPST model. This implies that the success of the model is dependent on the ability of the settleometer to produce accurate data. The settleometer can also be regarded a lab-scale PST given that it gives an

opportunity to study in detail the FS-PST critical parameters. To this date, however, the accurateness of the settleometer to produce reliable data as input to the DDPST model has not been evaluated against a real FS-PST unit. As a result, the DDPST model cannot, yet, be used with required confidence.

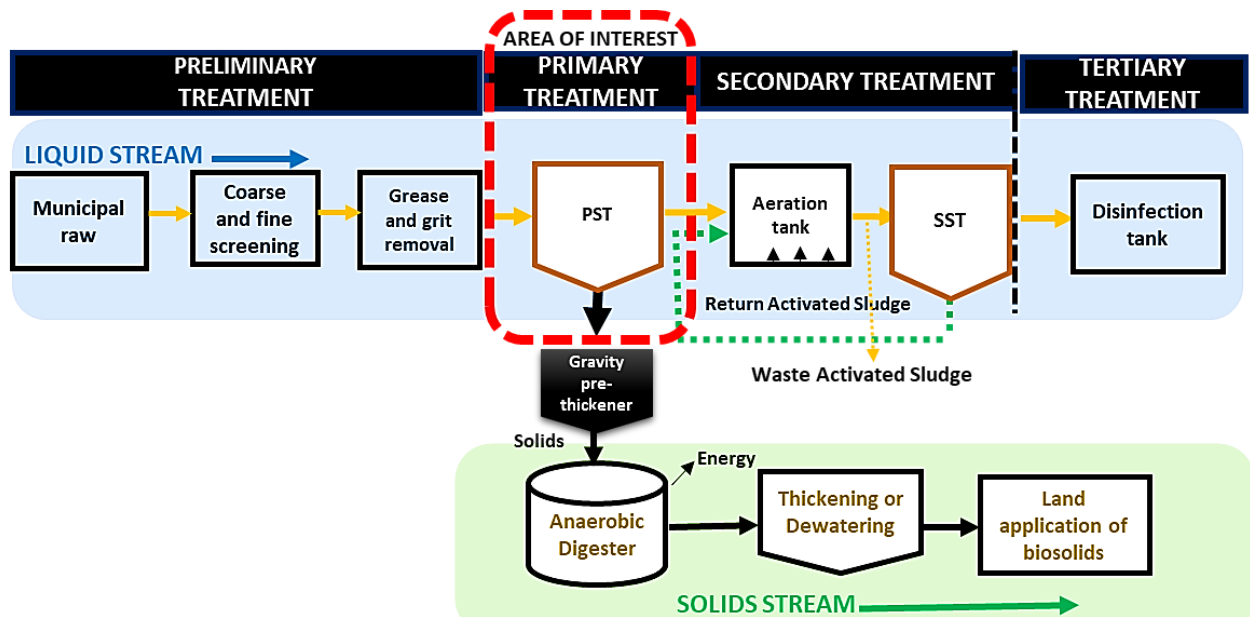


Figure 1.1: The schematic of the WWT process showing the area of interest surrounded by the red border

1.2. Research questions and hypothesis

This research seeks to verify the effectiveness of the settleometer as a primary data-generation tool towards validating the data-driven PST model. The following research questions are posed:

- How accurately can the settleometer separate the raw WW settleable solids into different SVGs? Is it an accurate representation of a real FS-PST unit?
- Will the settleometer alongside the biodegradability test method known as Augmented Biomethane Potential test by Gaszynski (2020) be effective for improving the DDPST model?
- If the DDPST model is not a good representation of the real FS-PST, what could be identified as the limiting requirement to improve the DDPST model predictions? Is this possibly:
 - The settleometer flow rates?
 - The settleometer design?
 - The model itself?
- How best to provide modifications to ensure that the identified limitations are addressed?

Poinapen *et al.* (2015) hypothesized that the settleometer is the best instrument to segregate particulate matter into different SVGs. From this hypothesis, it is assumed that the settleometer has a potential to generate data that replicates the settleability patterns of a FS-PST. The FS-PST accurate representation by the settleometer could mean that the DDPST model can potentially replicate the FS-PST accurately.

1.3. Goals and objectives

The primary goal of this present study is to evaluate the DDPST model by verifying the accuracy of the settleometer to mimic the settleability patterns of the FS-PST unit. To successfully achieve this, the following objectives are established:

- a. Carry out the settleometer runs to segregate the raw WW settleable organics into five different SVGs.
- b. Use the segregated sludge matter from the settleometer to run the biodegradability tests using the AugBMP test method to distinguish between the BPOset and UPOset proportions of the VSetS.
- c. Use a steady-state AD model, together with parameter estimation (PE) tools to reconcile errors between the experimentally data, such that (i) the BPOset, UPOset, and ISetS settling proportions, and (ii) the corresponding BPOset and UPOset elemental compositions (ECs) of the segregated sludge matter are accurately determined.
- d. Use the BPOset, UPOset and ISetS settling velocities and settling proportions from the settleometer (alongside AugBMP test) to run simulations on the DDPST model to predict the FS-PST outputs in terms of percentage removals and overflow characteristics.
- e. Carry out raw WW influent, underflow, and overflow composite sampling from a FS-PST at 2-hour intervals for 24 hours in parallel with the settleometer runs. Send the samples to the University of Cape Town (UCT) Water Quality Laboratory (WQL) to analytically determine the BPO, UPO, and ISS contents of the FS-PST.
- f. Compare the PST percentage removals and overflow characteristics from (i) the DDPST model, and (ii) the FS-PST to verify whether the model predictions accurately replicate the full-scale scenario.

1.4. Scope and limitations

As stated in **Section 1.3**, this study is limited to the evaluation of the DDPST model using comprehensively characterized PSS, that is, characterized in terms of (i) the settling velocities, (ii) the settling proportions, and (iii) the elemental compositions. As discussed in **Section 1.1**, the ability

of the settleometer to produce accurately segregated particles has not yet been confirmed, and so is the DDPST model. Therefore, while this study may provide recommendations related to improving the design of the settleometer or the DDPST model, such improvements or modifications will not be implemented as they fall outside the scope of the present study.

1.5. Research framework

Figure 1.2 outlines the research components of the present study. Having selected the research topic, formulated the research problem, specified the research questions and hypothesis, and determined the research objectives in this chapter (**Chapter 1**), **Chapter 2** reviews the related literature. The literature review is aimed at identifying research gaps and justifying the need for further research. Under this review, three important central units will be reviewed, namely, (i) the FS-PST units, (ii) the PST models (with a special reference to the UCTPSU model), and (iii) the settleometer. For the FS-PST units, the configurations including the settling styles are of importance. On the other hand, for the UCTPSU model, the fundamentals, including the model components, parameters, variables, and their relationship with the settleometer, are of importance. For the settleometer, the generation of the settleability data alongside the AugBMP biodegradability test will be reviewed. From here on, the proposed research methods will be detailed in **Chapter 3**. The research process from data collection, required material and equipment, and data analysis procedures will be described in detail. The results obtained from these research methods will be presented in **Chapter 4**. The outcomes from the DDPST model evaluation (using the results presented in Chapter 4 will be presented and analysed in **Chapter 5** with the intention to determine whether to support or reject the developed hypothesis. Once the data analysis process is complete, the conclusions and recommendations will be made in **Chapter 6**.

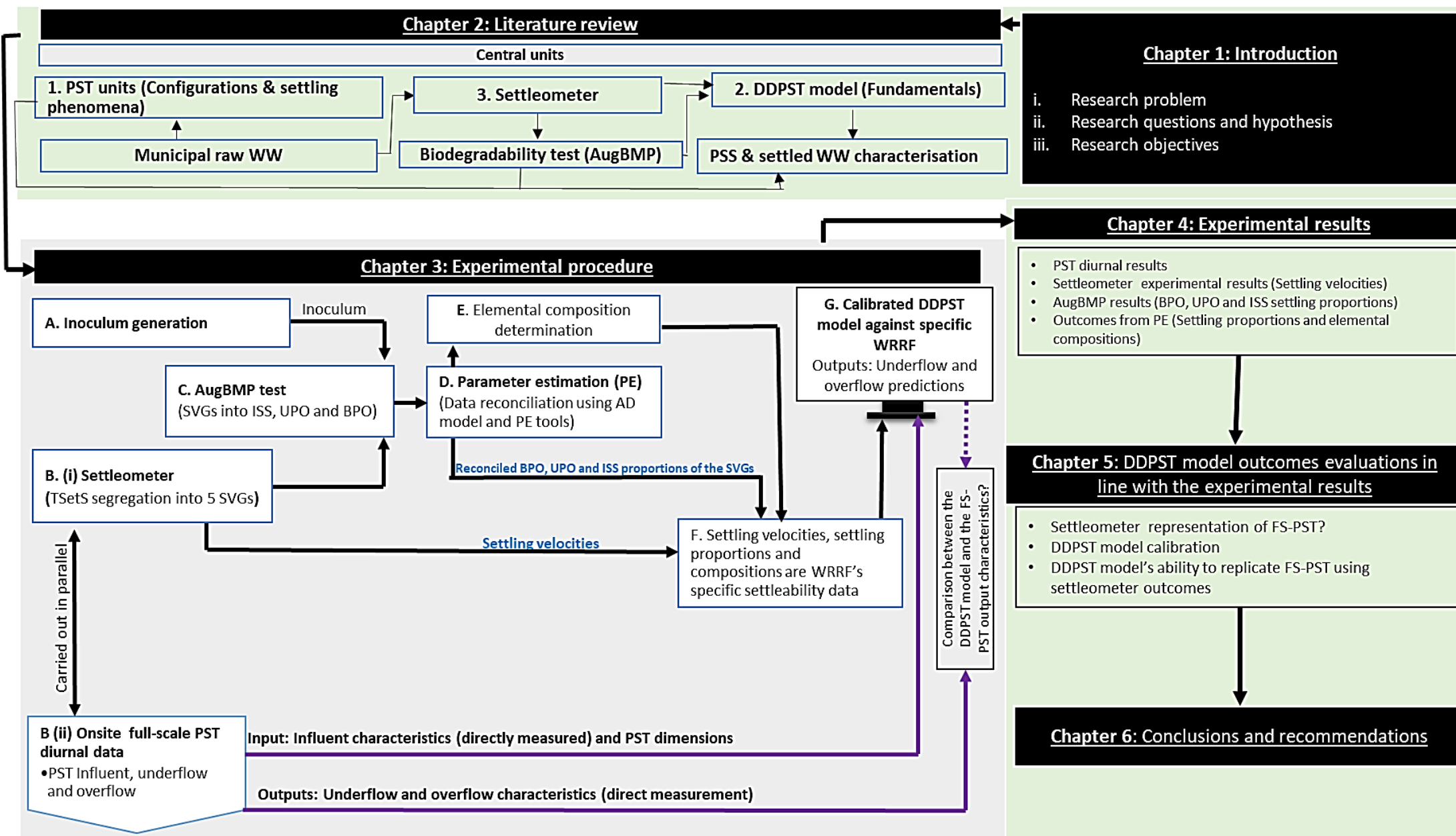


Figure 1.2: The research framework of the present study

CHAPTER 2:

LITERATURE REVIEW

Chapter 2: Literature review

2.1. Introduction

This chapter reviews the literature related to the key concepts essential for the present study. These concepts are detailed as subtopics within the review and include (i) the introduction to wastewater (WW) and its characterisation, (ii) the description of the primary sedimentation tank (PST), (iii) the PST hydraulic flow configurations, (iv) the particle settling characteristics, (v) the data-driven PST model, (iv) the description of the settleometer, and (v) the primary sewage sludge (PSS) and settled WW characterization in terms of settling velocities and biodegradability. **Figure 2.1** below illustrates how these concepts are interlinked.

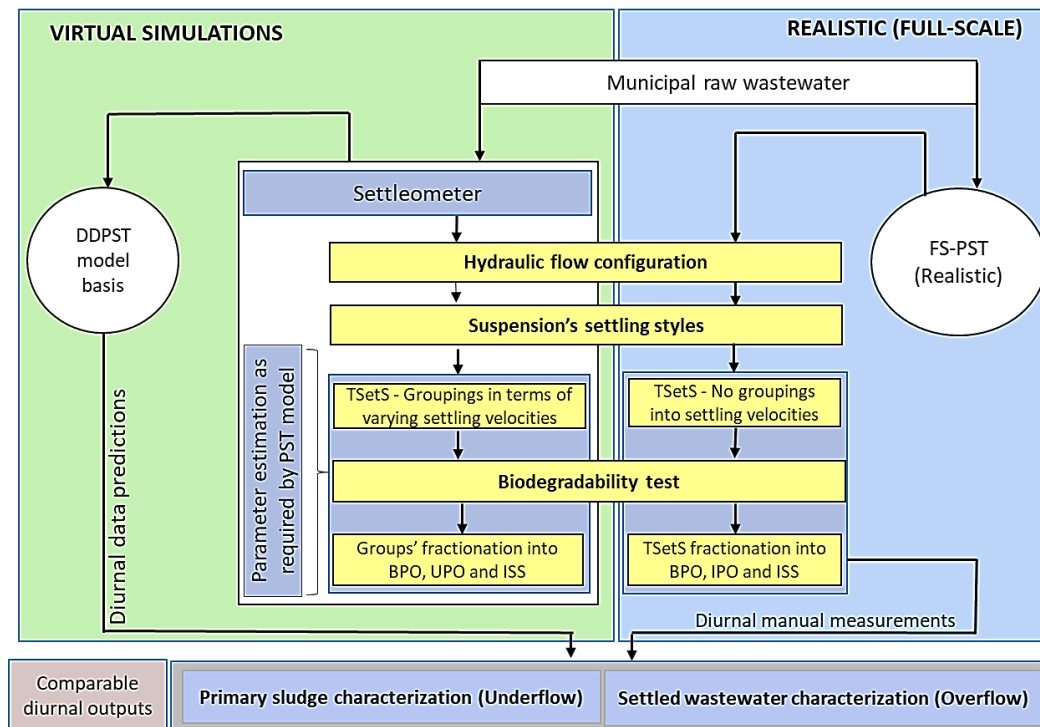


Figure 2.1: The relationship between the concepts making up the literature review

2.2. Municipal wastewater

2.2.1. Introduction to municipal wastewater

Water that contains waste products, such that it is regarded undesirable for use, be it from residential or industrial (manufacturing processes) areas, is referred to as wastewater (WW). Wastewater can be derived from different sources including (i) the industrial/commercial areas, (ii) the WWTP internally generated wastewater (that is, digester or thickener supernatant), and (iii) the municipal WW (that is, sewage from residential areas, storm water runoff, leachate, and infiltration into sewers) (Henze & Comeau, 2008: 33) (**Appendix A**). In addition, International Commission for the Protection of the

Rhine (2022) stated that municipal WW can comprise a mixture of industrial WW, domestic, and precipitation water. Depending on the geographic location, climate, water consumption behaviours, and population dietary practices, the characteristics of WW such as chemical oxygen demand (COD), total suspended solids (TSusS), volatile suspended solids (VSusS), and inorganic suspended solids (ISusS) are expected to vary. Therefore, the characteristics of WW are deemed specific to a given wastewater treatment plant (WWTP) at a given time period.

2.2.2. Primary sewage sludge and settled wastewater characterisation

The municipal wastewater (WW) is characterised by complex matter comprising both organic and inorganic constituents. As illustrated in **Figure 2.2**, Wentzel and Ekama (2006) divided these constituents into solubles and particulates. The particulate matter are divided into settleable and non-settleable solids. Essentially, the settleable solids accumulate at the bottom of a quiescent tank after 2 -3 hours to form the primary sewage sludge (PSS), while the non-settleable solids remain in suspension to form the settled WW. The PSS is of interest in the present study. It contains varying proportions of (i) settleable biodegradable particulate organics (BPOset) (40 to 60%), (ii) settleable unbiodegradable particulate organics (UPOset) (70 to 80%), and (iii) inorganic settleable solids (ISetS) (80 to 90%) (Ikumi *et al.*, 2014). The BPOset and UPOset collectively represent the volatile settleable solids (VSetS), and, together with the ISetS, form the total settleable solids (TSetS).



Figure 2.2: The wastewater constituents. Adapted from Wentzel and Ekama (2006).

2.3. Primary sedimentation tank

2.2.3. Overview

A typical WWTP consists of preliminary, primary, secondary, and tertiary treatment stages. The primary settling tank (PST) is located at the primary treatment stage. The presence of PSTs at a WWTP add benefits to the overall plant performance by (i) accumulating the PSS with biomethane potential, (ii) reducing the organic load proceeding to the activated sludge system (ASS), (iii) reducing the sizes of the required aeration and secondary treatment stage units (due to the decreased organic load), and (iv) reducing the overall design and operational costs (due to the decreased reactor size and aeration requirements, respectively) (Ekama, 2021). The related disadvantages, including (i) the PSS storage requirements (Polorigni, 2020: 2–7), (ii) the potential for odour generation due to poorly managed PST hydraulic retention time ($R_{hn,pst}$) (Byliński *et al.*, 2019: 5500 cited Chen *et al.*, 2011 and Roy *et al.*, 2011), and (iii) the further requirement for side stream processes to treat the dewatering liquor (DWL), generated from the PSS AD system effluent thickening (Nsengiyumva *et al.*, 2021), have been reported. While these disadvantages have been noted, a research by Ekama (2021), which explored the impact of the increased PST organic removal on the (i) effluent quality, (ii) PST succeeding unit designs, and (iii) overall energy consumption and recovery, revealed that although there are nutrient (N and P) loads found in the DWL generated by the PSS AD system, the N and P quantities generated by the AD system treating the WAS is usually significantly higher. Therefore, the evaluation of PSTs and their contribution towards the sustainable WRRF infrastructure requires a holistic approach such that a detailed understanding of the processes governing the PST performances and their relationships with their adjacent unit operations are achieved. This can be done by evaluating the PSTs within a plant-wide framework using the plant-wide mathematical models used to replicate the PSTs and adjacent operating units to which they are connected. Such mathematical models, which accurately replicate the WWTP, are useful tools that can be applied towards understanding and confirming the effectiveness of PSTs when it comes to optimisation and sustainability. This understanding will, with no doubt, add immensely to the benefits of transforming WWTPs into WRRFs.

2.2.4. Primary sedimentation tank hydraulic flow configuration

The Open University (2020) distinguished between the three main types of PST configurations, namely vertical, rectangular, and circular configurations (**Figure 2.3**). The vertical and circular sedimentation tank configurations are dominated by the vertical flow of particles, whereas the horizontal configurations are associated with the longitudinal flows and are predominant in rectangular tanks. The circular sedimentation tanks are said to be commonly associated with spiral or

radial flows. As opposed to both the vertical and rectangular tanks, the circular design configuration receives its influent WW from the centre of the tank. The influent flow is then swirled all around the tank creating a radial or spiral flow. The horizontal flow velocity, therefore, unceasingly decreases from the centre towards the tank perimeter. Consequently, the particle path of this type of tank follows a parabola plane curve in comparison with the vertical or rectangular tank straight-line particle path. Although vertical tanks are considered the simplest, rectangular tanks are said to be the most effective when it comes to solid separation since the particle settling process does not have to counteract any up-flow velocity and, owing to the longer path for particles to travel, a higher percentage of particle removal is expected (The Open University, 2020).

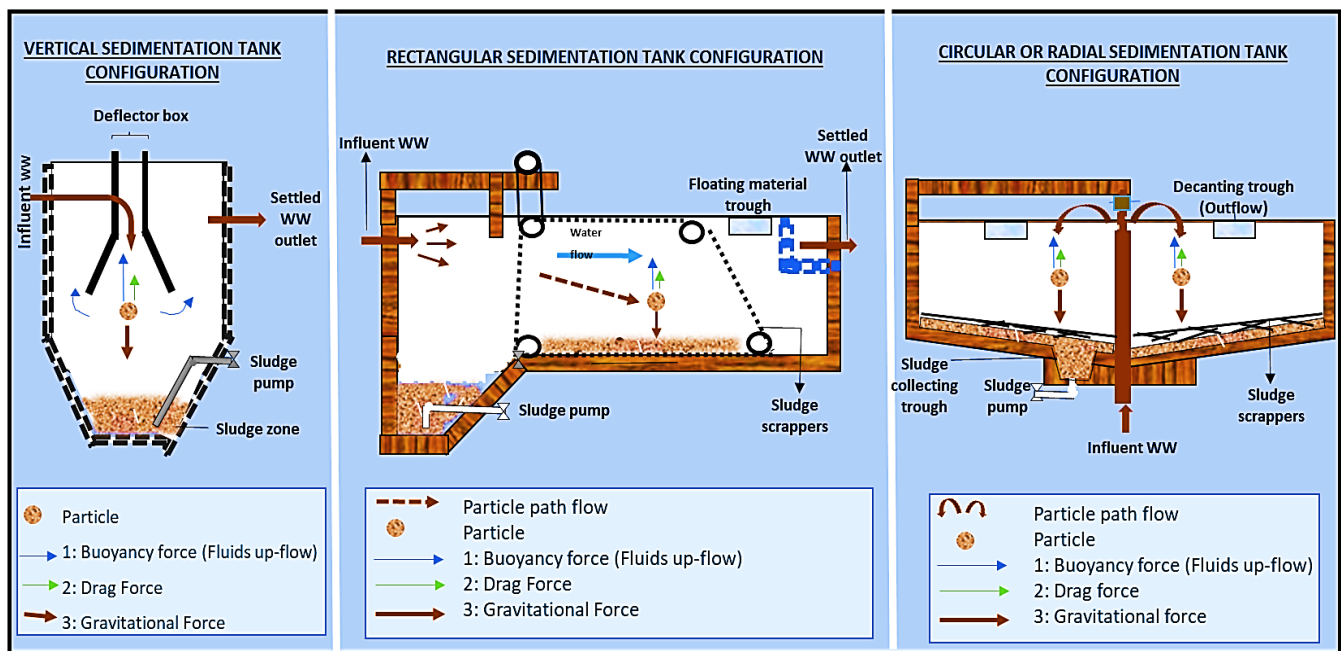


Figure 2.3: The different sedimentation tank configurations showing the different flow directions (Modified from The Open University (2019)).

2.2.5. Primary sedimentation tank settling processes

The PST incoming raw sewage is characterized by different particle sizes at generally low particle concentrations ranging between 100–1000 mg/l (Amerlinck, 2015: 58). The low particle concentration, compared with the concentration entering the preliminary stage, often results in a smooth laminar flow. The laminar flow is typically associated with discrete and flocculent settling mechanisms. Jover-Smet *et al.* (2017: 1-13) reported that the flow towards the PST is rarely flocculated, but, prone to flocculation. Depending on the characteristics of the particles and fluids, the flocculation process can be initiated in the PST. The longer the hydraulic retention time (HRT), the greater the chances of flocculation (Ekama & Wentzel, 2003: 3.30). The flocculation process results in the formation of flocs, which are the increased-size products. These products result in

increased settling velocities in comparison with the initial single particle settling velocities. Amerlinck (2015: 58) suggested the flocculent settling to be common in a particle concentration medium between 200–1000 mg/l, with discrete settling common in concentrations lower than 200 mg/l. The challenges posed by flocculation, which modifies the character of the original particle, make the discrete particle settling style more convenient (Polorigni, 2020: 3–1). Thus, to understand the settling properties of the original particles, the discrete particle settling is mostly relevant.

2.2.6. Discrete particle settling

Discrete particle settling (DPS), also referred to as Type 1 sedimentation, assumes that particles settle independent of one another. The particle settling velocity can be described using Stokes law (Amerlinck, 2015: 60). This law is quantified using the measurement data on the particle specific gravity, size, shape, and liquid properties (**Equation (2.1)**) (Amerlinck, 2015: 60). As shown in **Figure 2.3**, the gravitational, buoyancy, drag, and viscosity coefficients are the important factors acting on a particle in a liquid medium (National Programme on Technology Enhanced Learning, 2006). Stokes law explains that under laminar conditions, the settling velocity is directly proportional to the square of the particle size (diameter) and inversely proportional to the viscosity of the liquid (National Programme on Technology Enhanced Learning, 2006). Stokes law only applies to the viscous force dominant flow systems (laminar), where the Reynolds number is less than 1 (National Programme on Technology Enhanced Learning, 2006). In addition to Stokes law, the horizontal settling velocity, as shown in **Equation (2.2)**, is required to determine the path of a particle in a rectangular sedimentation tank. The sum of vertical and horizontal settling velocities gives the overall particle settling velocity in rectangular sedimentation tanks (National Programme on Technology Enhanced Learning, 2006).

The degree of particle settlement or removal is dependent on the (i) overflow rate (upward force governed by the displaced liquid), (ii) particle size and density relationship with the liquid medium, (iii) HRT, and (iv) tank geometry (Ekama & Wentzel, 2003: 3.30). Wentzel & Ekama (2003: 3.30) noted that for deep PSTs (greater than 3 m), provided a 2 to 3-hour HRT and average overflow rate of nearly 1.5–2 m/h, approximately 50–80% TSS and 30–50% COD removal can be achieved. The authors further stated that increasing the HRT beyond 3 hours does not yield any observable removal increase; however, decreasing the HRT to approximately 1 hour reduces the removal by approximately 50%. In addition, Amerlinck (2015: 52) cited Christoulas *et al.* (1998) supporting that add-on factors, including the wind action, heat flux, and inlet conditions, can potentially affect the settling process by short circuiting or circulating flows, thereby also affecting the total particle removal.

$$V_s = \frac{g(\rho_s - \rho_f) d^2}{18\eta} \quad (2.1)$$

$$V_h = \frac{Q}{A} \quad (2.2)$$

Where: V_s = Particle settling velocity (m/s)

V_h = Horizontal settling velocity (m/s)

g = Acceleration due to gravity (m/s^2)

ρ_s = Particle specific gravity (g/m^3)

ρ_f = Fluid specific gravity (g/m^3) – Assumed very close to normal water

d = Particle diameter (m)

η = Liquid viscosity (m^2/s)

Q = Water flow (m^3/s)

A = Area of the tank (depth by width) (m^2)

2.4. Primary sedimentation tank modelling

2.4.1. Introduction to primary sedimentation modelling

PSTs have been reported to be the under-researched and underrated WRRF units. They are known to have unrepresentative mathematical models that often cannot realistically replicate the PST unit operation and its performance within the system in comparison with the ASS, SST, and AD systems (Palmer, 2011: 2; Bachis *et al.*, 2015: 2251; Polorigni, 2020). Bachis *et al.* (2015: 2251) stated that the currently dominating WWTP (or WRRF) models exclude the PST settling processes given that they model from the PST effluent, essentially, requiring the PST effluent to be measured as an input parameter for the connected operating units, including the ASS system. The modelling from the PST effluent reflects the complexity in mathematically demonstrating the dynamics of particle removal, mostly due to the different particle sizes and tendency for some particles to flocculate. Consequently, there is currently no existing PST model that can accurately replicate the FS-PST scenarios.

While there have been experimental studies dedicated to determining the elemental compositions (ECs) of the BPOset and UPOset in the PSS (Sötemann *et al.*, 2005a; Sötemann *et al.*, 2005b), there has been a challenge replicating these using the current PST models (Palmer, 2011: 2). A great deal of this challenge emanates from (i) the previously made assumption that BPOset, UPOset, and ISetS settle at the same velocities (Gernaey *et al.*, 2001: 76), and (ii) the fact that the existing advanced PST models by Maruejouis *et al.* (2012) and recently Bachis *et al.* (2015) are TSS-based and fail to fully

address the concept of biodegradability in conjunction with the settling velocities (Polorigni, 2020: 1–2). Matesun (2020: 2) stated that relative to the assumption that removable particulate components settle at the same velocities, these should settle at varying settling velocities to obtain accurate removal proportions. To address this issue, Polorigni *et al.* (2021) developed an improved data-driven PST (DDPST) model. This model is an improved version of the previously developed TSS-based model by Bachis *et al.* (2015). This improved model is critically reviewed in **Section 2.4.2**.

2.4.2. Data-driven primary sedimentation tank model overview

The UCTPSU model is developed within the plant-wide model of South Africa (PWM_SA, Ikumi *et al.*, 2015), which is within the WEST[®] simulation platform (Vanhooren *et al.*, 2003). This model adapted two modelling approaches, that is (i) the discrete particle settling (DPS) theoretical approach previously developed by Kowlesser (2014 cited by Polorigni *et al.*, 2021), and (ii) the five-classes particle settling velocity distribution (PSVD) approach by Bachis *et al.* (2015). The DPS approach was adapted to characterize settleable particles into different SVGs while the five-class PSVD model approach laid a platform to account for the TSS desegregation into five different SVGs (Polorigni, 2020). It is important to note that the DPS model by Kowlesser (2014 cited by Polorigni *et al.*, 2021: 2-4) included fifteen SVGs, hence, it was necessary to adapt the PSVD principles to simplify the segregation process into five SVGs. Although the TSS-based PSVD model by Bachis *et al.* (2015) has been successfully applied and led to accurate effluent TSetS predictions, one major downside has been reported (Polorigni, 2020: 3–1). This includes the inability of the model to distinguish between the respective TSetS components, i.e., BPOset, UPOset, and ISetS. Therefore, to realistically replicate the FS-PST, these components required to be determined for all the five different TSetS SVGs (Polorigni, 2020: 4–1). The successful data-driven PST model by Polorigni, Ikumi and Ekama (2021), which takes into consideration the TSS and compositional segregations, proved the possibility to realistically replicate the performance of the FS-PSTs.

2.4.3. Data-driven primary sedimentation tank model: Components, parameters, and variables

To track components in a holistic system, the UCTPSU and PWM_SA models make use of similar model components. A complete set of PWM_SA components is presented in **Figure 2.4**. Of these components, X_U_Inf, X_B_Inf, and X_ISS are of interest. X_U_Inf, X_B_Inf, and X_ISS are scientific notations for the unbiodegradable particulate organics (UPO), primary sludge biodegradable particulate organics (PS BPO or BPOset), and influent inorganic settleable solids (ISetS), respectively. These three components are chosen given that the UPO, BPO, and ISS form

part of the greater portion removed as PSS in a FS-PST. Therefore, although many components are identified from the holistic PWM_SA, only X_U_Inf, X_B_Inf, and X_ISS will be discussed further.

The X_U_Inf, X_B_Inf, and X_ISS are the three components that have undergone modifications within the UCTPSU model of Polorigni *et al.*, (2021). These components were modified by segregating each component into five different SVGs (**Table 2.1A**). This implies that each of the components will consist of five subcomponents made up of different settling velocities. The proportions at each SVG can be determined using a combination of TSS analysis and biodegradability test (**Section 2.6**). The proportions of these subcomponents are scientifically denoted, as illustrated in **Table 2.1B**, and they can be expressed as parameters, as shown in **Table 2.1C** (Polorigni, 2020: 15). In addition to the influent flow data and PST dimensions, these sets of subcomponents are regarded as the initial parameters required by the DDPST model to make predictions. These parameters cannot be changed during the simulation process; therefore, rigorous checks should be made before simulation to avoid incorrect predictions. From the sensitivity analysis performed by Matesun *et al.* (2021), using the standardised regression coefficient (SRC) method, the following were identified as the three important model output variables, namely (i) the ISS in the underflow, (ii) the subcomponent VSS in the underflow, and (iii) the subcomponent TSS in the underflow. These output variables were found to be greatly influenced by both the settling velocities and settling proportions in addition to the hydrolysis constants of the biodegradable components. Hence, it is evident that (i) the settling velocities, and (ii) the settling proportions of the UPO, BPO, and ISS matter are crucial when aiming to realistically replicate the FS-PST using the data-driven PST model.

Solvent H ₂ O :Water	S_H :Hydrogen ion S_Na :Sodium S_K :Potassium S_Ca :Calcium S_Mg :Magnesium S_NHx :Ammonium S_Cl :Chloride S_VFA :Acetate S_Pr :Propionate S_CO₃ :Carbonate S_SO₄ :Sulphate S_PO₄ :Phosphate	Total dissolved ionic concentrations	Microorganisms biomass X_OHO :Ordinary heterotrophic organisms X_PAO :Phosphate accumulating organisms X_ANO :Autotrophic nitrifying organisms X_AD :Acidogens X_AC :Acetogens X_AM :Acetoclastic methanogens X_HM :Hydrogenotrophic methanogens X_U_Org :Endogenous residue
	Gases G_CO₂ :Carbon dioxide G_CH₄ :Methane		
Soluble organics S_H₂ :Dissolved hydrogen S_O₂ :Dissolved Oxygen (DO) S_U :Unbiodegradable soluble organics (USO) S_F :Fermentable biodegradable soluble organics S_Glu :Glucose		Particulates	X_U_inf :Unbiodegradable particulate organics (UPO) X_B_Org :Biodegradable particulate organics (BPO) X_B_Inf : PS Biodegradable particulate organics (PS BPO) X_PAO_PP :Polyphosphate X_PAO_Stor :Poly-hydroxy-alkanoate Xtr_NH₄ :Struvite X_ACP :Calcium phosphate Xtr_K :K-struvite X_Cal :Calcite X_Mag :Magnesite X_Newb :Newberyite X_ISS :Influent inorganic settleable solids (ISS)

Figure 2.4: The notations and definitions of the PWM_SA model components

Table 2.1: The TSetS sub-components (B) set as parameters (C) at respective settling velocities (A)

Settling Velocity Groups	1	2	3	4	5
A					
TSS subcomponents settling velocities					
X_ISS	Vs_s(X_ISS1)	Vs_s(X_ISS2)	Vs_s(X_ISS3)	Vs_s(X_ISS4)	Vs_s(X_ISS5)
X_U_Inf	Vs_s(X_U_Inf1)	Vs_s(X_U_Inf2)	Vs_s(X_U_Inf3)	Vs_s(X_U_Inf4)	Vs_s(X_U_Inf5)
X_B_Inf	Vs_s(X_B_Inf1)	Vs_s(X_B_Inf2)	Vs_s(X_B_Inf3)	Vs_s(X_B_Inf4)	Vs_s(X_B_Inf5)
B					
Settling proportions set as TSetS subcomponents					
X_ISS	X_ISS1	X_ISS2	X_ISS3	X_ISS4	X_ISS5
X_U_Inf	X_U_inf1	X_U_inf2	X_U_inf3	X_U_inf4	X_U_inf5
X_B_Inf	X_B_inf1	X_B_inf2	X_B_inf3	X_B_inf4	X_B_inf5
C					
Settling proportions set as parameters					
f _{ISetS} 'SVG _n	Alpha_I (α_i)	Beta_I (β_i)	Gamma_I (γ_i)	Lambda_I (λ_i)	Theta_I (θ_i)
f _{UPOset} 'SVG _n	Alpha_U (α_u)	Beta_U (β_u)	Gamma_U (γ_u)	Lambda_U (λ_u)	Theta_U (θ_u)
f _{BPOset} 'SVG _n	Alpha_B (α_b)	Beta_B (β_b)	Gamma_B (γ_b)	Lambda_B (λ_b)	Theta_B (θ_b)

2.4.4. Particle settling modelling

While various settling models can be acknowledged (Polorigni *et al.*, 2021), the settler model of Takacs *et al.* (1991) is of importance in this study. This is because the principles behind the particle settling in the data-driven PST model are based on the one-dimensional flux theory (1DFT) adapted by Takacs *et al.* (1991) (Polorigni, 2020: 4–2). Essentially, the TSS total flux (J_T) in a sedimentation tank is the sum of the gravity settling flux (J_S) and the bulk liquid flux (J_B). The gravity settling flux is defined as the particle ability to settle under the force of gravity, while the bulk liquid flux is defined as the bulk movement of the liquids within a clarifier. The bulk liquid flux can either be upward or downward subject to the position of the n^{th} layer relative to the feed layer (H_F) (**Figure 2.5**). For instance, if the height (H) is greater than H_F , then the upward flux (J_{UP}) is considered. However, if $H < H_F$, then the downward flux (J_{DN}) is considered. **Equations (2.3) to (2.5)** formulate the flux theory accordingly.

Takacs *et al.* (1991) divided the settler height (H) into ten equal horizontal layers (**Figure 2.5**). The layers are classified into five main groups, namely (i) top layer, (ii) feed layer, (iii) bottom layer, (iv) layers below the feed layer, and (v) layers above the feed layer (**Figure 2.5**). Of the ten layers, the feed layer is assumed to occur in layer 5 (i.e., the middle layer). The flux theory is then applied to each layer by considering the gravity flux of the particles along with the bulk liquid flux through the different layers. The important concepts to consider in this regard are the limiting concentration (X_{LIM}) and minimum sludge blanket (X_{MIN}) (Polorigni, 2020). The X_{LIM} is defined as the bottleneck concentration given that it has the lowest flux, or solid transport to the bottom of the clarifier, of all

the existing concentrations within a clarifier (Ekama, n.d.: A7), while X_{MIN} has the highest flux or solid transport. This implies that particles entering the clarifier will only flow through to the bottom layer if the flux applied is set higher than the X_{MIN} . In accordance with the 1DFT, J_G can be determined in conformity with the following guidelines (Polorigni, 2020: 65):

i. For Layer 1 to 4:

If $X_i < X_{LIM}$, $J_G = X_i \times V_S$, but

If $X_i > X_{LIM}$, $J_G = \min(J_{Gi}, J_{Gi-1})$,

Where: J_{Gi-1} = Gravity settling flux of the layer just below the layer of concern.

ii. For layer 5 to 9:

Given that layer 5 is a feed layer: $J_G = \min(J_{Gi}, J_{Gi-1})$

The constraints above, as supported by Polorigni (2020: 65), indicate that the gravity settling flux is greatly dependent on the particle concentration exhibited by a layer just below the layer of interest.

$$J_G = V_S \times X_i \quad (2.3)$$

$$J_B = V_L \times X_i \quad (2.4)$$

$$J_T = J_B + J_G \quad (2.5)$$

Where: V_S : Particle settling velocity (m/h)

X_i : Particle concentration of the layer of interest.

J_G : Gravity settling flux (Kg/m²h)

J_T : Total flux (Kg/m²h)

J_B : Bulk liquid flux (Kg/m²h): $J_{DN} = C1 \times V_{DN}$ or $J_{UP} = C1 \times V_{UP}$

V_L : Bulk liquid settling velocity (m/hr):

If $H > H_F$, $V_L = V_{UP} = Q_{PST,eff}/A_{PST}$. If $H < H_F$, $V_L = V_{DN} = Q_{PST,R}/A_{PST}$

Where: V_{UP} is an upward velocity of the bulk liquid

V_{DN} is a downward movement of the bulk liquid

$Q_{PST,R}$ is a PST recycle flow rate (m³/h)

$Q_{PST,eff}$ is an effluent flow rate (m³/h)

H is the height level of the settler layers

H_F is the height level of the feed layer.

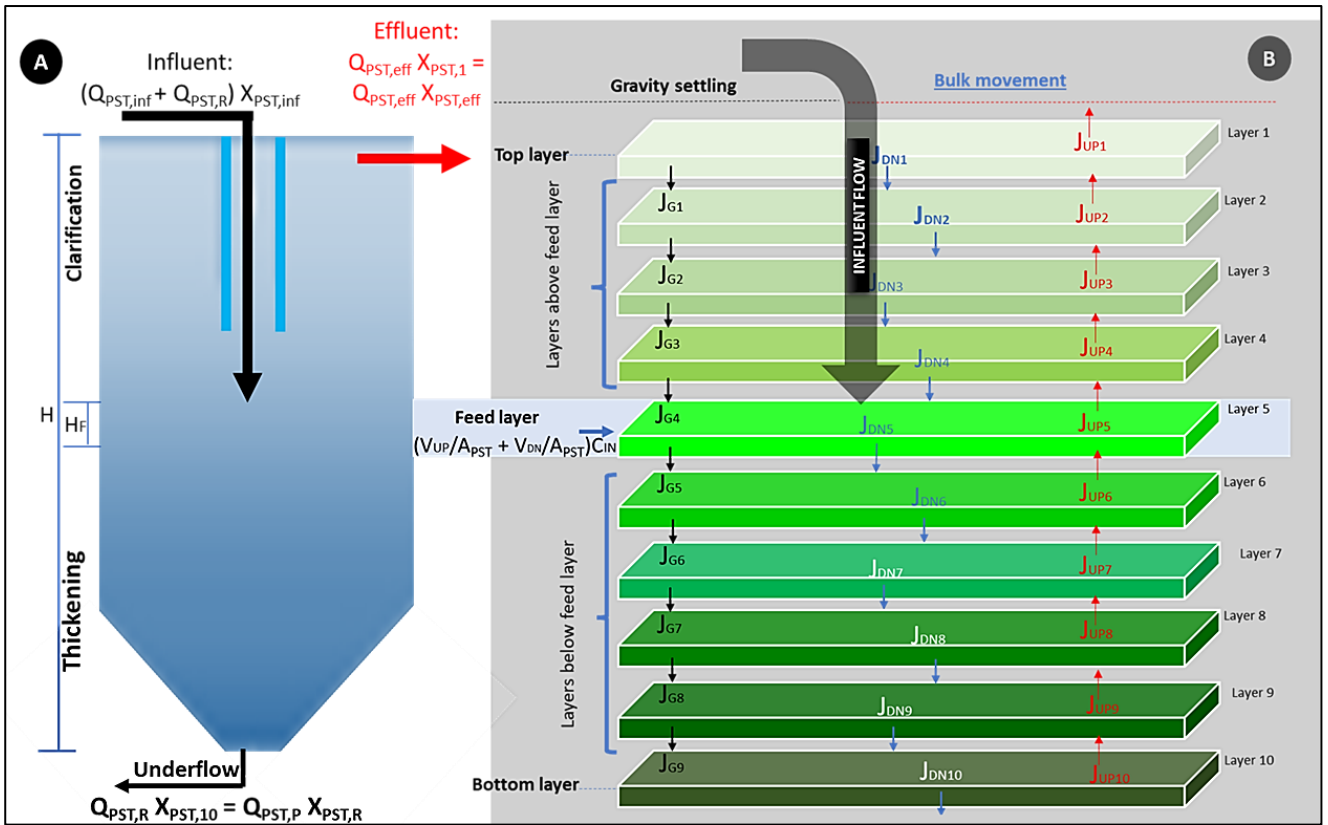


Figure 2.5: The flux movement representation around layers within a settler. Adapted from Takacs *et al.* (1991).

2.4.5. Data-driven primary sedimentation tank model: Mass balance verification

The mass balance check is a crucial control step in data acquisition of a given system (via measurement or predictive models). This is achieved by balancing the fluxes of matter over the selected system boundary. In addition to the DDPST model development, Polorigni (2020: 5-23) performed model verification to substantiate model consistency in relation to the UPOset, BPOset and ISetS removals for all the five SVGs. As illustrated in **Figure 2.5**, for the DDPST model, the mass balance was performed around each of the ten horizontal layers within a clarifier (Polorigni, 2020). Depending on the particle concentration of the influent (entering through layer 5), the J_G , J_{DN} , and J_{UP} can be determined for each layer assuming that the influent particle flux is uniformly distributed across the layer and that only vertical flow is considered (Takacs *et al.*, 1991).

The feed layer, and the layers below and above the feed layer, will be used as examples to show the mass balance relationship between layers using mathematical equations, i.e., **Equations (2.6) to (2.8)**. **Table 2.2** provides a summary of the flux movement between the 10 layers. In deriving the equations, the following are considered:

- $V_{UP,I}$ = Upflow velocity of the layer of interest
- $V_{UP,i+1}$ = Upflow velocity of the layer above the layer of interest

- $V_{DN,I}$ = Downward velocity of the layer of interest
- $V_{DN,i-1}$ = Downward velocity of the layer below the layer of interest
- $V_{S,I}$ = Particle gravity settling of the layer of interest
- $V_{S,i-1}$ = Particle gravity settling of the layer below the layer of interest
- $V_{S,i+1}$ = Particle gravity settling of the layer above the layer of interest
- X_{i-1} = Particle concentration of the layer below the layer on interest
- X_{i+1} = Particle concentration of the layer above the layer on interest

i. Layers above the feed layer: $H > H_F$

$$\frac{dX_I}{dt} = (V_{UP,i-1} \times X_{i-1}) - (V_{UP,i} + V_{UP,i}) + (V_{S,i+1} \times X_{i+1}) - (V_{S,i} \times X_i) = 0 \quad (2.6)$$

$$\text{Example: Layer 3: } \frac{dX_I}{dt} = J_{UP4} - J_{UP3} + J_{G2} - J_{G3} = 0$$

ii. Feed layer: $H = H_F$

Given:

$$(V_{UP}/A_{PST} + V_{DN}/A_{PST}) \times X_{PST,in} = (Q_{PST,eff} + Q_{PST,R}) \times X_{PST,in} = Q_{PST,in} \times X_{PST,in} = J_{in},$$

Where:

J_{in} = Influent particle flux.

Therefore,

$$\frac{dX_I}{dt} = J_{in} - (V_{UP,i} + V_{DN,i})X_i + (V_{S,i+1} \times X_{i+1}) - (V_{S,i} \times X_i) = 0 \quad (2.7)$$

$$\text{Layer 5: } \frac{dX_I}{dt} = J_{in} - J_{UP5} - J_{DN5} + J_{G4} - J_{G5} = 0$$

iii. Layers below the feed layer: $H < H_F$

$$\frac{dX_I}{dt} = (V_{DN,i-1} \times X_{i-1}) - (V_{DN,i} \times X_i) + (V_{S,i-1} \times X_{i-1}) - (V_{S,i} \times X_i) = 0 \quad (2.8)$$

$$\text{Example: Layer 7: } \frac{dX_I}{dt} = J_{DN6} - J_{DN7} + J_{G6} - J_{G7} = 0$$

Table 2.2: The summary of particles and bulk liquid movement across the settler. Adapted from Takacs *et al.*(1991) and Ribes *et al.* (2002).

Layer		Input			Output	
		Feed	Settling	Bulk liquid flux	Settling	Bulk liquid flux
Top layer	Layer 1	Not considered	Not considered	+ J _{UP2}	- J _{G1}	- J _{UP1} ; - J _{DN1}
	Layer 2	Not considered	+ J _{G1}	+ J _{UP3} ; + J _{DN1}	- J _{G2}	- J _{UP2} ; - J _{DN2}
	Layer 3	Not considered	+ J _{G2}	+ J _{UP4} ; + J _{DN2}	- J _{G3}	- J _{UP3} ; - J _{DN3}
	Layer 4	Not considered	+ J _{G3}	+ J _{UP5} ; + J _{DN3}	- J _{G4}	- J _{UP4} ; - J _{DN4}
Feed layer	Layer 5	(V _{UP} /A + V _{DN} /A) C _{IN}	+ J _{G4}	Not considered	- J _{G5}	- J _{UP5} ; - J _{DN5}
	Layer 6	Not considered	+ J _{G5}	+ J _{DN5} ; + J _{UP7}	- J _{G6}	- J _{DN6} ; - J _{UP6}
	Layer 7	Not considered	+ J _{G6}	+ J _{DN6} ; + J _{UP8}	- J _{G7}	- J _{DN7} ; - J _{UP5}
	Layer 8	Not considered	+ J _{G7}	+ J _{DN7} ; + J _{UP9}	- J _{G8}	- J _{DN8} ; - J _{UP8}
	Layer 9	Not considered	+ J _{G8}	+ J _{DN8} ; + J _{UP10}	- J _{G9}	- J _{DN9} ; - J _{UP9}
Bottom layer	Layer 10	Not considered	+ J _{G9}	+ J _{DN9}	Not considered	- J _{DN10}

Note: Amendments as applied by Polorigni (2020) were taken into consideration and these are indicated by light blue text.

While the principles in **Figure 2.5** apply well to the vertical PST configuration, they can also be applied to the circular and rectangular configurations. This is because the PST surface area (A_{PST}) can affect the total removals, the above mass balance principles are not shape-dependent, but rather, they describe how the particle layers in a PST can be represented.

2.4.6. Data-driven primary sedimentation tank model modifications

Following the DDPST model development by Polorigni *et al.* (2021), Matesun *et al.* (2021) carried out further study that involved (i) incorporating the hydrolysis and fermentation bioprocesses into the DDPST model, and (ii) developing a DDPST model calibration procedure. These modifications were necessary given the possibility of degradation in a PST depending on the HRT. The calibration procedure was developed using (i) the settleometer and augmented biomethane potential (AugBMP) test data, which are used towards comprehensively characterizing the PSS in terms of settling velocity and biodegradability, and (ii) the global sensitivity analysis (GSA), which is an important component of the model calibration according to the BIOMATH protocol of Vanrolleghem *et al.* (2003). As mentioned in **Section 2.4.3**, the GSA, which was performed using the SRC method, highlighted the importance of the settling velocities and settling proportions in running the DDPST model. The study by Matesun *et al.* (2021), therefore, proved the need to have a reliable tool that can provide accurate particle settleability information.

2.5. Towards validation of the data-driven primary sedimentation tank model

2.5.1. Overview

The DDPST model of Polorigni *et al.* (2021) was developed in such a way that it requires the settleability data specific to a WRRF to make predictions. Although the model itself is described to have the potential to make reliable predictions, a certain level of validation is required to increase the confidence in its application to predict the PSS and settled WW compositions. The first step to this validation is to verify the effectiveness of a suitable settleometer to segregate the settleable TSS into different SVGs. This step is crucial given that failure to generate accurate SVG data can require additional improvements on the existing DDPST model. The sections below critically review the concept of settleometer and its relationship with the DDPST model.

2.5.2. Settleometer

The settleometer can be defined as a settleability test device used to segregate the settleable solids of a mixed liquor suspended solids (MLSS) into different SVGs. Various protocols have been developed over the years with an intent to study and understand the particle settleability rates and behaviours. For instance, (i) Arasmith (1981) used one 2L cylinder to measure the settleability behaviour of the activated sludge MLSS; (ii) Maus *et al.* (2008) used a water elutriation system method consisting of three interconnected columns with varying diameters to allow particle settling in response to the upflow velocity; (iii) Chebbo and Gromaire (2009) used a single PVC column ViCAs protocol to measure the settleability characteristics of WW; and (iv) Poinapen (2008) used a four-column settleometer to measure the settleability of particulates in a UASB sludge bed. While different methods can be used to gather particle settleability information, the settleometer under verification follows the methods by Moosbrugger (1994), which were adapted by Poinapen (2008). This settleometer under investigation was constructed by the UCT engineering workshop approximately four years ago to segregate the settleable solids into five different SVGs. The ability of this device to segregate particles into five SVGs makes it preferable given that it fits the DDPST model requirements. For the purpose of the present study, this five-column settleometer will be referred to as the 5C-settleometer.

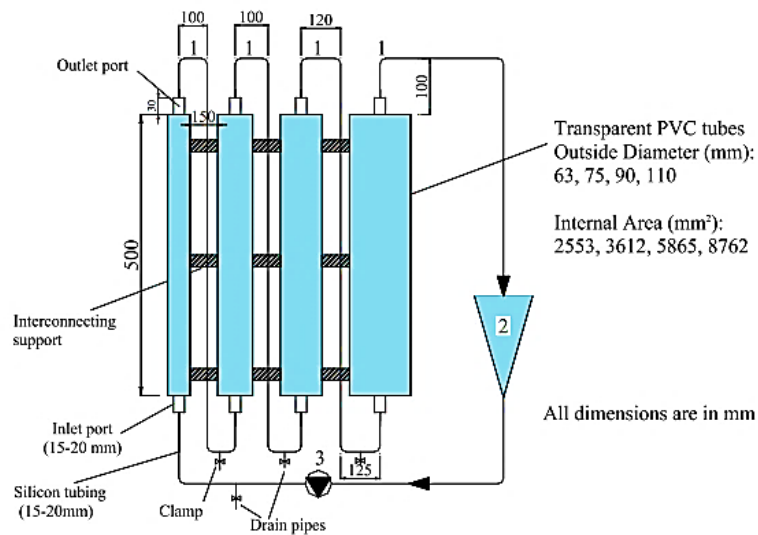


Figure 2.6: The settleometer conceptual design by Poinapen *et al.* (2009). The same methods adapted to this design were adapted to the settleometer under investigation.

2.5.3. Settleometer design

The design and functionality of the settleometer have evolved since the emergence of the idea by Poinapen (2008). The settleometer has advanced from a four-column settleometer to a five-column settleometer design (5C-settleometer) (**Figure 2.7**). The five-column design consists of five transparent polyvinyl chloride (PVC) columns each with its own diameter. The PVC columns are each approximately 1m in height and are arranged vertically in an ascending order, i.e., from 45.2, 67.6, 86.4, 105.6 to 134.4 mm (**Figure 2.7B**). In principle, all the PVC columns are supplied with a constant upflow velocity (V_{UP}), thus resulting in particle settling velocities (V_s) decreasing with the increase in the PVC column diameter (Poinapen *et al.*, 2015). This implies that the particle settlement can only occur if the V_s is greater than the V_{up} , i.e., the settleable particles with higher V_s will accumulate in the first small diameter column, while those with progressively smaller V_s will segregate accordingly in the subsequent columns. All matter not accumulated in any of the five columns will leave the 5C-settleometer as effluent or overflow ($Q_{5SET,eff}$).



Figure 2.7: The UCT- settleometer: (A) earlier four-column design and (B) current five-column design.

2.5.4. Factors governing five-column settleometer data generation

The flow rate, upflow velocity (V_{up}), and particle size are the three main factors governing the particle settling in a 5C-settleometer (Poinapen *et al.* 2015). The 5C-settleometer influent flow rate ($Q_{5SET,inf}$) is usually controlled by a pump, while the V_{up} is calculated by dividing the governing flow rate by each of the PVC column area (A_{PVCn}). In addition to these three factors, the relationship between (i) the HRT of the FS-PST and the 5C-settleometer, and (ii) the overflow rate of the FS-PST and the 5C-settleometer are considered important. The PST HRT ($R_{hn,pst}$) is defined as the PST volume (V_{PST}) divided by the PST influent flow rate ($Q_{PST,inf}$), and similarly, the 5C-settleometer HRT ($R_{hn,5SET}$) is defined as the 5C-settleometer volume (V_{5SET}) divided by the $Q_{5SET,inf}$. The overflow rate for PSTs can be defined as the $Q_{PST,inf}$ divided by the PST area (A_{PST}), whereas the 5C-settleometer overflow rate can be defined as the time taken for the effluent to fill up a specified volume. The HRT and overflow rate are considered important given that for the 5C-settleometer to reflect the FS-PST conditions, the operational settings must match. For instance, if the overflow rate of the FS-PST is 2.3 litre/hour, this should be set accordingly onto the 5C-settleometer. Similarly, the $R_{hn,5SET}$ should equal the $R_{hn,pst}$. The correct settings on the 5C-settleometer minimise the chances of releasing solids that would have otherwise formed part of the PSS. Although increasing the HRT by approximately 50% does not yield an observable increase in removal, decreasing the HRT by 50% does affect the percentage of solids removal (Ekama & Wentzel, 2003: 3.30). Also, although the 5C-settleometer consists of five varying column diameters, the biggest diameter column that would otherwise have the lowest V_{up} , would still not have a sufficiently low V_{up} to remove the necessary solids if the flow rate were too high.

While the previous studies on this topic did measure the overflow rate from the 5C-settleometer (see **Section 2.5.5** below), its relationship with the FS-PST was not fully addressed, and so was the relationship between the settleometer HRT and FS-PST. This aspect will be assessed when evaluating the accurateness of the 5C-settleometer to reflect the FS-PST.

2.5.5. Five-column settleometer previous work

The historical data related to the use of the 5C-settleometer have been generated from various mini-project that were conducted by numerous students at the UCT Department of Civil Engineering. The aim was to (i) test the functionality of the device, and (ii) investigate the capability of the device to generate accurate data to enable calibration of the DDPST model. The settleability study of the Potsdam raw WW (Paleker, 2018; Motokwane, 2019; Kirby, 2020) and Cape Flats raw WW (Notoane, 2020) were considered under average dry weather conditions. The 5C-settleometer data by Motokwane (2019) played a role in developing the calibration procedure for the DDPST model (Matesun *et al.*, 2021). Although the correctness of the data used in the calibration procedure development may still need to be substantiated through the 5C-settleometer verification, the procedure itself is regarded important given that it sets a mathematical foundation for the model calibration.

After evaluating the 5C-settleometer historical data, it appears that, for the Potsdam WWTW, the majority of the particles making up the PSS coincide with the V_{up} between 17 m/hr and 5 m/hr. The small particle concentrations are seen to coincide with the V_{up} greater than 24 m/hr and lower than 5m/hr (**Figure 2.9**). It is worth noting that these particle concentration ranges were not necessarily selected based on the PVC column number, but rather, the V_{up} as governed by the flow rate. This is due to a variation in the V_{up} rate, between the PVC columns, being expected depending on a flow rate applied to a given settleometer run (**Figure 2.9**). As illustrated in **Figure 2.9**, for the low $Q_{5SET,eff}$ of 0.63 l/min, the PVC1, PVC2, PVC3, PVC4, and PVC5 are subjected to the V_{up} of 23.6, 10.0, 6.4, 4.3, and 2.7 m/hr, respectively. On the other hand, for the high $Q_{5SET,eff}$ of 1.69 l/min (**Figure 2.8**), the PVC1, PVC2, PVC3, PVC4, and PVC5 are subjected to the V_{up} of 63.2, 28.3, 17.3, 11.6, and 7.1 m/hr, respectively. For 0.63 l/min, the maximum settling was recorded in the PVC2 and PVC3 coinciding with V_{up} 10.0 and 6.4 m/hr, while for 1.69 l/min, the maximum settling tended to shift to the PVC3, PVC4, and PVC5 coinciding with the V_{up} of 17.3, 11.6, and 7.1 m/hr, respectively. From this example, it is evident that the dependency of the V_{up} on the $Q_{5SET,eff}$ makes it difficult to determine a single column that mostly experience maximum settling at any flow rate. For instance, for the set of low $Q_{5SET,eff}$ of 0.63, 0.64, and 0.72 l/min, the maximum settling is recorded in the PVC2 and PVC3 (**Figure 2.9**), while for the set of high $Q_{5SET,eff}$ of 1.375 and 1.69 l/min, the maximum settling is

recorded in the PVC3, PVC4, and PVC5 (**Figure 2.9** and **Figure 2.8**). In addition to the above, the particulate matter in raw WW are associated with varying settling velocities, which are simplified by grouping them into five settling velocity ranges according to the particle sizes, densities, and their relationship with the V_{up} . For instance, if the V_{up} in the 5C-settleometer PVC1 is 23.6 m/hr, then all the particles with a V_s greater than 23.6 m/hr will accumulate in the PVC1. For the PVC2, if V_{up} is 10.0 m/hr, then all the particles with a V_s between 23.6 m/hr (from PVC1) and 10.0 m/hr will accumulate in the PVC2, and so on. For both the Cape Flats and Potsdam raw WWs, of the total TSS removal via the settling processes in the settleometer, the ISS particles appeared to be removed in the low fractions of 0.1–0.4 compared with the VSS fractions of 0.6–0.9 (Motokwane, 2019; Kirby, 2020; Notoane, 2020). This statement is however contradicted by the observation of the Potsdam WW total removals by Paleker (2018) where the ISS is removed in higher concentrations relative to the VSS (**Figure 2.10**).

The prevalence of variability in the outcomes from the same settleometer device is a clear indication of variation in the waste loads from one plant to another, depending on the sources of pollutants. This shows the need for a data driven approach in modelling PSTs since a generic model is not accurate. To achieve this, an appropriate measurement technique to generate the required data specific to a given system is needed. In the present study, the accurateness of the 5C-settleometer to provide a reasonable representation of the settling process in the full-scale system is investigated. This accurateness will be determined by how accurate the DDPST model output predictions are when the 5C-settleometer is used to generate the input parameters.

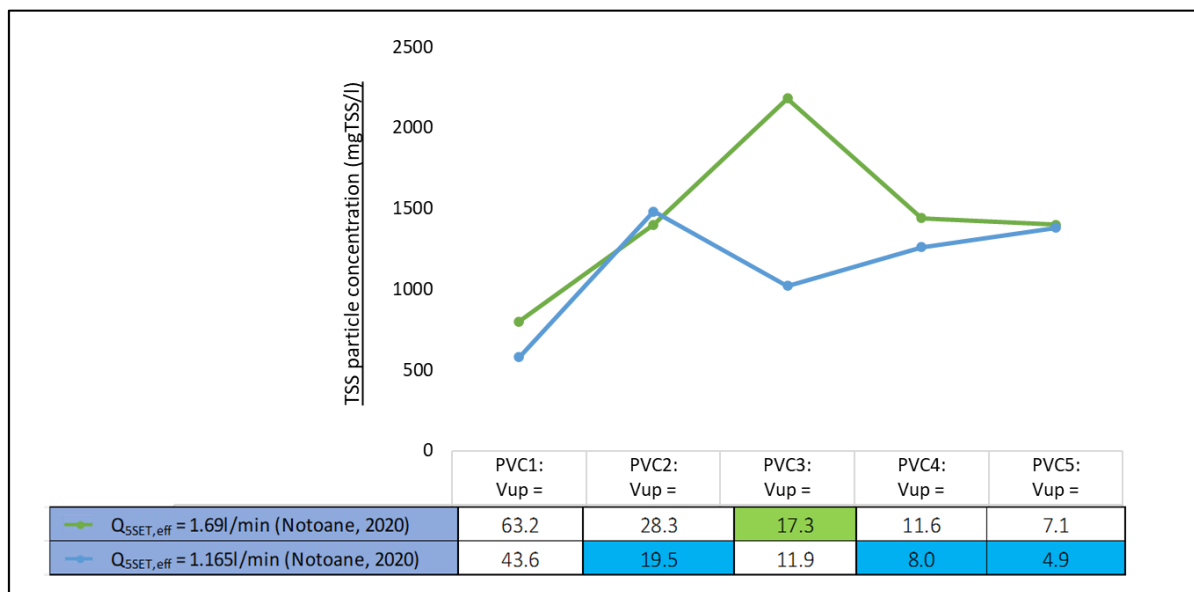


Figure 2.8: The 5C-settleometer TSS concentration per PVC column at different flow rates, for the Cape Flats WWTW. ($Q_{SET,eff}$ = Effluent flow rate, V_{UP} = Upflow velocity).

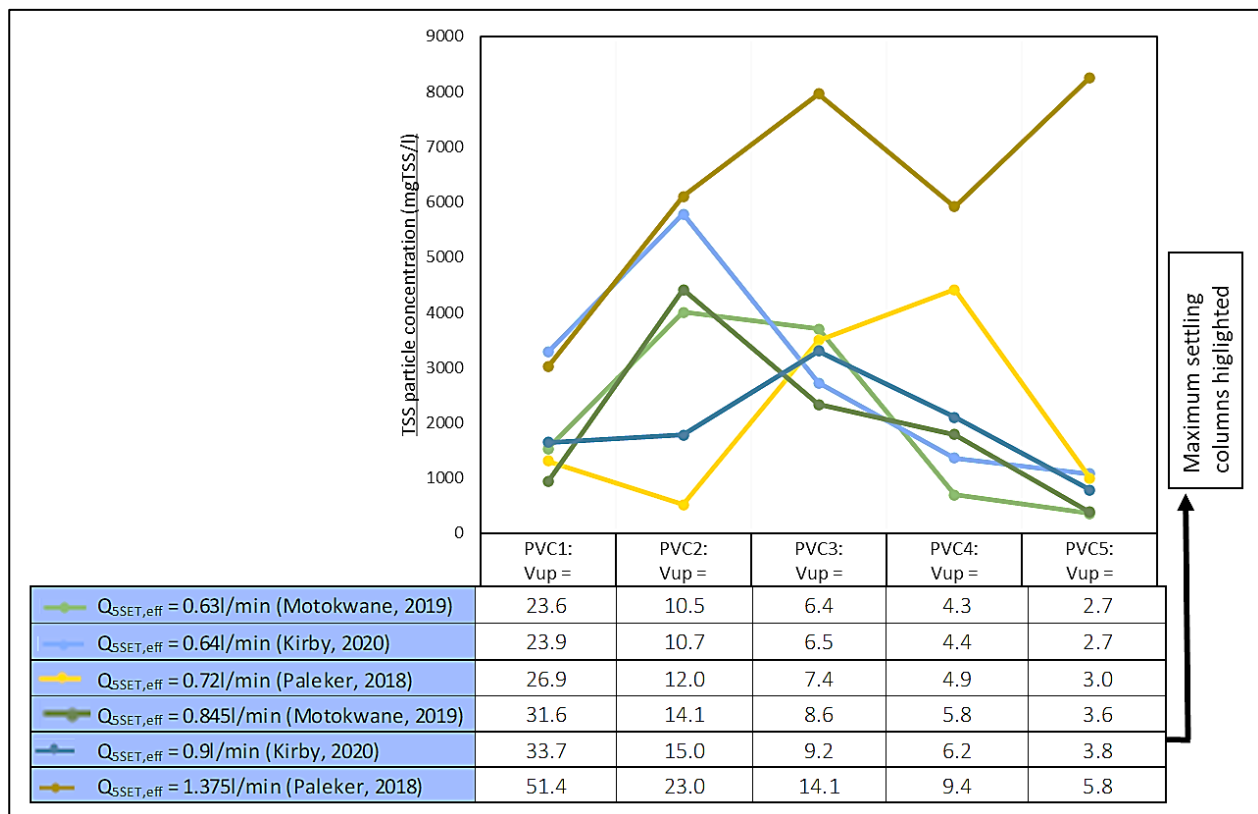


Figure 2.9: The 5C-settleometer TSS concentration per PVC column at different flow rates, for the Potsdam WWTW. $Q_{SET,eff}$ = Effluent flow rate, V_{UP} = Upflow velocity)

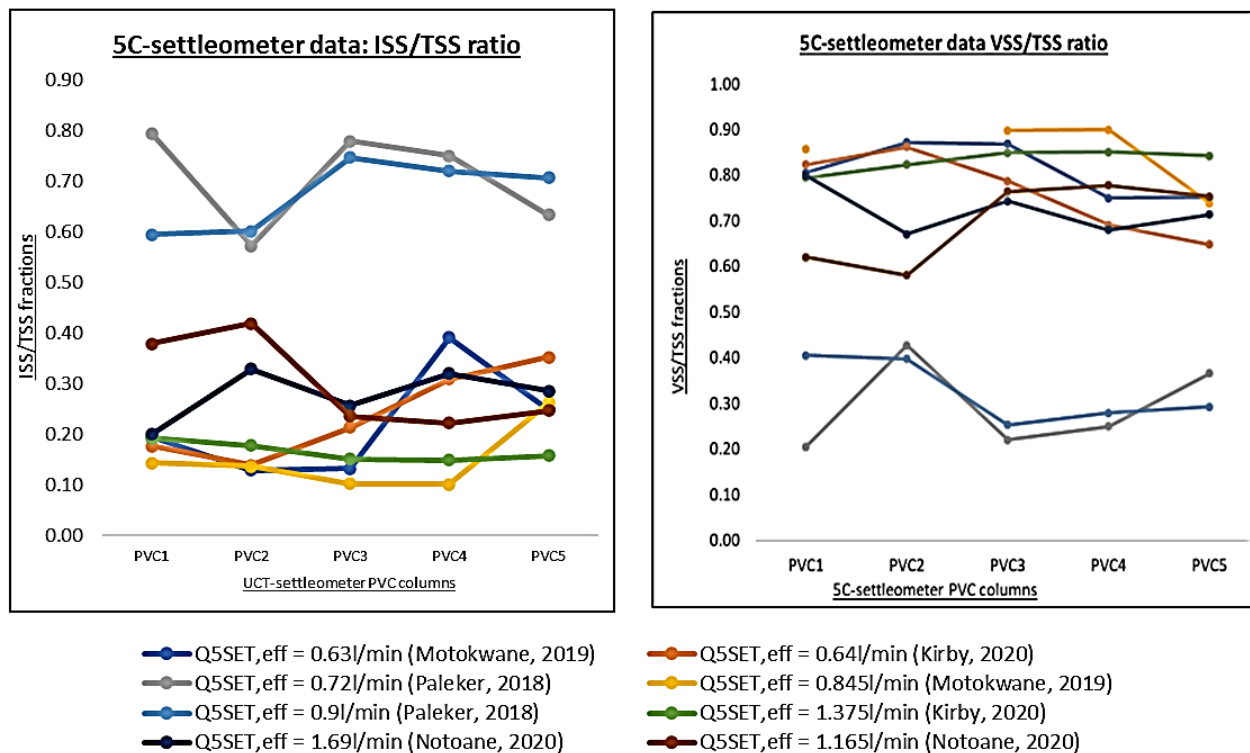


Figure 2.10: The VSS/TSS and ISS/TSS ratios for the 5C-settleometer TeRs at different flow rates

2.6. Biodegradability test

2.6.1. Overview

The biomethane potential (BMP) test is used to measure the content of the biodegradable organics by relating to the biogas yield (mainly methane [CH₄] and carbon dioxide [CO₂]). The BMP test follows the same degradation processes as an anaerobic digestion (AD) system (United State Environmental Protection Agency, 2022) (see **Section 2.6.3**). The difference in the bio-methane produced per gram of organic solids contained in a control sample (only containing seed inoculum) and test sample (containing a substrate in addition to the same seed inoculum as in the control sample) is an indication of the potential methane that can be produced through the AD of the biodegradable substrates (Ikumi et al., 2020). An experimental procedure called Augmented Biomethane Potential (AugBMP) test was recently recognized as a viable waste sludge biodegradability test method (Gaszynski, 2020). Similar to the BMP tests, the AugBMP batch test requires mixing of an inoculum, from an active AD system, and a substrate in a completely sealed mesophilic reactor to biologically degrade the biodegradable organics in the absence of oxygen, thereby producing biogas (CH₄ and CO₂). The difference between the BMP and AugBMP tests is that the AugBMP test also includes additional basic measurements, besides the CH₄ and CO₂ production measurements, viz. (i) the chemical oxygen demand (COD for both filtered and unfiltered samples), (ii) the total, volatile, and inorganic suspended solids (TSuspS, VSuspS and ISuspS), and (iii) the aqueous phase volatile fatty acids (Gaszynski, 2020: 28). More details on the AugBMP test are discussed below.

2.6.2. Augmented biomethane potential (AugBMP) test procedure

Gaszynski (2020) used the AugBMP batch test, together with the PWM_SA_AD model and parameter estimation (PE) function, to determine the biodegradable organic composition of a given PSS. To substantiate the outcomes, Gaszynski (2020) used two different substrates, one with a known biodegradable composition (casein) and the other with an unknown composition (PSS). Although the author reported high level of errors related to the AugBMP test gas measurements, the ability of the method to accurately predict the biodegradable composition of an unknown substrate, regardless of the gas measurement errors, makes it especially useful. This usefulness is recognized by understanding that (i) the determination of the substrate composition using the mathematical models does not require the methane gas volume as a variable (the change in the AugBMP COD can be used instead or in addition to the methane measurements), and (ii) the PWM_SA_AD model, together with the PE function, can be used to reconcile the parameters from the inaccurate gas measurement data, thus minimising the measurement errors (Gaszynski, 2020: 326). To allow for the statistical analysis and reproducibility, it is recommended that all the AugBMP experiments be carried out in triplicates

(Filer, Ding & Chang, 2019). The ability of the AugBMP test to distinguish between the unbiodegradable particulate organics (UPOs) and biodegradable particulate organics (BPOs) of an unknown substrate allows for the X_{U_Inf} and X_{B_Inf} proportions for each of the SVGs to be determined.

2.6.3. Anaerobic digestion microbiological processes

A typical PSS substrate fed into an AD (or undergoing the AugBMP test) is characterized by greater quantities of BPO, UPO, and ISS. The hydrolysis of the complex polymers, namely carbohydrates, proteins, and lipids, represents the first step in the anaerobic digestion process (**Figure 2.11A**). Unfortunately, the composition of the BPO in the PSS substrate to undergo degradation in an AD system is often unknown. As a result, Sötemann *et al.* (2005: 547) modified the composition of the influent complex matter from proteins, carbohydrates, and lipids to a more generic $C_xH_yO_zN_A$ composition (**Figure 2.11B**). As evident in **Figure 2.11**, the acidogenesis fermentation and anaerobic oxidation processes by Gujer and Zehnder (1983) to form acetate, hydrogen, and CO_2 fall off and are replaced by considering the acidogenesis at high and low partial pressures (p_{H_2}). Instead of amino acids, sugars, and fatty acids resulting from hydrolysis, a single hydrolysis product, namely glucose, is reported. Propionate forms at high p_{H_2} , while acetate, hydrogen, and CO_2 form at low and high p_{H_2} . This simplification was described to be sensible given that the hydrolysis end-products (CH_4 and CO_2) are comparable with those reported by Gujer and Zehnder (1983).

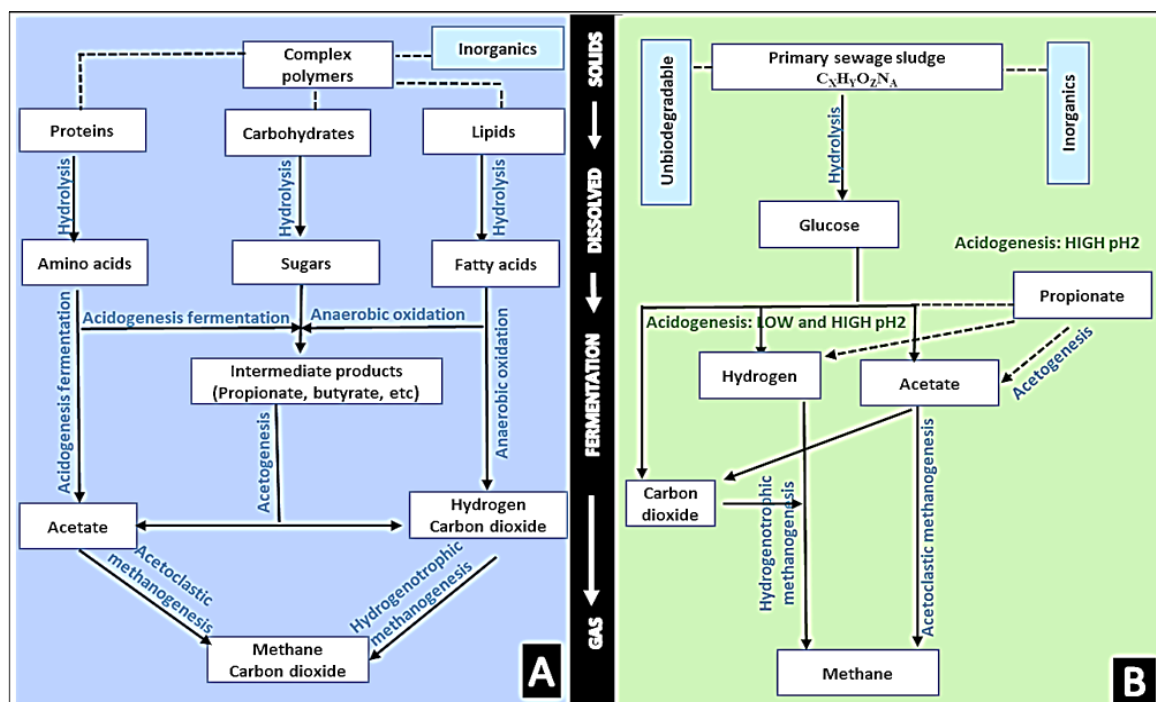


Figure 2.11: The AD microbiological processes of: (A) Gujer and Zehnder (1983) and (B) the primary sewage sludge generic microbiological processes. Adapted from Sötemann *et al.* (2005b).

2.6.4. Modelling anaerobic digestion processes

The modelling of the AD processes has progressed over the years aiming to precisely simulate the reality. The AD virtual models set a foundation for the optimised systems through the detailed understanding of the thermodynamics, reaction kinetics, and conservation laws. The AD modelling has focused on both the steady-state (SS) and dynamic models. The SS models consider variables to be constant relative to time, while the dynamic models are associated with a high level of detail, including the varying loads and flows relative to time. The SS models are often used to establish the system design parameters, including the sizing of the units, retention time, kinetic rates, sludge composition, and recycle ratios, which are subsequently optimised in line with the system dynamic behaviours. The AD system dynamics are rooted in the interactions between the biological processes and system weak acid-base (A/B) chemistry. The inclusion of these interactions in the early models is not as explicit due to the complexity of the related processes (Ghoor, 2019: 26). This has, however, improved in the recent AD models, which accounts for the necessary interactions in a more generalized way centred on (i) the bioprocess stoichiometry, and (ii) the mass and charge balances (Ghoor, 2019: 26). Such recent models include (i) the International Water Association Anaerobic Digestion Model No 1 (IWA ADM1) developed by Batstone *et al.* (2002), and (ii) the University of Cape Town Anaerobic Digestion Model No 1 (UCTADM1) developed by Sötemann *et al.* (2005b). The IWA ADM1 is a dynamic model based on the disintegration of complex matter into carbohydrates, proteins, and lipids, with the hydrolysis products being sugars, amino acids, and fatty acids (**Figure 2.11A**) (Batstone *et al.*, 2002). In contrast, the UCTADM1 is a two-phase (aqueous-gas) model in which the hydrolysis product of the complex organics is glucose, thus, it follows the micro-biological processes shown in **Figure 2.11B**. Sötemann *et al.* (2005b) mention that while the UCTADM1 was not validated for dynamic conditions, it can be applied to such conditions (dynamic conditions).

A steady-state (SS) model was developed by Sötemann *et al.* (2005a) by simplifying the two-phase UCTADM1 of Sötemann *et al.* (2005b). This SS AD model covers three key parts as follows:

- a. Kinetics: for a given R_s , the percentage COD removal and CH_4 production are determined.
- b. Stoichiometry: the CO_2 partial pressure (P_{CO_2}), NH_3 released, and alkalinity generated are determined from the percentage COD removal.
- c. Carbonate system weak A/B chemistry: the digester pH is determined from the P_{CO_2} , and the alkalinity generated.

The SS model by Sötemann *et al.* (2005a) was further extended towards the development of a SS UCTADM-3P model as follows:

- a. Stoichiometric part: extended by Harding *et al.* (2009) to include (i) the biomass phosphorus (P), and (ii) the polyphosphate-accumulating organisms (PAOs) polyphosphate (PP) with its counter-ion metals. Hence, the SS AD model of the nitrification-denitrification (ND) excess biological phosphorus removal (EBPR) waste activated sludge (WAS) was developed.
- b. Mixed weak acid/base chemistry part: extended by Brouckaert *et al.* (2010) to include the three-phase (aqueous-gas-solid) weak A/B chemistry to cater for the precipitation of multiple minerals from the AD of the NDBEPR WAS containing PAOs.
- c. Kinetic part: extended by Ikumi (2011) to include the hydrolysis kinetic rates of (i) the PSS, (ii) the ND WAS, (iii) the NDEBPR WAS, and (iv) the PS-WAS blends, each with a unique CHONP composition. This was included in the stoichiometric part of the SS AD model developed by Harding *et al.* (2009).

The SS AD models above served as foundations for the determination of sludge compositions and kinetic rates for the dynamic model inputs along with their calibration (Ikumi *et al.*, 2015). It is important to note that the SS and dynamic models are based on similar stoichiometric and mass balances principles.

After separately calibrating the models (Ikumi *et al.*, 2014), Ikumi *et al.* (2015) combined the UCTADM-3P and three-phase activated sludge dynamic model (ASM2-3P) to build an integrated mass balanced three-phase plant-wide model in WEST[®]. The increase in complexity to model a three-phase plant-wide configuration necessitated coding in the WEST[®] platform. The WEST[®] program is capable of simulating many WWTP bioprocesses. This plant-wide model was later extended to include the UCTPSU model (see **Section 2.4.2**). The ASM2-3P was developed by extending the NDBEPR model of Henze *et al.* (1995) to make it compatible with the UCTADM-3P. The UCTADM-3P in WEST[®] is referred to as the AD model subset PWM_SA (PWM_SA_AD) model and was later extended by Ghoor (2019) to include the biological sulphate reduction (BSR) process.

Although a plant-wide model is most useful to simulate a wholistic WWTP, Ikumi *et al.* (2015) stated that the UCTADM-3P model (also referred to as PWM_SA_AD model) can be used on its own to simulate the AD system performance. From this understanding, the PWM_SA_AD model has the potential to make the necessary predictions (i.e., COD removal, N, P, and alkalinity releases) as required for the present study. As supported by Gaszynski (2020), the parameter estimation tool

(discussed in **Section 2.7** below) can be used together with the PWM_SA_AD model to reconcile the input parameters for the most accurate predictions.

2.7. Parameter estimation

Gaszynski (2020: 42) defined the parameter estimation (PE) process as one that allows for the determination of the desired parameters using a given set of variables. The PE function is fixed in the DHI WEST[®] software. The parameters include (i) the composition of the organics (f_{cv} , f_c , f_n , f_p , and f_s), (ii) the growth and/or death rates of the organisms (K_M , b_H), and (iii) the fraction of the COD that is unbiodegradable particulate ($f_{s'up}$). The desired output concentrations (from the laboratory experimental data) are set as the target values. Thereafter, a single, or set of parameters, are adjusted accordingly until the target values are met. During the PE process, the experimentally measured target values and model predicted variables are compared until the error between the predicted and experimental values is minimal. The PE tool or function is essential for the present study, and it will be used to identify the accurate parameters using the experimentally measured data as a base.

2.8. Summary

In this literature review chapter, the WW characteristics, FS-PST configurations, PST settling characteristics, DDPST model, and the 5C-settleometer have been reviewed and described briefly. From this review, it emerged that although the 5C-settleometer instrument has previously been used to segregate the settleable solids into five different SVGs, the instrument accuracy and reliability have not yet been verified. This verification is regarded as important given that the DDPST model depends on it to simulate a specific FS-PST. The AugBMP experimental procedure accompanies the 5C-settleometer to allow the determination of the BPOset and UPOset contents of the settleometer underflow VSetS. In addition, the PE function and AD model can be used to reconcile the experimental data errors, thus leading to more accurate model parameters. The success in verifying the 5C-settleometer is regarded the first step towards gaining confidence in the DDPST model predictions.

CHAPTER 3:

RESEARCH

METHODOLOGY

Chapter 3: Research methodology

3.1. Introduction

This chapter details the research approach and investigative methods applied towards data collection and analysis, and the interpretation of the findings that are in line with the objectives set in **Chapter 1**. In the present study, a deductive research approach was followed such that the systematic experimental observations were made to test the hypothesis made from the existing theories (Rossiter, 2013: 16–17). Having synthesized the existing sources of information related to the effectiveness of a five column (5C) settleometer (described in **Section 2.5**), it has been hypothesized that this device has a potential to segregate the raw wastewater (WW) settleable particles into five different settling velocity groups (SVGs). Given that this hypothesis has not yet been verified, the primary experimental data will be collected to allow the necessary evaluations. The analysis of the results will determine whether to support or reject the developed hypothesis. Although the inclusion of the inductive research approach can play a role in modifying the existing theory in view of the experimental results, it falls outside the scope of the present study and therefore could only be recommended for future studies.

Since this study seeks to verify the effectiveness of the settleometer to provide the settleability data required to evaluate the DDPST model, two fundamental concepts are essential viz. (i) “accuracy” and (ii) “reliability”. The term accuracy refers to the proximity of the measured data to the actual value, while reliability refers to the consistency in the measured data (Middleton, 2019). These two concepts will be used to interpret the quality of the data generated. This implies that the level of accuracy at which the DDPST model is able to replicate the FS-PST data is dependent on the accuracy and reliability of the settleometer to generate the required input data for the model. Therefore, to begin this study, understanding the overall DDPST model variables and their relationship with the settleometer is of importance (see **Section 2.5**). The sections below describe how this study will be conducted.

Figure 3.1 outlines the flow of the research process for the present study. For the experimental part, the first step is to operate an anaerobic digestion (AD) system to generate an inoculum required to carry out an augmented biomethane potential test (AugBMP test; described in **Section 2.6**). The set-up, operation, feedstock, and monitoring processes of this AD system will be described. Following this, the processes to segregate the primary sewage sludge (PSS) into different settling velocity groups (SVGs) using the 5C-settleometer will be discussed for both the trial runs (TrRs) and test runs (TeRs).

Thereafter, the PST diurnal data collection for a selected full-scale wastewater treatment plant (WWTP) will be discussed. The real FS-PST diurnal data collection will generate data that will later be compared with the DDPST model predictions; therefore, the FS-PST data collection will be performed in parallel with the 5C-settleometer TeRs to allow the same wastewater to be used in both cases. The processes behind the AugBMP test, which are fundamental to determining the biodegradability of the 5C-settleometer TeR outputs, will follow. This is then followed by the processes used in interpreting and evaluating the data, including (i) the parameter estimation (PE) techniques used to determine the parameters from the measured data, and (ii) the procedures used in fractionating the sewage solids into the settleable biodegradable particulate organics (BPOset), settleable unbiodegradable particulate organics (UPOset), and inorganic settleable solids (ISetS). To conclude the methodology section, the holistic data processing and evaluation procedure will be provided. These processes are described in detail, and the related challenges and limitations concerned are highlighted.

Briefly, the DDPST model calibration involves three main steps, viz. (i) the mass balance verification to show the internal consistency and reasonable outputs, (ii) the general sensitivity analysis (GSA) to identify the most important parameters required by the DDPST model to allow the accurate predictions, and (iii) the physical acquisition of the plant-specific parameters to ultimately calibrate the DDPST model using a specific plant. As discussed in **Chapter 2** above, the first step related to the mass balance verification was performed by Polorigni *et al.* (2021), while the second step was performed by Matesun *et al.* (2021). The present study, therefore, concludes the process by evaluating the DDPST model through outlining the steps required to acquire the plant specific data. A special reference is made to the identified significant model parameters, that is, particle settling velocities and settling proportions.

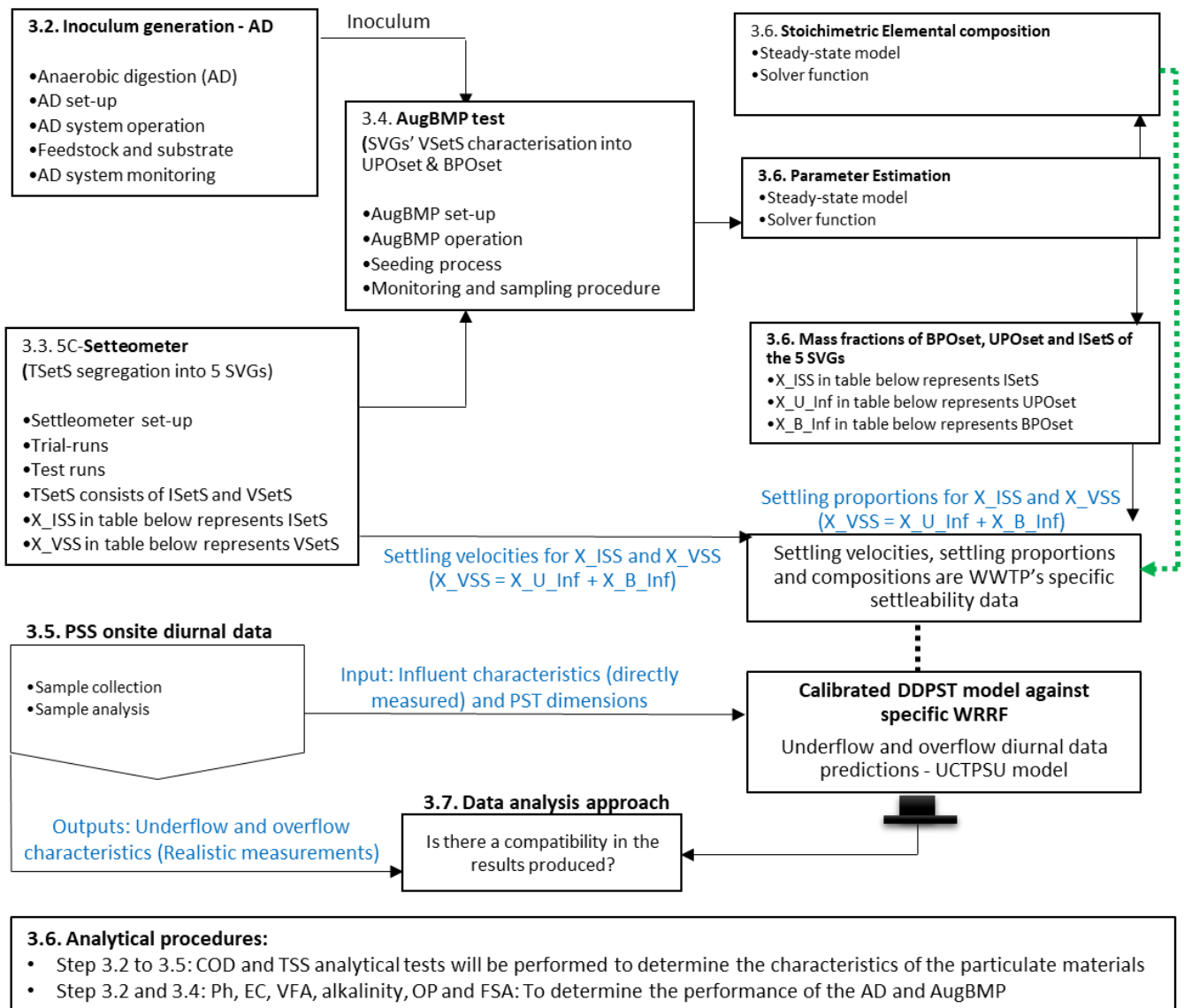


Figure 3.1: The experimental set-up flow for this project

3.2. Inoculum generation

3.2.1. Overview

The biodegradability test described in **Section 2.6** is performed to distinguish between the BPOset and UPOset components of the volatile settleable solids (VSetS). This test requires the inoculum mass to act as the microorganism seed essential to the breakdown of the BPOset component of the substrate. In the case of this study, the substrates to be tested are the solids collected in the 5C-settleometer during the TeRs. Two laboratory-scale anaerobic digestion (AD) systems with the design shown in **Figure 3.2** were used to generate this inoculum seed. These two AD systems will be referred to as the parent anaerobic digestion (PAD) systems in this study. The operation of the PAD systems took place at the University of Cape Town (UCT) Water Quality Laboratory (WQL). They were operated at a sludge age (R_s) of 36 days (each digester with an 18L digester operation volume divided by the

daily waste flow of 0.5L). Essentially, it took approximately two months for the AD systems to reach the steady state (SS) in terms of chemical oxygen demand (COD) and biogas production. The set-up operation, and the feeding and monitoring of the PAD systems towards generating the inoculum seed sludge are presented in **Sections 3.2.2 to 3.2.5** below.

3.2.2. Anaerobic digestion set-up

A continuously stirred tank (CSTR) PAD set-up was chosen for the present study. The configuration consisted of a 20L digester vessel that allowed an 18L operating volume and a 2L headspace. The two vessels were secured in a vertical position, and each connected to a mixer motor to allow for the completely mixed AD conditions. A free moving digester mixer is constructed parallel to the vertical position of the vessels (**Figure 3.2**). The PAD systems were operated between 36–38°C temperature to allow for mesophilic conditions. Each of the vessel lids, adjacent to the reactor headspace, contained three small openings, each playing a unique role, that is, allowing for (i) the system feeding, (ii) the temperature control, and (iii) the gas exit. The effluent opening was located at the bottom end of the vessel, for both digesters. An extended flexible tube was connected to the effluent opening to ensure minimal loss of effluent during the sludge withdrawal process. Silicone grease was applied to the contact surfaces, between the openings and connecting tubes, to ensure that there was no escape of gas. The gas opening was also equipped with a flexible tube connected to a gas meter to measure the content of produced gas. The PAD system can be difficult to operate, however, this specific set-up was regarded simple.

3.2.3. Parent anaerobic digestion operation

Prior to starting the operations of the PAD systems, a leak test around the digester vessels was performed. This was done using a water-soap spray method. According to this method, a mixture of water and soap is sprayed around the contact surface joints and valves. By pressurizing nitrogen gas into the system, the leak areas were identified by the occurrence of bubbles. The leaks were then sealed with silicone grease and let to dry. Once all the leaks were fixed, the systems were ready to operate. The effluent waste sludge from an existing laboratory AD system was collected and stored in a 4 °C room until a volume of approximately 15L was accumulated. This collected waste sludge contained the AD microorganism cultures required to start the PAD systems used in this study. Additional 3L of water were added to the 15L of AD effluent sludge to make up the operating volume of 18L with a 2L headspace, for each of the PAD systems. The system was operated for two consecutive days before commencing the actual PAD feeding process. It is important to note that, at

this stage, the mesophilic temperature was correctly set at 36°C, and the stirrer was completely mixing at 25 Hz/RPM.

The growth of the PAD inoculum was facilitated using the decanting-feeding process. This is a process whereby a specified effluent volume withdrawn from the system is replaced by equal volumes of feedstock or substrate. The decanting always followed the feeding process. Depending on the response of the system, in terms pH levels and alkalinity, the daily system flow ranged between 300–500 l/day until the system achieved steady state. The feedstock consisted of diluted primary sewage sludge (PSS). Prior to dilution, the COD of the PSS used as feed ranged between 28 000–46 000 mgCOD/l. This PSS was first diluted at a PSS:water (lukewarm) ratio of 4:1 each time before feeding to limit shocks to the operating PAD system (see **Section 3.2.4** below). When drawing out samples from the systems, one had to ensure that the opening cap used for feeding (See **Figure 3.2**) was primarily removed. This was to prevent a sudden pressure drop that could lead to water flowing from the gas-meter container into the digester. Also, before decanting, it was important to ensure that the system was completely mixed to avoid the withdrawal of the accumulated solids, which would reduce the system solids inappropriately.

3.2.4. Parent anaerobic digestion feedstock

The PSS used as the feedstock to the PAD systems was initially (for the first six weeks) sourced from the Potsdam Wastewater Treatment Works (WWTWs) located in Milnerton. However, after the decommissioning of the Potsdam PST, this was no longer possible. Hence, the Bellville WWTW was used as the alternate source of PSS for the remainder of the experimental investigation period. The Bellville PSS had lower pH levels of approximately 4.60–5.00, compared with the Potsdam PSS pH levels of approximately 6.23–6.52. In the first few days of feeding the PAD system with the Bellville PSS, slight drops in the pH levels of the systems were observed. The pH levels dropped from approximately 7.00 to approximately 6.70. The systems, however, rapidly recovered after dosing approximately 5g of sodium bicarbonate (NaHCO_3) for the first few days. The PSSs, from both Potsdam and Bellville, were collected in batches of 50L. Soon after the delivery to the UCT WQL, the PSS was immediately macerated and distributed into small bottles (approximately 5L), for daily use. The excess 5L sludge bottles were stored in a deep freezer to limit sludge biological and chemical alterations. These bottles were taken out, one after the other, and stored in a 4°C room to allow for defrost and be ready to feed the systems. As mentioned in **Section 3.2.3** above, before feeding, the PSS was first diluted with lukewarm water to adjust the feed temperature, thus avoiding temperature shock in the AD systems, which would decrease the PAD microorganism activities. This process was repeated until the microorganisms were stable enough for use as inoculum during the biodegradability

test. The stability of the microorganisms was determined by the consistency in the COD and biogas production.

3.2.5. Parent anaerobic digestion system monitoring

The temperature, pH, alkalinity, volatile fatty acid (VFA) concentrations, and biogas production were continuously monitored for the duration of the PAD system operations. These four indicators were used to detect the early signs of system failure. The temperature was kept at mesophilic condition to avoid the negative impacts on the microbiological processes, while the pH levels were kept well within the range of 6.8–7.2. The pH levels were always tested immediately after the effluent withdrawals to avoid the CO₂ escaping from the systems, which would raise the pH levels, thereby leading to incorrect readings. The buffering capacity, of the PAD systems, was also monitored by tracking the alkalinity and VFA concentrations. The alkalinity to VFAs ratio was kept lower than 3:1 with the alkalinity being continuous from approximately 800 mgCaCO₃/l, in the first week, to approximately 2500 mgCaCO₃/l, in the eighth week. The biogas production was monitored using the wet-tip gas meter method. Few leaks were detected during the system operations, which led to no gas readings on the gas meter. This defect was immediately corrected using a water-soap spray method (see **Section 3.2.3**). The temperature, biogas, and pH checks were done daily at each feeding cycle.

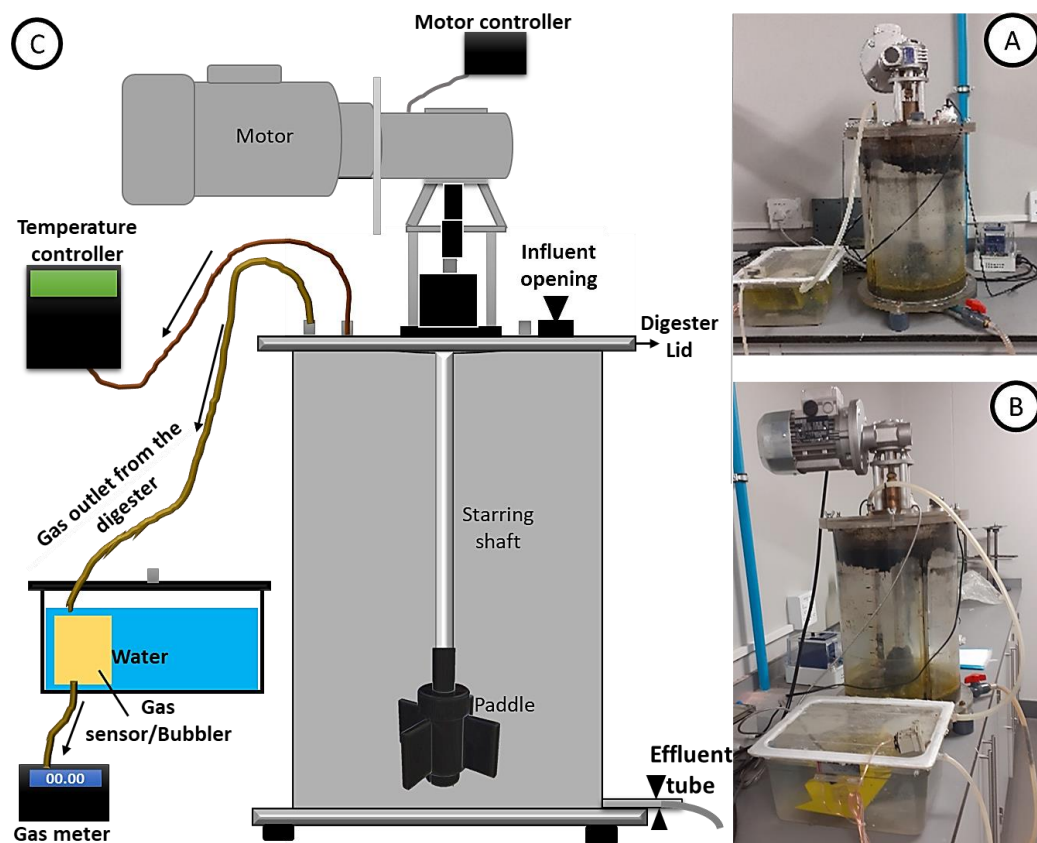


Figure 3.2: The PAD reactor set-up: (A) Front view, (B) side view, and (C) the PAD schematic diagram.

3.3. 5C-Settleometer

3.3.1. Overview

While generating the PSS inoculum, the 5C-settleometer set-up also commenced. The set-up began instantly after the stability in the biogas release and COD was observed from an active PAD system. The subsections below describe how the 5C-settleometer processes were carried out.

3.3.2. Five-column settleometer instrumentation set-up

The 5C-settleometer design, as described in **Section 2.5**, was used for this experimentation. As illustrated in **Figure 3.3A**, the settleometer column diameter increases progressively from left to right (45.2, 67.6, 86.4, 105.6, to 134.4mm), thus allowing the upflow velocity (V_{up}) to decrease across the columns. The decreasing V_{up} allows for the particle settling velocities (V_s) to also decrease across the columns. To facilitate the raw WW inflow into the 5C-settleometer, a pump, shown in **Figure 3.3B**, was used. This pump was controlled manually using a pump controller as shown in **Figure 3.3C**. The main purpose of the pump controller was to adjust the required flow rate into the 5C-settleometer.

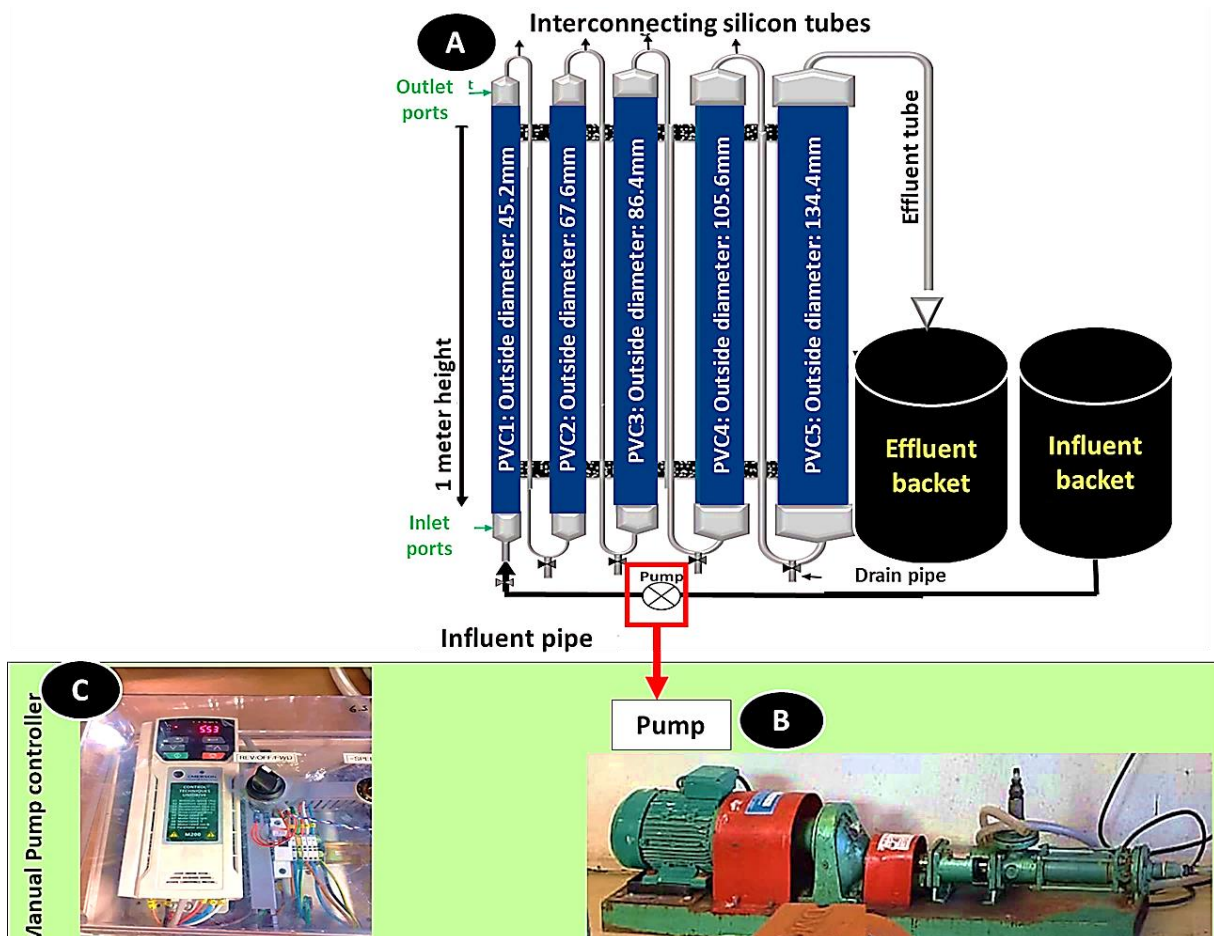


Figure 3.3: The five-column 5C-settleometer design (Amended from Poinapen et al. [2009]).

3.3.3. Five-column settleometer operational methods

Two methods were considered to draw the raw influent into the 5C-settleometer. These are (i) the pumping method, and (ii) the sucking method. As illustrated in **Figure 3.4A**, the pumping method involves pumping the influent WW from the influent bucket into the settleometer first column. Once the flow reaches the last column, it is released into the effluent bucket as overflow. The sucking method on the other hand, as illustrated in **Figure 3.4B**, involves drawing the influent from the influent bucket directly into the settleometer first column. Once the flow reaches the last columns, it is pumped out as effluent. Essentially, in the sucking method, the influent does not pass through the pump first, but rather, after flowing through the settleometer. This implies that the influent particles are not subjected to the pressures of the pump, while the effluent, which ideally should not contain any settleable particles, is.

Although the sucking method may add advantages, when it comes to limiting solids breakdown and eliminating the formation of bubbles that interfere with particles settling, it also has significant disadvantages as follows: it requires to first fill up the columns with liquids to allow suction. This is because when the columns are empty, the pump does not exert enough pressure to pull the inflow from the influent bucket into the settleometer. To fill the columns, water or influent WW can be used. In the present study, however, when water was used, an undesirable dilution effect that changed the characteristics of the influent prevailed; hence, the method could not be used. On the other hand, pumping WW to fill the columns before allowing suction defeats the whole purpose of the sucking method given that the first 35L inflow would have to go through the pump before reaching the settleometer effluent. For these reasons, a pumping method was rather preferred in this study. As for the concern of exposing the particles to the pressures of the pump, there is currently no substantial evidence confirming the particle breakdown inside the pump, hence, in this study, it was assumed that the pump does not change the state of the particles.

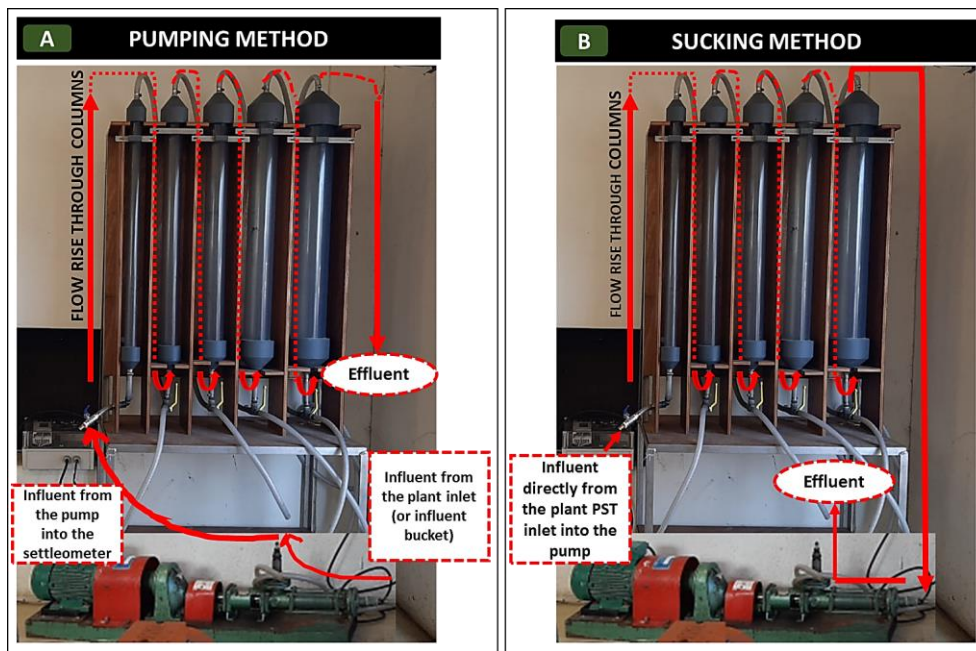


Figure 3.4: The illustrations of (A) the pumping method, and (B) the sucking method for the settleometer operation.

3.3.4. Five-column settleometer trial runs

Prior to the main onsite testing, the 5C-settleometer trial runs (TrRs) were carried out at the UCT WQL. This was to inspect the functionality of the system in terms of leakages or any other defects that may hinder provision of accurate results. To start the process, the device was first primed using clean water. Priming is important given that it minimises the odds of pump damage and sets a foundation for the system optimum functionality. The water was pumped into the 5C-settleometer from the smallest to the largest diameter column (from left to right). The 5C-settleometer influent pipe, as shown in **Figure 3.3**, carries the influent into the settleometer columns, while the effluent pipe carries the overflow from the last column into the effluent collection drum. Once all the leakages and defects were identified and fixed, the water in the device was emptied.

Before pumping the actual wastewater into the 5C-settleometer, trial-and-error pump settings were performed to identify the pump frequency required to achieve a desired flow rate. These trial-and-error pump settings were carried out using clean water. After a few attempts, it was found that setting a pump at a frequency between 5–6 Hz allows the settleometer effluent flow rate ($Q_{5SET,eff}$) of approximately 0.6 l/min. The $Q_{5SET,eff}$ is assumed to be equal to the settleometer influent flow rate ($Q_{5SET,inf}$). Basically, the $Q_{5SET,eff}$ is calculated using **Equation (3.1)** as previously adapted by Paleker (2018), Motokwane (2019), and Kirby (2020) and Notoane (2020). According to this equation, the time taken (t_{eff}) to fill up a specified volumetric flask (e.g., a 3L volumetric flask) by the 5C-settleometer effluent volume ($V_{5SET,eff}$) is recorded. Alternatively, the $V_{5SET,eff}$ occupying a

volumetric flask in 60 minutes is recorded. These readings were taken at time intervals of approximately 15 minutes each to get an average flow rate for a trial duration. The 0.6 l/min was set as the base flow rate, and the necessary adjustments were applied to the TrRs depending on the outcomes of the base flow rate.

The raw WW to be pumped into the settleometer columns during the TrRs comprised a mixture of 1% PSS and 99% settled WW. The aim of pumping raw WW into the settleometer is to create a full-scale scenario where raw WW enters the PST, thereby allowing settleable particulates to accumulate at the bottom, while settled WW flows into the activated sludge system (ASS). While it was possible to pump raw WW directly, without having to mix PSS and settled WW, the aim was to gather actual PSS and settled WW concentrations to check whether the initially recorded concentrations can be obtained when the WW flows through the settleometer. The ratio of 1:99 (PSS: Settled WW) was chosen assuming that 99% of the raw WW progresses to the ASS, as overflow, while the other 1% forms part of the underflow of a PST. It is important to note that the PSS and settled WW for these trials were collected during the rainy season (May 2021, Cape Town, South Africa), and therefore, the WW concentrations might be slightly lower than would be recorded under dry weather conditions.

Three sets of TrRs were performed, and it was necessary to prepare a new PSS-settled WW mixture for each trial. The first two trials comprised a PSS-settled WW mixture from the Potsdam WWTW, while the third TrR comprised a PSS-settled WW mixture from the Bellville WWTW (see **Section 3.2.4**). Although the Potsdam trials may have proved the system functionality, the shift to the Bellville WWTW (see **Section 3.2.4**) necessitated the TrRs on Bellville WW to provide basic understanding of the plant WW characteristics and WW behaviour in a settleometer. The three TrRs were carried out at different flow rates to determine the optimum flow rate in terms of (i) that which allowed the maximum settling with a definite particle distribution, and (ii) that which yielded settleometer effluent characteristics that were comparable with the primary settled WW (i.e., before mixing with the PSS).

3.3.4.1. 5C-settleometer trial run 1 (TrR1): ~ 0.6 l/min - Potsdam wastewater

The first trial was set to run at a flow rate of approximately 0.6 l/min, adapting a pump frequency of approximately 5.8 Hz. To start the run, the influent pipe was fully submerged into a continuously stirred raw WW bucket. The pump controller was then turned on to allow the WW inflow into the settleometer PVC1 (**Figure 3.3A**). Once the settled WW reached the last PVC column and started overflowing, the effluent volume occupying a volumetric flask after 60 minutes was recorded at intervals of 15 minutes. The average $Q_{5SET,eff}$ was then calculated using **Equation (3.1)**. From the

calculated $Q_{5SET,eff}$, the V_{up} of each of the respective columns was, thereafter, calculated using **Equation (3.2)**.

First trial outcomes, challenges, and attempted solutions

The pump controller was set at approximately 5.8 Hz, aiming for 0.6 l/min. However, the recorded $Q_{5SET,eff}$ was merely 0.3 l/min. This discrepancy raised questions and necessitated repeating the trial. After numerous repeats, an approximate 6 Hz pump frequency proved to correspond with the $Q_{5SET,eff}$ of approximately 0.35 l/min. Another attempt using clean water was made to verify the value of 0.6 l/min, previously obtained, and the outcomes yielded the same average value of 0.6 l/min, thereby proving it. The inconsistencies between the runs of $Q_{5SET,eff}$, obtained from the clean water versus WW, required further investigation on the relationship between the flow rates in the respective PVC columns. This step was necessary given that incorrect flow rate will, with no doubt, lead to incorrect V_{up} estimations, and ultimately incorrect particle velocities and segregations. To remediate this, the following approach, referred to as “Method 2” in **Table 3.1**, was considered:

- i. The $Q_{5SET,inf}$ was calculated for each column, instead of waiting for the flow to reach the last column and eventually to overflow. This was done by recording the time taken by the inflow to move through a selected distance of the column height (D_{sel}) (e.g., 50 mm distance of the 1 m PVC column height) (**Step 6.i. of Table 3.1**).
- ii. The volume occupying the D_{sel} was calculated (**Step 6. ii. of Table 3.1**) using the PVC column radius (r_{pvcn}) (**Step 3 and 4. of Table 3.1**).
- iii. The PVC column flow rate (Q_{pvcn}) was calculated (**Step 6. iv. of Table 3.1**) by dividing the volume by the recorded time (**Step 6.iii. of Table 3.1**).
- iv. The above steps were repeated from the PVC1 to PVC5, and the respective flow rates were recorded.

The outcomes from the Method 2 approach revealed that for a given constant pump rate, the flow rate decreases progressively from the PVC1 to PVC5, and subsequently overflows (**Figure 3.6** and **Figure 3.7A**). This gradual decrease implies that using the $Q_{5SET,eff}$ to calculate the column V_{up} may not be correct. For instance, as shown in **Figure 3.6**, using $Q_{5SET,eff}$ to calculate the V_{up} underestimates the PVC column V_{up} . Therefore, it is important to use the correct flow rate to avoid any V_{up} incorrect estimations.

Two main factors may have contributed to the flow rate decrease across the columns. These include (i) the presence of bends, rises, and falls on the designed 5C-settleometer (**Figure 3.5**), and (ii) the occurrences of particle accumulation in the PVC columns during operation, which increases the flow

resistance. According to Jayanti (2011), the presence of bends on a pipe system causes pressure losses, which then decreases the overall flow rates. These could be caused by friction and momentum exchanges, which result from the change in the direction of flow. The bends, rises, and falls are part of the design of the used 5C-settleometer device. To overcome this issue, the pressure losses during the 5C-settleometer operation may need to be investigated in further studies that seek to improve its design.

From the discussion above, it is evident that while it is possible for the influent flow to move from one column to the other, the pressure loss effects compromise the proper segregation of particles through incorrect V_{UP} . For convenience, in the present study, the pump controller (which controls the flow rate into the settleometer, see **Section 3.3.2**) required to be manually adjusted, as necessary, throughout the settleometer columns to maintain a constant flow rate right across the PVC columns. The easy way to do this is to decide on a flow rate to operate the settleometer. Then, decide on the D_{sel} to use as a base for these measurements. The D_{sel} should be at least 10 times smaller than the column height to allow multiple time duration measurements per column. For the present study, the value of 50 mm (which is approximately 20 times smaller than the average PVC column height) is selected. Therefore, using **Equation (3.3)**, T_{sel} for the PVC1, PVC2, PV3, PVC4, and PVC5 can be calculated. It is important to note that for a constant flow rate, the T_{sel} would continuously increase across the columns due to the increase in the column diameter. Essentially, for each D_{sel} , at a given point, the corresponding T_{sel} should be achieved. Any deviations from the calculated T_{sel} would mean that the flow rate in that specific column has diverged and some careful pump controller adjustments may be necessary. The careful adjustments are vital to prevent the formation of bubbles, which may affect the particle settling or cause other issues related to the shooting of particles from one column to the other. By applying these steps, the approximate constant flow rate would be improved across the columns, thus improving the particle segregation.

$$Q_{5SET,eff} = \frac{V_{5SET,eff}}{T_{5SET,eff}} \quad (3.1)$$

$$V_{UP} = \frac{Q_{5SET,eff}}{A_{pvc,n}} \quad (3.2)$$

$$T_{Dsel} = \frac{A_{pvc,n} \times D_{sel}}{Q_{5SET,inf}} \quad (3.3)$$

Where: $Q_{5SET,eff}$ = 5C-settleometer effluent flow rate (outflow from PVC5) (l/min)

$Q_{5SET,inf}$ = 5C-settleometer influent flow rate (l/min)

$T_{5SET,eff}$ = Time taken to fill up a specified volumetric flask with the 5C-settleometer effluent (min)

$V_{5SET,eff}$ = 5C-settleometer effluent volume occupied in $T_{5SET,eff}$ (m³)

V_{UP} = Upflow velocity in the respective PVC1, PVC2, PVC3, PVC4, and PVC5 (m/hr)

$A_{pvc,n} = \pi r^2$ = Internal area for each of the five PVC columns (ie. n = 1, 2, 3, 4, 5) (m²)

D_{sel} = Selected distance on a PVC column height

$A_{pvc,n} \times D_{sel}$ = Volume (m³) occupied at D_{sel}

Table 3.1: The flow rate (Q) and upflow velocities (V_{UP}) calculation steps.

Step	Description	Symbol	Formula/Source	PVC1	PVC2	PVC3	PVC4	PVC5	Units
1	Column Volume	Vol_{pvcn}	Direct measurement	1.8	4.3	6.2	9.5	15	L
2	Column Height	H_{pvcn}	Direct measurement	1	1	1	1	1	m
3	Column Diameter	ϕ_{pvcn}	n th PVC column diameter	45.2	67.6	86.4	105.6	134.4	mm
4	Column Radius	r_{pvcn}	$(\phi_{PVCn}/2)/1000$	0.0226	0.0338	0.0432	0.0528	0.0672	m
5	Column Area	A_{pvcn}	$\pi \times (r_{pvcn})^2$	0.0016	0.0036	0.0059	0.0088	0.0142	m ²
METHOD 1: Using effluent flow rate to calculate PVC columns upflow velocities									
6.a.	Effluent flow rate	$Q_{5SET,eff}$	Effluent volume/Time	Specific to a run	Specific to a run	Specific to a run	Specific to a run	Specific to a run	l/min
6.b.	Upflow velocity	V_{up}	$(Q_{5SET,eff} / A_{PVCn}) \times 60$	Specific to a run	Specific to a run	Specific to a run	Specific to a run	Specific to a run	m/hr
METHOD 2: Using PVC columns' flow rate to calculate the respective upflow velocities									
6.i.	Selected distance to measure flow rate	D_{sel}	Selected	50	50	50	50	50	mm
6.ii.	Volume at D_{sel}	Vol_{Dsen}	$(\pi r^2 D_{sel}) \times 1000$	0.0802	0.0802	0.0802	0.0802	0.0802	litre
6.iii.	Time taken for inflow to occupy D_{sel}	T_{Dsel}	Direct measurement						sec
6.iv	Flow rate	Q	$(Vol_{Dsen} / \text{time}) \times 60$	Specific to a run	Specific to a run	Specific to a run	Specific to a run	Specific to a run	l/min
6.v	Upflow velocity	V_{up}	$(Q_{PVCn} / A_{PVCn}) \times 60$						m/hr

Note: Method 1 represents a V_{up} calculation method previously adapted by Paleker(2018); Motokwane (2019); Kirby (2020) and Notoane (2020). Method 2 represent an alternate method to calculate V_{up} specific to a PVC column.

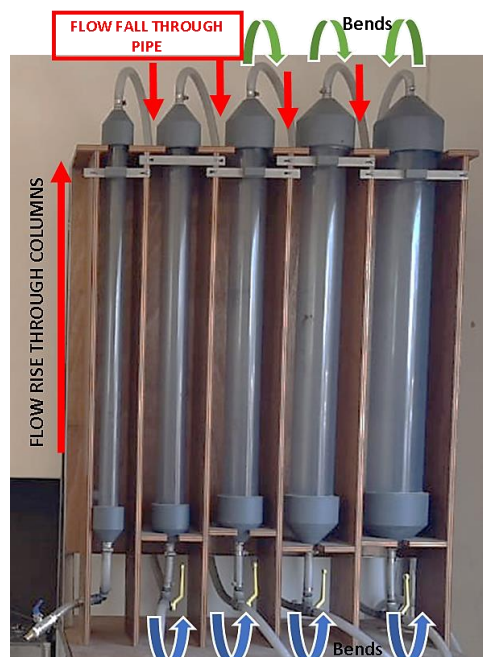


Figure 3.5: The bends, rises, and falls of the designed 5C-settleometer.

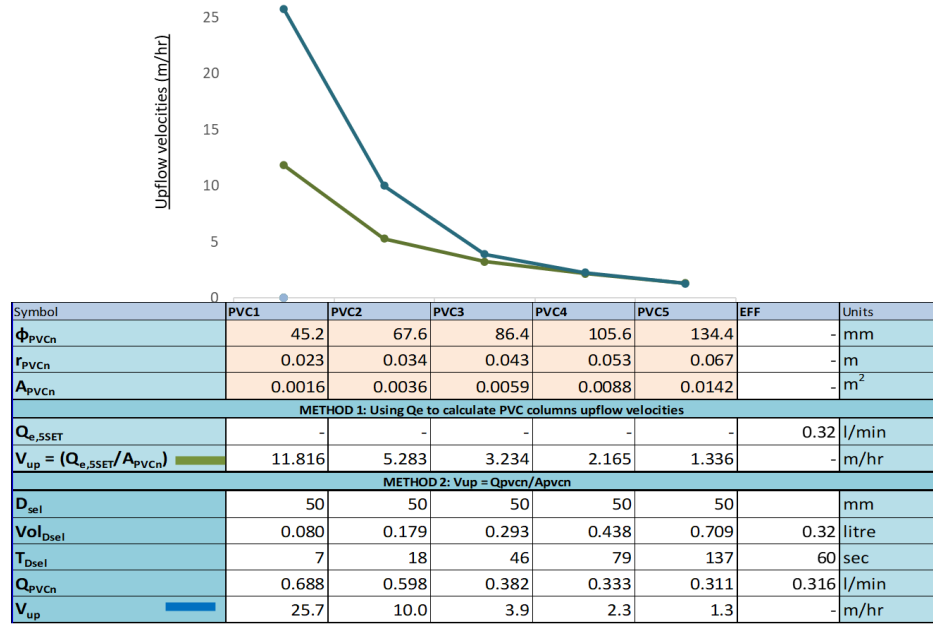


Figure 3.6: The V_{up} from $Q_{5SET,eff}$, versus V_{up} from the individual PVC flow rate. The steps followed to calculate these upflow velocities are presented in **Table 3.1**.

3.3.4.2. Repeat: 5C-settleometer TrR1: Constant flow rate: ~ 0.6 l/min - Potsdam WW

The trial run at approximately 0.6 l/min was repeated with the necessary adjustments on the pump to ensure constant flow rate across the PVC columns. The overall outcomes from this corrected trial are presented in **Figure 3.7**. The adjusted outcomes are plotted against the initial unadjusted flow rates to allow comparisons. As evident from the outcomes, the effect of decreasing the flow rate is apparent from the PVC3 to PVC5 (**Figure 3.7A**). As shown in **Figure 3.7B**, for a constant flow rate (green line graph), there is a greater particle accumulation in the PVC1, PVC2, and PVC3, corresponding with the V_{up} of 22.8, 10.2, and 6.2m/hr (green bars), respectively. The minimum particle accumulations are observed in the PVC4 and PVC5 corresponding with 4.2 and 2.6 m/hr, respectively. For the unadjusted flow rate (purple line graph), however, the greater particle accumulations occur in the PVC1 and PVC2 corresponding with 22.5 and 10m/hr (purple bars), respectively. A sharp drop in the flow rate, from the PVC2 to PVC3 (purple line graph), leads to the PVC3 having a V_{up} of approximately 3.9 m/hr, which then results in the minimum particle accumulation (**Figure 3.7B** - purple bars). The sharp drop in the particles from the PVC3 might be due to greater particle accumulations in the PVC1 and PVC2, which obstruct the inflow, and subsequently, hinder the particle upward movement. The particle segregation in **Figure 3.7B** makes it evident that an incorrect flow rate can potentially lead to an incorrect particle segregation.

The optimality of the selected flow rate is determined by similarities between the starting settled WW and the settleometer effluent characteristics. As shown in **Table 3.2**, for a constant flow rate of

approximately 0.6l/min, the settled WW TSS from the settleometer (278 mgTSS/l) appear to be slightly higher than the starting settled WW (167 mgTSS/l). This implies that the 0.6 l/min settleometer flow rate may need to be slightly lowered to ensure that all the necessary solids are captured in the settleometer. In terms of the mass balance (MB), an approximate 95.2% TSS mass balance was recorded, proving that the measured TSS mass in the system was reliable, i.e., there was reasonably good internal consistency in how the solids were tracked through the settleometer (**Table 3.2C**).

Table 3.2: The Potsdam WW characteristics: (A) the directly measured settled WW and PSS concentrations to generate a raw WW mixture; (B) the 5C-settleometer outcomes after the TrR using the raw WW mixture generated from A; and (C) the MB around the 5C-settleometer.

A: Potsdam approximate concentrations and masses/fluxes used to run settleometer TrRs									
Volume	53.5 L			0.535 L			52.965 L		
	100%			1%			99%		
	Raw (Calculated)			Primary sludge (Measured from actual PSS)			Settled WW (Measured)		
	mgTSS/l	gTSS		mgTSS/l	gTSS		mgTSS/l	gTSS	
TSS	443	23718		26908	14396		176	9322	
B: 5C-Settleometer outcomes									
	Raw (Calculated)			Primary sludge (Measured from actual PSS)			Settled WW (Measured)		
	mgTSS/l	gTSS		mgTSS/l	gTSS		mgTSS/l	gTSS	
TSS	486	26001		↓	↓		278	4587	
C: Settleometer Mass balance									
Symbol	Formula or Source	INF	PVC1	PVC2	PVC3	PVC4	PVC5	EFF	Units
Volume	Direct measurement	53.5	1.8	4.5	6.2	9.5	15.0	16.5	litre
TSS	Solids dried at 103-105 °C	486	1142	1224	944	318	236	278	mgTSS/l
M _{TSS}	Volume x TSS	26001	2056	5508	5853	3021	3540	4587	mgTSS
M _{TSS'PVC1-5}	M _{TSS'PVC1} + M _{TSS'PVC2} + M _{TSS'PVC3} + M _{TSS'PVC4} + M _{TSS'PVC5}				19977				mgTSS
M _{TSS'eff}	M _{TSS'eff}				4309				mgTSS
MB	((M _{TSS'PVC1-5} +M _{TSS'eff})/M _{TSS'int}) x 100				95.2				%

Note: M_{TSS'pvc,t} = Total TSS mass, i.e., in the PVC columns; M_{TSS'PVC1}, M_{TSS'PVC2}, M_{TSS'PVC3}, M_{TSS'PVC4}, and M_{TSS'PVC5} = TSS mass, i.e., in the PVC1, PVC2, PVC3, PVC4, and PVC5, respectively; M_{TSS'inf} and M_{TSS'eff} = TSS mass, i.e., in the influent and effluent, respectively.

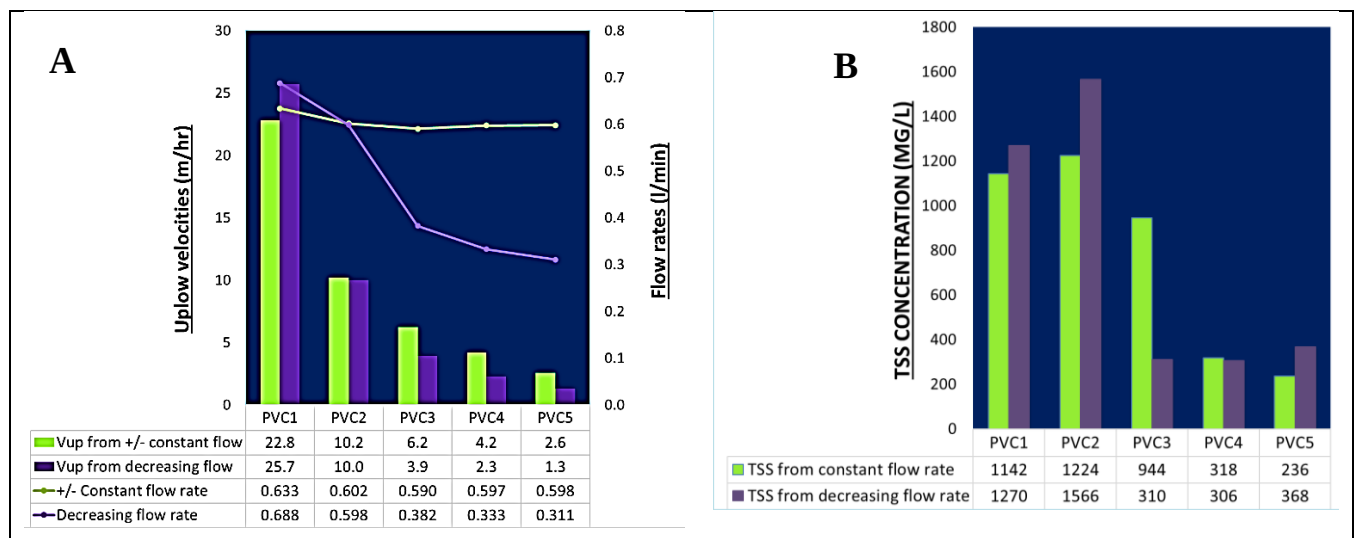


Figure 3.7: The plots of: (A) the adjusted (Method 2 in Table 3.1) versus the unadjusted (Method 1 in Table 3.1) flow rates with the corresponding upflow velocities, and (B) the TSS segregation between the columns for the adjusted versus the unadjusted upflow velocities.

3.3.4.3. 5C-settleometer trial run 2 (TrR2): ~ 1.21/min - Potsdam wastewater

The TrR2 was run at a flow rate of approximately 1.21 l/min. A high flow rate was selected to investigate the effect of the increased pressure on the particle segregation and flow inconsistencies. Two sets of trials were performed at this specific flow rate, i.e., (i) with the unadjusted pump controller and, (ii) with the adjusted pump controller, to maintain a constant flow rate as was previously done for TrR1. As illustrated in **Figure 3.8A**, unless the pump controller is adjusted to maintain a constant flow (green line graph), the flow rate decreases across the PVC columns (purple line graph). As opposed to a constant flow rate of 0.6 l/min, where the maximum settling is in the PVC1 and PVC2, the maximum settling, for the 0.6 l/min flow rate, shifted towards the PVC3 corresponding with the V_{up} of 12.0 m/hr. For the unadjusted flow rate (purple line graph), the settleometer PVC4 and PVC5 seem to be associated with lower flow rates corresponding with the V_{up} of 3.33 and 1.7 m/hr, respectively. The V_{up} of 3.33 and 1.7 m/hr are associated with the lower particle accumulations (**Figure 3.8B**). Lower particle accumulation has also been recorded in the PVC1 associated with the higher V_{UP} between 42–47m/hr.

The downside of running the 5C-settleometer at the higher flow rate of 1.2 l/min is that the overflow characteristics of the 5C-settleometer comprised higher TSS concentrations (382 mgTSS/l) than the starting settled WW (167 mgTSS/l). This implies that the flow rate was too high and needed to be lowered limit the escape of solids, which would otherwise form part of the PSS.

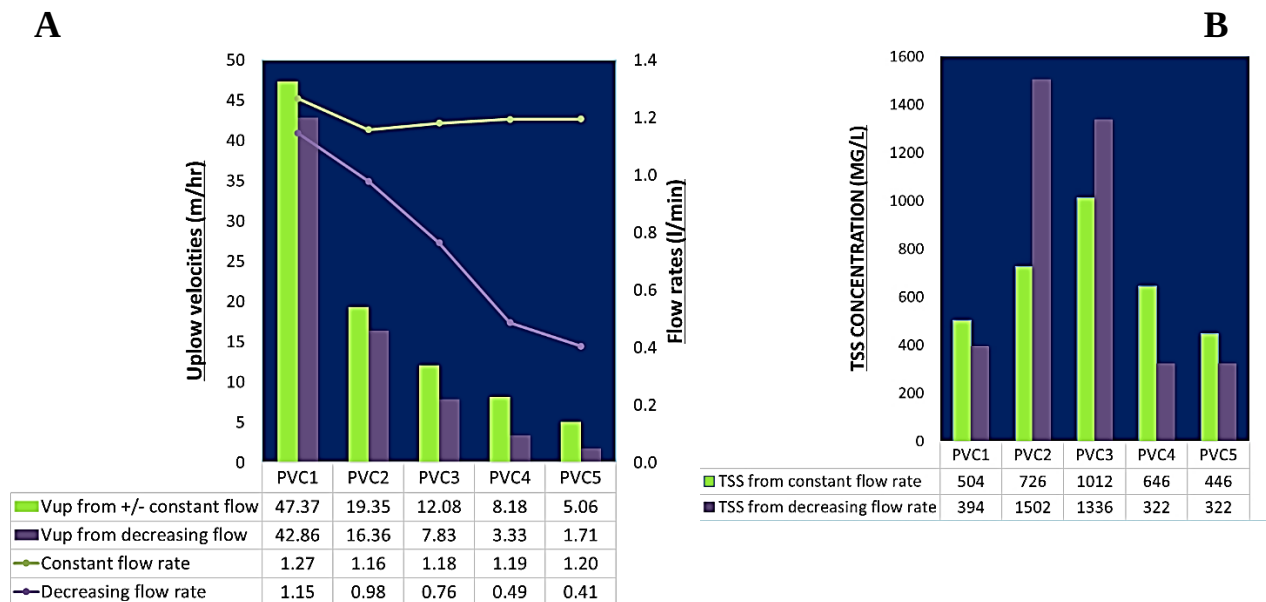


Figure 3.8: The plots of (A) the adjusted (Method 2 in **Table 3.1**) versus the unadjusted (Method 1 in **Table 3.1**) flow rates with their respective V_{up} at approximately 1.2 l/min, and (B) the TSS segregation between the columns for both the adjusted (green bars) and unadjusted (purple bars) upflow velocities.

3.3.4.4. 5C-settleometer trial run 3 (TrR3): ~ 0.52 l/min: Bellville wastewater

The TrR3, which comprised the mixture of the Bellville PSS and settled WW, was ran at a flow rate of approximately 0.52 l/min. Initially, it was planned that the flow rate would be lowered to approximately 0.4 l/min, corresponding with the pump frequency of approximately 4 Hz. However, maintaining such low flow rate became challenging. Lowering the pump frequency to approximately 4Hz resulted in major effects, including (i) the pump vibrations, and (ii) the frequent pump stoppage during the system operations. This might have been due to the fact that 4 Hz was below the pump operation capacity. While it may be tempting to relate this to pump inefficiency, Dyson (2020) explained the effects of operating a pump at low flows and stated that low flow operations set a great amount of pressure on the pump. To overcome this issue, in the present study, an alternative option was considered. A two-way flow valve was added to the horse pipe connecting the pump to the 5C-settleometer. This two-way valve served to split the inflow into two directions, i.e., (i) the flow split into the 5C-settleometer, and (ii) the excess return to the influent bucket (**Figure 3.10**). Using this method, the pump would be operated at its capacity rate of over 10 Hz, and the two-way valve would control the 5C-settleometer inflow. This method eliminated the issues of pump ceasing and allowed the lowest flow rate (approximately 0.4 l/min) to be achieved.

Although the two-way valve method played a significant role in eliminating the pump failure problems, the issues of particle accumulation and presence of bends on the 5C-settleometer were still evident. As the inflow reached the PVC3, greater quantities of the inflow were returned to the influent than flew into the settleometer. This could have been due to reduced disturbances on the pipe redirecting the inflow back to the influent bucket (in comparison with the particle accumulation and several steep-angled bends on the 5C-settleometer device). To overcome this problem, the same inflow adjustment as applied onto TrR1 and TrR2 was applied to control the flow rate into each of the 5C-settleometer columns.

The outcomes from the TrR3 are presented in **Figure 3.9**. The overall flow rate achieved was approximately 0.52 l/min at a pump frequency of 10.13 Hz (with the two-way valve method). Greater particle accumulations were observed in the PVC1 and PVC2 corresponding with the V_{up} of 20.0 and 8.6 m/hr, respectively. The settleometer effluent TSS concentration of 262 mgTSS/l was considered close to the Bellville WWTW PST settled WW concentration of approximately 152 mgTSS/l (See **Table 3.3**). Although it may be tempting to further lower the flow rate to achieve closer effluent concentrations between the 5C-settleometer and FS-PST, than obtained, the difference between 262 and 152 mgTSS/l is significantly low considering the experimental errors that may have occurred during operation or analytical testing. As illustrated in **Table 3.3**, a MB of 80% was obtained, and

this is deemed acceptable given the possibility of losing solids in the settleometer pipes (due to the design of the instrument).

A notable difference between (i) TrR1 (on the Potsdam WW) at ~0.6l/min, (ii) TrR2 (on the Potsdam WW) at ~1.2l/min, and (iii) TrR3 (on the Bellville WW) at ~0.52l/min indicates how particles segregate between the columns. For TrR1 and TrR3, a greater particle accumulation is seen in the first two or three columns corresponding with the V_{UP} between 22.8–8.6 m/hr. For TrR2 (with a higher flow rate than TrR1 and TrR3), there is a shift in the columns with greater particle accumulation. Higher flow rates yield greater particle accumulations in the middle columns, which are associated with the V_{UP} between 19.35–8.18 m/hr. From these observations (and those of previous studies, as described in **Section 2.5.5**), it is evident that there is a noticeable relationship between the flow rates and particle segregation between the five columns.

Table 3.3: The characteristics of the Bellville WW: (A) the directly measured settled WW and PSS concentrations to generate a raw WW mixture; (B) the 5C-settleometer outcomes after a TrR using the raw WW mixture generated from A; and (C) the mass balance (MB) around the 5C-settleometer.

A: Potsdam approximate concentrations and masses/fluxes used to run settleomeeter TrRs									
Volumes	60.9		0.6086					60.3	
	100%		1%					99%	
	Raw (Calculated)		Primary sludge (Measured from actual PSS)					Settled WW (Measured)	
	mgTSS/l	gTSS	mgTSS/l		gTSS		mgTSS/l		gTSS
TSS	487	29616	33614		20457		152		9158
B: 5C-Settleometer outcomes									
	Raw (Calculated)		Primary sludge (Measured from actual PSS)					Settled WW (Measured)	
	mgTSS/l	gTSS	mgTSS/l		gTSS		mgTSS/l		gTSS/
TSS	462	28117					262		6288
C: Settleometer Mass balance									
Symbol	Formula or Source	INF	PVC1	PVC2	PVC3	PVC4	PVC5	EFF	Units
Volume	Direct measurement	60.86	1.81	4.35	6.2	9.5	15	24	litre
TSS	Solids dried at 103-105 °C	462	648	1438	362	276	262	262.0	mgTSS/l
M _{TSS}	Volume x TSS	28117	1173	6255	2244	2622	3930	6288	mgTSS
M _{TSS'PVC1-}	M _{TSS'PVC1} + M _{TSS'PVC2} + M _{TSS'PVC3} + M _{TSS'PVC4} + M _{TSS'PVC5}				16225				mgTSS
MB	((M _{TSS'PVC1-5} +M _{TSS'eff})/M _{TSS'inf}) x 100				80				%

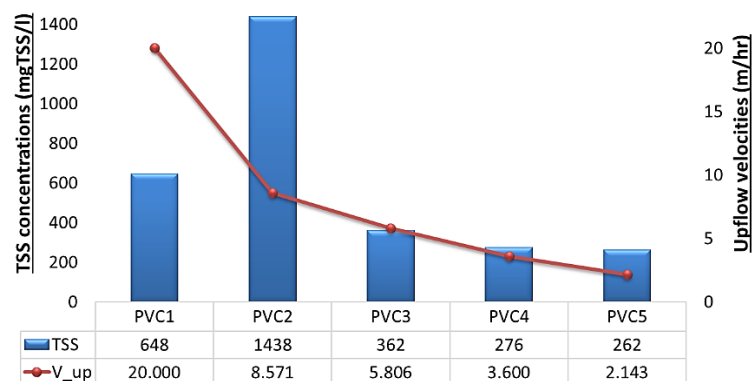


Figure 3.9: The outcomes of TrR3 on the Bellville WW 5C-settleometer

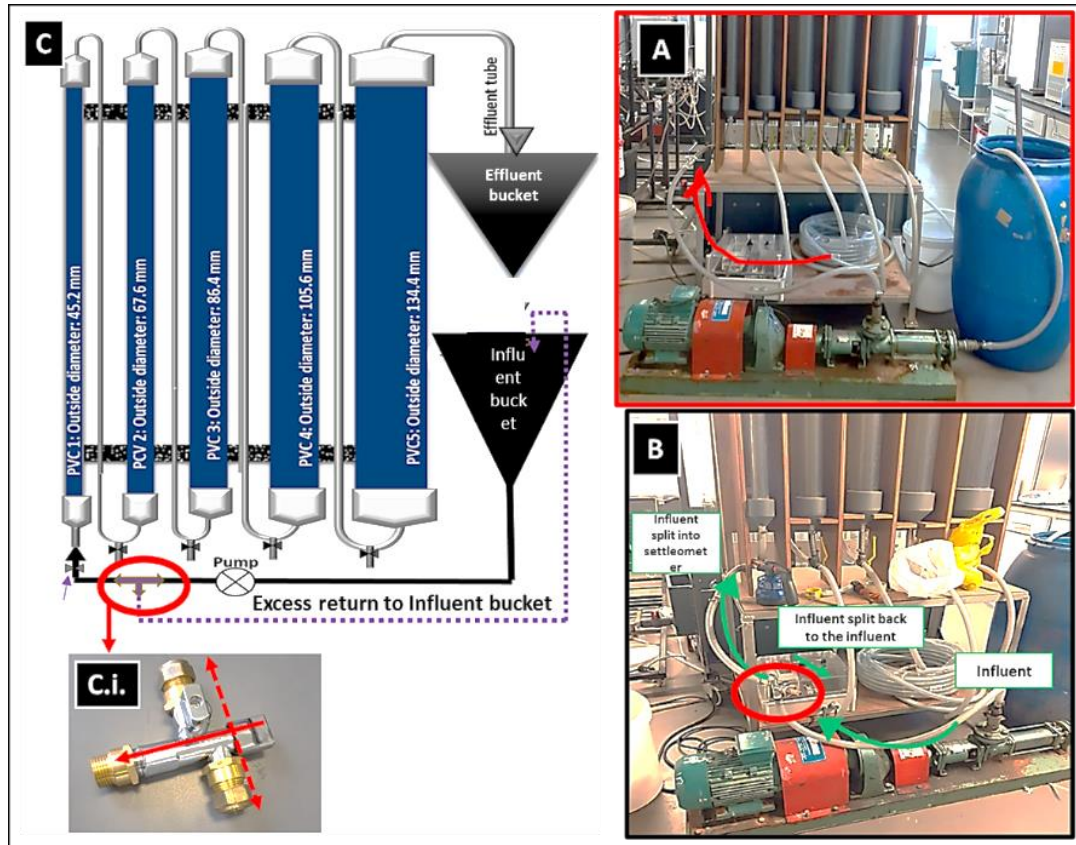


Figure 3.10: The 5C-settleometer set-ups: (A) first set-up, (B) second set-up, and (C) the schematic diagram illustrating the flow split between the settleometer and return to the influent. (C.i.) the two-way flow valve used to split the inflow into two to achieve the second set-up required to achieve the lowest flow rates.

3.3.5. Five-column settleometer runs' sampling procedure

After each TrR, the PVC column accumulated matter were transferred into separate labelled containers and stored in a 4 °C cold room before testing. **Figure 3.11** illustrates the sampling procedure around the 5C-settleometer. Essentially, the PVC column matter are collected from the largest- to the smallest-diameter column (PVC5 to PVC1). To start the process, an empty bucket is placed at the PVC5 bottom outlet for the PVC5 MLSS collection (**Figure 3.11a**). Thereafter, a clamp tightening the overflow hosepipe to the PVC column from the top is loosened (**Figure 3.11b**). This step is done to release the pressure holding the PVC column liquor in place. Once the bucket is in place and the top clamp has been loosened, the faucet is rotated forward to release the liquor into the bucket (**Figure 3.11c**). Once all the liquor has been released from the PVC5, the same process is repeated for the PVC4 down to the PVC1 (**Figure 3.11d**). Once all the five PVC column matter have been collected, the clamps at the top are tightened back, and the bottom faucets are closed. Clean water is used to flush out any residual solids from the columns to ensure that the system is clean and free from solids before starting a new run.

The matter collected include (i) the 5C-settleometer influent, (ii) the 5C-settleometer overflow matter (effluent), and (iii) the matter accumulated in each of the five 5C-settleometer PVCs. The overflow and matter in the columns form part of the overall 5C-settleometer outputs. The accuracy of the output matter is evaluated using the principle of MB. The TSS component of the samples from PVC1 to PVC5 and the effluent were analytically tested to determine their relationship with the original raw influent samples. This same sampling procedure will also apply to the main TeRs. The TSS analytical technique is explained in **Section 3.6.3**.

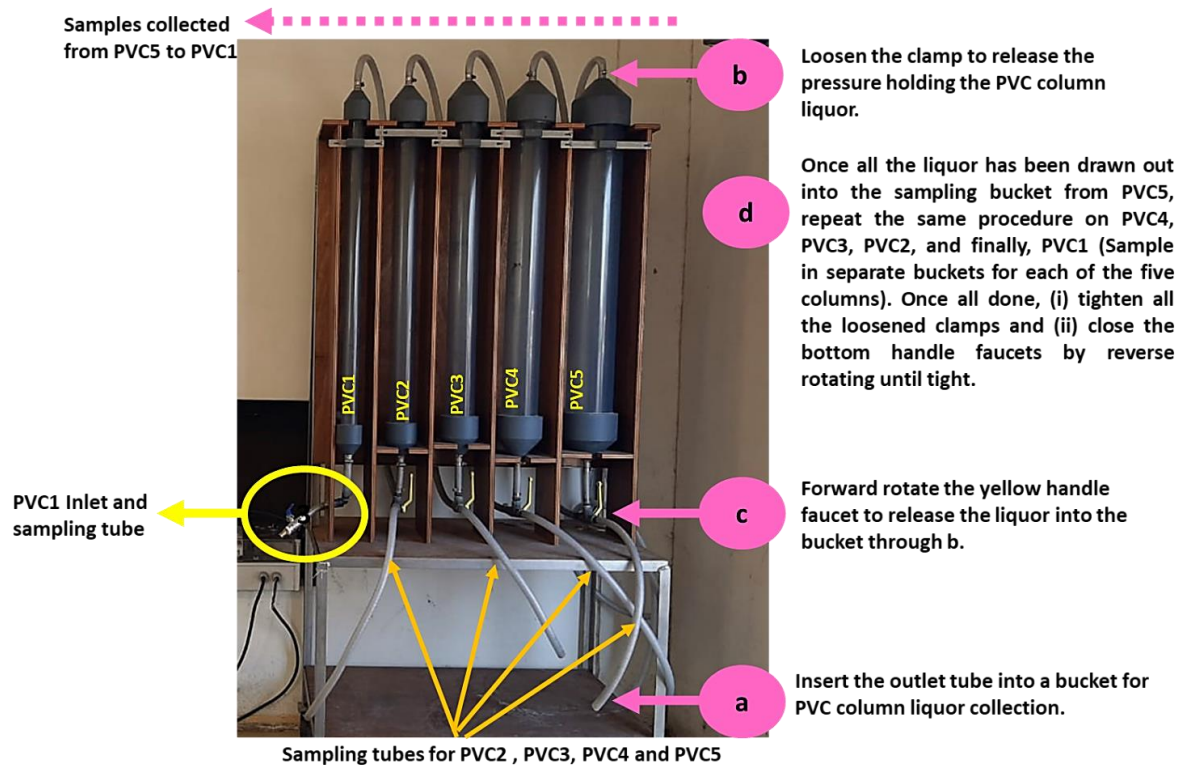


Figure 3.11: The illustration of the 5C-settleometer sampling procedure.

3.3.6. Five-column settleometer test runs

After successful TrRs at the UCT WQL, the 5C-settleometer device was transported to the Bellville WWTW. This is where the main settleometer test runs (TeRs) took place. The Bellville WWTW is located at Sacks Circle Industrial, Cape Town, South Africa (**Figure 3.12**). The raw WW for the TeRs was pumped directly from the plant inlet (i.e., the influent to the settleometer was not synthesized by mixing the settled WW and PSS as was done for the TrRs). Two sets of flow rate were considered, i.e., (i) a flow rate that yielded satisfactory outcomes from the TrRs, i.e., a flow rate between 0.5 and 0.7l/min (See **Section 3.3.4**), and (ii) a flow rate that allowed the 5C-settleometer HRT to be equal to the FS-PST under study. A flow rate yielding the settleometer effluent outcomes that are closest to the FS-PST effluent, while allowing reasonable particle segregation between the PVC columns, will be considered optimum.

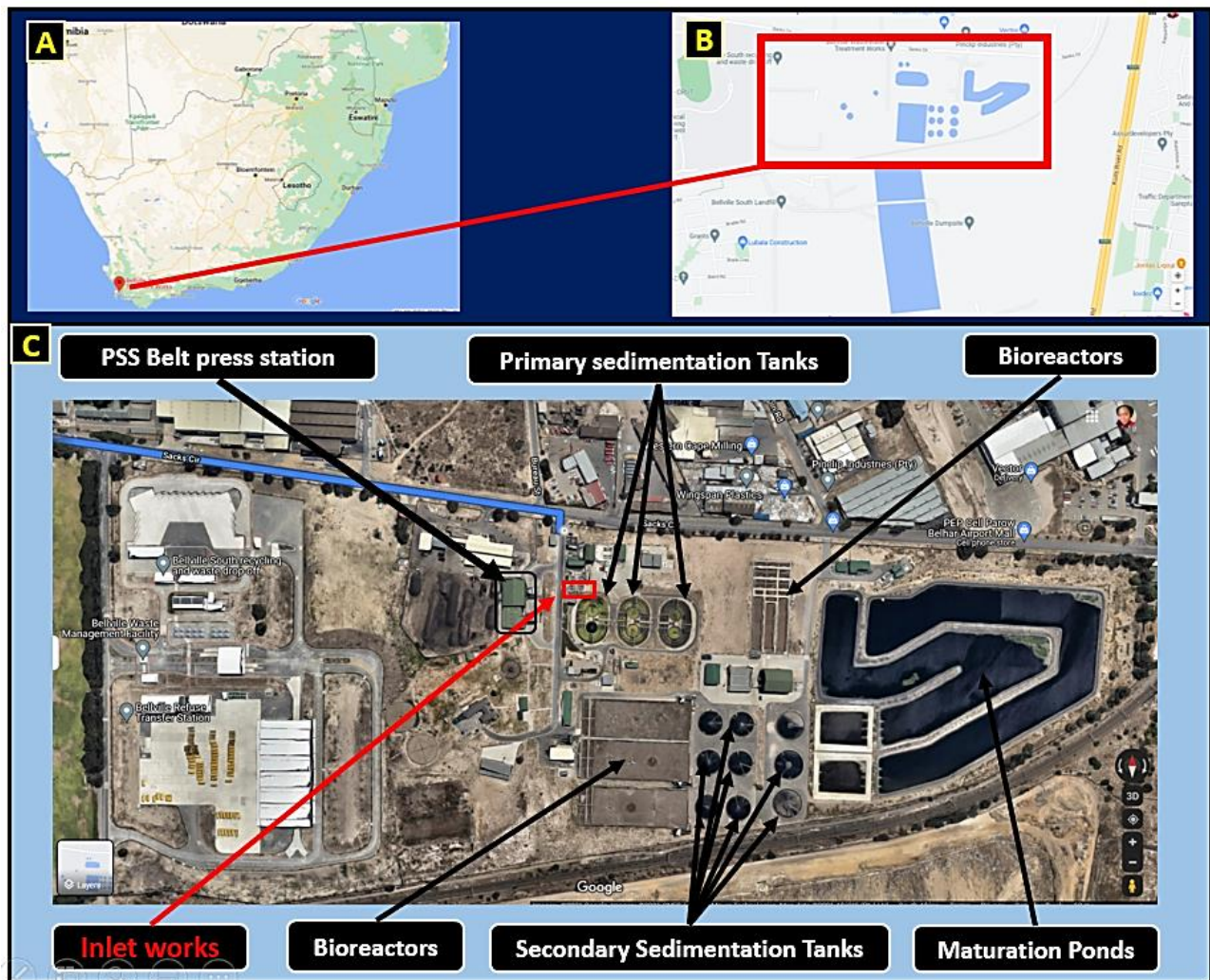


Figure 3.12: The Bellville WWTW geographic location: (A) a default Google map indicating the location in South Africa (SA); (B) a zoom in from the default Google map; and (C) a satellite or photographic Google map.

3.3.6.1. 5C-settleometer test run 1 (TeR1): ~ 0.63 l/min: Bellville WWTW

The 5C-settleometer TeR1 was carried out on a sunny day on 02 June 2021 (maximum temperature of 20 °C). This day was well within the wet weather flow (WWF) conditions in Cape Town, Western Cape. The TeR1 was conducted from 09:30 am to 11:30 am at an average flow rate of approximately 0.63 l/min (**Table 3.4**). The two-way valve method as described in **Section 3.3.4.4** above was used. According to this method, a bulk influent pumped into the 5C-settleometer via the two-way valve is split into two directions, i.e., (i) the flow split into the 5C-settleometer, and (ii) the excess influent (depending on the selected flow rate) returned to the plant inlet. The raw WW influent flows through the PVC1, allowing particle accumulation in the respective columns, and exits as effluent via the settleometer PVC5.

On the testing day, the 5C-settleometer was well-positioned next to the plant inlet with (i) the 5C-settleometer influent pipe fully submerged into the inlet; (ii) the effluent tube connected to the settleometer last PVC column and placed inside the effluent collection drum; and (iii) the pipe carrying the excess influent re-directed back to the inlet (**Figure 3.13**). The shortfall of this method is that, unlike TrRs where the quantity of the influent was determined by the quantity prepared in an influent drum, the total influent into the pump is unknown. To close the MB in terms of volume, the PVC column volumes ($V_{pvc1-5} = V_{PVC1}, V_{PVC2}, V_{PVC3}, V_{PVC4}, \text{ and } V_{PVC5}$) of 1.81, 4.3, 6.2, 9.5, and 15, respectively, added up to 37L, and the $V_{5SET,eff}$ was deemed equal to the total settleometer influent volume ($V_{5SET,inf}$). It is important to note that this $V_{5SET,inf}$ is different from the total influent passing through the pump ($V_{pmp,inf}$). The $V_{pmp,inf}$ includes the excess influent volume returned to the inlet (V_{eri}).

To start the actual TeR, the 5C-settleometer was primed and flushed with plant effluent to ensure that the system was free from solids and ready to start. At exactly 09:30 am, the 5C-settleometer TeR commenced. A 1L influent sample was collected at approximately 15 minutes intervals and stored in a bucket for the duration of the TeR. This was done to get an average influent sample flowing to the 5C-settleometer. The $V_{5SET,eff}$ occupied in 60 seconds was also recorded to determine the $Q_{5SET,eff}$. A volumetric flux was used to get the accurate $V_{5SET,eff}$. The settleometer pump was manually adjusted, as required, to ensure that the flow rate in the settleometer columns was constant (see **Section 3.3.4.1**). After completing TeR1, the respective influent, effluent, and PVC column accumulated matter were collected using the sampling procedure described in **Section 3.3.5**. The samples were then sent to the UCT WQL to perform the required analytical tests. Thereafter, the WWTP effluent was used to flush out the column residual solids in preparation for the second TeR.

Table 3.4: The 5C-settleometer TeR1: the respective flow rate in the five PVC columns and their effluent.

Symbol	Formula or Source	Influent	PVC1	PVC2	PVC3	PVC4	PVC5	Effluent	Ave	Units
A_{PVCn}	πr^2	-	0,0016	0,0036	0,0059	0,0088	0,0142	-		m ²
D_{sel}	Selected: see Section 3.3.4.1	-	50	50	50	50	50			mm
Vol_{Dsel}	$(A_{PVCn} \times (D_{sel}/1000)) \times 1000$	-	0,080	0,179	0,293	0,438	0,709	0,691		litre
T_{Dsel} (1)	Direct measurement	-	7	16	22	41	68	60		sec
T_{Dsel} (2)	Direct measurement	-	8	18	26	42	77	60		sec
T_{Dsel} (3)	Direct measurement	-	9	21	33	46	62	60		sec
T_{Dsel}	T_{Dsel} (1) (2) and (3) Average	-	8,0	18,3	27,0	43,0	69,0	60,0		sec
Q_{pvcn}	$(Vol_{Dsel} / time) \times 60$	-	0,60	0,59	0,65	0,61	0,62	0,69	0,63	l/min
V_{up}	$(Q_{pvcn} / A_{PVCn}) \times 60$	-	22,50	9,82	6,67	4,19	2,61	-		m/hr

Note: D_{sel} represents the selected distance of the column height, Vol_{Dsel} represents the MLSS volume occupying the D_{sel} , and T_{Dsel} represents the time taken to occupy Vol_{Dsel} . T_{Dsel} (1), T_{Dsel} (2), and T_{Dsel} (3) represent the different times taken to occupy the same Vol_{Dsel} .

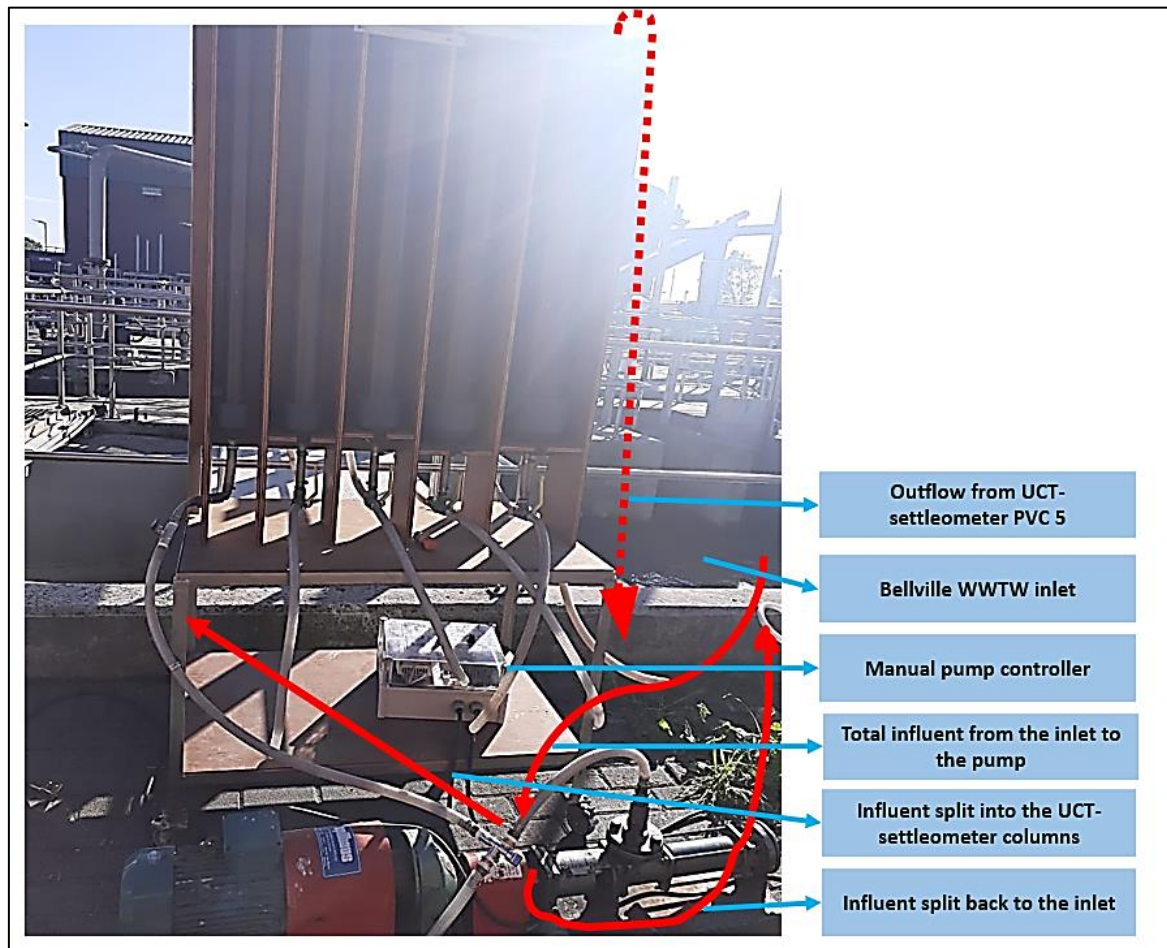


Figure 3.13: The 5C-settleometer set-up next to the Bellville WWTW inlet

3.3.6.2. Second 5C-settleometer TeR - 0.34 l/min: Bellville WWTW

The second TeR was conducted from 12:00 pm to 15:30pm on 02 June 2021. This test followed the same procedure as TeR1 (**Section 3.3.6.1**). The only difference is that the flow rate was lowered to achieve the same HRT between the 5C-settleometer and FS-PST at the Bellville WWTW. The Bellville WWTW PSTs have HRT of approximately 2.5 hours each (See **Figure 4.3** in **Section 4.2.6**). Therefore, for the influent to have a 2.5-hour HRT in the 5C-settleometer, a flow rate of 0.25 l/min (equal to $37 \text{ L} \div [2.5 \text{ hours} \times 60 \text{ minutes}]$) is required (**Equation (3.4)**). While it was challenging to get an exact flow rate of 0.25 l/min, an average flow rate of approximately 0.34 l/min was achieved. **Table 3.5** presents the respective flow rates in the five PVC columns and effluent, for this specific TeR. The resulting influent, accumulated PVC material, and effluent were collected using the sampling procedure described in **Section 3.3.5**, and thereafter, sent to the UCT WQL for further testing. Upon arrival at UCT WQL, the samples were stored in a 4 °C walk-in cold room before analytical testing.

$$HRT_{5SET} = \frac{V_{pvc1-5}}{Q_{5SET}} \quad (3.4)$$

Where: HRT_{5SET} = 5C-settleometer hydraulic retention time (hrs)

Q_{5SET} = 5C-settleometer flow rate (l/min)

V_{pvc1-5} = 5C-settleometer PVC column total volume (l): $PVC1+PVC2+PVC3+PVC4+PVC5 = 37\text{L}$

Table 3.5: The 5C-settleometer TeR2: the respective flow rate in the five PVC columns and effluents.

Symbol	Formula or Source	Influent	PVC1	PVC2	PVC3	PVC4	PVC5	Effluent	Ave	Units
A_{pvcn}	πr^2	-	0,0016	0,0036	0,0059	0,0088	0,0142	-		m ²
D_{sel}	Selected	-	50	50	50	50	50			mm
Vol_{Dsel}	$(A_{pvcn} \times (D_{sel}/1000)) \times 1000$	-	0,080	0,179	0,293	0,438	0,709	0,388		litre
$T_{Dsel} (1)$	Direct measurement	-	15	26	48	76	119	60		sec
$T_{Dsel} (2)$	Direct measurement	-	16	32	56	82	125	60		sec
$T_{Dsel} (3)$	Direct measurement	-	17	36	57	83	125	60		sec
T_{Dsel}	Average	-	16,0	31,3	53,7	80,3	123,0	60,0		sec
Q_{pvcn}	$(Vol_{Dsel} / \text{time}) \times 60$	-	0,30	0,34	0,33	0,33	0,35	0,39	0.34	l/min
V_{up}	$(Q_{pvcn} / A_{pvcn}) \times 60$	-	11,25	5,74	3,35	2,24	1,46	-		m/hr

Note: D_{sel} represents the selected distance of the column height, Vol_{Dsel} represents the MLSS volume occupying the D_{sel} , and T_{Dsel} represents the time taken to occupy Vol_{Dsel} . $T_{Dsel} (1)$, $T_{Dsel} (2)$, and $T_{Dsel} (3)$ represent the different times taken to occupy the same Vol_{Dsel} .

3.3.7. 5C-settleometer analytical testing

The analytical tests performed on the influent, five settling velocity groups (SVGs from the PVC1 to PVC5), and effluent of the two TeRs (**Section 3.3.6.1** and **3.3.6.2**) are COD, TSS, VSS, ISS, orthophosphate (OP), and free and saline ammonia (FSA) (**Figure 3.14**). The analytical testing took place at the UCT WQL. To limit the biological alteration, it was important that the samples were tested in their freshest state possible. For this reason, the total COD, 0.45µm membrane filtered samples, TSS, VSS, and ISS tests were all performed within the first 48 hours following the sample collection. While these analytical tests cannot distinguish between the BPO and UPO contents of the VSS, the AugBMP test (see **Section 3.6** below) provides greater detail on the relevant processes required to ensure that the BPO and UPO components are well distinguished.

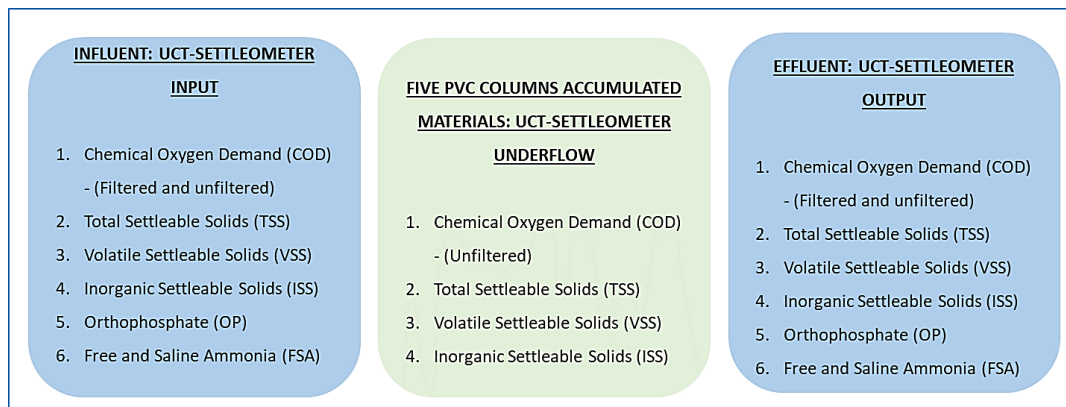


Figure 3.14: The 5C-settleometer analytical tests conducted at the UCT WQL

3.3.8. 5C-settleometer data evaluation method

The principles of mass balance (MB) were used to evaluate the accuracy of the 5C-settleometer's output material with respect to the inputs. The volume of the influent, effluent, and the five respective PVC columns are fundamental to MB calculations. The $V_{5SET,inf}$ is equal to the sum of the $V_{5SET,eff}$ and the volumes accumulated in PVC column 1 to 5 (V_{PVC1-5}) (**Equation (3.5)** and **(3.6)**). Knowing these volume distributions, the corresponding masses can be calculated by multiplying a specified volume with a respective concentration (**Equation (3.7)** to **(3.10)**). The principles can be applied to COD, TSS, VSS or ISS components. In accordance, the 5C-settleometer influent mass ($M_{5SET,inf}$) of either COD ($M_{5SET,inf} \cdot COD$), TSS ($M_{5SET,inf} \cdot TSS$), VSS ($M_{5SET,inf} \cdot VSS$) or ISS ($M_{5SET,inf} \cdot ISS$) should equal the sum of the 5C-settleometer effluent mass ($M_{5SET,eff}$), which can be in the form of COD ($M_{5SET,eff} \cdot COD$), TSS ($M_{5SET,eff} \cdot TSS$), VSS ($M_{5SET,eff} \cdot VSS$) or ISS ($M_{5SET,eff} \cdot ISS$), and the total PVC columns masses (M_{PVC1-5}), which can also be recorded in terms of COD ($M_{COD \cdot PVC1-5}$), TSS ($M_{TSS \cdot PVC1-5}$), VSS ($M_{VSS \cdot PVC1-5}$) or ISS ($M_{ISS \cdot PVC1-5}$). Using **Equations (3.11)**, a MB for the 5C-settleometer system can be calculated. As stated by Gaszynski (2020: 77), material MB within 80-120% range is acceptable,

provided supporting reasons are given. From these applications, the inaccuracies related to the flow of masses within the system can be detected.

The principles of MB were used to evaluate the accuracy of the 5C-settleometer outputs with respect to the inputs. The volumes of the influent, effluent, and five respective PVC columns are fundamental for the MB calculations. The $V_{5SET,inf}$ is equal to the sum of the $V_{5SET,eff}$ and volumes accumulated in the PVC columns 1 to 5 (V_{PVC1-5}), refer to **Equations (3.5)** and **(3.6)**. Knowing these volume distributions, the corresponding masses can be calculated by multiplying a specified volume with a respective concentration, refer to **Equations (3.7)** to **(3.10)**. The principles can be applied to the COD, TSS, VSS or ISS components. Essentially, the 5C-settleometer influent mass ($M_{5SET,inf}$) should equal the sum of the 5C-settleometer effluent mass ($M_{5SET,eff}$) and the total PVC column masses (M_{PVC1-5}). Using **Equation (3.11)**, a MB for the 5C-settleometer system can be calculated. As stated by Gaszynski (2020: 77), a MB within the range of 80–120% is acceptable, provided it can be well explained. From these applications, the inaccuracies related to the flow of masses within the system can be detected.

Volumes

$$V_{PVC1-5} = V_{PVC1} + V_{PVC2} + V_{PVC3} + V_{PVC4} + V_{PVC5} \quad (3.5)$$

$$V_{5SET,inf} = V_{PVC1-5} + V_{5SET,eff} \quad (3.6)$$

Masses

$$M_{5SET,eff} = V_{5SET,eff} \times C_{5SET,eff} \quad (3.7)$$

$$M_{PVCn} = V_{PVCn} \times C_{PVCn} \quad (3.8)$$

$$M_{PVC1-5} = M_{PVC1} + M_{PVC2} + M_{PVC3} + M_{PVC4} + M_{PVC5} \quad (3.9)$$

$$M_{5SET,inf} = V_{5SET,inf} \times C_{5SET,inf} \quad (3.10)$$

$$Mass\ balance = \left(\frac{M_{PVC1-5} + M_{5SET,eff}}{M_{5SET,inf}} \right) \times 100 \quad (3.11)$$

Where: V_{PVC1} , V_{PVC2} , V_{PVC3} , V_{PVC4} and V_{PVC5} = Cumulative volumes in PVC1, PVC2, PVC3, PVC4, and PVC5 respectively (L)

V_{PVC1-5} = 5C-settleometer PVC column total volume (l): $PVC1+PVC2+PVC3+PVC4+PVC5 = 37L$

$V_{5SET,inf}$ = 5C-settleometer influent volume (L)

$V_{5SET,eff}$ = 5C-settleometer effluent volume (outflow from PVC5) (L)

V_{PVCn} = 5C-settleometer nth PVC column volume (n = 1, 2, 3, 4, or 5) (L)

M_{PVC1} , M_{PVC2} , M_{PVC3} , M_{PVC4} and M_{PVC5} = Cumulative masses in PVC1, PVC2, PVC3, PVC4, and PVC 5 respectively (mg). Mass can either be of COD, TSS, VSS, and ISS, written as $M_{COD:PVCn}$, $M_{TSS:PVCn}$, $M_{VSS:PVCn}$ and $M_{ISS:PVCn}$, respectively.

M_{PVC1-5} = 5C-settleometer PVC column total mass (mg). Total masses can either be of COD, TSS, VSS, and ISS, written as $M_{COD,PVC1-5}$, $M_{TSS,PVC1-5}$, $M_{VSS,PVC1-5}$ and $M_{ISS,PVC1-5}$, respectively.

$M_{5SET,inf}$ = 5C-settleometer influent mass (mg). Masses can either be of COD, TSS, VSS, and ISS, written as $M_{5SET,inf,COD}$, $M_{5SET,inf,TSS}$, $M_{5SET,inf,VSS}$ and $M_{5SET,inf,ISS}$, respectively.

$M_{5SET,eff}$ = 5C-settleometer effluent mass (outflow from PVC5) (mg). Masses can either be of COD, TSS, VSS, and ISS written as $M_{5SET,eff,COD}$, $M_{5SET,eff,TSS}$, $M_{5SET,eff,VSS}$ and $M_{5SET,eff,ISS}$, respectively.

C_{PVC1} , C_{PVC2} , C_{PVC3} , C_{PVC4} and C_{PVC5} = Concentration of matter accumulated in PVC1, PVC2, PVC3, PVC4, and PVC5 respectively (mg/l). Concentration can either be of COD, TSS, VSS, and ISS, written as $C_{COD,PVCn}$, $C_{TSS,PVCn}$, $C_{VSS,PVCn}$ and $C_{ISS,PVCn}$, respectively.

$C_{5SET,inf}$ = 5C-settleometer influent concentrations (mg/l). Concentrations can either be of COD, TSS, VSS, and ISS, written as $C_{5SET,inf,COD}$, $C_{5SET,inf,TSS}$, $C_{5SET,inf,VSS}$ and $C_{5SET,inf,ISS}$, respectively.

$C_{5SET,eff}$ = 5C-settleometer effluent concentrations (outflow from PVC5) (mg/l). Concentrations can either be of COD, TSS, VSS, and ISS written as $C_{5SET,eff,COD}$, $C_{5SET,eff,TSS}$, $C_{5SET,eff,VSS}$ and $C_{5SET,eff,ISS}$, respectively.

3.4. Primary settling tank onsite diurnal data

3.4.1. Overview

The purpose of the DDPST model is to predict the FS-PST overflow and underflow characteristics. To confirm the accuracy of the predictions, direct measurements of the diurnal influent, underflow, and overflow from the FS-PST are required. These direct measurements will be compared with the DDPST model. The dimensions of the PST under study, i.e., (i) area, (ii) depth, and (iii) diameter, were provided by the Bellville WWTW plant operator (see **Section 4.2.6** for the values). This section intends to describe the processes, including the diurnal sample collection, flow rates acquisition, analytical testing requirements, and data analysis approach followed to gather the FS-PST data.

3.4.2. Diurnal sample collection

In parallel with the 5C-settleometer TeRs, composite samples were collected at 2-hour intervals over a period of 24 hours from the (i) inlet area (towards the PST), (ii) PST underflow (PSS), and (iii) PST overflow (settled WW). Initially, it was planned that the three selected autosamplers, as shown in **Figure 3.15**, would be used to automatically collect the respective diurnal samples from the inlet, underflow, and overflow areas. Although all the autosamplers proved to operate correctly during the pre-inspection (confirmed by the plant operator), lots of issues arose during the main sampling. One of the recurrent issues included the falling of the sampling bottles inside the autosamplers, which interrupted the sampling process. All the three autosamplers appeared to have the same issue. After multiple attempts to fix the problem, it was decided to rather grab the samples at 2-hour intervals for

all the three areas. A total number of 36 samples, (i) 12 from the inlet area, (ii) 12 from the PST underflow, and (iii) 12 from the PST overflow, were collected. It is important to note that the same raw WW entering the FS-PST was pumped into the 5C-settleometer columns. This was to allow comparisons between the full-scale and settleometer outcomes. Once the sample collection was complete, the 36 dynamic samples were sent to the UCT WQL and stored in a 4°C cold room while awaiting testing.



Figure 3.15: The three selected autosamplers for the influent, underflow, and effluent flow automatic sampling

3.4.3. Diurnal sample analytical testing

The analytical testing for the 36 diurnal samples took place at the UCT WQL. The (i) raw WW (from the inlet), (ii) settled WW (from the PST overflow), and (iii) PSS (from the PST underflow) were all tested for COD, TSS, VSS, and ISS. Additional analytical tests, including filtered COD, FSA, and OP, were made for the settled WW (see **Section 3.6**). **Figure 3.16** presents a summary of the complete analytical tests on the diurnal samples. From this test set-up, it is assumed that the settled WW filtered COD, OP, and FSA are equal to the filtered COD, OP, and FSA of the influent and underflow samples. The total COD, 0.45µm membrane filtered samples, and TSS, VSS, and ISS analytical tests, were all performed within the first 72 hours after sample collection. Although the biodegradability of these samples was not tested, the following will be used to determine the respective contents for the collected diurnal data using **Equation (3.12)** to **Equation (3.14)** viz. (i) the UPO fractions from a lab-scale Modified Ludzack-Ettinger (MLE) system treating the raw and settled WWs (Ikumi *et al.*, 2022 in progress), and (ii) the PSS UPO fraction from the AugBMP test by Angula (2022 in progress). The UPO fractions by Ikumi *et al.* (2022 in progress) and Angula (2022 in progress) are preferred given that the respective systems are run in parallel with the system in the present study and are treating Bellville WW.

3.4.4. Flow rates

The WWTP flow rates are fundamental to understanding the variations in fluxes in and out of the system. The influent flow rates into the Bellville PSTs were provided by the plant operator, and they are measured in m³/h (see **Section 4.2**). The PST underflow at the plant is said to be 0.5% of the influent flow rate. The settled WW flow rate is then calculated by assuming a flow balance around the PST, i.e., 100% influent raw WW flow rate minus 0.5% underflow rate equals 99.5% settled WW flow rate. It is important to note that while 1% PSS underflow was assumed during the 5C-settleometer trial runs (selected as such to obtain a substantial culture of PSS solids), the Bellville PST actual underflow rate is 0.5%.

$$S_{up,Set,timex} = f_{S'up,Set} \times S_{Set,timex} \quad (3.12)$$

$$S_{up,Raw,timex} = f_{S'up,Raw} \times S_{ti,timex} \quad (3.13)$$

$$S_{up,PSS,timex} = f_{S'up,PSS} \times S_{PSS,timex} \quad (3.14)$$

Where: $f_{S'up,Raw}$, $f_{S'up,Set}$, and $f_{S'up,PSS}$ = Fraction of the unbiodegradable particulate organics that is in the raw WW, settled WW and PSS.

$S_{ti,timex}$ = Total influent (Raw) WW COD at time x (x = 06h00, 08h00, 10h00, and so forth)

$S_{Set,timex}$ = Total settled WW COD at time x (x = 06h00, 08h00, 10h00, and so forth)

$S_{PSS,timex}$ = Total PSS COD at time x (x = 06h00, 08h00, 10h00, and so forth)

$S_{up,Set,timex}$ = Unbiodegradable particulate COD that is in the settled WW at time x (x = 06h00, and so forth)

$S_{up,Raw,timex}$ = Unbiodegradable particulate COD that is in the raw WW at time x (x = 06h00, and so forth)

$S_{up,PSS,timex}$ = Unbiodegradable particulate COD that is in the PSS at time x (x = 06h00, and so forth)

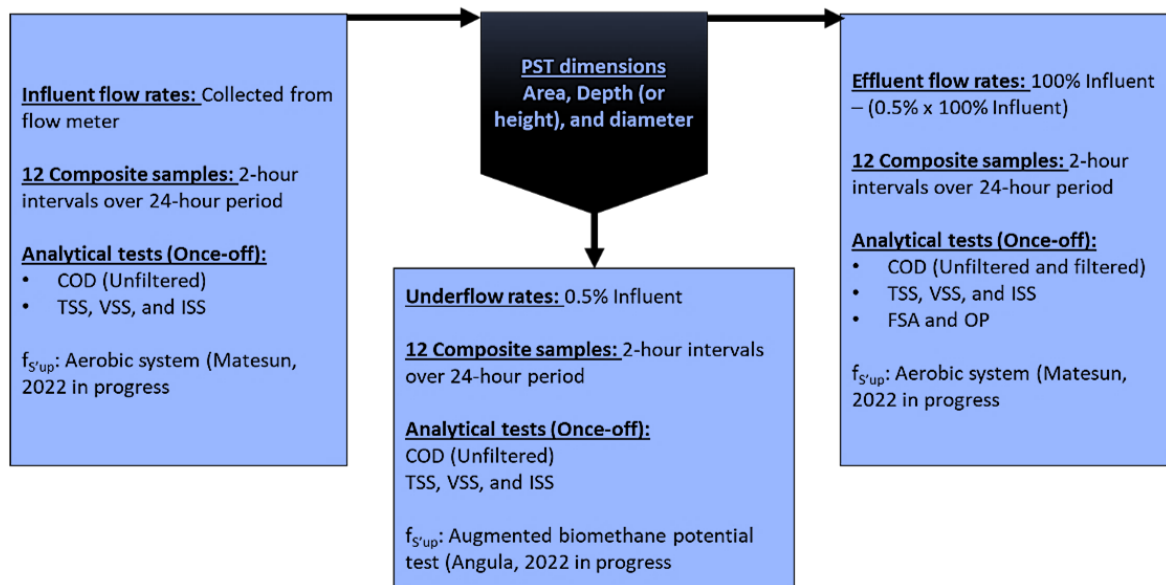


Figure 3.16: The collection summary of the diurnal samples and respective analytical tests

3.4.5. Diurnal samples data validity

Following the analytical tests, the diurnal data comprising varying flows and concentrations were recorded on a spreadsheet. The Simpson's rule was then applied to the calculated diurnal fluxes of COD, TSS, VSS, ISS, FSA, OP, and flow rates to get the flow weighted averages (FWAs). The Simpson's rule is based on the numerical approximation of definite integrals as formulated in **Equation (3.15)**. It is important to note that simply using the mean averages does not give accurate results given that it may underestimate the measured parameters (Ekama & Wentzel, 2008). As a result, the Simpson's rule is applied to obtain the accurate FWAs. The reliability of the overall diurnal measurements is determined by observing the relationship between the fraction of the COD relative to VSS (f_{cv}). Although there is a possibility for experimental errors during testing, this fraction is expected to show some consistency and relationship as supported by Wentzel, *et al.* (2008).

$$\int_a^b f(x)dx = \frac{\Delta x}{3} [First + last + 4(evens) + 2(odds)] \quad (3.15)$$

Where: $\int_a^b f(x)dx$: Area

$$\Delta x: \text{Interval} = \frac{b-a}{n}$$

a and b: Hourly TeR from 0 to 24 hours

n: Number of tests per parameter

First: First concentration result, i.e., at 06h00

Last: Last concentration result obtained as the cycle restart, i.e., at 06h00 the following day

Evens: Concentrations obtained at even numbers, i.e., 2,4,6, and so on

Odds: Concentrations obtained at odd numbers, i.e., 3,5,7, and so on.

3.5. Biodegradability test

3.5.1. Overview

The AugBMP test of Gaszynski (2020) is used in the present study to distinguish between the BPOset and UPOset of the accumulated VSetS materials in the five settleometer columns. This AugBMP test took place at the UCT WQL. Although two settleometer TeRs were performed, i.e., one taking into consideration a flow rate that yielded satisfactory outcomes during the trial runs (TeR1), and the other considering the HRT of the FS-PST (TeR2), a TeR that yielded (i) effluent characteristics comparable to the FS-PST effluent, and (ii) settleometer accumulated matter exhibiting reasonable particle segregation, will be used to run the AugBMP test.

In terms of the particle distribution between the five settleometer columns, the TeR1 outcomes show a widely dispersed particle accumulation relative to those of TeR2 (**Figure 3.17** and **Figure 3.18**). The TSS maximum particle accumulation for TeR2 appears to be in the PVC1 and PVC2, while in the PVC3 to PVC5 the TSS particle accumulation is almost comparable to that of the settled WW (**Figure 3.18**). The TeR2 PVC1 and PVC2 also appear to have accumulated small-sized particles which, in principle, should have accumulated in the proceeding PVC columns with lower V_{up} . For TeR1, however, the TSS particles are widely distributed between the PVC1 to PVC5, with greater particle accumulation in the PV1, PVC2, and PVC3 (**Figure 3.18**). As discussed in **Section 3.3.6.2**, setting an equal HRT for both the 5C-settleometer and PST HRT requires a lowest possible flow rate. From the TeR2 outcomes (with a flow rate of 0.34l/min), while it is logical to ensure that the FS-PST and settleometer environments have the same settings for reasonable comparisons, the settleometer instrumentation does not really yield satisfactory particle segregation at lowest flow rates. This is possibly because lower flow rates require an extended wastewater HRT in each column. As a result, the greater particle accumulation occurs in the first columns. The greater particle accumulation in the leading columns affects the particle movement of the incoming flow through the inter-particle forces. In addition, as stated by Ekama and Wentzel (2003: 3.30), although raw WW rarely flocculates when entering the PST, it is prone to flocculation, especially in a system with a long HRT. For future studies intending to segregate the WW settleable solids into different settling velocity groups, it is recommended to opt for a flow rate of at least 0.6–0.8l/min. In cases where quantities of solids are recorded in the effluent, re-running the settleometer, using the collected effluent, at a decreased flow rate may decrease the chances of significant inter-particle force interactions.

Table 3.6 outlines the average COD, TSS, VSS, and ISS concentrations for the diurnal raw and settled WW samples at the selected slots of the settleometer TeRs. The average diurnal samples collected at (i) 10 am and 12 pm were compared with the TeR1 outcomes, and (ii) 12 pm, 2 pm, and 4 pm were compared with the TeR2 outcomes. For TeR1, the FS-PST settled WW average concentrations, between 10 am and 12 pm, are 755 mgCOD/l, 486 mgTSS/l, 304 mgVSS/l, and 182 mgISS/l, respectively. These concentrations are significantly close to the TeR1 settleomer effluent concentrations of 692 mgCOD/l, 310 mgTSS/l, 274 mgVSS/l, and 36 mgISS/l. For TeR2, the settleometer effluent concentrations recorded are 394 mgCOD/l, 174 mgTSS/l, 170 mgVSS/l, and 4 mgISS/l, while the corresponding PST settled WW averages between 12pm, 2pm, and 4pm are 658 mgCOD/l, 220 mgTSS/l, 183 mgVSS/l, and 28mgISS/l. The TeR2 outcomes clearly indicate that more solids were captured in the settleometer than in the FS-PST. In addition to interparticle forces, the HRT is another possible factor that may have contributed to high solids capture in the serttleometer than in the FS-PST. For instance, it appears that there was a higher WW HRT in the

settlemeter ((37l/0.34l/min)/60min = 2 hours, see **Section 3.3.6.2**) than in the FS-PST between 12 pm (2886 m³/1944 m³/hr = 1.5 hours see **Figure 4.3**) and 2 pm (2886 m³/1944 m³/hr = 1.7 hours see **Figure 4.3**). The increased PST raw influent between 12 pm and 2 pm (see **Section 4.2.6**) is the main reason for the decreased HRT. It is important to note that the HRT is directly proportional to the PST volume and inversely proportional to the influent flow rate. As discussed in the previous paragraph, marginally decreasing the WW HRT in the settlemeter allows a marginally increased flow rate, which is beneficial to the settlemeter particle movement, and subsequently segregation.

Given the widely dispersed particle segregation of TeR1, and that the TeR1 effluent concentrations are relatively close to the FS-PST settled WW average concentrations, the TeR1 outputs are more preferable for the biodegradability test than the TeR2 outputs. The subsections below describe the procedure followed to run the AugBMP experimentation for the chosen TeR1.

Table 3.6: The comparisons between the diurnal and 5C-settlemeter raw and settled WW characteristics for both TeR1 and TeR2

TeR1 (09:30AM to 11:30PM): Settlemeter flow rate = 0.63 l/min												
Time	Raw WW (Influent)						Settled WW					
	Total COD (mg/l)	Total Soluble (mg/l)	Total particulate (mg/l)	TSS (mg/l)	VSS (mg/l)	ISS (mg/l)	Total COD (mg/l)	Total Soluble (mg/l)	Total particulate (mg/l)	TSS (mg/l)	VSS (mg/l)	ISS (mg/l)
10:00AM	1551	296	1256	1070	838	232	799	296	503	503	370	133
12:00PM	1075	242	833	620	468	152	710	242	468	468	238	230
Average	1313	269	1044	845	653	192	755	269	486	486	304	182
Settlemeter	1284	282	1002	842	704	138	692	282	410	310	274	36
TeR2 (12:00PM to 15:15PM): Settlemeter flow rate = 0.34l/min												
Time	Influent						Settled WW					
	Total COD (mg/l)	Total Soluble (mg/l)	Total particulate (mg/l)	TSS (mg/l)	VSS (mg/l)	ISS (mg/l)	Total COD (mg/l)	Total Soluble (mg/l)	Total particulate (mg/l)	TSS (mg/l)	VSS (mg/l)	ISS (mg/l)
12:00PM	1075	242	833	620	468	152	710	242	468	238	170	68
14:00PM	1087	257	829	606	522	84	664	257	407	230	224	6
16:00PM	991	234	756	528	450	78	599	234	365	166	156	10
Average	1051	244	806	585	480	105	658	244	413	220	183	28
Settlemeter	884	380	504	602	496	106	394	204	190	174	170	4

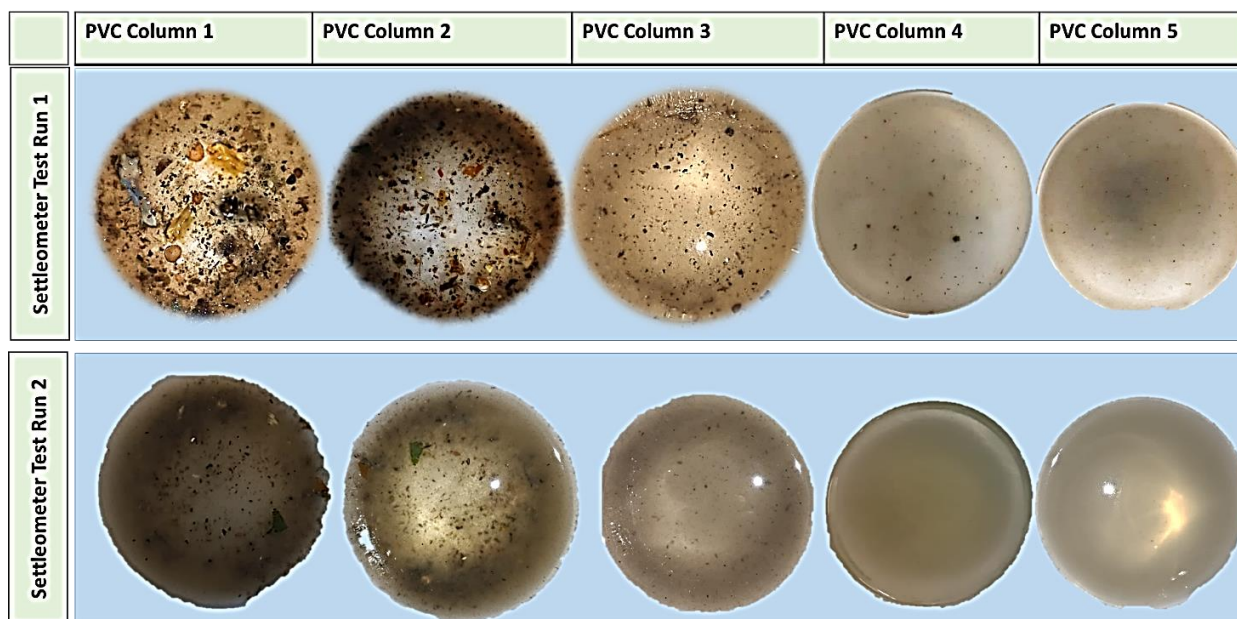


Figure 3.17: The particle segregation between the five PVC columns for TeR1 and TeR2

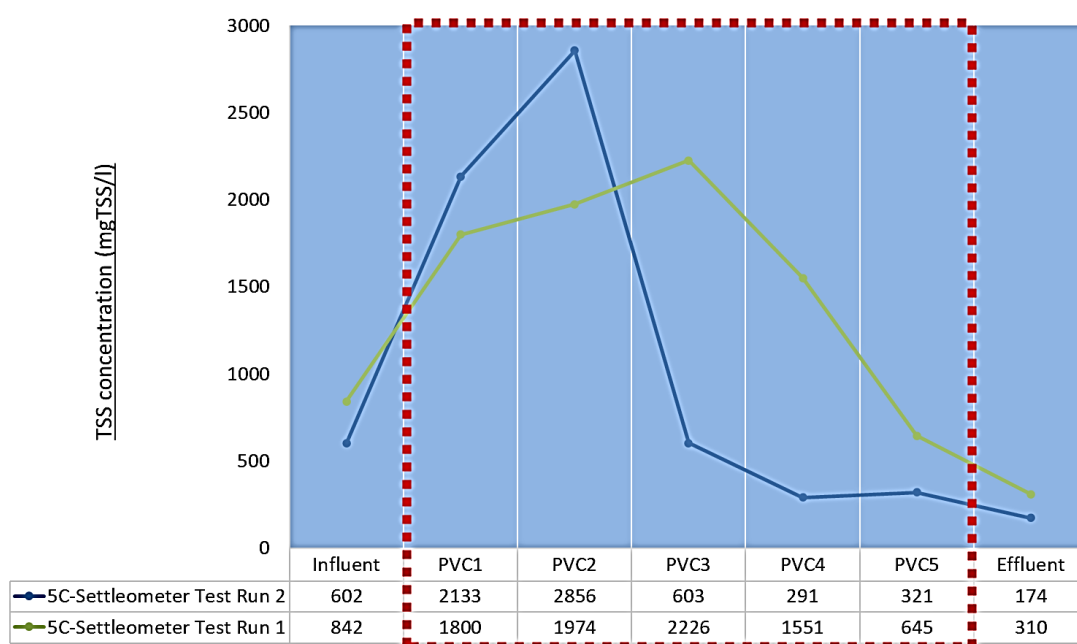


Figure 3.18: The TSS distribution between the PVC columns for TeR1 and TeR2

3.5.2. Five-column settleometer substrate preparation for AugBMP experimentation

As discussed in **Section 3.5.1**, the settleometer TeR1 is selected for the AugBMP experimentation. The particulate COD concentrations for the PVC1, PVC2, PVC3, PVC4, and PVC5 collected matter are 1992 mgCOD/l, 2428 mgCOD/l, 2918 mgCOD/l, 1656 mgCOD/l, and 876 mgCOD /l, respectively. Although the 5C-settleometer is designed to segregate settleable particles into five different SVGs, the PVC column matter comprises some volume of supernatant (settled WW)

(**Figure 3.19**). Practically, it is not possible to have the whole PVC column occupied by settleable particles only. This is due to the following:

- (i) The greater the particle accumulation in the successive columns, the greater the chance for tube blockages. A 5C-settleometer can only be run until just enough particles are observed in the columns. This is to avoid tube blockages, or excessive adjustment to the flow rate, which may risk particle inappropriately shooting into the next column.
- (ii) The greater particle accumulation can act as hindrance or obstruction to the incoming low settling velocity particles to move to the next columns.

For the above listed reasons, each PVC column is bound to comprise both the supernatant and settleable components. To prepare the five PVC column matter for the AugBMP experiment, it then became necessary to eliminate the supernatant from each PVC column. It is important to note that the removal of the supernatant was only done after the mass balance around the 5C-settleometer was completed. This is due to the mass balance requiring that the mass flowing into the system be equal to the masses flowing out of the system.

To separate the settleable particles from the supernatant, a well-mixed liquor from each of the PVC column was transferred into a 1 L Imhoff cone to allow quiescent particle settling for 2 hours (**Figure 3.19**). After 2 hours, the supernatant was discarded, and the settleable fraction was transferred into the collection bottles. This was done for all the MLSS collected from the five PVC columns. Since the total volumes for the PVC1, PVC2, PVC3, PVC4, and PVC5 are 1.8 L, 4.5 L, 6.2 L, 9.5 L, and 15 L, respectively, an underflow volume of 3.1 L was targeted for the PVC2 to PVC5. For the PVC1 (1.8 L), only 1.6 L volume were collected. The 3.1 L collected from the PVC2 to PVC5 was so that 100 mL could be used for immediate COD, TSS, VSS, and ISS analysis on the resulting settleable proportions, with the remaining volume of 3 L reserved for the AugBMP experiment. Similarly, 100 mL from the PVC1 were used for analysis, and the remaining 1.5 L set aside for the AugBMP test. The 1.5 L for the PVC1 is two times smaller than the 3 L volume collected from each of the PVC2 to PVC5. The new COD concentrations for the settleable matter from the Imhoff cone are well presented in in **Table 3.7**.

The removal of the supernatant from the PVC column matter not only increases the particulate concentration to reflect the PSS, but it also increases the chance of yielding accurate results. For instance, as shown in **Table 3.8**, if the PVC1 with a total volume of 1.8 L contains 500 mL settleable solids with a BPO concentration of 10 000 mgCOD/L, and 1.3 L supernatant with a BPO concentration

of 865 mgCOD/l, the overall liquor concentration becomes 3403 mgCOD/l. On the other hand, if the PVC5 with a total volume of 15 L contains 500 mL settleable solids with a BPO concentration of 50 000 mgCOD/l, and 14.5 L supernatant with a BPO concentration of 865 mgCOD/l, the overall liquor concentration becomes 2503 mgCOD/l. From this example, it is evident that although the overall settleable BPO of the PVC5 is 5 times greater than that of the PVC1, the supernatant dilution effect causes the PVC5 to have a low particle concentration, which is incorrect. For this reason, the supernatant required to be removed from the total PVC liquor prior to the AugBMP experimentation.

Table 3.7: The COD concentrations of the five PVC columns: (i) for the total volume, and (ii) after the settleable solids have been separated from the supernatant.

Source	PVC1	PVC2	PVC3	PVC4	PVC5
Total liquor volumes in the PVC columns (Litres)	1.8	4.5	6.2	9.5	15
Initial substrate concentrations from the PVC columns (mgCOD/l)	1992	2428	2918	1656	876
Settleable volumes collected from the Imhoff cone	1.5	3	3	3	3
Imhoff cone substrate settleables (mgCOD/l)	3360	9520	9920	4020	1608

Table 3.8: The effect of the supernatant on the overall PVC liquor concentration, for a PVC column

Source	Settleable		Supernatant		PVC Column Total liquor	
	Volume (L)	BPO (mgCOD/l)	Volume (L)	BPO (mgCOD/l)	volume (L)	BPO (mgCOD/l)
PVC1	0,5	10 000	1,3	865	1,8	3403
PVC5	0,5	50 000	14,5	865	15	2503

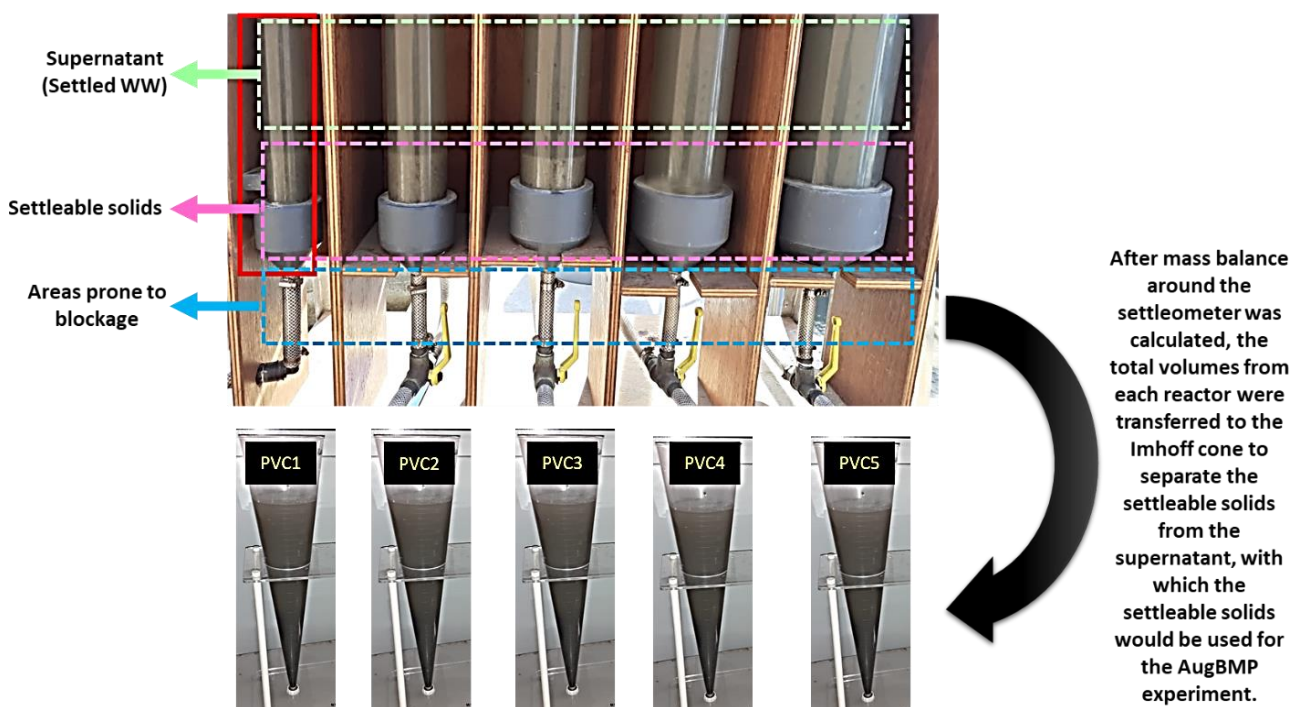


Figure 3.19: The process of separating the settleable solids from the supernatant

3.5.3. Augmented biomethane potential test: Set-up

The AugBMP experimentation was carried out in triplicates. This implies that three batch reactors (BRs) of the same control, three BRs of the PVC1 test sample, three BRs of the PVC2 test sample, and so forth, were prepared. Basically, the total number of the original samples under study is six (6), and considering the triplicates, it makes up eighteen (18) BRs. A schematic representation of the AugBMP test set-up is shown in **Figure 3.21**. Essentially, each of the BRs was connected to a graduated inverted column that was placed in a water bath. These inverted columns were used to monitor the biogas release by each respective batch reactor. The point at which these columns indicated no sign of biogas production is of importance for the present study given that it was taken to signify the point at which the biodegradable components of the substrate had been completely utilized.

A combination of 6 L and 2.5 L reactor vessels were used for this experimentation due to the limited number of 6 L vessels at the UCT WQL. Although the 6 L reactor vessels were preferable, given that they allow for a greater working volume, the use of the 2.5 L vessels has not yet been proven unacceptable. A selection of the reactor sizes for the unique test samples was in such a way that each sample had two 6 L BRs and one 2.5 L BR to make up a triplicate. The control sample, on the other hand, had two 6 L BRs and two 2.5 L BRs. Each of these 6L and 2.5L reactor vessels had two big openings, one located at the top of the reactor bottle and the other just at the lower end of the bottle. The top opening was capped with a rubber stopper with three holes, one holding the submerged 100 W aquarium heater, the second connected to the inverted columns by a flexible tubing to allow for biogas escape, and the last to connect the gas sampling bag filled with N₂ gas during the effluent sampling. The aquarium heaters ensured that the BRs were maintained under mesophilic reactor conditions. The opening at the bottom of the reactor was closed with a rubber stopper connected to a syringe. The syringe was pulled out for effluent sampling and pushed back into the reactor after sampling. This syringe method was preferred over the tap method (**Figure 3.20**). With the tap method, a syringe is replaced by a tap for effluent withdrawal. The tap is rotated anticlockwise to release the sample and clockwise to stop the effluent flow. Although the tap is rotated back clockwise to stop the effluent, it does not push all the liquid back inside the reactor. Some of the liquid remains around the tap area and does not undergo proper degradation, which would then result in a greater chance of incorrect outcomes (i.e., sampling would be on the partially degraded effluent that is not representative of the reactor liquor). For this reason, the syringe method is preferable as it allows the whole effluent to be pushed back into the reactor to undergo the necessary degradation. To consistently achieve the completely mixed conditions in all the reactors, manual stirring was

performed 2–3 times a day. This was done by physically lifting the reactor vessel and gently rotating it in a circular motion until complete mixing is observed. This process was repeated daily for the duration of the experiment and, most importantly, during sampling.

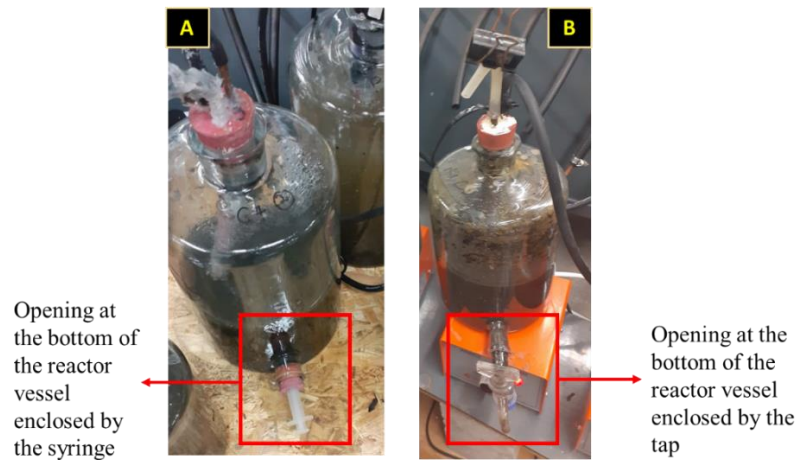


Figure 3.20: The methods for effluent withdrawal: (A) the syringe method, and (B) the tap method

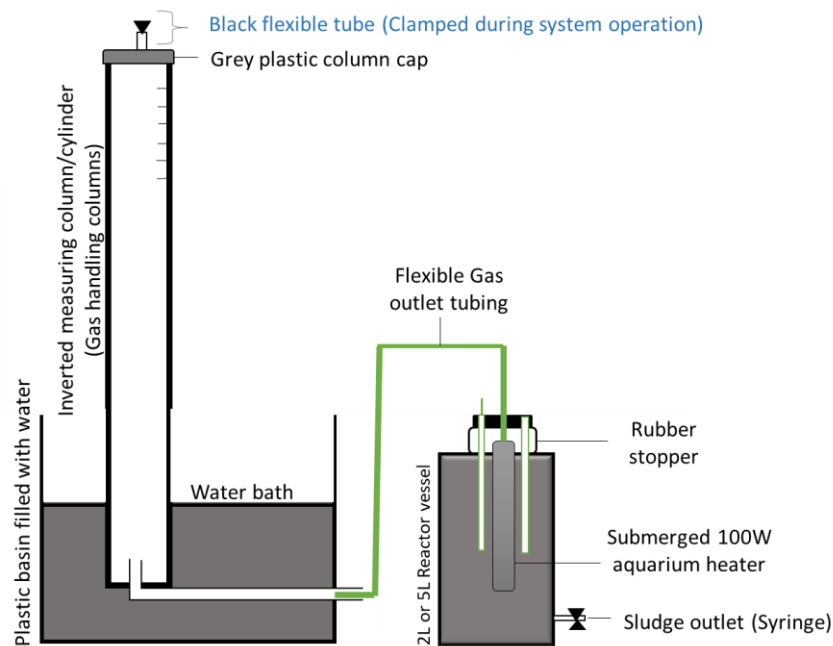


Figure 3.21: The schematic of the side view of the AugBMP set-up

3.5.4. Augmented biomethane potential test: Operation

The initial step of the AugBMP experiment comprised performing a leak test around the inverted columns and reactor vessels (**Figure 3.22A**). To start the leak test, the water bath holding the transparent inverted columns was filled with clean water. The individual inverted columns were connected to the respective reactor vessels by black flexible tubes via the bottom column opening (**Figure 3.21**). The top column opening was covered by a plastic column cap, which was connected

to another black flexible tube that was usually clamped during the system operation to hold the pressure that kept the column water in place. To fill up the inverted columns to maximum level, the water from the bath was sucked in using the vacuum pump. A metal clip was used to clamp the black tubes at the top of the column shut. Thereafter, all leaks were monitored for the subsequent 24 hours. The water levels within these columns had to remain stable to confirm that there were no leakages. The water displacement inside the inverted columns should only be caused by biogas release, implying that any movement in the water level, after the top was clamped (before connecting to BRs), meant that there were leakages around the columns which required urgent attention. Within a period of 24 hours, two of the inverted columns presented signs of leakage. After inspection, it was discovered that the leakage was caused the top plastic column cap not being sufficiently tightened (**Figure 3.22B–C**). To stop the leakage, silicon grease was applied around the leaking column cap and let to dry. The silicon application appeared to work sufficiently well. The reactor vessel leak tests were performed by filling each of the eighteen vessels with clean water and leaving them overnight to detect any form of leakage, which may affect the system operation. After a night of doing so, it was confirmed that the reactor vessels had no leaks and were ready to operate.

The second step towards initiating the AugBMP experiment was to set up the correct mesophilic temperature in each reactor (at 35–38 °C). This was done by submerging a 100 W aquarium heater in each AugBMP reactor, filled with water (the sample and inoculum was only added once the leak test and temperature checks were completed). The electronic power cable used for connecting the submerged heater to its power source was passed through the top vessel opening rubber stopper (**Figure 3.21**). The liquid temperature was continuously monitored every 2 to 4 hours, for the first 48 hours, using an immersion glass thermometer to ensure that the temperature remained well within the range of 35–38 °C. The systems were left to run overnight to confirm that they could sustain continuous operation. Once this was confirmed, the reactor vessels were emptied of their water, and the vessels were ready for the AugBMP tests.

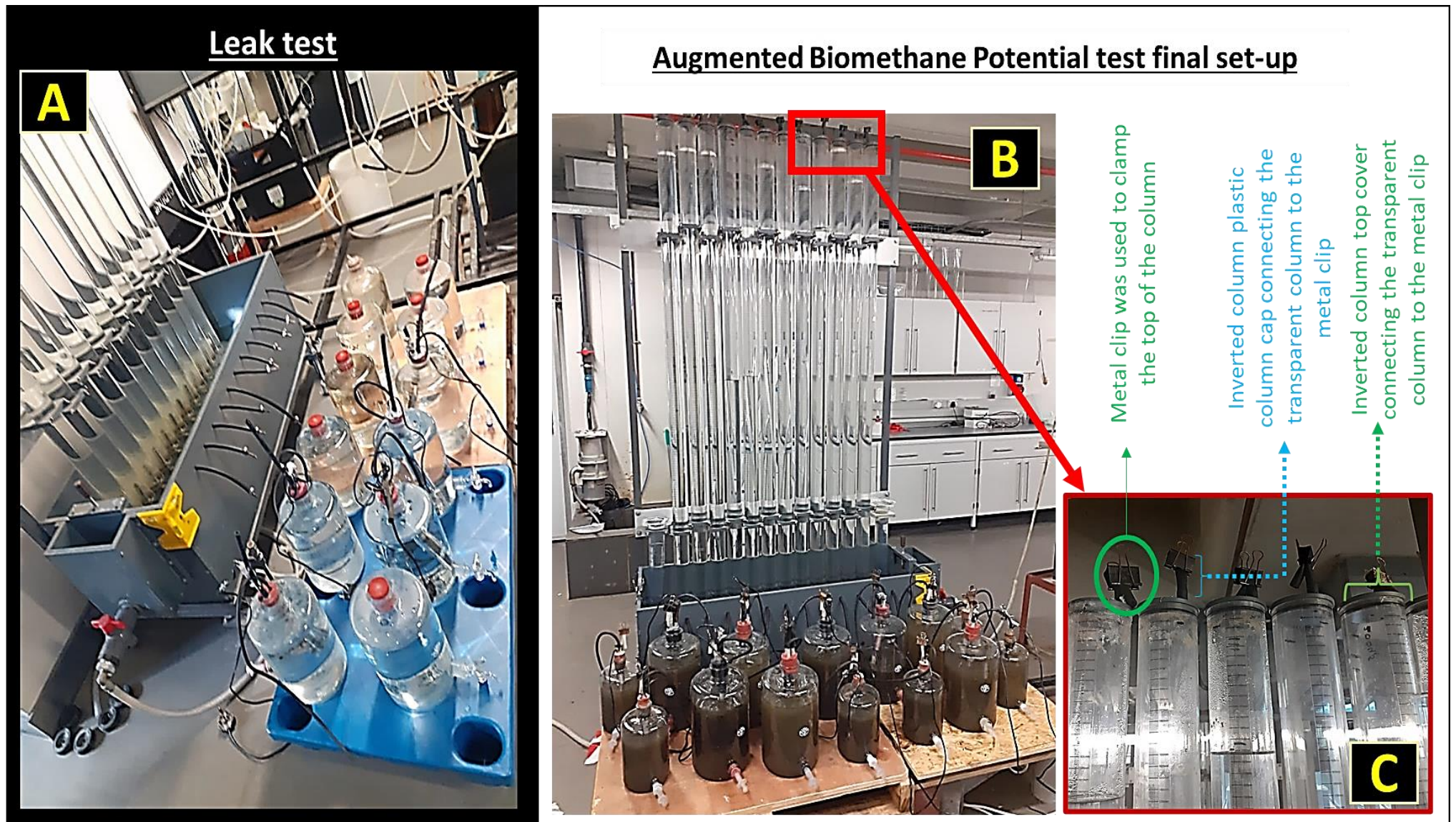


Figure 3.22: The set-ups: (A) the inverted columns and reactor vessel leak test, (B) the AugBMP inverted columns with a complete AugBMP test set-up, and (C) the inverted column covered with a plastic cap that connects to the metal clip.

3.5.5. Seeding procedure

Two main seeding processes were used for the AugBMP test. These are (i) the control seeding, and (ii) the test seeding. These two main seeding processes are described in detail below.

3.5.5.1. Control mixture preparation and seeding process

A control seeding batch reactor (BR) comprised a homogeneous mixture of clean water and inoculum. The inoculum was a methanogenic culture withdrawn directly from an active PAD system. To prepare the homogeneous mixture for the control BRs, the concentrations of the inoculum (biomass culture) and substrate needed to be known as they are used when selecting the biomass to substrate ratio (Bio: Subs ratio) for the AugBMP experiment. This is because while it is important to ensure that the biomass concentration in the BR is sufficient to degrade the biodegradable component of the substrate, it is equally critical to ensure that the Bio: Subs ratio is kept between 1:1 and 3:1 to warrant accurate results from a well-represented substrate.

As shown in **Table 3.9**, the initial inoculum concentration is 11 000 mgCOD/l, whereas in the PVC1, PVC2, PVC3, PVC4, and PVC5, the initial substrate concentrations are 3360 mgCOD/l, 9520 mgCOD/l, 9920 mgCOD/l, 4020 mgCOD/l, and 1608 mgCOD/l, respectively (see **Section 3.5.2**). Clearly, the biomass (or inoculum) concentration was higher than the substrate, especially in the PVC5. This concentration gap required that the initial biomass be diluted 50% of its mass to have a more suitable ratio with the substrate mass. In addition, it was important that enough diluted inoculum mixture was prepared to ensure that all the starting inoculum mixtures of the control reactors and SVG test reactors are considered. As a result, a 24 L fresh methanogenic culture was mixed with a 24 L clean distilled water, in a 200 L drum, to yield 48 L of a 2-fold diluted inoculum. From this mixture, an 8 L volume was mixed with another 6 L water to make up 14 L control liquor, thus resulting in a concentration of 3143 mgCOD/l (**Table 3.9**). The remaining 40 L (i.e., 48 L – 8 L) were used for the test reactors. The 8 L is a selected standard inoculum volume for both the control and test BRs. This is to simplify the process of subtracting the inoculum masses from the test reactors (see **Section 3.9**). Approximately 10 L of this control liquor were transferred into 2 x 6 L reactor vessels (5 L added to each, allowing for 1 L headspace), and the remaining 4 L liquor were transferred into 2 x 2.5 L reactor vessels (2 L added to each, allowing for 0.5 L headspace), thus making up four control reactor vessels. Each of these four control BRs had a liquor COD concentration of 3143 mgCOD/l.

3.5.5.2. *Test mixture preparation and seeding process*

The test seeding was divided into five sub-seedings to accommodate the five settling velocity groups (SVGs) of the 5C-settleometer. Each BR for the test seeding comprised homogeneous mixtures of the solids from a given settleometer column, plus the inoculum (the 2-fold diluted inoculum prepared in **Section 3.5.5.1** was used in the test reactors). All five settleometer columns were sampled accordingly to provide the substrates for the five corresponding test BRs (see **Section 3.3.6**). The same procedure followed for the control seeding was repeated for the test seeding, with the only difference being that the respective substrate was used in place of water. Importantly, although the control reactors were in quadruplicates, the test reactors were only performed in triplicates, i.e., 2 x 6 L reactor vessels and 1 x 2.5 L reactor vessel. For the 6 L reactor vessels, 5 L operating volume with a 1 L headspace was prepared, whereas, for the 2.5 L reactor vessels, 2 L operating volume with a 0.5 L headspace was prepared.

Essentially, for the PVC1, a 1.5 L substrate volume was mixed with 4.5 L clean water and 8 L of the 2-fold diluted inoculum to make up 14 L. This implies that the same inoculum mass as added to the control reactors was added to the test reactors. It would then be assumed that the substrate was 4-fold diluted to make up 6L (i.e., 4 x 1.5) substrate (plus 8 L inoculum makes up 14 L). A 10 L volume of this test liquor was transferred into 2 x 6 L reactor vessels (5 L added to each, allowing for 1 L headspace) and 2 L liquor were transferred into 2.5 L reactor vessels (allowing for 0.5 L headspace). The other remaining 2 L were discarded, and this had no impact on the initial concentrations. In terms of masses, the overall inoculum to substrate ratio for the PVC1 is 8.7:1 (**Table 3.9**). Although Gaszynski (2020) recommends an inoculum to substrate ratio between 1:1 and 3:1 to get a more representative substrate culture for an AugBMP test, the 5C-settleometer is designed in such a way that the PVC1 has a volume capacity of only 1.8 L, and therefore, it could only be operated at such volume. To improve this aspect in future studies, multiple settleometer test runs can be performed at the same flow rates (preferably on the same day). The output masses can then be combined to run the AugBMP test.

The same process as followed for the PVC1 was repeated for the PVC2 to PVC5, with the only difference being that a 3 L substrate volume was mixed with 3 L clean water and 8 L of the 2-fold diluted inoculum to make up 14 L. It was assumed that the substrate was 2-fold diluted to make up 6 L (i.e., 2x3 substrate), plus 8 L inoculum makes up 14 L. Approximately 10 L of this test liquor were transferred into 2 x 6 L reactor vessels, 2 L liquor were transferred into 2.5 L reactor vessels, and the remainder 2 L were discarded. The PVC2 and PVC3 were both able to achieve a quite good inoculum to substrate ratio of 1.5:1 given that the columns had high particle concentrations (and much greater

volumes). The PVC4 showed an inoculum to substrate ratio of 3.6:1, which is relatively close to the recommended range. The ratio for the PVC5 was higher 9:1 given that the particle concentration in the column was low. Once more, the multiple settleometer runs would be useful in this case. The final concentrations of the SVG columns are shown in **Table 3.9**.

3.5.5.3. AugBMP reactor start-ups

Before starting the seeding process for the AugBMP test, the reactor vessels were all flushed with nitrogen gas (N₂) for few minutes to get rid of all unwanted gas reservoir, thus creating an anaerobic environment. This was done by connecting the gas tube to the influent opening and pumping in N₂ gas to flush out (displace) the gases initially present in the reactor vessels. After the N₂ gas had been pumped into the reactor vessels, their openings were immediately closed with a rubber stopper. Thereafter, the respective control, PVC1, PVC2, PVC3, PVC4, and PVC5 mixtures, as prepared in **Sections 3.5.5.1** and **3.5.5.2**, were transferred into the respective anaerobic reactor vessels.

Immediately after transferring the mixtures into the reactor vessels, the reactor liquors were flushed with N₂ gas and sealed. After completing this process, the BRs were then regarded as being “in operation”, and the gas line (which connects the reactor vessels to the inverted gas measuring column) remained unclamped to allow the biogas to flow through to the inverted PVC columns. Biogas is expected when the reactor vessels show stable operation from the biological breakdown of the biodegradable reactor contents. The control sample will help determine the biodegradable, unbiodegradable and inorganic portions of the inoculum used in the test samples. Given that equal volumes (and masses) of the diluted inoculum are added to both the control and test BRs, the difference between the test sample and inoculum sample gives the substrate portions.

Table 3.9: The biomass/inoculum, substrate, and water proportions in terms of the volume and concentration prepared for the AugBMP test

Source (and unit)	Value	Fraction of Biomass to Water: 0,5					
Initial biomass concentration (mgCOD/l)	11000						
Volume of biomass (Litre)	24						
Volume of water (Litre)	24						
Total volume (Litre)	48						
Mass of biomass (mgCOD)	264000						
New biomass concentration (mgCOD/l)	5500						
Volume (Litre)	Control	PVC1	PVC2	PVC3	PVC4	PVC5	Total volume
Biomass (Litre)	8.0	8.0	8.0	8.0	8.0	8.0	48
Substrate (Litre)	0	1,5	3	3	3	3	13.5
Water (Litre)	6.0	4.5	3.0	3.0	3.0	3.0	22.5
Mixture (Litre)	14	14	14	14	14	14	78
COD concentrations	Control	PVC1	PVC2	PVC3	PVC4	PVC5	
Biomass (mgCOD/l)	5500	5500	5500	5500	5500	5500	
Imhoff cone substrate settleables (mgCOD/l)	0	3360	9520	9920	4020	1608	
Water (mgCOD/l)	0	0	0	0	0	0	
Masses per total mixture	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5	
Biomass	44000	44000	44000	44000	44000	44000	
Substrate	0	5040	28560	29760	12060	4824	
Water	0	0	0	0	0	0	
Biomass/Inoculum: Substrate Ratio (Using masses)		8,7	1,5	1,5	3,6	9,1	
Mixture (mgCOD/l)	3143	3503	5183	5269	4004	3487	
Biomass concentration in a mixture (mgCOD/l)	3 143	3143	3143	3143	3143	3143	
Substrate concentration in a mixture (mgCOD/l)	0	360	2040	2126	861	345	
Water (mgCOD/l)	0	0	0	0	0	0	

3.5.6. Augmented biomethane potential test: Monitoring and sampling procedure

The performance of the AugBMP test was monitored daily. This was done by (i) manually stirring the reactor vessels twice a day (see **Section 3.5.3** for the stirring process), (ii) monitoring the occurrence of leaks, and (iii) monitoring the biogas release from the inverted columns. The amount of biogas released is an important measure of the biodegradable component present in a sample. This measure was monitored by checking the movement of the water level on the water-inverted columns. The water displacement readings, due to biogas release, were recorded daily. A gradual decline in biogas release (and subsequently very low water displacement) was observed after the first two weeks. The overall water displacement recordings formed the basis for the curve generation of the biogas release (**Appendix B**). Gas chromatography (GC) was used to determine the content of the methane forming part of the produced biogas. More information on GC is provided in **Section 3.5.7**.

The intense AugBMP testing was carried out on the (i) first day of experimentation, (ii) fourteenth day, and (iii) fortieth day when no biogas production was observed. The analyses of pH, COD (both filtered and filtered), FSA, TKN, OP, TP, TSS, VSS, and ISS were made. These analytical tests are described in detail in **Section 3.6**. To sample the effluent from the reactor vessels, the biogas tubing was clamped with a binding metal clip to prevent the column water from drawing into the reactor vessels due to the pressure drop. To balance the pressure, a gasbag, filled with N₂ gas, was connected to the influent line. This implies that instead of water drawing into the reactor, the N₂ gas, which has

no effects on the AD process, compensates for the lost pressure. When the effluent withdrawal is complete, the biogas tubing is unclamped, and the influent line is clamped back to allow the biogas release into the appropriate columns. This sampling procedure is shown in **Figure 3.23**.

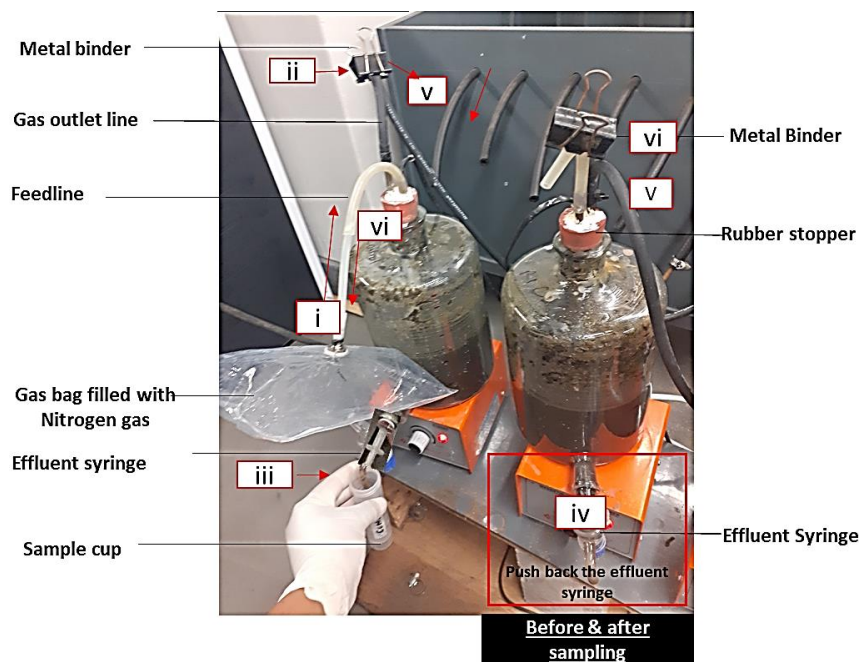


Figure 3.23: The AugBMP test effluent sampling process: (i) the nitrogen gasbag is first connected and tightened to the influent line, then (2) unclamp the influent line and clamp the gas line to ensure that the bath water do not draw into the digester when drawing the sample. Thereafter, (3) gently pull out the syringe to draw the sample. After enough sample has been drawn, the syringe is pushed back into the reactor vessel, and (iv) immediately close the sample tube to avoid CO₂ escape, which may affect the pH results. The gas outlet line is then unclamped. (v) The influent line is clamped, and (vi) the nitrogen gas bag is removed. Then, the entire procedure is repeated for to the next reactor.

3.5.7. Gas chromatography

The Perkin-Elmer Auto system gas chromatograph (GC) was used to analyse the biogas produced by the AugBMP test reactors. This equipment is unavailable at the UCT WQL, and therefore, an arrangement was made with the Chemical Engineering Department (UCT) to provide necessary access. The methane (CH₄) proportion of the biogas was of particular importance for the present study as it contains COD. The COD equivalent of the CH₄ proves useful particularly when conducting the COD mass balance. The CH₄ proportion was determined using the flame ionisation detector (FID). The FID is paired with the GC instrument to allow the necessary analyses. Essentially, a 100 µl volume of biogas was injected into the GC with the FID set at 280 °C and temperature set at 50 °C. Using 25% and 50% CH₄ standards, a curve used as a reference to calculate the reactor methane content was generated and used in this case. It was assumed that the biogas comprised CH₄ and CO₂, implying that all gas not recorded as methane was assumed to be CO₂. To put into context, the GC outcomes into the COD mass balance, volume, and CH₄ COD equivalent produced had to be

determined. The CH₄ volume in the biogas was determined by multiplying the sum of the total volume recorded, per inverted column, and the biogas sampled for the GC analysis with the GC percentage outcome (calculated from a linear function generated by the 25% and 50% CH₄ standards). To account for the larger volume occupied by biogas in the column, than in the atmosphere (Gaszynski, 2020:62), a universal gas law was applied (**Equation (3.16)**). From this law (**Equation (3.16)**), the CH₄ molar equivalent was determined. Thereafter, the equivalent COD was calculated by multiplying the number of moles by the COD per mol of CH₄ (i.e., 64 gCOD/mol). This CH₄ proportion analysis was repeated every second day for the first two weeks of the AugBMP experimentation. The first two weeks was preferred since the biogas release was intense and for the purpose of this study, accepted that the biogas during this period comprised representable CH₄ proportions. While the first two weeks was used to analyse the quality of the biogas produced, the total biogas volume recorded in the entire AugBMP test duration was used to determine the overall CH₄ molar equivalent per AugBMP test batch reactor.

$$P_{std}V = nRT_{std} \quad (3.16)$$

$$n = RT_{std}/P_{std}V \quad (3.17)$$

Where: P_{std}: Standard pressure (101.32 kPa)
T_{std}: Standard temperature (293 K)
R: Gas constant (8.314 l.kPa/K.mol)
V: Gas volume (Methane gas volume)
n: Methane molar equivalent (mol)

3.5.8. Augmented biomethane potential test: Data experimental error

Laboratory experimental work can be subject to both human and instrument errors. Human errors can include mistakes during dilutions, while instrument errors can be related to the weigh scale imprecisions, for instance. Experimental errors can be defined as discrepancies between the measured and actual values. These experimental errors can be evaluated using (i) the percentage error, and (ii) the mean and standard deviation (Gaszynski, 2020:84). The percentage error, mean, and standard deviation are described in detail in the subsections below.

3.5.8.1. Percentage error

Gaszynski (2020:85) defined a percentage error as a measure that is used to evaluate the comparability between the actual value (A) and experimental value (E). This can be well represented using

Equation (3.19). Essentially, the percentage error provides information on how accurate the experimentally measured value is to the actual value.

$$\%Error = \frac{[E - A]}{A} \% \quad (3.18)$$

Where: E: Experimental value

A: Actual value

3.5.8.2. Mean and standard deviation

The mean and standard deviation represent two of the concepts used to evaluate the experimental outcomes in terms of precision. The precision refers to the reproducibility or closeness of the measured data. Holliger *et al.* (2016: 2517) highlighted the importance of standard deviation (SD) when testing a large number of samples (N). Gaszynski (2020: 86) defined SD (σ) as a mean square deviation that measures how the collected data spread out with respect to the mean (**Equation (3.19)**). The author further defined the mean ($\bar{x}$) as the average value of multiple samples collected at a particular point/time (**Equation (3.20)**). Holliger *et al.* (2016: 2518) stated that test results should be rejected if the SD is greater than 10%. As described in **Section 3.5.3**, the biodegradability test for each PVC column was performed in triplicates. Each of the COD, TSS, VSS, and ISS tests was performed in duplicates, thus multiplying by the triplicate makes up a total of six (6) samples per PVC column biodegradability test. The application of the standard deviation (**Equation (3.20)**) will determine how precise the measured data is. The results are rejected if the standard deviation between the six sample points is greater than 10%.

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad (3.19)$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2} \quad (3.20)$$

Where: $\bar{x}$ = Mean concentration for multiple samples collected at a particular point.

N = Number of samples collected at a particular point to calculate the mean concentration.

σ = Standard deviation

X_i = Concentration at a given point)

3.5.9. Mass balance around the AugBMP test batch reactors

3.5.9.1. Overview

The principles of MB were applied around each of the AugBMP test reactors to confirm the validity of the measured data (Gaszynski, 2020: 78). The MB principles are based on the concept of mass conservation. The careful evaluations on the measured data were performed prior to the MB applications mainly using (i) the percentage error (**Section 3.5.8.1**), and (ii) the standard deviation principles (**Section 3.5.8.2**). All the outliers identified during these evaluations were removed. The MB was applied to the COD, N, and P for all the individual AugBMP test BRs. As stated by Gaszynski (2020: 78), a 20% over or below a 100% MB is acceptable, provided the underlying reasons are given. A MB beyond 80% and 120% is an indication of incorrectly measured data and may require thorough interpretations.

3.5.9.2. Chemical oxygen demand, Nitrogen, and Phosphorus balance

Since the anaerobic BRs are subject to biological alterations, it is essential to understand the fate of all the components making up the input material. In terms of COD, the input matter comprises both biodegradable and nonbiodegradable components in the form of particulates and solubles. Under anaerobic and mesophilic conditions, approximately 90% of the biodegradable COD are converted to biogas, comprising CH_4 and CO_2 , with the remaining fraction converted to biomass. The (i) influent, sample withdrawals, and remaining COD concentrations for each individual BR, (ii) volumes of the produced biogas measured in the inverted columns, (iii) volumes of biogas sampled for the GC analysis (see **Section 3.5.7**), (iv) liquid volumes sampled for wet chemistry analysis (see **Section 3.6**), and (v) remaining liquid volume at the end of the experiment needed to be known. The subsections below discuss the applications of these different concentrations and volumes towards the COD, N, and P MBs.

3.5.9.2.1. Chemical oxygen demand (COD) balance

As illustrated in **Equation (3.21)**, for control reactors, multiplying the influent COD concentrations by the influent volumes gives the influent COD mass. For each sampling cycle, the sample volume withdrawn and corresponding sample concentrations were recorded. Using **Equation (3.22)**, the sum of the withdrawn sample masses was calculated. As briefly mentioned above, a greater content of the COD is converted to biogas. Therefore, to calculate the CH_4 COD equivalent, the corresponding GC percentage outcome was multiplied by the (i) sum of the withdrawn sample biogas volumes, and (ii) respective inverted column volume to get the CH_4 volume produced (see **Section 3.5.7**). Using the universal gas law, the CH_4 mole equivalent was determined (**Equation (3.17)**), by which the

equivalent COD mass was calculated by multiplying by 64 000 mgCOD/mol (**Equation (3.23)**) (Gaszynski, 2020:79). To close the mass balance, the remaining liquid volume, in each BR, was multiplied by the corresponding COD concentrations (**Equation (3.24)**). From these masses, the COD balance was then performed. Essentially, the influent COD mass is the sum of the COD masses converted to biogas, total sampled COD mass, and remainder COD mass on the last day of the experimentation (**Equation (3.25)**). The same control COD mass balance principles were applied to the batch test reactors as represented by **Equations (3.21) to (3.25)**.

3.5.9.2.2. Nitrogen (N) balance

The N balance for both the control and test reactors were performed. Although the anaerobic degradation of the organics results in the release of N into the liquid, none of the N is converted to the gas state or lost in any way. This implies that all the released N remains in the liquid. As a result, the total N entering the batch reactor should equal the total N exiting the batch reactor. The steps taken to measure the TKN are well described in **Section 3.6.9**. To calculate the TKN mass entering the batch reactor, the TKN influent concentration is multiplied by the total influent volume (**Equation (3.26)**). The influent mass must equal the sum of the sampled TKN masses and remaining total TKN mass (**Equations (3.27) to (3.29)**).

3.5.9.2.3. Phosphorus (P) balance

The P balance, i.e. P MB, will use the same principles as for the N balance. The P released during the anaerobic degradation of the organics remains in the liquids. Therefore, the total P entering the batch reactor should equal the total P existing the batch reactor. The steps taken to measure the TP content is discussed in **Section 3.6.8**. Similarly, to calculate the P balance, **Equations (3.30) to (3.33)** are used.

COD mass balance for both control and test reactors

$$MCOD_{inf} = COD_{inf} \times Vol_{inf,Liq} \quad \text{mgCOD} \quad (3.21)$$

$$MCOD_{Samp} = \sum_{i=Day\ 1}^{Last\ day} (COD_{Samp} \times Vol_{Samp,Liq}) \quad \text{mgCOD} \quad (3.22)$$

$$MCOD_{CH_4} = 64\ 000n \quad \text{mgCOD} \quad (3.23)$$

$$MCOD_{rem} = COD_{rem} \times Vol_{rem,Liq} \quad \text{mgCOD} \quad (3.24)$$

$$Mass\ balance = \left(\frac{MCOD_{Samp} + MCOD_{rem} + MCOD_{CH_4}}{MCOD_{inf}} \right) \times 100 \quad \% \quad (3.25)$$

TKN mass balance for both control and test reactors

$$MN_{inf} = N_{inf} \times Vol_{Inf,Liq} \quad \text{mgN} \quad (3.26)$$

$$MN_{Samp} = \sum_{i=Day\ 1}^{Last\ day} (N_{Samp} \times Vol_{Samp,Liq}) \quad \text{mgN} \quad (3.27)$$

$$MN_{rem} = N_{rem} \times Vol_{rem,Liq} \quad \text{mgN} \quad (3.28)$$

$$TKN\ mass\ balance = \left(\frac{MN_{Samp} + MN_{rem}}{MN_{inf}} \right) \times 100 \quad \% \quad (3.29)$$

TP mass balance for both control and test reactors

$$MP_{inf} = P_{inf} \times Vol_{Inf,Liq} \quad \text{mgP} \quad (3.30)$$

$$MP_{Samp} = \sum_{i=Day\ 1}^{Last\ day} (P_{Samp} \times Vol_{Samp,Liq}) \quad \text{mgP} \quad (3.31)$$

$$MP_{rem} = P_{rem} \times Vol_{rem,Liq} \quad \text{mgP} \quad (3.32)$$

$$TP\ mass\ balance = \left(\frac{MP_{Samp} + MP_{rem}}{MP_{inf}} \right) \times 100 \quad \% \quad (3.33)$$

Where: $MCOD_{inf}$ = Mass of influent COD in the control or test reactor

COD_{inf} = Concentrations of influent COD in the control or test reactor

$Vol_{Inf,Liq}$ = Influent liquid volume in the control or test reactor

$MCOD_{Samp,inf}$ = Mass of COD sampled from the control or test reactor (For wet chemistry analysis)

COD_{Samp} = Concentrations of COD sampled from the control or test reactor (For wet chemistry analysis)

$Vol_{Samp,Liq}$ = Sampled liquid volume from the control or test reactor (For wet chemistry analysis)

$MCOD_{rem}$ = Mass of remaining COD in the control or test reactor (For wet chemistry analysis)

COD_{rem} = Concentrations of remaining COD in the control or test reactor (For wet chemistry analysis)

$Vol_{rem,Liq}$ = Remaining liquid volumes in the control or test reactor (For wet chemistry analysis)

MN_{inf} = Mass of influent N in the in the batch reactor

N_{inf} = Concentrations of influent N in the batch reactor

MN_{Samp} = Mass of N sampled from the batch reactor

N_{Samp} = Concentrations of N sampled from batch reactor

MN_{rem} = Mass of remaining N in the batch reactor

N_{rem} = Concentrations of remaining N in the batch reactor

MP_{inf} = Mass of influent P in the in the batch reactor

P_{inf} = Concentrations of influent P in the batch reactor

MP_{Samp} = Mass of P sampled from the batch reactor

P_{Samp} = Concentrations of P sampled from batch reactor

MP_{rem} = Mass of remaining P in the batch reactor

P_{rem} = Concentrations of remaining P in the batch reactor

3.5.10. Additional comments

One of the SVG4 sample reactors leaked during the experimentation and its operation had to be discontinued. This is given that the reactor lost significant amounts of liquid, and hardly any solids, thereby resulting in an unrepresentative mixture in the system. To compensate for the lost reactor, more samples were taken from the remaining SVG4 duplicate reactors to ensure that enough measurement points were recorded to get accurate representations.

3.6. Analytical procedures

3.6.1. Overview

The COD, TSS, VSS, ISS, pH, FSA, OP, TP, TKN, VFA, and alkalinity measurements were done on the samples collected from the (i) 5C-settleometer, (ii) AugBMP BRs, (iii) PAD system, and (iv) FS-PST. These analytical tests were performed immediately after sampling to avoid biological or chemical alterations that may hinder the provision of accurate results. The subsections below briefly discuss each of these analytical tests. **Table 3.10** provides a summary of the required analytical tests per experimental set-up.

3.6.2. Chemical Oxygen Demand (COD)

As presented in **Table 3.10**, the COD analysis was performed for the PAD system, AugBMP test reactors, 5C-settleometer and FS-PST filtered and unfiltered samples. The unfiltered sample is the original sample, including both particulate and soluble constituents, while the filtered sample is the 0.45 µm membrane filtered sample, i.e. the soluble part of the original sample. Given that the present study focus is on the segregation of particles, both the filtered and unfiltered COD measurements were necessary (the difference between the unfiltered and filtered COD gives the particulate COD) (See **Table 3.10**). The open reflux method by APHA *et al.* (2017: 588) was adapted. Essentially, a 10 ml sample, with a known excess of 5 ml potassium dichromate ($K_2Cr_2O_7$), was refluxed with 15 ml strong sulphuric acid in a COD digestion tube, then placed on a test tube rack for subsequent digestion at 150 °C in the pre-heated COD digestion block shown in **Figure 3.25A**. A 2-hour standard digestion or reflux time was used. After digestion, the digested content was titrated with ferrous ammonium sulphate (FAS) ($Fe (NH_4)_2(SO_4)_2$). The remaining unreduced $K_2Cr_2O_7$ gives an indication of how much $K_2Cr_2O_7$ was consumed, and therefore using the oxygen equivalent method, the oxidizable matter can be calculated (**Equation (3.34)**).

$$COD = \frac{(a - b) \times N \times 8000}{10 \text{ ml sample}} \quad \text{mgCOD/l} \quad (3.34)$$

Where: a = Average volume $Fe (NH_4)_2(SO_4)_2$ used to titrate blank (ml)

b = Average volume $Fe (NH_4)_2(SO_4)_2$ used to titrate sample (ml)

N = Normality of $Fe (NH_4)_2(SO_4)_2$

3.6.3. Mixed liquor total suspended/settleable/settled solids (MLTSS) analysis

The mixed liquor total settleable solids (MLTSetS) was obtained by performing the TSS analysis on the primary sludge, or Imhoff cone settleable solids, after 2 hours. On the other hand, the mixed liquor total settled solids (MLTSovS) was obtained by performing the TSS analysis on the settled WW, or

Imhoff cone supernatant, after 2 hours. The sum of the MLTSetS and MLTSovS is called mixed liquor total suspended solids (MLTSuS). The MLTSuS can also be obtained by performing the TSS analysis on the raw WW. The TSS analysis (for MLTSuS, MLTSetS, or MLTSovS) was performed using the standard operating procedure by Ekama *et al.* (n.d.). Essentially, a 50 ml sample was centrifuged at 6000 rpm for 10 minutes using the Centurion Scientific centrifuge, shown in **Figure 3.25B**. The supernatant was discarded, and the accumulated solids were transferred into a pre-weighed clean and dry crucible. This was then dried in the 105 °C pre-heated oven shown in **Figure 3.25C** for 24 hours. The pre-weighed clean and dry crucible denotes Mass 1 (g). After 24 hours of drying, the crucible was cooled down in a desiccator (**Figure 3.25L**), and then the resulting mass was weighed using the scalar shown in **Figure 3.25J**, thus denoting Mass 2 (g). The crucible with dried solids was then placed in the 550–600°C incinerator shown in **Figure 3.25G** for approximately 20 minutes to evaporate all the volatile solids. The remaining solids after incineration are called mixed liquor inorganic settleable solids (MLISetS), mixed liquor inorganic settled solids (MLISovS) or mixed liquor inorganic suspended solids (MLISusS). The crucible with MLISetS, MLISovS, or MLISusS was then cooled down in a desiccator, and the final mass was weighed, thus denoting Mass 3 (g). From these measurements, the final MLTSS and MLISS were calculated; also calculated thereof were the mixed liquor volatile suspended, settleable or settled solids (MLVSS), which are denoted as MLVSusS, MLVSetS or MLVSovS, respectively (see **Equations (3.35), (3.36), and (3.37)**).

For the PAD system fed PSS, the terms MLTSetS, MLVSetS, and MLISetS are used. For the FS-PST diurnal samples, the terms MLTSusS, MLVSusS, and MLISusS are used for raw WW (influent); MLTSetS, MLVSetS, and MLISetS for PSS (underflow); and MLTSovS, MLVSovS, and MLISovS for settled WW (overflow). Lastly, for the 5C-settleometer, the TSS outcomes for the PVC columns settleable matter are represented by MLTSetS, MLVSetS, and MLISetS, while the overflow or settled WW from the settleometer is represented by MLTSovS, MLVSovS, and MLISovS.

$$MLTSS = (Mass\ 1 - Mass\ 2) \times 20000 \quad (3.35)$$

$$MLVSS = (Mass\ 2 - Mass\ 3) \times 20000 \quad (3.36)$$

$$MLISS = MLTSS - MLVSS \quad (3.37)$$

Where: MLTSS = Mixed liquor total suspended/settleable/settled solids (mgTSS/l)

MLVSS = Mixed liquor volatile suspended/settleable/settled solids (mgVSS/l)

MLISS = Mixed liquor inorganic suspended/settleable/settled solids (mgISS/l)

20 000 = conversion of settleable solids from 50ml sample measured in g to mgSS/l sample as follows:

$$\left(\frac{g}{50ml} \times \frac{1\,000mg}{g} \times \frac{1\,000ml}{l} \right)$$

3.6.4. pH

As presented in **Table 3.10**, the pH of the 5C-settleometer outputs, PAD system, AugBMP test reactors, and FS-PST samples were tested. The pH of the PAD system and individual AugBMP test reactors were tested on a regular basis to monitor the overall system performance, and the pH of settleometer outputs and FS-PST samples were recorded to monitor the acidity level of the WW. A pH meter, shown in **Figure 3.25D**, was used for measuring the pH. Before use, the pH meter was calibrated using 4.01 and 7.01 pH buffer solutions. As stated by Cioabla *et al.* (2012), the pH of the PAD and AugBMP systems should remain between 6.8–7.2. Any deviation from this pH range can become a threat to the system-driving microorganisms. The two methods used to remediate the low pH levels are (i) the addition of sodium bicarbonate (NaHCO₃), and (ii) the decreasing of the feeding frequency until the system pH levels recovers. The pH levels of all the systems were monitored individually.

3.6.5. H₂CO₃* alkalinity and VFAs

The H₂CO₃* alkalinity (expressed as mgCaCO₃/l) and the VFAs (expressed as mgAcetate/l) were measured using the 5-point titration method proposed by Moosbrugger *et al.* (1993). According to this method, a normalized diluted hydrochloric acid solution is gradually added into a 50 ml filtered sample to reach the four pH set points of 6.7, 5.9, 5.2, and 4.3 (or +/-0.1). These four pH point values, initial pH, and corresponding titrant volumes were recorded into a VFA and alkalinity calculation program coded in Microsoft (MS) Excel as shown in **Figure 3.24**. The electric conductivity (EC) (expressed as mS/m and measured using the conductivity meter shown in **Figure 3.25H**), FSA (expressed as mgFSA-N/l), and OP (expressed as mgOP-P/l) (See **Section 3.6.7** below) were also measured and recorded into the VFA and alkalinity calculation program. By running the “calculate” function (**Figure 3.24**), the corresponding alkalinity and VFAs present in the sample were estimated. The alkalinity of the samples played a major role in understanding the respective WW buffering capacity. As supported by Ripley *et al.* (1986), the VFA/Alkalinity ratio levels had to be kept below 0.3 for a system to operate optimally.

Sample Data				Titration Data		
diluted	Initial pH	7,179	7,024	0,0841	Acid normality	
Volumes (ml)	before dilution	10		20,8	Temperature °C	
	After dilution	50		Titration		
Conductivity Correlation	FSA (mgN/L)	271,1		mL Acid	pH	Corrected pH
Ionic strength /EC25	Temp coeff	OrthoP (mgP/L)	21	1,496	6,713	6,558
7,22E-05	0,0198	Sulphide (mgS/L)	0	3,8	5,924	5,769
EC _T (mS/m)	23,6			4,722	5,165	5,01
EC ₂₅ (mS/m)	25,74	Ionic strength	1,86E-03	4,994	4,3	4,145
				-0,155		

Fill in all the input data (blue cells), then click the Calculate button.

Results		
Molalities	Alkalinities (mg CaCO ₃ /l)	VFA
0,04719379	Carbonate+H ₂ O	1936,64
0,019354608	Ammonia	4,38
0,000677988	Phosphate	13,90
0	Sulphide	0,00
0,000510654	VFA	25,42
	Total	1980,35
0,056681316	Total H+	

30,6433 (mg/L as acetate)

Colour key

Inputs

Outputs

Status

Calculation succeeded

Calculate

Figure 3.24: The alkalinity and VFA calculation program in MS Excel

3.6.6. Total organic carbon (C) concentrations

Two methods used to measure the total organic carbon (TOC) are the high temperature combustion method and Persulfate-Ultraviolet or Heated-Persulfate Oxidation method (APHA *et al.* (2017: 599)). Unfortunately, the UCT WQL is not currently equipped with the necessary instrument to carry out this test. As a result, the C contents of the particulates, at the start and end of the AugBMP experiment, were not experimentally measured. Although the C bound in particulates was not measured, the C released was quantified by measuring the C released from the CO₂, CH₄, and H₂CO₃⁻ alkalinity. The masses of C released from the CO₂ and CH₄ were calculated by multiplying the C molecular weight (12.01 g/mol) by the respective CO₂ and CH₄ number of moles (see **Section 3.5.7** for the CO₂ and CH₄ mole calculations and **Appendix G** for the results). The H₂CO₃⁻ alkalinity released was quantified by taking the difference between the “start” and “end” concentrations (see **Section 3.6.5** for the H₂CO₃⁻ alkalinity measurement procedure). The difference is then multiplied by 0.24 to get the equivalent C in alkalinity released. This measured C represented the C released during the degradation of the BPO components.

The C analysis of the UPOs was obtained using the UPOTOC: COD of 0.348 from the literature. This fraction was multiplied by the f_{cv} calculated from “c” above. The ratio of 0.348 was obtained by dividing the PSS UPO f_c of 0.515 mgC/mgVSS by f_{cv} , of 1.48 mgCOD/mgVSS (Ekama & Brink, 2007: 5). The value 0.348 very close to TOC: COD calculated from f_{cv} and f_c of Wentzel *et al.* (2003: 273), that is, $0.502/1.48 = 0.339$.

The C analysis of the UPOs was obtained using the UPOTOC: COD ratio of 0.348 from the literature. This fraction was multiplied by the f_{cv} . The ratio of 0.348 was obtained by dividing the PSS UPO f_c of 0.515 mgC/mgVSS by the f_{cv} of 1.48 mgCOD/mgVSS (Ekama & Brink, 2007: 5). The value of 0.348, obtained in by Ekama and Brink (2007: 5), is significantly close to the TOC: COD ratio calculated from the f_{cv} and f_c of Wentzel *et al.* (2006: 273), i.e., 0.339 (0.502/1.48).

Note:

The following applies when converting the $H_2CO_3^-$ alkalinity from mg $CaCO_3/L$ to mgC/L:

- $CaCO_3$ and C have molecular weights of 100,0869 g/mol and 12 g/mol, respectively.
 $CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2CO_3$
 $2HCO_3^- + 2H^+ \rightarrow 2H_2CO_3$
- Therefore, in consuming $2H^+$, one mole of $CaCO_3$ (100,0869 g/mol) corresponds to 2 moles of HCO_3^- and contains 24 g of C (2 x Carbon 12).
- Thus, conversion follows: $12 \times 2 / 100,0869 = 0.24$ mg of C.
- Thus, $H_2CO_3^-$ alkalinity as mg $CaCO_3/L$ = 0.24 x Carbonate Alkalinity as $CaCO_3$ (mg/L).

Or



- Therefore, each mole of $Ca(HCO_3)_2$ corresponds with one mole of $CaCO_3$ 100,0869 g/mol and contains 24g of C (2 x Carbon 12 g).
- Thus, conversion follows: $12 \times 2 / 100,0869 = 0.24$ mg of C.
- Thus, $H_2CO_3^-$ alkalinity as mg $CaCO_3/L$ = 0.24 x Carbonate Alkalinity as $CaCO_3$ (mg/L)



3.6.7. Orthophosphates (OP) and free and saline ammonia (FSA)

The OP and FSA components, as required for the VFA and alkalinity tests, were measured using the titrimetric method (APHA *et al.*, 2017: 366). The titrimetric method is a method whereby the concentrations of the desired components in a sample are determined using suitable reagents of known concentrations. Essentially, the known reagent is slowly added into the sample up to a point when the added content equals the sample concentration. To simplify this process, the gallery discrete analyser shown in **Figure 3.25E** was used. Ammonia R1 and Ammonia R2 reagents are used to determine the FSA concentrations, while Phosphate R1 and Phosphate R2 reagents are used to determine the OP concentrations. All samples sent to the gallery had to be filtered through the 0,45 μm membrane filter.

3.6.8. Total phosphates (TP)

The vanadomolybdate colorimetric method outlined by (APHA *et al.*, 2017: 523) was used to determine the total phosphates (TP) present in the samples collected from the 5C-settleometer, PAD system and AugBMP test reactor systems. The phosphorus (P) compound is characterised into soluble and particulate components, which are further subdivided into the biodegradable, unbiodegradable, and inorganic fractions. For the sewage sludge, the inorganic portion of P is mainly present in the

soluble component, which can be determined as orthophosphate (OP). Essentially, the P present in the soluble organics can be classified into the P-bound in the biodegradable soluble organics (denoted as P_{obsi}) and P-bound in the unbiodegradable soluble organics (denoted as P_{ousi}). Similarly, the P present in the particulate component can be classified into the P-bound in the biodegradable particulate organics (denoted as P_{obpi}) and P-bound in the unbiodegradable particulate organics (denoted as P_{oupi}). The OP is measured using the method described in **Section 3.6.7**, while the total soluble phosphorus (denoted as $P_{tsi} = OP + P_{obsi} + P_{ousi}$) is measured using the same steps as described in the next paragraph, with the only difference being that a filtered sample is used. The difference between the P_{tsi} and OP gives the total soluble organic phosphorus (denoted as P_{osi}).

To measure the TP, a digestion step was necessary to degrade and release all the organically bound P into the solution. The hot water bath shown in **Figure 3.25F** was used for the digestion and was set at 96 °C. After 60 minutes of digestion, the samples were filtered through the 0.45 µm membrane filter to eliminate the residual solids. Thereafter, a 5 ml digested and filtered sample was mixed with 5 ml vanadomolybdate solution and left to react for approximately 20 minutes, which thereafter was analysed through the spectrophotometer. Essentially, the phosphorus in the form of orthophosphate ions react with molybdate in the presence of vanadate to form the yellow vanadomolybdate phosphorus solution. The absorbance of the yellow solution is then measured spectrophotometrically at a wavelength of 470 µm. The yellow colour intensity reflects the OP concentration. The standards 5ppm, 10ppm, 15ppm, 20ppm, and a blank (distilled water) were used to plot the concentration versus absorbance linear curve from which a linear equation would be generated. The generated linear equation was then used to calculate the TP concentrations of a sample.

While the measurements of both the filtered and unfiltered TP would help determine the P_{ousi} , P_{obsi} , P_{oupi} , and P_{obpi} , it has been reported that the P_{ousi} and P_{obsi} fractions, relative to P_{ti} , are generally significantly low (being <0.004) (Wentzel & Ekama, n.d : 3.41) (see **Section 4.4.5** below). For this reason, (i) the P_{ousi} will be lumped with P_{oupi} , and (ii) the P_{obsi} will be lumped with P_{obpi} for simplification (see **Table 3.10**). The measurement of TP played an additional role in the MB **Equation (3.39)**. Although MB errors within 10–20% are acceptable (Gaszynski 2020:320), the total TP mass had to remain constant throughout the experimentation.

3.6.9. Total Kjeldahl Nitrogen (TKN)

The Total Kjeldahl Nitrogen (TKN) is the sum of Nitrogen (N) present in the FSA (denoted as N_{ai}) and organic matter (Org-N denoted as N_{oi}). The organically bound Nitrogen (Org-N) can occur in both the soluble and particulate forms, which can be further subdivided into the biodegradable and

unbiodegradable fractions. Similar to P, the soluble N (i.e., N present in the soluble fraction) can be classified into three, namely FSA (N_{ai}), N-bound in the biodegradable soluble organics (denoted as N_{obsi}), and N-bound in the unbiodegradable soluble organics (denoted as N_{ousi}). On the other hand, the particulate N (i.e., N present in the particulate fraction) can be classified only into two, namely N-bound in the biodegradable particulate organics (denoted as N_{obpi}) and N-bound in the unbiodegradable particulate organics (denoted as N_{oupi}). The FSA was measured using the method described in **Section 3.6.7**. The total N, i.e., N in an unfiltered sample, was measured using the micro-distillation method described by APHA *et al.* (2017: 503). To measure the TKN in the unfiltered sample, the digestion step was necessary to release all the organically bound N into solution, after which it was steam distilled using the micro-distillation apparatus shown in **Figure 3.25I**. After the steam distillation, the sample was titrated with 0.001N sulphuric acid until the green solution turned purple. The volume titrated is directly proportional to the TKN concentration in the sample. Thereafter, the sample TKN was calculated using **Equation (3.38)**. The filtered TKN sample gives a measure of the total N that is soluble (N_{tsi}). The measurement of the sample filtered TKN does not require the digestion step, but instead the sample is directly micro-distilled, given that the N is already in a soluble state. The difference between the N_{tsi} and FSA gives the total soluble organic N (denoted as N_{osi}). Similar to the TP, the N_{ousi} and N_{obsi} fractions relative to N_{ti} are generally significantly low (being < 0.004) (Wentzel & Ekama, n.d : 3.41) (see **Section 4.4.5** below). Hence, (i) the N_{ousi} is lumped with N_{oupi} , and (ii) the N_{obsi} is lumped with N_{obpi} , for simplification (see **Table 3.10**). As described in **Section 3.5.9.2.2**, the TKN mass had to remain constant throughout the experimentation.

$$TKN = \frac{(a - b) \times N \times 14000}{A} \quad \text{mgN/l} \quad (3.38)$$

$$Mass\ Balance = \frac{Effluent\ Mass}{Influent\ Mass} \times 100 \quad \% \quad (3.39)$$

Where: N: Sulphuric acid solution normality (0.001)

a: Sulphuric acid titrated for test sample

b: Sulphuric acid titrated for blank sample

A: 10ml sample added to the micro-Kjeldahl flask

14 000 = Conversion of Nitrogen molecular mass from 14gN/l to mgN/l sample:

$$\left(\frac{1\,000\text{mg}}{g} \times \frac{14g}{1} \right)$$

Table 3.10: The analytical tests performed on the 5C-settleometer samples, FS-PST samples, PAD system, and AugBMP test BRs. LR represents the fractions that are obtained from literature.

Analytical test	Denotation	Determination Method	Settleometer	FS-PST	PAD	AugBMP BRs	Units
pH		Direct measurement: pH meter	✓	✓	✓	✓	
EC		Direct measurement: Conductivity meter	✓	✓	✓	✓	mS/m
Alkalinity	H ₂ CO ₃ *	5-point titration method			✓	✓	mg CaCO ₃ /l
FSA	N _{ai}	Influent Filtered sample: Titrimetric method	✓	✓	✓	✓	mgN/l
TKN	N _{ti}	Unfiltered TKN: Micro-distillation method	✓		✓	✓	mgN/l
Organic N	N _{oi}	Influent sample: N _{ti} - N _{ai}	✓	✓	✓	✓	mgN/l
USO	N _{ousi}	Last day of AugBMP or PAD effluent: Filtered TKN - N _{ai} N _{ousi} will be lumped with N _{oupi} for this project, and accept that TKN at Day last equals N _{oupi} and N _{ousi} = 0			✓	✓	mgN/l
BSO	N _{obsi}	Influent sample: Filtered TKN - N _{ai} - N _{ousi} N _{obsi} will be lumped with N _{obpi} for this project, and accept that ΔFSA = N _{obpi} , and N _{obsi} = 0			✓	✓	mgN/l
UPO	N _{oupi}	N _{ti} - Filtered TKN on Last day AugBMP				✓	mgN/l
BPO	N _{obpi}	Last day AugBMP PAD effluent: Unfiltered TKN - Filtered TKN - N _{oupi}			✓	✓	mgN/l
OP	P _{ai}	Influent Filtered sample: Titrimetric method	✓	✓	✓	✓	mgP/l
TP	P _{ti}	Unfiltered TP: Micro-distillation method	✓		✓	✓	mgP/l
Organic P	P _{oi}	Influent sample: P _{ti} - P _{ai}	✓	✓	✓	✓	mgP/l
USO	P _{ousi}	Last day of AugBMP or PAD effluent: Filtered TP - P _{ai} P _{ousi} will be lumped with P _{oupi} for this project, and accept that TP at Day last equals P _{oupi} and P _{ousi} = 0			✓	✓	mgP/l
BSO	P _{obsi}	Influent sample: Filtered TP - P _{ai} - P _{ousi} P _{obsi} will be lumped with P _{obpi} for this project, and accept that ΔOP = P _{obpi} , and P _{obsi} = 0			✓	✓	mgP/l
UPO	P _{oupi}	P _{ti} - Filtered TP on last day of AugBMP			✓	✓	mgP/l
BPO	P _{obpi}	Last day AugBMP: Unfiltered TP - Filtered TP - P _{oupi}				✓	mgP/l
VFA	S _{bsai}	Centrifuged sample - 5-point titration method	✓	✓	✓	✓	mgHAc/l
Total COD	S _{ti}	Unfiltered influent sample - Open flux method (OFM)	✓	✓	✓	✓	mgCOD/l
Total solubles	S _{tsi}	Filtered sample before PAD or AugBMP - OFM	✓	✓	✓	✓	mgCOD/l
Total particulate	S _{tpi}	Sti - S _{tsi}	✓	✓	✓	✓	mgCOD/l
USO	S _{use}	PAD & AugBMP filtered effluent - OFM		LR	✓	✓	mgCOD/l
FBSO	S _{bsfi}	S _{tsi} - S _{use,LastDayAugBMP} - S _{bsai}			✓	✓	mgCOD/l
UPO	S _{upi}	Sti - S _{tsi,LastDayAugBMP} (Assumed all biodegradables has been degraded)	✓	LR	✓	✓	mgCOD/l
BPO	S _{bpi}	S _{tpi} - S _{upi} = S _{ti} - S _{tsi,LastDayAugBMP} - S _{upi}	✓	LR	✓	✓	mgCOD/l
TSS		Settleable solids - Dried at 103-105 °C	✓	✓	✓	✓	mgTSetS/l
ISS		Settleable solids - Ignited at 600°C	✓	✓	✓	✓	mgISetS/l
VSS		TSS - ISS	✓	✓	✓	✓	mgVSetS/l
UPO VSS		VSS Last Day AugBMP				✓	
BPO VSS		VSS First Day AugBMP - VSS Last Day AugBMP				✓	
UPO TSS		Equal UPO VSS					
BPO TSS		Equal BPO VSS					

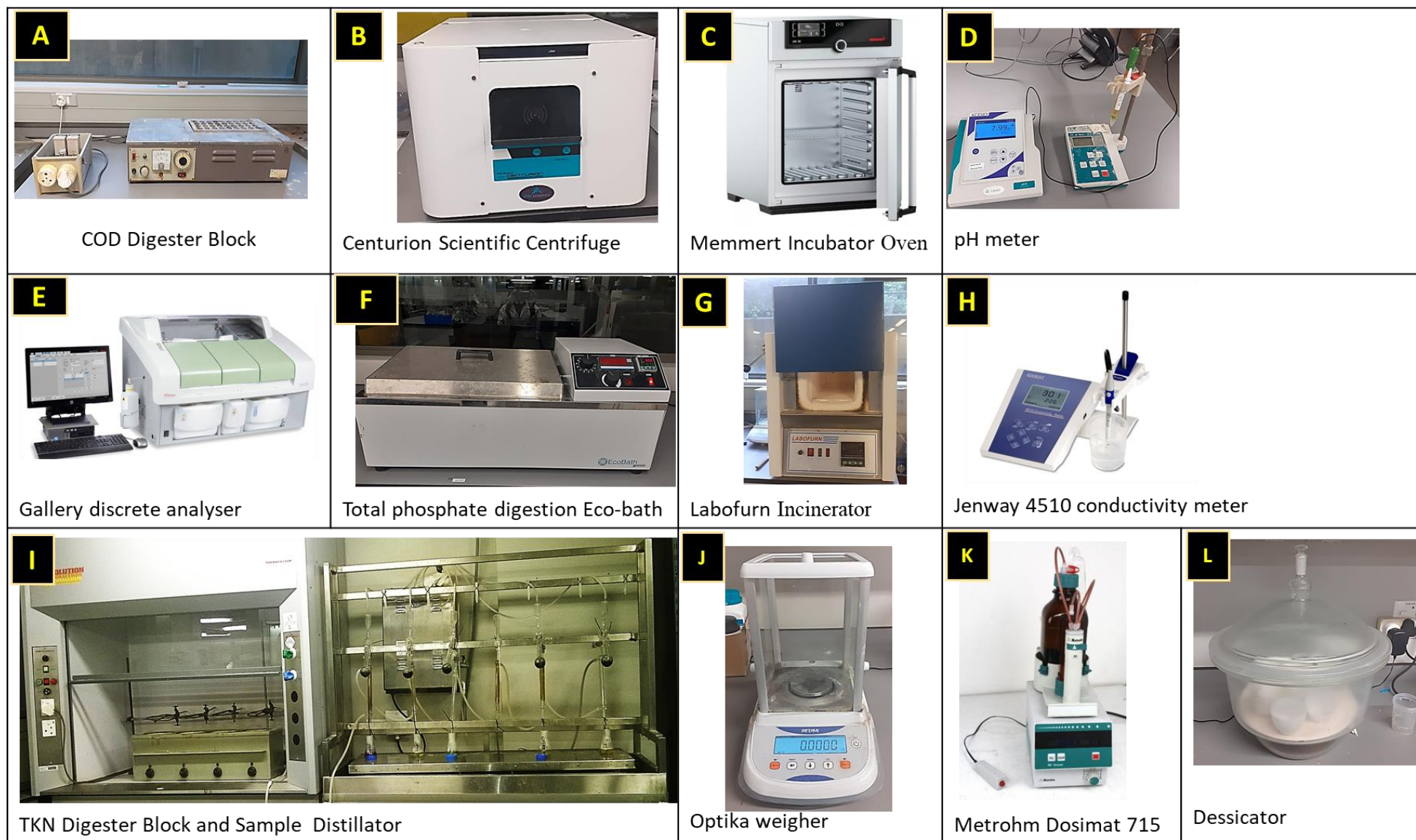


Figure 3.25: The depiction of the lab instrumentation used for the analytical tests in this present study

3.7. Parameter estimation

3.7.1. Overview

The parameter estimation (PE) process has been described as the process that minimises the errors between the experimentally measured and model simulated data (Gaszynski, 2020: 42). While Gaszynski (2020) used the “parameter estimation” tool present in WEST[®], together with the PWM_SA_AD model to make simulations, the present study uses the Microsoft (MS) Excel “solver” add-in together with mass-balanced SS AD model of Ikumi *et al.* (2015), programmed in MS Excel, to make the necessary simulations. The PE process is run for both the control and test reactors. The modelling of the control reactor is essential given that it sets a base for estimating the substrate concentrations from the test reactors. As illustrated in **Figure 3.26**, the control mass is characterized by the AD biomass (represented by Z_{AD} from PAD), effluent BPO (S_{bpe} from PAD), UPOs, USOs, and BSOs. On the other hand, the test reactor masses are characterized by UPOs, BPOs, BSOs, and USOs, in addition to the afore-mentioned control mass components (**Figure 3.26**). During the anaerobic digestion, the BPOs and BSOs are usually degraded within the first 10 days, while the Z_{AD} undergoes significantly slow degradation due to the low death rate of the microorganisms. For instance, considering that Z_{AD} has a death rate (b_{AD}) of 0.041/d (Sötemann *et al.*, 2005a: 523), increasing the R_s from 36 to 94 days results in merely 0.702gCOD/L (from the difference of 1.468 and 0.766) loss (**Table 4.15**), whereas the production of biogas as a result of the BPO degradation is nearly complete within the first 10 days of the AugBMP experiment, as shown in **Figure 8.2**. Although the UPOs and USOs can undergo significantly slow degradation, it is assumed in the present study that they do not undergo any degradation. Given that similar inoculum constituents are fed into both the control and test reactors, the test reactor concentrations that have values, beyond those determined from the control reactor, represent the substrate concentrations.

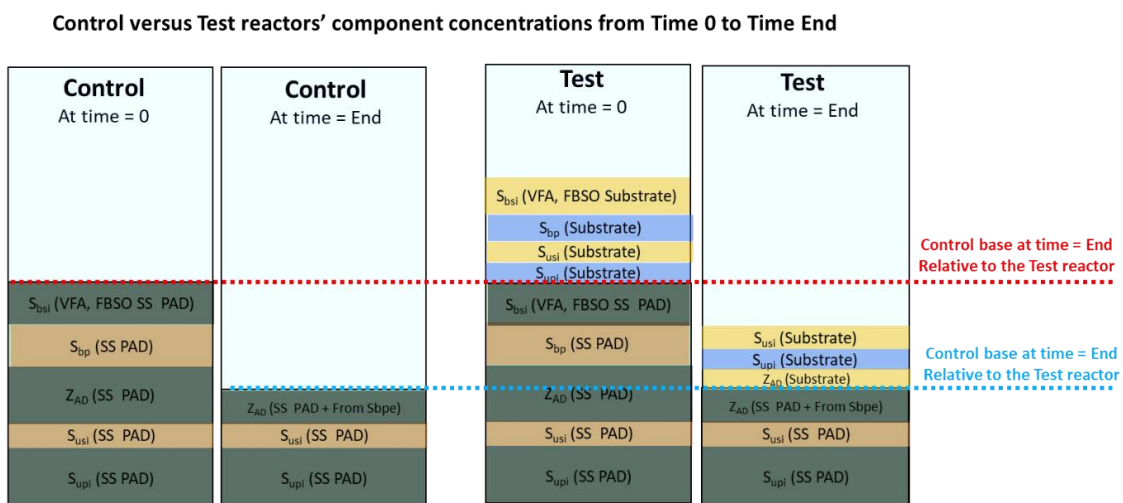


Figure 3.26: The control and test reactor component distribution in the BRs (Amended from Gaszynski, 2020:100).

3.7.2. Parameter estimation process

To start the PE process, the input characteristics, parameters (operational and elemental mass fractions), objective values (variables), and target values, as tabulated in **Table 3.11**, require to be known. The SS AD (Excel) model of Ikumi *et al.* (2015) was used to run the PE for the control and test BRs. The control PE is run first to obtain the baseline concentrations, which are used to establish the substrate characteristics for the test reactors. It is important to mention that, although the AugBMP test was performed in triplicates, the average concentrations were used in the PE process. These averages were calculated taking into consideration the accuracy in terms of the percentage error (**Section 3.5.8.1**), precision calculated in terms of the standard deviation (**Section 3.5.8.2**), and total mass balance around each reactor (see **Section 3.5.9**).

The model input WW characteristics include the influent total COD, VSS, ISS, FSA, OP, alkalinity, pH, inoculum Z_{AD} , and filtered COD (see **Figure 3.27** and **Figure 3.28**). These characteristics directly impact the PE process. To simplify the process, the Z_{AD} was first removed from the total COD, such that the model only dealt with the BPO, UPO, USO, BSO, and ISS. The subtracted Z_{AD} is however considered during the MB process to ensure that no mass is lost. All the input WW characteristics are measured experimentally at the beginning of the AugBMP test. To verify the accuracy between the starting concentrations, the percentage error was determined between the calculated and experimentally measured concentrations (see **Sections 4.4.2.1** and **4.4.3.1** below). While the influent total COD, filtered COD, inoculum Z_{AD} , ISS, VSS, FSA, OP, alkalinity, and pH were obtained using the experimental methods, as illustrated in **Table 3.10**, the Z_{AD} was determined using the SS equations of Sötemann *et al.*, (2005a: 523) (see **Section 4.5.3**). After determining the PAD Z_{AD} , the necessary dilutions were applied to reflect the biomass concentration in the control and test reactors, i.e., divide original inoculum mass by a factor of 3.5 (i.e., 3.5 obtained from [14 L total inoculum mixture prepared) / [8 L inoculum x 0.5 initial biomass dilution factor)) (see **Section 3.5.5**).

The operating conditions of the AugBMP tests comprised a reactor liquid volume of 5 L and a sludge age of 58 days. Although the 2.5 L and 6 L reactor vessels were used during the experimentation process, both reactors were fed the same concentrations of the input WW characteristics as listed in **Table 3.11**. This implies that although the influent and effluent masses may vary, the influent and effluent concentrations should, ideally, be the same. The PSS Monod hydrolysis kinetics (K_m) and half saturation constant (K_s) values of 1.8 and 7.96, respectively, as obtained by Ikumi (2011: 255), were used in the PE process. Essentially, the effluent concentrations are set as the objective values, and the experimentally observed effluent concentrations as the target values. This implies that the

composition of the substrate should not be affected provided the influent and effluent characteristics are modelled correctly to reflect the experimentally observed characteristics.

The parameters $f_{S'up}$, f_{cv} , f_c , f_n , and f_p are governed by the input characteristics along with the target effluent concentrations. Each of the respective parameters is obtained using the solver function added onto the SS AD (Excel) model of Ikumi *et al.* (2015). The process is presented in the subsections below.

3.7.2.1. Inoculum characteristics

The SS AD (Excel) model of Ikumi *et al.* (2015) was loaded with the PAD effluent characteristics (influent to the control reactor). The required characteristics are listed in **Table 3.11A** below. Using the MS Excel solver function, the corresponding $f_{S'up}$, f_{cv} , f_c , f_n , and f_p parameters were then estimated by running numerous iterations, until the model predicted effluent characteristics were equal to the experimentally measured effluent characteristics. The iteration process was performed using the following procedure:

- i. The solver function iterated the $f_{S'up}$ value until the recorded $f_{S'up}$ gave the lowest error between the experimental effluent COD (target) and modelled (or predicted or estimated) effluent COD (objective).
 - UPOCOD: multiply the $f_{S'up}$ by S_{ti} at the start of the AugBMP experiment (AugBMP_{start}).
 - BPOCOD: subtract the filtered COD at AugBMP_{start}, UPOCOD, and inoculum biomass COD at AugBMP_{start} from the S_{ti} at AugBMP_{start}. The inoculum biomass COD was obtained from the PAD effluent with the necessary dilutions applied, i.e., the PAD Z_{AD} at 36 days sludge age (**Table 4.15**) divided by the 3.5 dilution factor.
- ii. The BPO f_{cv} that plays a role in determining the BPO VSS was determined by running the f_{cv} trial and error iterations until the lowest error between the experimental effluent VSS (target) and predicted effluent VSS (objective) was obtained.
 - UPOVSS: subtract the inoculum biomass at AugBMP_{start} and BPO VSS from VSS_{start}.
 - UPO f_{cv} : divide the UPOCOD by UPOVSS.

- iii. The BPO f_n , and f_p iterations were run until the lowest errors between the experimental effluent FSA and OP, respectively, and the predicted effluent FSA and OP (objective) were obtained.
 - BPO N: divide the change in FSA between AugBMP_{start} and AugBMP_{end} by the BPO VSS ($\Delta\text{FSA}/\text{BPOVSS}$).
 - BPO P: divide the change in OP between AugBMP_{start} and AugBMP_{end} by the BPOVSS ($\Delta\text{OP}/\text{BPOVSS}$).
- iv. Since there was not much confidence in the biogas measurement during the experimental process, the BPO f_c was determined using the alkalinity and pH levels at AugBMP_{end} as follows:
 - The P_{CO_2} was calculated using **Equation (4.1)**. Once the P_{CO_2} was calculated, the f_c was then determined by running the solver iterations such that the AD model predicted effluent P_{CO_2} equals to the calculated P_{CO_2} .
 - BPOTOC: provided the BPO f_c obtained using the above method was close to what had been reported in the literature, the BPOTOC was then calculated by multiplying the estimated BPO f_c by the BPO VSS.
- v. The calculated inoculum UPOCOD, BPOCOD, UPOVSS, and BPOVSS were then used as a baseline to determine the UPOCOD, BPOCOD, UPOVSS, and BPOVSS of the substrate in the test reactors.

3.7.2.2. *Test reactors characteristics*

The PEs, for the test reactors, were performed using the same steps as for the control reactors. Although the seed (inoculum) characteristics could be entered directly into the model, such that the substrate was predicted directly, the present study used similar steps for both the control and test reactors. Thereafter, the control reactor concentrations obtained from PE were subtracted from the test reactor concentrations obtained from PE to get estimations of the substrate concentrations (see **Figure 3.26**).

Table 3.11: The input parameters, parameters, objective values, target values, and operational parameters applicable to the PE process

Parameters			Objective values (variables)	
A	B	C	D	E
Input (Experimentally measured)	Operational parameters	Elemental mass fractions	Objective values (Parameter estimated)	Target values (Experimentally measured)
Influent COD	Reactor liquid volume Sludge age (R_s) K_s K_M	$f_{S'up}$	Effluent COD	Effluent COD
Influent ZAD		f_{cv}	Effluent VSS	Effluent VSS
ISS		f_c	Effluent Alkalinity, Ph, and p_{CO2}	Effluent Alkalinity, pH, and p_{CO2}
VSS		f_n	Effluent FSA	Effluent FSA
filt COD		f_p	Effluent OP	Effluent OP
FSA				
Ortho-P				
Influent Alkalinity				
Influent pH				

3.7.2.3. Parameter estimation outcomes evaluation

The squared error criterion was used to evaluate the individual errors between the predicted and observed experimental data during the PE process (**Table 3.12**). Essentially, the model predicted data are compared with the experimental data, and the closer the squared error is to zero, the more precise the predicted parameters are (Gaszynski, 2020: 161). The overall PE error (accounting for all the selected parameters - $f_{S'up}$, f_{cv} , f_c , f_n , and f_p) was determined using the mean squared error (MSE). The MSE measures the average squared difference between the predicted and observed experimental data. As illustrated in **Table 3.12**, calculating the MSE required each of the selected variables to be weighed. The weighing process was used to give more weight to the components measured with confidence during the experimental process and contributed greatly to the outcomes of the model. For instance, more confidence was given to the released VSS and COD than was to the C or P content. The weighing process then allows the error (from more confident experimental measurement) to be distributed across the selected parameters. This is true given the fact that the release of VSS or COD during the degradation does not only affect the effluent VSS or COD, but also the release of C, P, N, alkalinity, and pH. This confirms the relationship between the different components making up the inoculum or substrate, and this relationship is linked through the compositional parameters.

Table 3.12: The parameters mean squared errors and weightings

Parameters	Squared error criteria	Weighting	
UPO	$(\text{Experimental COD}_{\text{end}} - \text{Modelled COD}_{\text{end}})^2$	10.00	Squared error criteria x Weighting
BPO fcv	$(\text{Experimental VSS}_{\text{end}} - \text{Modelled VSS}_{\text{end}})^2$	10.00	Squared error criteria x Weighting
BPO fn	$(\text{Experimental FSA}_{\text{end}} - \text{Modelled FSA}_{\text{end}})^2$	1.00	Squared error criteria x Weighting
BPO fp	$(\text{Experimental OP}_{\text{end}} - \text{Modelled OP}_{\text{end}})^2$	1.00	Squared error criteria x Weighting
BPO fc	$(\text{Experimental Alkalinity}_{\text{end}} - \text{Modelled Alkalinity}_{\text{end}})^2$	1.00	Squared error criteria x Weighting
P _{CO2}	$(\text{Experimental } P_{\text{CO2, end}} - \text{Modelled } P_{\text{CO2, end}})^2$	1.00	Squared error criteria x Weighting
pH	$(\text{Experimental pH}_{\text{end}} - \text{Modelled pH}_{\text{end}})^2$	1.00	Squared error criteria x Weighting
		Sum weighting	Sum (Squared error criteria x Weighting)
		MSE	(Sum weighting)/(Sum (Squared error criteria x Weighting))

3.7.3. Direct UPO and BPO determination from experimental data (No PE function)

While the present study used the “solver” function, together with the SS AD model, to estimate the parameters required for the determination of the elemental composition and SVG settling proportions of the BPO, UPO, and ISS, this subsection describes how each of the required components can be determined directly from the experimental data. It is important to note that, ideally, the outcomes from this method should give similar results as the PE provided that (i) all the target value are met (**Table 3.12**), and (ii) 100% MB is achieved around the system. A mass balanced system implies that all possible errors have been accounted for when performing the calculations. One of the possible reasons for the potential discrepancies between the PE and experimentally measured data is the assumption made regarding the biomass component for simplification purpose. More details on the determination process and underlying assumptions are as follows:

The BPO components and mass fractions can be determined as follows:

- The BPOCOD (S_{bpi}): the change in the particulate COD concentrations (ΔS_{pi}) between the start and end of the AugBMP experiment. Although the difference between the $\text{COD}_{\text{start}}$ and COD_{end} can be accepted to represent the BPO, provided there is a long R_s (say 58 days), it is important to note that during the AD, a fraction of the biodegradable component is conserved into biomass. For instance, Sötemann *et al.* (2005b: 552) indicated that during the degradation process, approximately 11.7% of the biodegradables are conserved in biomass, while the other 88.3% are transformed into biogas. The 11.7% take into consideration the 2.4% acetoclastic methanogens (Z_{AM}), 0.3% hydrogenotrophic methanogens (Z_{HM}), and 9% acidogens (Z_{AD}). Hence, the difference between the $\text{COD}_{\text{start}}$ and COD_{end} may slightly underestimate the substrate BPO. While the reactor biomass starts the decay process at a given death rate (b_{AD}), soon after the BPO component has been consumed, the b_{AD} is so slow that even at long R_s , the live biomass may still exist. To simplify the process, it can be accepted that, provided

there is a significantly long R_s , the residual active biomass BPO is negligible (relative to the BPO converted into biogas). It can then be assumed that the ΔS_{pi} represent the BPOCOD. As stated by Sötemann *et al.* (2005b: 550), as biomass dies, they add to S_{pb} , which undergoes the same AD process as the original influent BPO. Hence, it can be accepted that the BPO contribution, due to the Z_{AD} decay, counteracts the actual BPO that forms part of the Z_{AD} during the influent S_{pb} hydrolysis. As shown in **Table 4.15**, it is evident that for a R_s as long as 58 days, only a small BPO fraction (less than 5%) remains conserved in biomass. This fraction is significantly small and can be considered negligible.

- b. The BPOVSS concentrations can be quantified by taking the change in the VSS concentrations (ΔVSS) between the start and end of the AugBMP experiment. Thus, provided there is a long R_s , the VSS contribution due to the Z_{AD} decay counteracts the actual VSS that forms part of the Z_{AD} during the influent BPO hydrolysis. Dividing the BPOCOD by BPOVSS gives the BPO f_{cv} .
- c. The changes in FSA and OP (ΔFSA and ΔOP) represent the N and P that is bound in BPOs. Therefore, provided there is a long R_s , the N and P released during the Z_{AD} decay counteracts the N and P fractions that forms the biomass. Dividing the respective BPO N and P by the BPOVSS calculated above gives the f_n and f_p , respectively.
- d. The calculation of the C content released during the degradation of the BPOs is described in **Section 3.6.6**.

The UPO components and mass fractions can be determined as follows:

- a. The UPOCOD (S_{upi}): take the difference between the unfiltered and filtered COD concentrations at AugBMP_{end}. As discussed for the BPO above, the residual BPO at a significantly long R_s is significantly small and can be assumed to be zero. From this simplification, the particulate organic at AugBMP_{end} can be considered UPO.
- b. The UPOVSS: considering the negligible Z_{AD} at AugBMP_{end} (R_s of 58 days), the experimental VSS measured at AugBMP_{end} quantifies the UPOVSS.
- c. The UPO f_{cv} : from the UPOCOD and UPOVSS calculated above, the f_{cv} (gCOD/gVSS) can be calculated.
- d. The UPO f_n : the difference between the unfiltered and filtered TKN concentration at AugBMP_{end} equals the N content bound in the UPOs. From this N content, the f_n can be calculated by dividing the UPO N by the UPOVSS.

- e. The UPO f_P : the difference between the unfiltered and filtered TP concentration at $\text{AugBMP}_{\text{end}}$ equals the P content bound in the UPOs. From this P content, the f_P can be calculated by dividing the UPO P by the UPOVSS.
- f. The carbon (C) analysis for the UPOs was not performed during the experiment of the present study. Therefore, a procedure to calculate the C related to the UPOs, described in **Section 3.6.6**, can be followed.

The steps described above can be applied to both the control and test reactors. To isolate the substrate concentrations from the test reactors, consider the differences between the inoculum and test reactor components. From these components, the corresponding mass fractions can be determined using the steps described in **Section 3.8.2** above.

Primary Characterisation		Particulate (Residually remaining on .45 micro filter)										Soluble							Mixed Liquor
Secondary Characterisation		TSS	ISS	VSS								Organic Soluble			Inorganic Soluble				
Tertiary Characterisation				Total VSS	UPO (including ER)	Seed BPO		Substrate BPO		Total BPO	Total UPO	Acetate		F-RBCOD	USCOD	FSA	Ortho-P	PolyP inside PAOs	
				Substrate Charactistation	Units	BPO	-	BPO	-	Hac	Ac-								
Concentration	mg/l	2560.4	682.0	1878.4	1441.9	436.5	0.00	0.00	0.00	436.5	1441.9	0.00	0.00	45.35	44.73	106.25	14.03	0.00	2560
Biodegradablle org or VSS	mgVSS/l	436.5		436.5	0.00	436.5	0.00	0.00	0.00	436.5	0.00	0.00	0.00	45.35	0.00				
Unbio. Organics or VSS	mgVSS/l	1441.9		1441.9	1441.9	0.00	0.00	0.00	0.00	0.00	1441.9	0.00	0.00	0.00	44.73				
Total COD	mgCOD/l	3283.2		3283.2	1717.6	1007.17	0.00	0.00	0.00	1407.7	1717.6	0.00	0.00	104.6	53.3			0.00	3283
Sbi (influent Bio. COD)	mgCOD/l	1407.7		1407.7	0.00	1007.17	0.00	0.00	0.00	1407.7	0.00	0.00	0.00	104.64	0.00				
Sui (influent Unbio. COD)	mgCOD/l	1717.6		1717.6	1717.6	0.00	0.00	0.00	0.00	0.00	1717.6	0.00	0.00	0.00	53.28				
N	mgN/l	115.8		115.8	90.4	25.42	0.00	0.00	0.00	25.42	90.4	0.00	0.00	2.64	2.80	82.6		0.00	204
X _{PGBM}	mgP/l	6.25		6.25		6.25				6.25	0.00								
X _{PGRP (PolyP)}	mgP/l	0.00		0.00						0.00	0.00							0.0	
X _{PHBM}	mgP/l	0.00		0.00				0.00		0.00	0.00								
X _{BP}	mgP/l	6.25		6.25		6.25		0.00		6.25	0.00						4.58		
X _{PU}	mgP/l	40.66		40.7	40.7	0.00	0.00	0.00	0.00	0.00	40.66								
X _{TP}	mgP/l	46.90		46.9	40.7	6.25	0.00	0.00	0.00	6.2	40.7	0.00	0.00	0.65	1.26		4.6	0.00	53.39
Carbon	mgC/l	796.18		796.2	597.7	198.45	0.00	0.00	0.00	198.5	597.7	0.00	0.00	20.62	18.54	0.00	0.00	0.00	835.34
Hydrogen	mgH/l	184.35		184.4	104.4	79.98	0.00	0.00	0.00	80.0	104.4	0.00	0.00	8.31	3.24	23.61	0.29	0.00	219.80
Oxygen	mgO/l	735.19		735.2	608.8	126.38	0.00	0.00	0.00	126.4	608.8	0.00	0.00	13.13	18.89	0.00	9.26	0.00	776.46
Mg	mg/l	0.00																0.00	0.00
K	mg/l	0.00																0.00	0.00
Ca	mg/l	0.00																0.00	0.00

Figure 3.27: The screenshot of the characteristics of the inoculum in the SS AD (Excel) model

Primary Characterisation		Particulate (Residually remaining on .45 micro filter)										Soluble							Mixed Liqueur
Secondary Characterisation		TSS	ISS	VSS								Organic Soluble			Inorganic Soluble				
Tertiary Characterisation				Total VSS	UPO(including ER)	Seed BPO		Substrate BPO		Total BPO	Total UPO	Acetate		F-RBCOD	USCOD	FSA	Ortho-P	PolyP inside PAOs	
Substrate Characterisation	Units					BPO	-	BPO	-			Hac	Ac-						
concentration	mg/l	3043	827	2217	1666	436	0.00	114.03	0.00	551	1666	0.00	0.00	78.9	58.94	156.79	18.04	0.00	3043.34
Biodegradable org or VSS	mgVSS/l	551		551	0	436	0.00	114.03	0.00	551	0	0.00	0.00	78.9	0.00				
Unbio. Organics or VSS	mgVSS/l	1666		1666	1666	0	0.00	0.00	0.00	0	1666	0.00	0.00	0.0	58.94				
Total COD	mgCOD/l	3872		3872.00	2008	1007	0.00	227.47	0.00	1235	2008	0.00	0.00	157.44	71.04			0.00	3872.00
Sbi (influent Bio. COD)	mgCOD/l	1235		1235	0	1007	0.00	227.47	0.00	1235	0	0.00	0.00	157.4	0.00				
Sui (influent Unbio. COD)	mgCOD/l	2008		2008	2008	0.00	0.00	0.00	0.00	0	2008	0.00	0.00	0.0	71.04				
N	mgN/l	127		127	95	27.04	0.00	4.37	0.00	31	95	0.00	0.00	3.0	3.37	121.95		0.00	254.97
X _{PGBM}	mgP/l	6.65		6.65		6.65				6.65	0.00								
X _{PGPP (PolyP)}	mgP/l	0.00		0.00						0.00	0.00							0.00	
X _{PHBM}	mgP/l	0.00		0.00				0.00		0.00	0.00								
X _{BP}	mgP/l	6.65		6.65		6.65		0.00		6.65	0.00						5.89		
X _{PU}	mgP/l	42.59		42.59	42.59	0.00	0.00	0.00	0.00	0.00	42.59								
X _{TP}	mgP/l	49.23		49.23	42.59	6.65	0.00	0.00	0.00	6.65	42.59	0.00	0.00	0.00	1.51		5.89	0.00	56.63
Carbon	mgC/l	943.65		943.65	698.91	198.45	0.00	46.28	0.00	244.73	698.91	0.00	0.00	32.03	24.72	0.00	0.00	0.00	1000.40
Hydrogen	mgH/l	219.70		219.70	120.26	80.01	0.00	19.44	0.00	99.44	120.26	0.00	0.00	13.45	4.25	34.84	0.37	0.00	272.62
Oxygen	mgO/l	877.47		877.47	709.19	124.33	0.00	43.94	0.00	168.27	709.19	0.00	0.00	30.41	25.09	0.00	11.90	0.00	944.87
Mg	mg/l	0.00																0.00	0.00
K	mg/l	0.00																0.00	0.00
Ca	mg/l	0.00																0.00	0.00

Figure 3.28: The screenshot of the characteristics of test reactors in the SS AD (Excel) model. These steps are repeated for all the BRs representing the five SVGs

3.8. Stoichiometric determination of the elemental compositions

3.8.1. Overview

This section describes the stoichiometric processes followed to determine the elemental compositions (ECs) of the UPOs and BPOs present in the inoculum and five SVG PSS substrates. The stoichiometry is based on the principle that, though different in forms, the fluxes of the reactants exiting a biological system should equate the fluxes of the matter entering the system (Ekama & Brouckaert, 2022). A typical AD influent (PSS) is characterized by the BPO, UPO, BSO (comprising FBSO and VFA), USO, and ISS components. Each of the components is characterized by a unique $C_xH_yO_zN_aP_bS_c^{ch}$ composition. While the UPOs, USOs, and ISS flow through an AD system with no change in concentrations (non-degradable), the BPOs and BSOs undergo biological degradation via the stoichiometric shown in **Equation (3.40)**. Although the reactant $C_xH_yO_zN_aP_bS_c^{ch}$ include sulfur and the charge, the present study mainly focuses on the COD, C, H, O, N, and P ($C_xH_yO_zN_aP_b$).

$$\begin{aligned} C_xH_yO_zN_aP_b + \left(2x + a + b(2 + f) - z - (2k - m + n + p(2 + f))E \frac{\gamma_s}{\gamma_b} - (1 - E) \frac{\gamma_s}{4}\right) H_2O \rightarrow & \left(x - a + b(2 - f) \right. \\ & - (k - n + p(2 - f))E \frac{\gamma_s}{\gamma_b} - (1 - E) \frac{\gamma_s}{8}\bigg) CO_2 + \left((1 - E) \frac{\gamma_s}{8}\right) CH_4 \\ & + \left(E \frac{\gamma_s}{\gamma_b}\right) C_kH_lO_mN_nP_p + \left(a - nE \frac{\gamma_s}{\gamma_b}\right) NH_4 + f \left(b - pE \frac{\gamma_s}{\gamma_b}\right) H_2PO_4 \\ & + (1 - f) \left(b - pE \frac{\gamma_s}{\gamma_b}\right) HPO_4 + \left(a - b(2 - f) - (n - p(2 - f))E \frac{\gamma_s}{\gamma_b}\right) HCO_3 \end{aligned} \quad (3.40)$$

Where: $\gamma_s = 4x + y - 2z - 3a + 5b - ch$ = Electron donating capacity (EDC) per mole $C_xH_yO_zN_aP_b$ (biodegradable organics)

$\gamma_b = 4k + l - 2m - 3n + 5p$ = COD EDC/mole $C_kH_lO_mN_nP_p$ (biomass)

E = The fraction of biodegradable organics conserved in biomass

$f = H_2PO_4^-$ fraction of the OP species formed ($OP = H_2PO_4^- + HPO_4^{2-}$)

x = Carbon molar content in $C_xH_yO_zN_aP_b$

y = Hydrogen molar content in $C_xH_yO_zN_aP_b$

z = Oxygen molar content in $C_xH_yO_zN_aP_b$

a = Nitrogen molar content in $C_xH_yO_zN_aP_b$

b = Phosphorus molar content in $C_xH_yO_zN_aP_b$

k = Carbon molar content in $C_kH_lO_mN_nP_p$

l = Hydrogen molar content in $C_kH_lO_mN_nP_p$

m = Oxygen molar content in $C_kH_lO_mN_nP_p$

n = Nitrogen molar content in $C_kH_lO_mN_nP_p$

p = Phosphorus molar content in $C_kH_lO_mN_nP_p$

3.8.2. Elemental composition stepwise determination

The first step to determining the ECs is to quantify the mass fractions (MFs) gCOD/gVSS (f_{cv}), gC/gVSS (f_c), gH/gVSS (f_h), gO/gVSS (f_o), gN/gVSS (f_n), and gP/gVSS (f_p) for both the UPOs and BPOs in the substrate. The determination of f_{cv} , f_c , f_n , and f_p for the inoculum and test mixtures is well described in **Section 3.7**. In addition to this, the determination of the UPOCOD, BPOCOD, UPOVSS, BPOVSS, BPOTOC, Δ FSA, Δ OP, UPO N, and UPO P components was discussed in **Section 3.7**. The contents of the later components, for both the control and the test reactors, are important for the present study as they set a foundation for determining the substrate components (the inoculum components are subtracted from the test components to get an estimate of the substrate components). **Table 3.13** gives an example of how the substrate UPOs in the form of COD, C, N, P, and VSS can be determined. The same steps are repeated for the BPO to obtain the corresponding BPO concentrations. Once the UPOCOD, BPOCOD, UPOVSS, BPOVSS, BPOTOC, Δ FSA, Δ OP, UPO N, and UPO P components for the five SVG substrates have been determined, the corresponding UPO and BPO f_{cv} , f_c , f_n , and f_p are determined as follows:

- a. $f_{cv} = \text{gCOD/gVSS}$
- b. $f_c = \text{gC/gVSS}$
- c. $f_n = \text{gN/gVSS}$
- d. $f_p = \text{gP/gVSS}$

Using the f_{cv} , f_c , f_n , and f_p , the f_h and f_o are then calculated using **Equations (3.41)** and **(3.42)**. The sum of the f_c , f_h , f_o , f_n , and f_p should equal 1.00. Once all the five necessary MFs have been determined (f_c , f_h , f_o , f_n , and f_p), the “x” in $C_xH_yO_xN_aP_b$ is set to 1. Thereafter, the y, z, a, and b are calculated by dividing each respective fraction by the element molar mass, and then multiplying by 12/ f_c (**Table 3.14**).

$$f_h = \frac{2}{18} \left(1 + f_{cv} - \frac{44}{12} f_c + \frac{10}{14} f_n - \frac{71}{31} f_p \right) \quad (3.41)$$

$$f_o = \frac{16}{18} \left(1 - \frac{1}{8} f_{cv} - \frac{8}{12} f_c - \frac{17}{14} f_n - \frac{26}{31} f_p \right) \quad (3.42)$$

Table 3.13: illustration of the determination of the substrate UPOs in the form of COD, C, N, P, and VSS

	Control	Test - SVG1	Test - SVG2	Test - SVG3	Test - SVG4	Test - SVG5
COD	$S_{\text{upi,Control}}$	$S_{\text{upi,TSVG1}}$	$S_{\text{upi,TSVG2}}$	$S_{\text{upi,TSVG3}}$	$S_{\text{upi,TSVG4}}$	$S_{\text{upi,TSVG5}}$
Carbon	$C_{\text{upi,Control}}$	$C_{\text{upi,TSVG1}}$	$C_{\text{upi,TSVG2}}$	$C_{\text{upi,TSVG3}}$	$C_{\text{upi,TSVG4}}$	$C_{\text{upi,TSVG5}}$
OrgN	$N_{\text{oupi,Control}}$	$N_{\text{oupi,TSVG1}}$	$N_{\text{oupi,TSVG2}}$	$N_{\text{oupi,TSVG3}}$	$N_{\text{oupi,TSVG4}}$	$N_{\text{oupi,TSVG5}}$
OrgP	$P_{\text{oupi,Control}}$	$P_{\text{oupi,TSVG1}}$	$P_{\text{oupi,TSVG2}}$	$P_{\text{oupi,TSVG3}}$	$P_{\text{oupi,TSVG4}}$	$P_{\text{oupi,TSVG5}}$
VSS	VSS_{Control}	VSS_{TSVG1}	VSS_{TSVG2}	VSS_{TSVG3}	VSS_{TSVG4}	VSS_{TSVG5}
	Substrate - SVG1	Substrate - SVG2	Substrate - SVG3	Substrate - SVG4	Substrate - SVG5	
COD	$S_{\text{upi,TSVG1}} - S_{\text{upi,Control}}$	$S_{\text{upi,TSVG2}} - S_{\text{upi,Control}}$	$S_{\text{upi,TSVG3}} - S_{\text{upi,Control}}$	$S_{\text{upi,TSVG4}} - S_{\text{upi,Control}}$	$S_{\text{upi,TSVG5}} - S_{\text{upi,Control}}$	
Carbon	$C_{\text{upi,TSVG1}} - C_{\text{upi,Control}}$	$C_{\text{upi,TSVG2}} - C_{\text{upi,Control}}$	$C_{\text{upi,TSVG3}} - C_{\text{upi,Control}}$	$C_{\text{upi,TSVG4}} - C_{\text{upi,Control}}$	$C_{\text{upi,TSVG5}} - C_{\text{upi,Control}}$	
OrgN	$N_{\text{oupi,TSVG1}} - N_{\text{oupi,Control}}$	$N_{\text{oupi,TSVG2}} - N_{\text{oupi,Control}}$	$N_{\text{oupi,TSVG3}} - N_{\text{oupi,Control}}$	$N_{\text{oupi,TSVG4}} - N_{\text{oupi,Control}}$	$N_{\text{oupi,TSVG5}} - N_{\text{oupi,Control}}$	
OrgP	$P_{\text{oupi,TSVG1}} - P_{\text{oupi,Control}}$	$P_{\text{oupi,TSVG2}} - P_{\text{oupi,Control}}$	$P_{\text{oupi,TSVG3}} - P_{\text{oupi,Control}}$	$P_{\text{oupi,TSVG4}} - P_{\text{oupi,Control}}$	$P_{\text{oupi,TSVG5}} - P_{\text{oupi,Control}}$	
VSS	$VSS_{\text{TSVG1}} - VSS_{\text{Control}}$	$VSS_{\text{TSVG2}} - VSS_{\text{Control}}$	$VSS_{\text{TSVG3}} - VSS_{\text{Control}}$	$VSS_{\text{TSVG4}} - VSS_{\text{Control}}$	$VSS_{\text{TSVG5}} - VSS_{\text{Control}}$	

Table 3.14: The calculation of the elemental composition x, y, z, a, and b

					Molar mass	y,z,a and be calculation formular (x set to 1)
X	C	f_c	x/x	$f_c/12$	12	1
Y	H	f_h	y/x	$f_h/1$	1	$f_h/1 \times (1/(f_c/12))$ or $f_h/1 \times 12/ f_c$
Z	O	f_o	z/x	$f_o/16$	16	$f_o/16 \times (1/(f_c/12))$ or $f_o/16 \times 12/ f_c$
A	N	f_n	a/x	$f_n/14$	14	$f_n/14 \times (1/(f_c/12))$ or $f_n/14 \times 12/ f_c$
B	P	f_p	b/x	$f_p/31$	31	$f_p/31 \times (1/(f_c/12))$ or $f_p/31 \times 12/ f_c$

3.9. BPO, UPO and ISS fractionations

3.9.1. Overview

The AugBMP test, together with the PE function and SS AD model as described in **Sections 3.5** and **3.7**, made it possible to distinguish between the UPOs and BPOs of the five SVG substrates. Together with the ISS concentrations, the X_{U_Inf} and X_{B_Inf} SVG proportions required for the DDPST model can be determined (see **Section 2.4.3**). The SVG X_{U_Inf} , X_{B_Inf} , and X_{ISS} components require to be expressed in terms of the fractions, which can be regarded as parameters within the DDPST model (see **Table 2.1**). Essentially, Alpha (α), Beta (β), Gamma (γ), Lambda (λ), and Theta (θ) represent the parameters for the SVG1, SVG2, SVG3, SVG4, and SVG5, respectively.

Since the AugBMP test requires mixing of the substrate with the inoculum in a test reactor to allow degradation, the control reactor (comprising only the inoculum) acted as a base to isolate the substrate UPOs and BPOs. To simplify the calculations, it was necessary that during the seeding step, all the BRs be fed equal masses (and concentrations) of inoculum (**Section 3.5.5** and **Figure 3.29A**). From this simplification, the mass or concentration of the substrate for a given BR can be calculated using similar steps as tabulated in **Table 3.13**. Essentially, the excess COD concentration from the test BRs

would represent the substrate. The sections below describe the process used to calculate the BPO, UPO and ISS fractions.

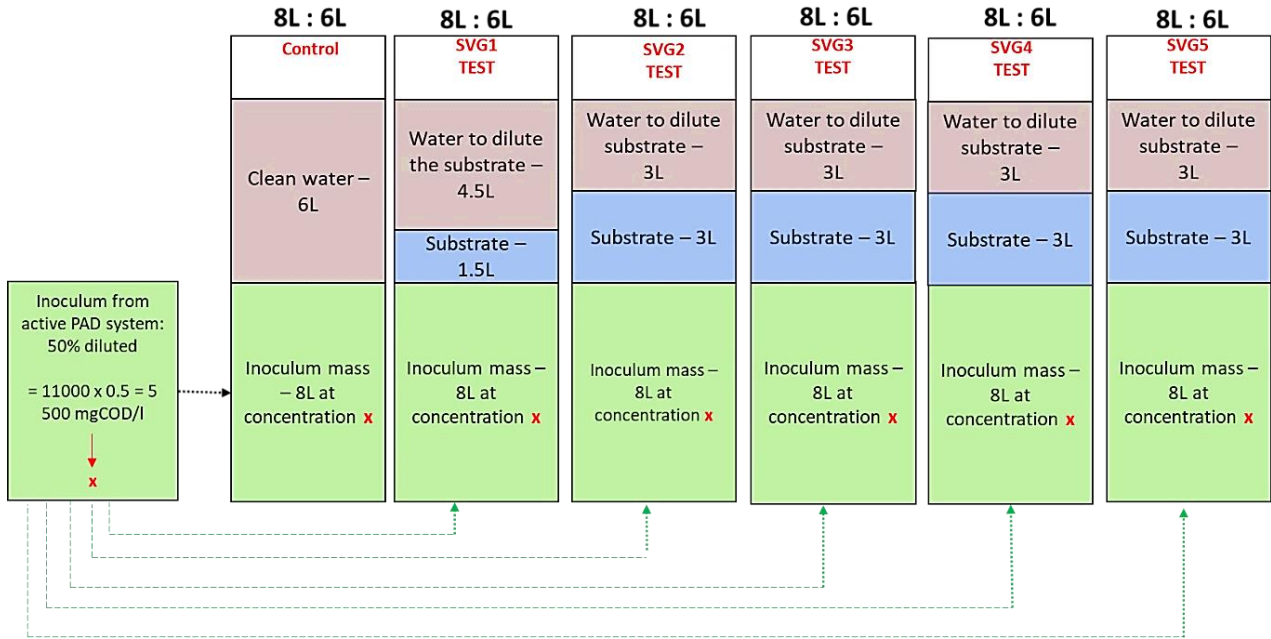


Figure 3.29: The inoculum to substrate (plus water for dilution) ratio (by volume). Important to note is that the 6L of the substrate in the test reactor comprise volumes of the original substrates plus water to dilute the substrate.

3.9.2. BPO fractions (BPO parameters)

The DDPST model requires that the settleable BPO (settleable X_{B_Inf}) for each of the five SVGs is expressed in terms of the fractions represented by (i) α_B (BPO in SVG1), (ii) β_B (BPO in SVG2), (iii) γ_B (BPO in SVG3), (iv) λ_B (BPO in SVG4), and (v) θ_B (BPO in SVG5). After obtaining the five SVG BPOs from the PE, the BPO fractions in each SVG were determined in terms of $M_{BPOset'inf}$. $M_{BPOset'inf}$ is a notation for mass of total settleable BPO that is in the influent. The $M_{BPOset'inf}$ was obtained by adding the five SVG BPO masses. As discussed in **Section 3.5**, the substrate fed into the BRs were settleable particles collected from each of the five PVC columns with different settling velocities. As described in **Section 3.7.2**, the substrate concentration of the settleable BPO in each of the SVGs ($C_{s,BPOset'SVGn}$) is obtained by taking the difference between the test reactor settleable BPO in each of the SVGs ($C_{t,BPOset'SVGn}$) and the control reactor BPO in each of the SVGs ($C_{c,BPOset'SVGn}$). Multiplying these concentrations by the total reactor liquid volume of 2 L or 5 L gives their respective masses, see **Equation (3.47)**. Once the BPO masses for the five SVGs are calculated, the sum is obtained, with which each of the SVG settleable BPO mass is divided, thus obtaining the respective fractions (**Equations (3.49)**). The sum of these fractions should equal 1.00.

3.9.3. UPO fractions (UPO parameters)

Having been able to determine the UPO concentrations, as described in **Section 3.7.2**, the UPO fractions can now be determined using the same procedure as described in **Section 3.9.2** for the BPO fractions. The UPO fractions are represented by (i) α_U (UPO in SVG1), (ii) β_U (UPO in SVG2), (iii) γ_U (UPO in SVG3), (iv) λ_U (UPO in SVG4), and (v) θ_U (UPO in SVG5). **Equations (3.50) to (3.53)** summarise the steps taken to calculate the UPO fractions for the five respective SVGs.

3.9.4. ISS fractions (ISS parameters)

The ISS fractions can be determined from two experimental sources, i.e., the settleometer and AugBMP experiment. The ISS concentrations do not undergo any biological or chemical alterations during AD, therefore, the concentration from the settleometer can be used directly. This implies that after determining the ISS concentrations using the TSS test (see **Section 3.6.3**), the respective concentrations from SVG1 to SVG5 can be added together to determine the total ISetS present in the influent in terms of mass ($M_{ISSset,inf}$). Thereafter, the respective ISS fractions can be determined by dividing a given SVG ISS mass by $M_{ISSset,inf}$. Alternatively, the ISS fractions can be determined from the AugBMP experiment. Ideally, since the ISS does not undergo alterations, subtracting the control ISS concentrations from the test reactor ISS concentrations for a given SVG, at any point, should give the substrate ISS concentrations equal to the settleometer ISS. Determining the ISS fractions from the AugBMP experiment can be carried out following **Equations (3.54) to (3.57)**. Similarly, the ISS fractions are represented on the DDPST model by (i) α_I (ISS in SVG1), (ii) β_I (ISS in SVG2), (iii) γ_I (ISS in SVG3), (iv) λ_I (ISS in SVG4), and (v) θ_I (ISS in SVG5).

$$Z_{AD} = Y_{AD} \times (S_{bpi} - S_{bpe}) / [1 + b_{AD} \times R_S \{1 + Y_{AD} \times (1 - f_{AD})\}] \quad (3.43)$$

$$E = Y_{AD} \times (1 + f_{AD} b_{AD} R_S) / [1 + b_{AD} \times R_h \{1 + Y_{AD} \times (1 - f_{AD})\}] \quad \text{OR} \quad (3.44)$$

$$E = (Z_{AD} + Z_{ED}) / (S_{bpi} - S_{bpe}) \quad (3.45)$$

BPO

$$C_{S_{BPOset,SVGn}} = C_{t_{BPOset,SVGn}} - C_{C_{BPOset,SVGn}} \quad \text{mgCOD/l} \quad (3.46)$$

$$M_{S_{BPOset,SVGn}} = (C_{t_{BPOset,SVGn}} \times Vol_{LIQ,TEST}) - (C_{C_{BPOset,SVGn}} \times Vol_{LIQ,cont}) \quad \text{mgCOD/l} \quad (3.47)$$

$$M_{S_{BPOset,inf}} = M_{S_{BPOset,SVG1-5}} = M_{S_{BPOset,SVG1}} + M_{S_{BPOset,SVG2}} + M_{S_{BPOset,SVG3}} + \quad \text{mgCOD} \quad (3.48)$$

$$M_{S_{BPOset,SVG4}} + M_{S_{BPOset,SVG5}}$$

$$X_{B_Inf_n} = f_{BPOset,SVGn} = M_{S_{BPOset,SVGn}} / M_{BPOset,inf} \quad (3.49)$$

UPO

$$C_{S_{UPOset'SVGn}} = C_{t_{UPOset'SVGn}} - C_{c_{UPOset'SVGn}} \quad \text{mgCOD/l} \quad (3.50)$$

$$M_{S_{UPOset'SVGn}} = (C_{t_{UPOset'SVGn}} \times Vol_{LIQ,TEST}) - (C_{c_{UPOset'SVGn}} \times Vol_{LIQ,cont}) \quad \text{mgCOD/l} \quad (3.51)$$

$$M_{S_{UPOset,inf}} = M_{S_{UPOset'SVG1-5}} = M_{S_{UPOset'SVG1}} + M_{S_{UPOset'SVG2}} + M_{S_{UPOset'SVG3}} + M_{S_{UPOset'SVG4}} + M_{S_{UPOset'SVG5}} \quad \text{mgCOD} \quad (3.52)$$

$$X_{U_Inf_n} = f_{UPOset'SVGn} = M_{S_{UPOset'SVGn}} / M_{UPOset,inf} \quad (3.53)$$

ISS – Can be taken directly from settleometer and go to **Equation (3.56) and (3.57)**

$$C_{S_{ISset'SVGn}} = C_{t_{ISset'SVGn}} - C_{c_{ISset'SVGn}} \quad \text{mgISS/l} \quad (3.54)$$

$$M_{S_{ISset'SVGn}} = (C_{t_{ISset'SVGn}} \times Vol_{LIQ,TEST}) - (C_{c_{ISset'SVGn}} \times Vol_{LIQ,cont}) \quad \text{mgISS} \quad (3.55)$$

$$M_{S_{ISset,inf}} = M_{S_{ISset'SVG1-5}} = M_{S_{ISset'SVG1}} + M_{S_{ISset'SVG2}} + M_{S_{ISset'SVG3}} + M_{S_{ISset'SVG4}} + M_{S_{ISset'SVG5}} \quad \text{mgISS} \quad (3.56)$$

$$X_{ISS_n} = f_{ISset'SVGn} = M_{S_{ISset'SVGn}} / M_{ISset,inf} \quad (3.57)$$

Where: Z_{AD} = Acidogen biomass (mgCOD/l)
 Z_{ED} = Acidogen biomass endogenous residue (mgCOD/l)
 E = The fraction of biodegradable organics conserved in biomass
 Y_{AD} = Biomass yield (0.113 gCODbiomass/gCODorganics), Sötemann *et al.* (2005a: 512)
 b_{AD} = Biomass death rate (0.041 /d)
 f_{AD} = Biomass unbiodegradable fraction
 R_S = Sludge age (d)

Concentrations: $C_{S,BPOset'SVGn}$, $C_{t,BPOset'SVGn}$ and $C_{c,BPOset'SVGn}$: Concentrations of settleable BPO in each of the SVGs for substrate, test, and control samples.

$C_{S,UPOset'SVGn}$, $C_{t,UPOset'SVGn}$ and $C_{c,UPOset'SVGn}$: Concentrations of settleable UPO in each of the SVGs for substrate, test, and control samples.

$C_{S,ISset'SVGn}$, $C_{t,ISset'SVGn}$ and $C_{c,ISset'SVGn}$: Concentrations of settleable ISS in each of the SVGs for substrate, test, and control samples.

Masses: $M_{S,BPOset'SVGn}$, $M_{t,BPOset'SVGn}$ and $M_{c,BPOset'SVGn}$: Masses of settleable BPO in each of the SVGs for substrate, test, and control samples.

$M_{S,UPOset'SVGn}$, $M_{t,UPOset'SVGn}$ and $M_{c,UPOset'SVGn}$: Masses of settleable UPO in each of the SVGs for substrate, test, and control samples.

$M_{S,ISset'SVGn}$, $M_{t,ISset'SVGn}$ and $M_{c,ISset'SVGn}$: Masses of settleable ISS in each of the SVGs for substrate, test, and control samples.

$M_{BPOset,inf}$ = Mass of total settleable BPO that is in the influent

$M_{UPOset,inf}$ = Mass of total settleable UPO that is in the influent

$M_{\text{ISetS,inf}}$ = Mass of total settleable ISS that is in the influent

$M_{\text{SBPO,SVG1-5}}$ = Sum of SVG1, SVG2, SVG3, SVG4, and SVG5 BPO masses

$M_{\text{SUPO,SVG1-5}}$ = Sum of SVG1, SVG2, SVG3, SVG4, and SVG5 UPO masses

$M_{\text{SISS,SVG1-5}}$ = Sum of SVG1, SVG2, SVG3, SVG4, and SVG5 ISS masses

Volumes: $\text{Vol}_{\text{LIQ,TEST}}$ = Batch reactor liquor volume for a test reactor

$\text{Vol}_{\text{LIQ,cont}}$ = Batch reactor liquor volume for a control reactor

Fractions: $f_{\text{BPOset*SVGn}}$ = Fraction of BPO that is in the given SVG

$f_{\text{UPOset*SVGn}}$ = Fraction of UPO that is in the given SVG

$f_{\text{ISetS*SVGn}}$ = Fraction of ISS that is in the given SVG

3.10. Summary

This chapter discussed in detail the processes followed to (i) collect the FS-PST data, and (ii) gather the required data to evaluate the DDPST model. The DDPST model was previously subjected to mass balance verification (Polorigni *et al.*, 2021) and general sensitivity analysis (GSA) to identify the most important parameters required to successfully run the model (Matesun *et al.*, 2021). Using the methods described in this chapter, the required data will be generated to allow the DDPST model evaluation. The data collected include the settleometer data (**Section 3.3**), FS-PST diurnal data (**Section 3.4**), and AugMP test data (**Section 3.5**). The supporting processes, which include the inoculum generation (**Section 3.2**), analytical testing (**Section 3.6**), parameter estimations (**Section 3.7**), and elemental composition determinations (**Section 3.8**), were also described. From these processes, the following were determined: (i) the BPOset, UPOset, and ISetS settling velocities; and (ii) the BPOset, UPOset, and ISetS settling proportions for the five SVGs. Together with the FS-PST influent data and FS-PST dimensions (PST area and depth), the DDPST model can be run to simulate the overflow and underflow characteristics. The model-predicted overflow and underflow characteristics will then be compared with the FS-PST diurnal data to check whether there is a relationship between the real data and model predictions.

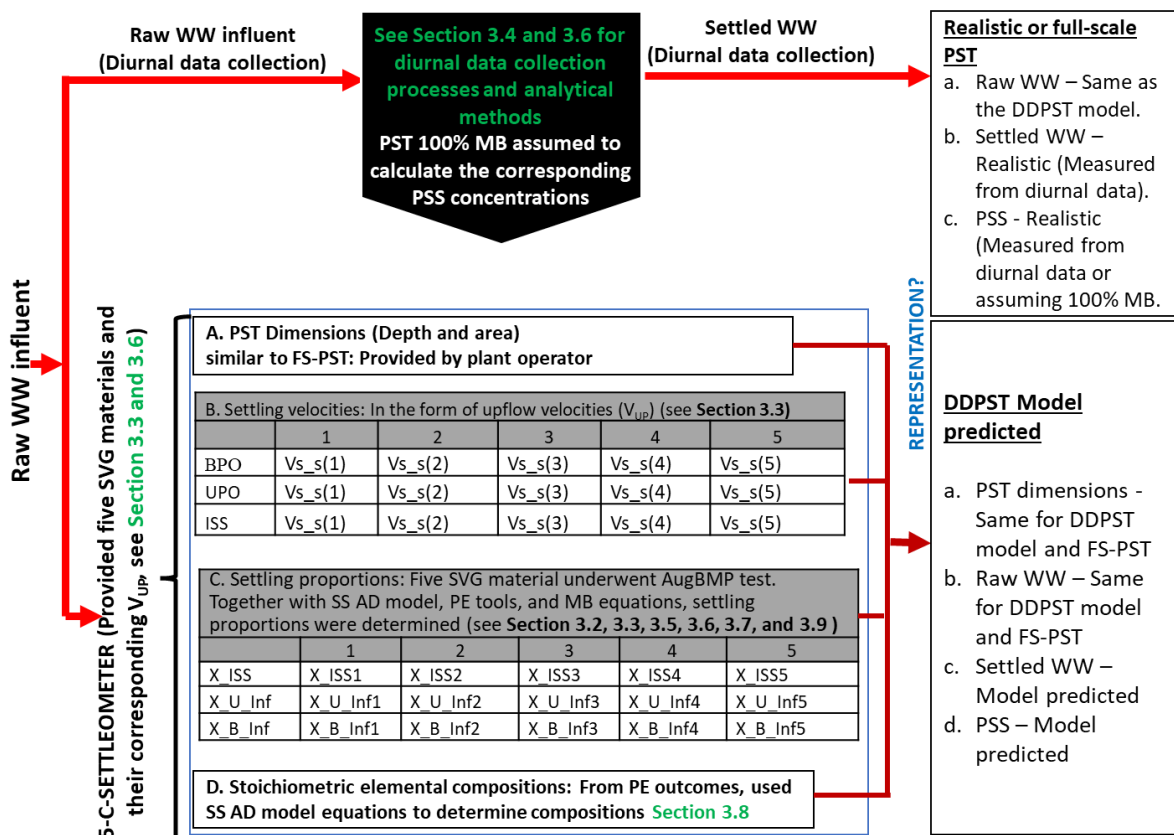


Figure 3.30: Illustration of methods used to gather the FS-PST data and the parameters required to run the DDPST model

CHAPTER 4:

RESULTS

Chapter 4: Results

4.1. Introduction

The methodological processes approached to (i) collect the full-scale (FS-PST) diurnal data (influent, settled WW, and PSS), (ii) segregate the raw wastewater (WW) settleable particulates into five different settling velocity groups (SVGs), (iii) determine the BPO, UPO, and ISS proportions of the five SVGs, and (iv) confirm the validity of the overall outcomes using mass balances (MBs), standard deviations, and percentage errors were discussed in **Chapter 3**. This chapter presents the results obtained from each of the three experimental set-ups accompanied by the evaluation processes taken to meet the objectives set in **Chapter 1**.

4.2. Diurnal data: Raw WW, settled WW and PSS general characteristics

The flow rates and WW samples of the Bellville wastewater treatment works (WWTWs) were collected during the wet weather conditions in the Cape Town area on the 02nd of June 2021. The samples were tested for their COD, TSS, VSS, ISS, pH, and alkalinity. The outcomes of these measurements are discussed in the subsections below. The related methodological processes are described in **Section 3.4**.

4.2.1. pH and alkalinity

Figure 4.1 shows the pH and alkalinity levels of the raw WW, settled WW, and PSS samples collected from the Bellville WWTWs. The raw WW and settled WW pH levels are well buffered at a range between 6.7–7.0. The alkalinity concentrations between 208–294 mg/l as CaCO₃ were recorded for the settled WW samples. Given that the alkalinity concentrations are measured on the filtered samples, it is accepted that the settled WW alkalinity equals the influent WW alkalinity. Ron Trygar (2014) stated that raw WW containing approximately 200 to 250 mgCaCO₃/l can be said to have sufficient buffering capacity, which is useful in preventing low pH values or sudden pH level drops. The pH values as low as 6.2 were recorded for the PSS samples in the present study. This could be due to the marginal increase in the particle residence time in the PST, which increases the hydrolysis processes leading to the VFA accumulation and subsequently, to the reduced pH levels.

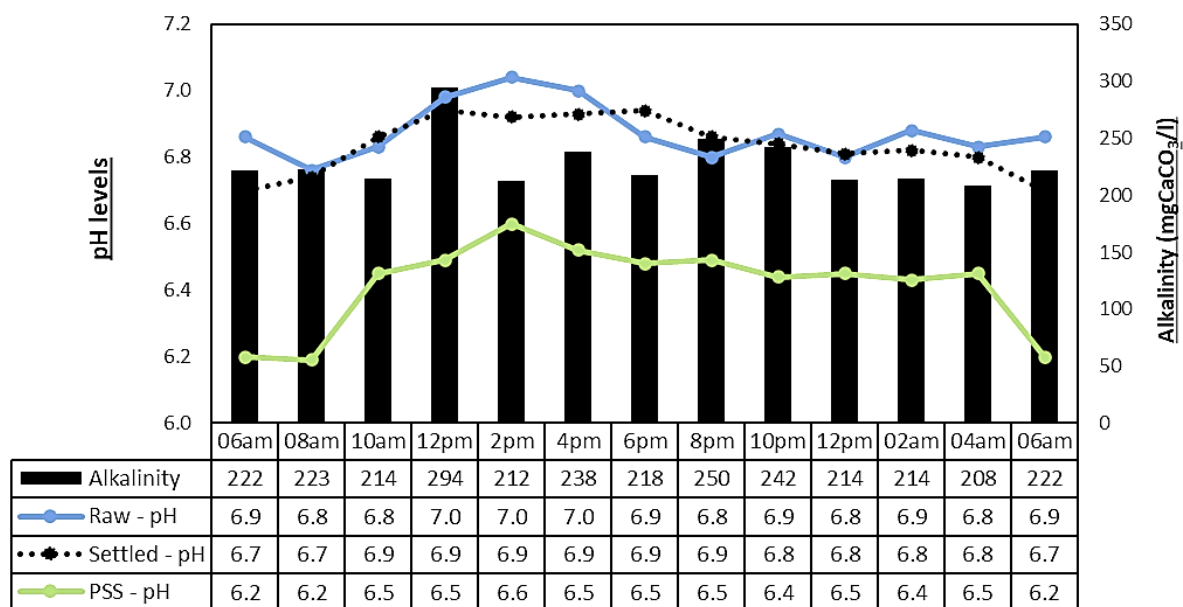


Figure 4.1: The diurnal pH and alkalinity levels for the raw WW, settled WW, and PSS

4.2.2. COD, TSS, VSS and ISS concentrations

Figure 4.2 presents the Bellville WWTWs diurnal COD, TSS, VSS, and ISS concentrations for the raw WW, settled WW, and PSS. Also included in the data are the diurnal PST raw WW influent, settled WW effluent, and PSS underflow rates. The diurnal settled WW flow rates were obtained by subtracting 0.5% PSS underflow rates from the respective influent flow rates. The minimum and maximum COD concentrations of 768 mgCOD/l (6 am) and 1 551 mgCOD/l (10 am), respectively, were recorded for the raw WW. Higher concentrations were observed from 10 am to 2 pm, with generally low concentrations from 10 pm to 6 am (**Figure 4.2A**). For the settled WW, the respective COD, TSS, VSS, and ISS concentrations were almost the same throughout the day with (i) the COD ranging between 599–680 mgCOD/l, (ii) the TSS between 166–370 mgTSS/l, and (iii) the VSS between 156–336 mgVSS/l. The overall higher concentrations for the settled WW were recorded between 10 am and 12 pm (**Figure 4.2B**). The observed PSS concentrations were lower than expected. The maximum concentration range of 7 910 to 9 137 mgCOD/l was observed for the samples collected from 6 am to 10 am, with the minimum concentration range of 1 087 and 3 821 mgCOD/l recorded from 4 pm to 4 am the following day (**Figure 4.2C**). These considerably low PSS concentrations were due to the PST actuator valve failure. This failure resulted in the loss of solids (solids not being able to accumulate in the PST), thus lowering the observed PSS concentrations.

4.2.3. COD, TSS, VSS and ISS flux balance

The material MB was performed around the PST to confirm the validity of the obtained results (see **Section 3.4.5**). After performing the MBs, the percentages as low as 53.8% and 59.6% were recorded

at 10 am and 6 pm (**Figure 4.2C**). As stated by Gaszynski (2020: 77), the MB range below 80% is regarded poor. As discussed in **Section 4.2.3** above, the PSS concentrations are by far a contributing factor to the poor MB. Given that the PSS concentrations recorded were not considered as a satisfactory representation of the PST performance, a 100% MB around the PST was assumed to calculate the new PSS diurnal concentrations from the raw WW and settled WW concentrations. According to the MB principles, the diurnal PSS fluxes are calculated by subtracting the settled WW fluxes from the raw WW influent fluxes. The resulting PSS fluxes are then divided by the respective diurnal underflow rates to get the corresponding PSS concentrations. The complete results from these computations are tabulated in **Figure 4.3C**. The average concentration of 68 903 mgCOD/l was obtained for the PSS generated, assuming 100% MB.

4.2.4. Particulate COD/VSS (f_{cv}), VSS/TSS, and ISS/TSS mass fractions

The particulate f_{cv} , VSS/TSS, and ISS/TSS fractions for the raw WW, settled WW, and initially measured PSS concentrations (prior to the MB) are presented in **Figure 4.2**. A consistent relationship between these fractions were observed diurnally. The following particulate f_{cv} ratios are noted:

- a. 1.50 to 2.08 (with a daily average of 1.70) for the raw WW;
- b. 1.24 to 2.76 (with a daily average of 1.83) for the settled WW; and
- c. 1.41 to 2.84 (with a daily average of 2.62) for the PSS.

The VSS/TSS mass ratios recorded are as follows:

- a. 0.75 to 0.94 (with a daily average of 0.83) for the raw WW;
- b. 0.71 to 0.99 (with a daily average of 0.93) for the settled WW; and
- c. 0.66 to 0.94 (with a daily average of 0.86) for the PSS.

The ISS/TSS mass ratios recorded are as follows:

- a. 0.06 to 0.25 (with a daily average of 0.17) for the raw WW;
- b. 0.01 to 0.29 (with a daily average of 0.075) for the settled WW; and
- c. 0.06 to 0.34 (with a daily average of 0.14) for the PSS.

Assuming 100% MB around the PST changes the diurnal and average f_{cv} , VSS/TSS, and ISS/TSS for the PSS marginally (**Figure 4.3C**). The PSS corrected outcomes can be summarised as follows:

- a. f_{cv} : 1.23 to 2.26 (with a daily average of 1.70);
- b. VSS/TSS: 0.39 to 0.92 (with a daily average of 0.7); and
- c. ISS/TSS: 0.08 to 0.61 (with a daily average of 0.3).

While the f_{cv} , VSS/TSS, and ISS/TSS mass ratios for the initially observed PSS are marginally different from the ratios after the MB applications, the VSS appears to generally dominate the PSS, in comparison with ISS.

4.2.5. TKN, TP, FSA, and OP concentrations

The FSA and OP diurnal concentrations were also measured, and the results are presented in **Figure 4.4**. These two components were measured only for the settled WW since it is accepted that, FSA and OP occurring in a soluble component (0.45 μ m membrane filtrate), remain the same for the raw WW, settled WW, and PSS. The FSA/COD and OP/COD fractions were considered to check the consistency in the measured components (**Figure 4.4**). The average FSA/COD ratios for the raw WW, settled WW, and PSS are 0.060, 0.085 and 0.0013, respectively. These ratios are quite reasonable given the fact that nitrogen (N) in the form of FSA is found in the soluble rather than the particulate portion (the N in the particulates is only released during the degradation of the biodegradable matter to form part of the FSA). These ratios are also closer to the FSA/COD ratios of 0.058, 0.096, and 0.0007 for the raw WW, settled WW, and PSS, respectively, obtained by Ekama (2021: 145). Given that the COD of the raw WW accounts for both the settleable and non-settleable particulates, while the settled WW COD excludes the settleable particulates, the FSA/COD fraction of the settled WW is greater relative to that of the raw WW.

The OP/COD ratios of the raw WW, settled WW, and PSS are 0.008, 0.012, and 0.00018, respectively. Similarly, these OP/COD ratios are close to those obtained by Ekama (2021: 145) of 0.0108, 0.018, and 0.00013 for the raw WW, settled WW, and PSS, respectively. Similar to the FSA/COD ratio, the variations in the OP/COD ratio of the raw WW and settled WW are linked to the existence of both the settleable and non-settleable particulates, in the raw WW, and only the non-settleable particulates, in the settled WW.

4.2.6. Summary

Table 4.1 presents the complete flow weighed averages (FWAs) for (i) the raw WW, (ii) the settled WW, and (iii) the filtered component of the well-buffered WW from the Bellville WWTWs. In terms of the flow rates, the weather flow patterns vary diurnally yielding the average weather flow ($Q_{i,AWF}$) of 1 160 m³/h, minimum weather flow ($Q_{i,MWF}$) of 746 m³/h, and peak weather flow ($Q_{i,PWF}$) of 1 551 m³/h. The respective COD, TSS, VSS, and ISS concentrations are summarised in **Figure 4.2**, **Figure 4.3**, and **Figure 4.4**. The underflow (PSS) and overflow (settled WW) output data will, at a later stage, be compared with the 5C-settleometer outputs that are to be used as parameters into the DDPST model to allow the model evaluation (see **Chapter 5**).

Table 4.1: The complete flow weighed average concentrations for the Bellville WWTWs

Components	Total COD	VFA	FSA	OP	TSS	ISS	VSS
Units	mgCOD/l	mg/l	mgN/l	mgP/l	mgTSS/l	mgISS/l	mgVSS/l
Unfiltered (Raw WW)	1012	-	-	-	549	98	450
Supernatant (Settled WW)	671	-	-	-	239	23	216
Filtered (0.45um Filtrate)	272	98	58	8	-	-	-

A. RAW

Time	Flow	COD	COD	Particulate	TSS	VSS	ISS			
dt (h)	m ³ /h	mgCOD/l	kgCOD/2hr	mgCOD/l	mgTSS/l	mgVSS/l	mgISS/l	f _{cv}	VSS/TSS	ISS/TSS
6am	966	768	1484	476	374	314	60	1.52	0.84	0.16
8am	1128	895	2018	576	440	384	56	1.50	0.87	0.13
10am	1872	1551	5808	1256	1070	838	232	1.50	0.78	0.22
12pm	1944	1075	4180	833	620	468	152	1.78	0.75	0.25
14pm	1663	1087	3615	829	606	522	84	1.59	0.86	0.14
16pm	1753	991	3474	756	528	450	78	1.68	0.85	0.15
18pm	1182	1144	2705	883	548	516	32	1.71	0.94	0.06
20pm	1134	852	1933	553	428	368	60	1.50	0.86	0.14
22pm	1008	745	1502	449	314	254	60	1.77	0.81	0.19
12am	408	852	696	561	348	270	78	2.08	0.78	0.22
2am	383	864	661	599	394	320	74	1.87	0.81	0.19
4am	473	818	773	522	374	282	92	1.85	0.75	0.25
6am	576	768	885	476	374	314	60	1.52	0.84	0.16
Mean	1160	970		691	504	415	88	1.70	0.83	0.17

B. SETTLED

Time	q _A	Flow	COD	COD	Particulate	Soluble	TSS	VSS	ISS			
dt (h)	m/h	m ³ /h	mgCOD/l	kgCOD/2hr	mgCOD/l	mgCOD/l	mgTSS/l	mgVSS/l	mgISS/l	f _{cv}	VSS/TSS	ISS/TSS
6am	1.00	961	626	1203	334	292	224	208	16	1.61	0.93	0.07
8am	1.17	1122	653	1465	334	319	284	270	14	1.24	0.95	0.05
10am	1.95	1863	799	2975	503	296	370	336	34	1.50	0.91	0.09
12pm	2.02	1934	710	2748	468	242	238	170	68	2.76	0.71	0.29
14pm	1.73	1655	664	2199	407	257	230	224	6	1.82	0.97	0.03
16pm	1.82	1744	599	2090	365	234	166	156	10	2.34	0.94	0.06
18pm	1.23	1176	680	1599	419	261	220	214	6	1.96	0.97	0.03
20pm	1.18	1128	687	1551	388	300	258	256	2	1.52	0.99	0.01
22pm	1.05	1003	676	1356	380	296	230	222	8	1.71	0.97	0.03
12am	0.42	406	649	527	357	292	186	180	6	1.98	0.97	0.03
2am	0.40	381	622	474	357	265	204	188	16	1.90	0.92	0.08
4am	0.49	470	603	567	307	296	214	186	28	1.65	0.87	0.13
6am	1.00	573	626	717	334	292	224	208	16	1.61	0.93	0.07
Mean ave	1.21	1153.7	664.0		385.0	279.0	235.3	217.5	17.8	1.831	0.925	0.075

PST DIMENSIONS

DEPTH: 3m
DIAMETER: 35m
AREA: 962.1 m²
VOLUME: 2886 m³

C. PSS

Time	Flow	COD	COD	Particulate	TSS	VSS	ISS				
dt (h)	m ³ /h	mgCOD/l	kgCOD/2hr	mgCOD/l	mgTSS/l	mgVSS/l	mgISS/l	f _{cv}	VSS/TSS	ISS/TSS	MB%
6am	4.8	8467	82	8175	6072	5166	906	1.64	0.85	0.15	86.6
8am	5.6	9139	103	8820	9598	6352	3246	1.44	0.66	0.34	77.7
10am	9.4	7910	148	7615	6912	5622	1290	1.41	0.81	0.19	53.8
12pm	9.7	2909	57	2667	1306	1188	118	2.45	0.91	0.09	67.1
14pm	8.3	3821	64	3564	2254	1946	308	1.96	0.86	0.14	62.6
16pm	8.8	2966	52	2732	440	372	68	7.97	0.85	0.15	61.7
18pm	5.9	1140	13	879	458	410	48	2.78	0.90	0.10	59.6
20pm	5.7	1098	12	799	562	526	36	2.09	0.94	0.06	80.9
22pm	5.0	1194	12	899	474	420	54	2.84	0.89	0.11	91.1
12am	2.0	1229	5	937	666	596	70	2.06	0.89	0.11	76.5
2am	1.9	1171	4	906	604	520	84	2.25	0.86	0.14	72.3
4am	2.4	1087	5	791	468	428	40	2.54	0.91	0.09	74.0
6am	2.9	8467	49	8175	6072	5166	906	2.627	0.856	0.144	86.6
Mean	6	3511		3232	2484	1962	522	2.62	0.86	0.14	mg/l

The load shedding affected the PST 1 actuator valve. The valve failed to close, solids were lost, thus resulting in the low PSS concentrations.

The MB around the PST would be assumed to calculate the corresponding PSS concentrations. There is some level of confidence in the measured raw and settled WW given that the calculated f_{cv} , VSS/TSS, ISS/TSS, FSA/COD, and OP/TCOD values are close to the literature values (Ekama, 2021) (see Section 4.1.4).

Figure 4.2: The COD, TSS, VSS, and ISS concentrations of the raw WW, settled WW, and PSS and their related f_{cv} , VSS/TSS, and ISS/TSS fractions. The samples were collected on the 02nd June 2021 at the Bellville WWTWs.

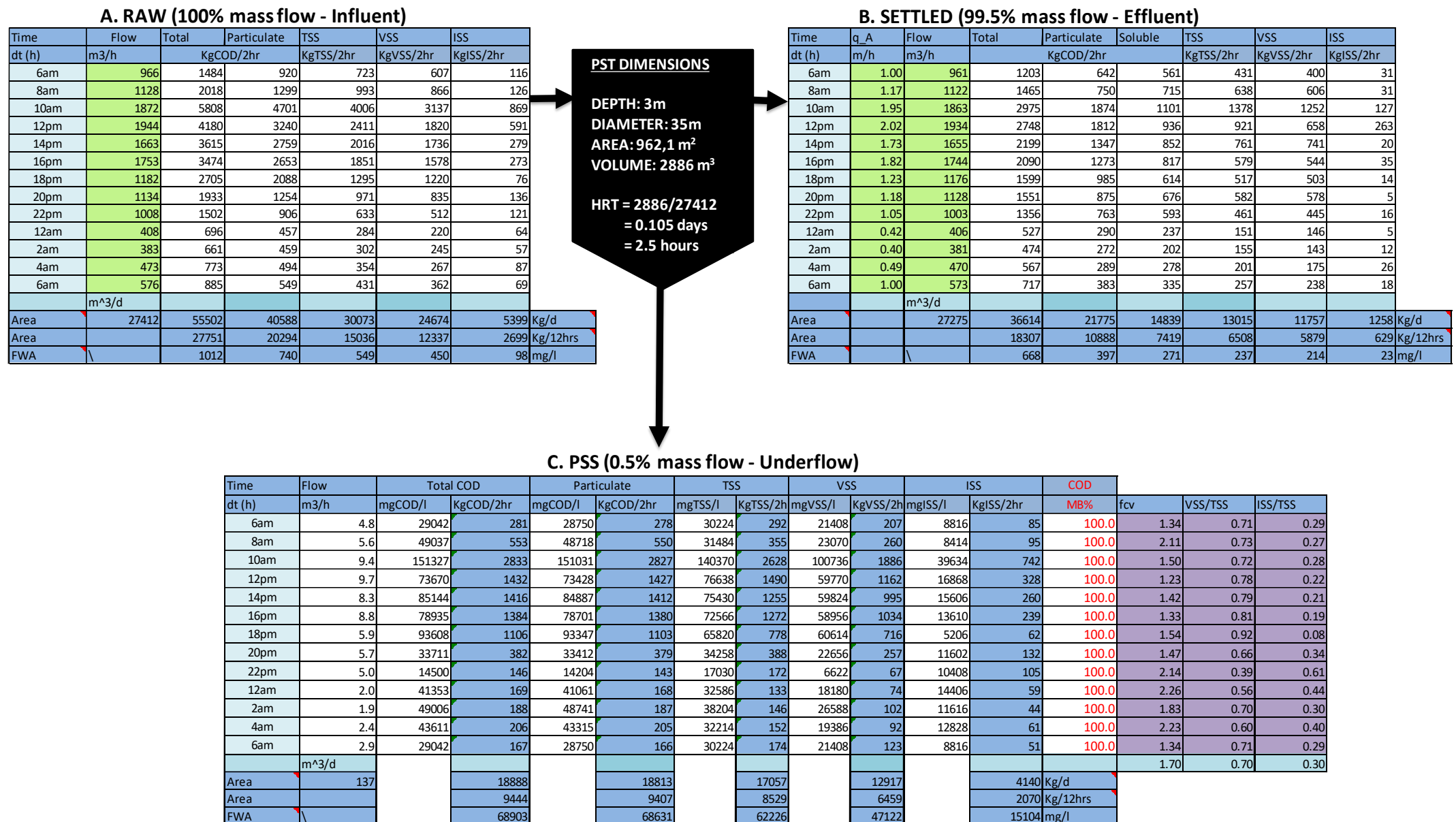
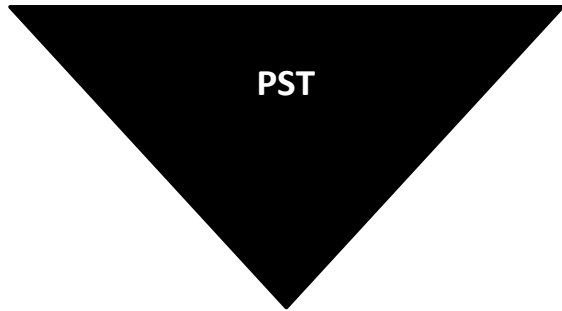


Figure 4.3: The raw WW, settled WW, and PSS fluxes. The respective PSS concentrations were calculated assuming 100% MB around the PST.

RAW

Time	Flow	FSA/COD	OP/COD
dt (h)	m3/h		
06H00	966	0,067	0,010
08H00	1128	0,067	0,008
10H00	1872	0,041	0,005
12H00	1944	0,058	0,007
14H00	1663	0,051	0,006
16H00	1753	0,060	0,008
18H00	1182	0,052	0,007
20H00	1134	0,070	0,010
22H00	1008	0,068	0,011
00H00	408	0,061	0,010
02H00	383	0,068	0,008
04H00	473	0,058	0,009
06H00	576	0,067	0,000
		0,060	0,008
Area	27412	1	Kg/d
Area		1	Kg/12hrs
FWA		0	mg/l



SETTLED

Time	Flow	FSA		OP		FSA/COD	OP/COD
dt (h)	m3/h	mgN/l	KgN/2hr	mgP/l	KgP/2hr		
06H00	961	51	99	7	14	0,082	0,012
08H00	1122	60	134	8	17	0,092	0,012
10H00	1863	63	236	7	27	0,079	0,009
12H00	1934	63	242	7	29	0,088	0,010
14H00	1655	55	182	7	22	0,083	0,010
16H00	1744	59	206	8	28	0,099	0,013
18H00	1176	59	140	8	18	0,087	0,011
20H00	1128	60	135	8	18	0,087	0,012
22H00	1003	51	102	8	17	0,075	0,012
00H00	406	52	42	9	7	0,080	0,013
02H00	381	58	44	7	6	0,094	0,012
04H00	470	47	44	7	7	0,078	0,012
06H00	573	51	59	0	0	0,082	0,000
						0,085	0,012
Area	27275		3189		410		Kg/d
Area			1594		205		Kg/12hrs
FWA			58		7		mg/l

PSS Assuming 100% mass balance

Time	Flow	FSA/COD	OP/COD
dt (h)	m3/h		
06H00	4,8	0,0018	0,0003
08H00	5,6	0,0012	0,0002
10H00	9,4	0,0004	0,0000
12H00	9,7	0,0008	0,0001
14H00	8,3	0,0006	0,0001
16H00	8,8	0,0007	0,0001
18H00	5,9	0,0006	0,0001
20H00	5,7	0,0018	0,0002
22H00	5,0	0,0035	0,0006
00H00	2,0	0,0013	0,0002
02H00	1,9	0,0012	0,0001
04H00	2,4	0,0011	0,0002
06H00	2,9	0,0018	0,0000
		0,001	0,000
Area	137		Kg/d
Area			Kg/12hrs
FWA			mg/l

Figure 4.4: The TKN, TP, FSA, and OP diurnal concentrations for the raw WW, settled WW, and PSS

4.3. Five-column settleometer experimental results

As discussed in **Section 3.2**, the 5C-settleometer was used to segregate the PSS particulates into five different SVGs. Essentially, a part of the influent WW flowing into the FS-PST was diverted into the 5C-settleometer to segregate the settleable particles into five SVGs. The outcomes from the five SVGs in terms of the COD, TSS, VSS, and ISS concentrations and masses for the two performed TeRs were discussed in **Sections 3.5.1** and **3.5.2**. The precedent settleometer outcome evaluation was necessary for the following reasons:

- (i) The MB around the settleometer needed to be confirmed before proceeding with the biodegradability test, and
- (ii) Since two TeRs were performed, it was necessary to select the most preferable TeR outputs to undergo biodegradability test.

Thus, the section below presents the biodegradability test outcomes from the selected 5C-settleometer TeR1.

4.4. AugBMP experimental results

4.4.1. Overview

The particulate matter from the TeR1 SVGs were subjected to the biodegradability test using the AugBMP test procedure (see **Section 3.5.1** and **3.5.2**). This test was performed to distinguish between the BPO and UPO fractions of the segregated settleable VSS (see **Section 3.5**). The AugBMP test experimental results are discussed in the subsections below. It is important to note that the results presented in these subsections are the raw outcomes of the concentrations prepared in **Section 3.5.5**. The subsequent **Section 4.5.4** will present the finalised SVG substrate concentrations where the inoculum masses are subtracted from the test reactors. Thereafter, the necessary dilution factors will be applied to get the exact settleable proportions (**Section 4.7**).

4.4.2. AugBMP test COD concentrations

4.4.2.1. Starting COD concentrations

The calculated versus measured COD concentrations for the control and five SVGs are presented in **Figure 4.5**. The calculated COD points were obtained as follows:

- a. Control: (i) take fresh inoculum COD concentration (collected from an active PAD system, see **Section 3.2**), and (ii) apply the necessary dilutions as presented in **Table 3.9**, to get the control approximate starting COD (see **Section 3.5.5**).

- b. Five SVGs: (i) take the respective substrate COD mass, (ii) apply the necessary dilutions to the substrate, and (iii) add a specified volume of the inoculum COD mass prepared in (a) to obtain the respective starting test concentrations (see **Table 3.9** in **Section 3.5.5**).

The measured COD concentrations (also referred to as “observed concentrations”) were obtained by testing the prepared starting mixtures for both the control and five SVG test samples. As shown in **Figure 4.5**, the percentage errors (see **Section 3.5.8.1**), between the measured and calculated total COD, of both the control and five SVGs were found to be well within 10%. This is an indication of how close the measured values are to the calculated values. The starting COD concentrations (together with the corresponding percentage errors) were measured for (i) the total COD, (ii) the soluble COD, and (iii) the particulate COD components. The % error, for the soluble COD, appears to be greater than 10%. This could be due to the lower soluble COD concentrations in the samples. Although the total, soluble, and particulate concentrations are presented in this specific section, the proceeding discussions will focus on the particulate material (in accordance with the objectives of the present study).

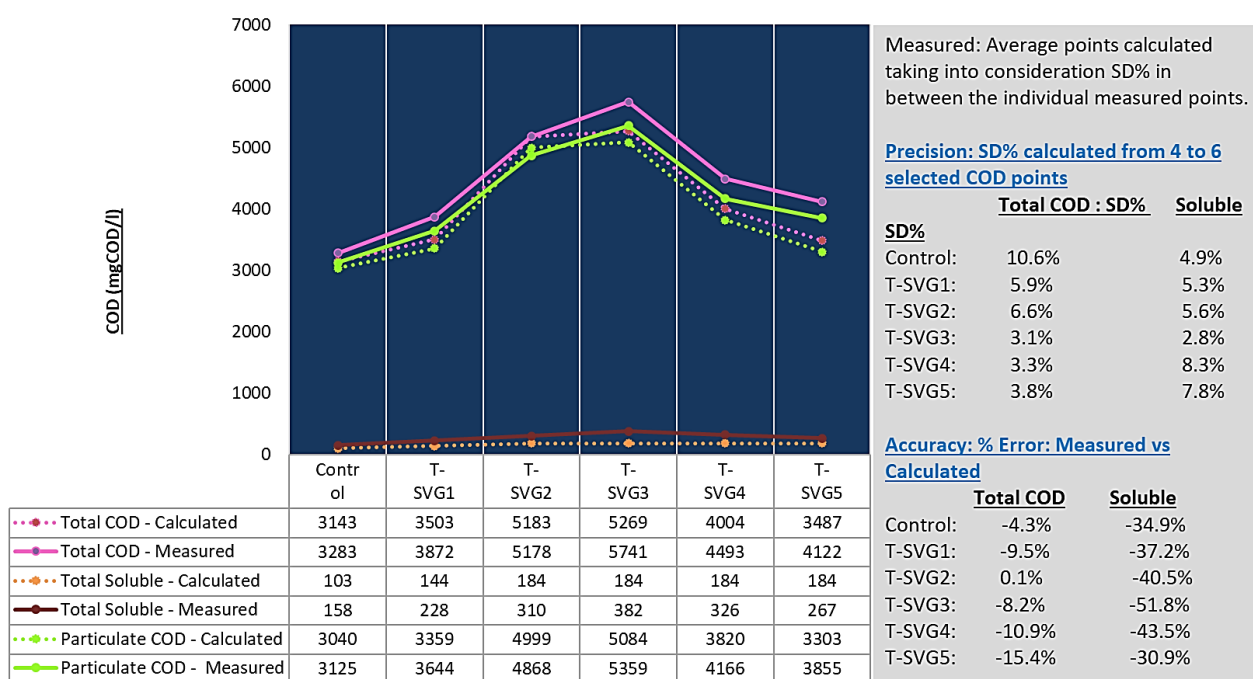


Figure 4.5: The measured versus calculated starting total, particulate, and soluble COD concentrations. The precision and accuracy expressed as SD% and % error, respectively, are shown on the right-hand side. T-SVG1, T-SVG2, T-SVG3, T-SVG4, and T-SVG5 represent the test reactor concentrations for the respective SVGs.

4.4.2.2. Ending COD concentrations

Figure 4.6 presents the decreases in the average particulate COD concentrations from Day 0 (24th of June 2021) to Day 58 (21st of August 2021) for the control and five SVG test samples. It was assumed

that 58 days is a long enough sludge age (R_s) for the complete breakdown of BPO. This assumption is based on the fact that there were no records of biogas production from as low R_s as 30 days. The particulate COD measured on Day 58 is assumed to be unbiodegradable particulate (UPO) COD. This UPOCOD may contain a significantly small fraction of the residual active biomass that did not degrade at R_s of 58 days. As discussed in **Section 3.7.3**, the residual active biomass at a significantly long R_s is considerably low and may be regarded negligible for simplification in this discussion. The difference between the particulate COD values, from Day 0 and Day 58, is considered to represent the biodegradable particulate COD (BPO) (see **Section 3.7.3**). The BPO is also referred to as particulate COD removed (or converted to biogas). The COD concentrations removed is represented in percentage in **Figure 4.6**. The lowest average particulate COD removal of 31.1% was observed on the control samples. This is quite reasonable given the fact that (i) the “control” batch reactors only comprised the inoculum and clean water (blank), and (ii) equal masses of inoculum were seeded in both the control and five SVG test reactors (**Section 3.5.5**). This implies that the difference between any of the SVG test samples and control equals the substrate concentrations. Greater particulate COD removals were observed in the SVG2 (45.4%) and SVG3 (46.6%). This simply implies that greater biodegradable particulate contents accumulated in the SVG2 and SVG3 (corresponding with V_{up} of 12.9 and 6.9 m/hr, respectively) in comparison with the SVG1 (V_{up} = 25.7 m/hr), SVG4 (V_{up} = 6.0 m/hr), and SVG5 (V_{up} = 3.8 m/hr). More details on the BPO utilized and corresponding biogas production are discussed in **Section 4.4.2.3**.

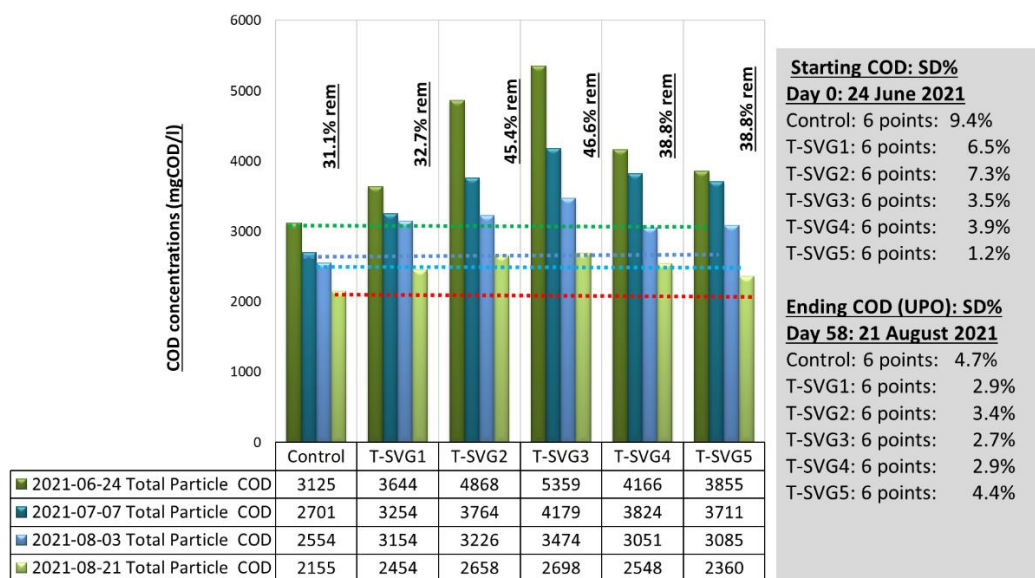


Figure 4.6: The starting and ending particulate COD concentrations. The standard deviation percentage (SD%) as indicated on the right-hand side (grey block) is only for the starting and ending COD concentrations. The SD% were obtained from the indicated number of selected points. The average concentrations as presented on the graph were obtained from points that gave a lower SD% value. The percentage removal (%rem) from Day 0 to Day 58 (last day) is also indicated for the control and five SVG groups. T-SVG1, T-SVG2, T-SVG3, T-SVG4, and T-SVG5 represent the test reactor concentrations for the respective SVGs.

4.4.2.3. Particulate COD removal and corresponding biogas produced

Figure 4.7 presents the relationship between the BPO utilized and biogas volume produced. As evident from the figure, the control reactors produced the lowest biogas volume in comparison with the SVG test reactors. This corresponds with the lowest BPO utilized or removed from the control reactors. On the other hand, the SVG2 and SVG3 produced greater biogas volumes in comparison with the SVG1, SVG4 and SVG5. Once more, this corresponds to the greater BPO removed or utilized (**Section 4.4.2.2**). More details on the individual reactor biogas released can be found in **Appendix B**.

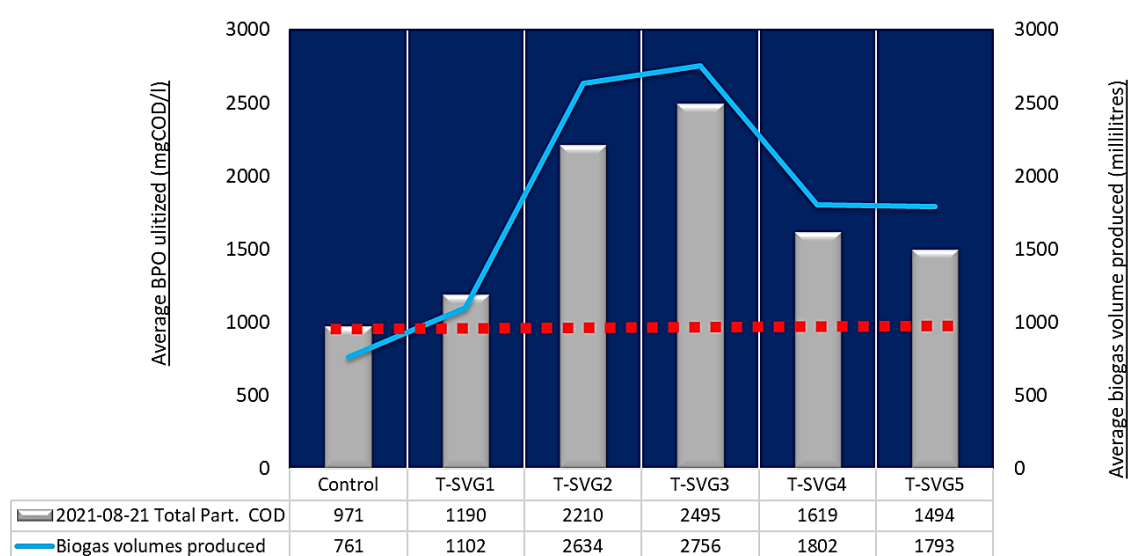


Figure 4.7: The average BPO utilized and corresponding biogas produced. The BPO concentrations presented in this figure are the actual concentrations of the percentages presented in **Figure 4.6**. The red dotted line represents the “control” baseline right across the five SVG test samples.

4.4.2.4. COD mass balance

Table 4.2 and **Table 4.3** present the material MB around each of the control and test batch reactors. The steps taken to complete the MBs are described in **Section 3.5.9.2.1**. The CH₄ COD mass calculation steps for the control and five SVG groups are given in **Appendix C**. While all batch reactors yielded a MB within 80–120%, a satisfactory MB was observed on Day 14. The MB around most of the bath reactors continuously decreased from Day 14 to Day 58. The drop in the MB could be related to the relationship between the biodegradable COD lost and methane gas recorded. A study conducted by Gaszynski (2020: 179) proved the existence of high level of inaccuracies related to the gas measurements in an AugBMP test experiment. Although Day 40 shows a satisfactory MB, the measurement on Day 58 proves that the reactor contents on Day 40 still had biodegradable contents. Given that the present study requires the exact proportions of UPO and BPO, Day 58 is selected as the preferred last day.

Table 4.2: The COD mass balance for the four control bioreactors

COD Balance: $COD_{inf} \times Vol_{inf,Liq} = 64\,000n + (COD_{rem} \times Vol_{rem,Liq}) + \text{Sum of } (COD_{smp} \times Vol_{smp,Liq})_{\text{sampledFromDay,1 to DayLast}}$							
Symbol	Formular or source	Units	Control 1	Control 2	Control 3	Control 4	Average
Vol_{inf}	Direct measurement	Litre	5	5	2	2	3.5
Vol_{smp1}	Direct measurement	Litre	0.112	0.101	0.093	0.082	0.1
Vol_{rem1}	Direct measurement	Litre	4.888	4.899	1.907	1.918	3.4
Vol_{smp4}	Direct measurement	Litre	0.074	0.118	0.084	0.08	0.1
Vol_{rem4}	Direct measurement	Litre	4.814	4.781	1.823	1.838	3.3
Vol_{smp14}	Direct measurement	Litre	0.082	0.106	0.096	0.096	0.1
Vol_{rem14}	Direct measurement	Litre	4.732	4.675	1.727	1.742	3.2
Vol_{smp16}	Direct measurement	Litre	0.085	0.089	0.09	0.079	0.1
Vol_{rem16}	Direct measurement	Litre	4.647	4.586	1.637	1.663	3.1
Vol_{smp40}	Direct measurement	Litre	0.0875	0.095	0.071	0.076	0.1
Vol_{rem40}	Direct measurement	Litre	4.5595	4.491	1.566	1.587	3.1
Vol_{smp42}	Direct measurement	Litre	0.11	0.09	0.113	0.138	0.1
Vol_{rem42}	Direct measurement	Litre	4.4495	4.401	1.453	1.449	2.9
$Vol_{smpLast_58}$	Direct measurement	Litre	0.137	0.142	0.131	0.129	0.1
$Vol_{rem_Last_58}$	Direct measurement	Litre	4.3125	4.259	1.322	1.32	2.8
Vol_{CH4}	Direct measurement	Litre	0.245	0.452	0.219	0.128	0.261
COD_{inf}	Direct measurement	mgCOD/l	3052.8	3091.2	3033.6	3398.4	3144.0
COD_{smp1}	Direct measurement	mgCOD/l	3052.8	3091.2	3033.6	3398.4	3144.0
COD_{rem1}	Direct measurement	mgCOD/l	3052.8	3091.2	3033.6	3398.4	3144.0
COD_{smp4}	Direct measurement	mgCOD/l	3696	3840	3744	3648	3732.0
COD_{rem4}	Direct measurement	mgCOD/l	3696	3840	3744	3648	3732.0
COD_{smp14}	Direct measurement	mgCOD/l	2726.4	2860.8	2860.8	2995.2	2860.8
COD_{rem14}	Direct measurement	mgCOD/l	2726.4	2860.8	2860.8	2995.2	2860.8
COD_{smp16}	Direct measurement	mgCOD/l	1838	2863	2829	3456	2746.5
COD_{rem16}	Direct measurement	mgCOD/l	1838	2863	2829	3456	2746.5
COD_{smp40}	Direct measurement	mgCOD/l	2899.2	2342.4	2668.8	2688	2649.6
COD_{rem40}	Direct measurement	mgCOD/l	2899.2	2342.4	2668.8	2688	2649.6
COD_{smp42}	Direct measurement	mgCOD/l	2227	2275	2381	2688	2392.8
COD_{rem42}	Direct measurement	mgCOD/l	2227	2275	2381	2285	2292.0
$COD_{smpLast58}$	Direct measurement	mgCOD/l	2188.8	2304	2102.4	2236.8	2208.0
COD_{rem_Last58}	Direct measurement	mgCOD/l	2188.8	2304	2102.4	2236.8	2208.0
COD_{CH4}	Gas chromatography	mgCOD/l	130.5	240.4	291.9	170.0	198.5
$MCOD_{inf}$	$Vol_{inf} \times COD_{inf} \times 10^{-3}$	gCOD	15.3	15.5	6.1	6.8	11.0
$MCOD_{smp1}$	$Vol_{smp1} \times COD_{smp1} \times 10^{-3}$	gCOD	0.3	0.3	0.3	0.3	0.3
$MCOD_{rem1}$	$Vol_{rem} \times COD_{rem} \times 10^{-3}$	gCOD	14.9	15.1	5.8	6.5	10.7
$MCOD_{smp4}$	$Vol_{smp4} \times Vol_{smp4} \times 10^{-3}$	gCOD	0.3	0.5	0.3	0.3	0.3
$MCOD_{rem4}$	$Vol_{rem4} \times Vol_{rem4} \times 10^{-3}$	gCOD	17.8	18.4	6.8	6.7	12.4
$MCOD_{smp14}$	$Vol_{smp14\&16} \times COD_{smp14\&16} \times 10^{-3}$	gCOD	0.2	0.3	0.3	0.3	0.3
$MCOD_{rem14}$	$Vol_{rem14\&16} \times COD_{rem14\&16} \times 10^{-3}$	gCOD	12.9	13.4	4.9	5.2	0.2
$MCOD_{smp16}$	$Vol_{smp14\&16} \times COD_{smp14\&16} \times 10^{-3}$	gCOD	0.2	0.3	0.3	0.3	0.2
$MCOD_{rem16}$	$Vol_{rem14\&16} \times COD_{rem14\&16} \times 10^{-3}$	gCOD	8.5	13.1	4.6	5.7	0.2
$MCOD_{smp40}$	$Vol_{smp40} \times COD_{smp40} \times 10^{-3}$	gCOD	0.3	0.2	0.2	0.2	0.2
$MCOD_{rem40}$	$Vol_{rem40} \times COD_{rem40} \times 10^{-3}$	gCOD	13.2	10.5	4.2	4.3	8.1
$MCOD_{smp42}$	$Vol_{smp40} \times COD_{smp40} \times 10^{-3}$	gCOD	0.2	0.2	0.3	0.4	0.3
$MCOD_{rem42}$	$Vol_{rem40} \times COD_{rem40} \times 10^{-3}$	gCOD	9.9	10.0	3.5	3.3	6.7
$MCOD_{smpLast58}$	$Vol_{smpLast58} \times COD_{smpLast58} \times 10^{-3}$	gCOD	0.3	0.3	0.3	0.3	0.3
$MCOD_{rem_Last58}$	$Vol_{remLast58} \times COD_{remLast58} \times 10^{-3}$	gCOD	9.4	9.8	2.8	3.0	6.2
$MCOD_{CH4}$	$Vol_{CH4} \times COD_{CH4} \times 10^{-3}$	gCOD	0.6525	1.2022	0.5839	0.3401	0.6947
%Error - Day 14	$(COD_{out}/COD_{in}) \times 100$	%	90.0	93.4	95.8	89.4	10.5
%Error - Day 40	$(COD_{out}/COD_{in}) \times 100$	%	79.0	83.9	92.8	78.8	82.3
%Error - Day 58	$(COD_{out}/COD_{in}) \times 100$	%	77.9	84.7	86.1	77.8	80.1

Table 4.3: The COD balance for the SVG1 to SVG5 triplicate AugBMP batch reactors

COD Balance: $COD_{inf} \times Vol_{Inf,Liq} = 64\,000n + (COD_{rem} \times Vol_{rem,Liq}) + \text{Sum of } (COD_{samp} \times Vol_{samp,Liq})_{\text{sampledFromDay,1 to DayLast}}$																						
			T-SVG1				T-SVG2				T-SVG3				T-SVG4				T-SVG5			
Symbol	Formular or source	Units	T-SVG1	T-SVG1D	T-SVG1T	Ave	T-SVG2	T-SVG2D	T-SVG2T	Ave	T-SVG3	T-SVG3D	T-SVG3T	Ave	T-SVG4	T-SVG4D	T-SVG4T	Ave	T-SVG5	T-SVG5D	T-SVG5T	Ave
Vol _{inf}	Direct measurement	Litre	5	5	2	4	5	5	2	4	5	5	2	4	5	2	5	4	5	5	2	4
Vol _{samp1}	Direct measurement		0.09	0.08	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.09	0.09	0.08	0.09	0.08
Vol _{rem1}	Direct measurement		4.9	4.8	1.8	3.8	4.9	4.9	1.9	3.9	4.9	4.8	1.8	3.8	4.9	1.9	4.9	3.9	4.9	4.9	1.9	3.9
Vol _{samp14}	Direct measurement		0.09	0.11	0.12	0.11	0.09	0.09	0.11	0.10	0.10	0.11	0.09	0.10	0.10	0.12	0.10	0.10	0.09	0.10	0.11	0.10
Vol _{rem14}	Direct measurement		4.8	4.7	1.7	3.7	4.8	4.8	1.8	3.8	4.8	4.7	1.7	3.7	4.8	1.8	4.8	3.8	4.8	4.8	1.8	3.8
Vol _{samp40}	Direct measurement		0.08	0.08	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.10	0.09	0.09	0.08		0.08	0.08	0.08	0.08	0.08	0.08
Vol _{rem40}	Direct measurement		4.8	4.7	1.7	3.8	4.7	4.7	1.7	3.7	4.7	4.6	1.6	3.6	4.7		4.7	3.7	4.7	4.7	1.7	3.7
Vol _{sampLast58}	Direct measurement		0.13	0.14	0.14	0.14	0.13	0.14	0.16	0.14	0.14	0.15	0.15	0.15	0.14		0.13	0.14	0.15	0.15	0.14	0.15
Vol _{rem_Last58}	Direct measurement		4.7	4.6	1.6	3.6	4.6	4.6	1.6	3.6	4.6	4.4	1.5	3.5	4.6		4.6	3.6	4.6	4.6	1.6	3.6
Vol _{CH4}	Direct measurement		0.32	0.43	0.35	0.37	1.42	1.48	0.46	1.12	1.52	1.55	0.47	1.18	0.83	0.77	0.41	0.67	0.68	0.68	0.68	0.68
COD _{inf}	Direct measurement	mgCOD/l	3898	3821	3898	3872	5299	5088	5146	5178	5587	5587	5549	5574	4435	4474	4570	4493	4147	4109	4109	4122
COD _{samp1}	Direct measurement		3898	3821	3898	3872	5299	5088	5146	5178	5587	5587	5549	5574	4435	4474	4570	4493	4147	4109	4109	4122
COD _{rem1}	Direct measurement		3898	3821	3898	3872	5299	5088	5146	5178	5587	5587	5549	5574	4435	4474	4570	4493	4147	4013	3955	4080
COD _{samp14}	Direct measurement		3590	3283	3494	3456	4051	4147	3917	4038	4205	4666	4474	4448	4243	6394	3840	4826	3802	4013	3955	3907
COD _{rem40}	Direct measurement		3264	3110	3283	3219	3226	3264	3475		3494	3706	3437	3546	3226		2938	3082	2918	3053	3494	2986
COD _{sampLast58}	Direct measurement		2573	2554	2448	2525	2832	2726	2630	2730	2822	2813	2678	2771	2573		2630	2602	2381	2467	2448	2432
COD _{rem_Last58}	Direct measurement		2573	2554	2448	2525	2832	2726	2630	2730	2822	2813	2678	2771	2573		2630	2710	2381	2467	2448	2432
COD _{CH4}	Gas chromatography		173	229	471	291	758	789	615	721	808	823	632	754	443	1021	217	560	362	223	491	359
MCOD _{inf}	Vol _{inf} x COD _{inf} x 10 ⁻³	gCOD	19.5	19.1	7.8	15.5	26.5	25.4	10.3	20.7	27.9	27.9	11.1	22.3	22.2	8.9	22.8	18.0	20.7	20.5	8.2	16.5
MCOD _{samp1}	Vol _{samp1} x COD _{samp1} x 10 ⁻³		0.3	0.3	0.3	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3
MCOD _{rem1}	Vol _{rem} x COD _{rem} x 10 ⁻³		19.2	18.4	7.0	14.9	26.1	25.0	9.8	20.3	27.4	26.8	10.1	21.4	21.8	8.6	22.4	17.6	20.4	19.7	7.6	16.0
MCOD _{samp14}	Vol _{samp14} x Vol _{samp14} x 10 ⁻³		0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.4	0.7	0.4	0.4	0.4	0.4	0.4	0.4
MCOD _{rem14}	Vol _{rem14} x Vol _{rem14} x 10 ⁻³		17.3	15.4	5.9	12.9	19.5	20.0	7.1	15.4	20.2	21.9	7.7	16.6	20.5	11.5	18.5	15.4	18.3	19.3	7.2	14.9
MCOD _{samp40}	Vol _{rem40} x COD _{rem40} x 10 ⁻³		0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.3		0.2	0.2	0.2	0.2	0.3	0.2
MCOD _{rem40}	Vol _{samp40} x COD _{samp40} x 10 ⁻³		15.8	14.7	5.7	12.1	15.3	15.5	6.0	0.0	16.5	17.0	5.6	12.9	15.3		13.9	11.5	13.8	14.5	6.0	11.2
MCOD _{sampLast58}	Vol _{sampLast58} x COD _{sampLast58} x 10 ⁻³		0.3	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4		0.3	0.4	0.4	0.4	0.3	0.4
MCOD _{rem_Last58}	Vol _{remLast58} x COD _{remLast58} x 10 ⁻³		12.1	11.7	3.9	9.2	13.1	12.5	4.1	9.8	12.9	12.5	4.0	9.7	11.8		12.1	9.7	10.9	11.3	3.9	8.7
MCOD _{CH4}	Vol _{CH4} x COD _{CH4} x 10 ⁻³		0.9	1.1	0.9	1.0	3.79	3.95	1.23	3.0	4.0	4.1	1.3	3.1	2.2	2.0	1.1	1.8	1.8	1.1	1.0	1.3
%Error - Day 14	(COD _{out} /COD _{in})*100	%	97	90	97	94	91	97	89	93	116	114	110	114	112	131	106	112	110	105	114	109
%Error - Day 40	(COD _{out} /COD _{in})*100		90	88	97	91	76	81	81	20	78	81	73	78	84	35	70	80	80	81	98	81
%Error - Day 58	(COD _{out} /COD _{in})*100		73	74	79	74	69	71	67	69	67	66	62	65	70	35	64	72	68	67	76	69

Note: Reactor SVG4D leaked during experiment, therefore MB on Day 40 and 58 could not be calculated. The “D” next to T-SVG1 to T-SVG5 (e.g. T-SVG1D) represents “duplicate”, and the “T” next to T-SVG1 to T-SVG5 (e.g. T-SVG1T) represents “triplicate”.

4.4.3. AugBMP test TSS, VSS and ISS concentrations

4.4.3.1. *Starting TSS, VSS and ISS concentrations*

The calculated versus measured TSS, VSS, and ISS concentrations for the control and five SVGs are presented in **Figure 4.8**. Similar to the COD calculated points, the starting TSS, VSS, and ISS concentrations of the inoculum were obtained by taking fresh inoculum TSS, VSS, and ISS concentrations, respectively, and applying the necessary dilutions (similar dilutions as applied for the COD presented in **Table 3.9** of **Section 3.5.5**). In contrast, the calculated TSS, VSS, and ISS masses of the five SVGs were obtained by mixing the substrate TSS, VSS, and ISS mass (plus water for dilution) with the specified mass of the inoculum TSS, VSS, and ISS prepared for the control. The total mass of the mixture was then divided by the volume of the reactor content to obtain the respective starting concentration. Similarly, the measured TSS, VSS, and ISS concentrations were obtained by testing the prepared starting mixtures of both the control and five SVG test samples.

As shown in **Figure 4.8**, while the majority of the % errors, between the measured and calculated concentrations of TSS, VSS, and ISS of the control and five SVGs, are well within 10%, some approximate 20%. The % errors above 10% between the measured and calculated TSS, VSS, and ISS could be related to (i) the weighing machine error, and (ii) the fact that merely three points, per settling velocity group and control, were used to calculate this % error (the total number of crucibles required for the AugBMP TSS test was $(1 \times 4 \text{ control reactors}) + (1 \times 3 \times 5 \text{ SVG}) = 19$ crucibles). Performing the TSS test would then require $19 \times 2 = 38$ crucibles, which were unavailable in the WQL. The conclusion in the statement made in (i), above, is based on the fact that the measured and calculated particulate COD values show a % error that is not high (below 10%) (**Figure 4.5**) in comparison with the VSS (**Figure 4.8**). Similarly, the conclusion in the statement made in (ii), above, is based on the fact that the values are not significantly different from each other as shown by the average concentration values between the calculated and measured TSS, VSS, and ISS in **Figure 4.8**.

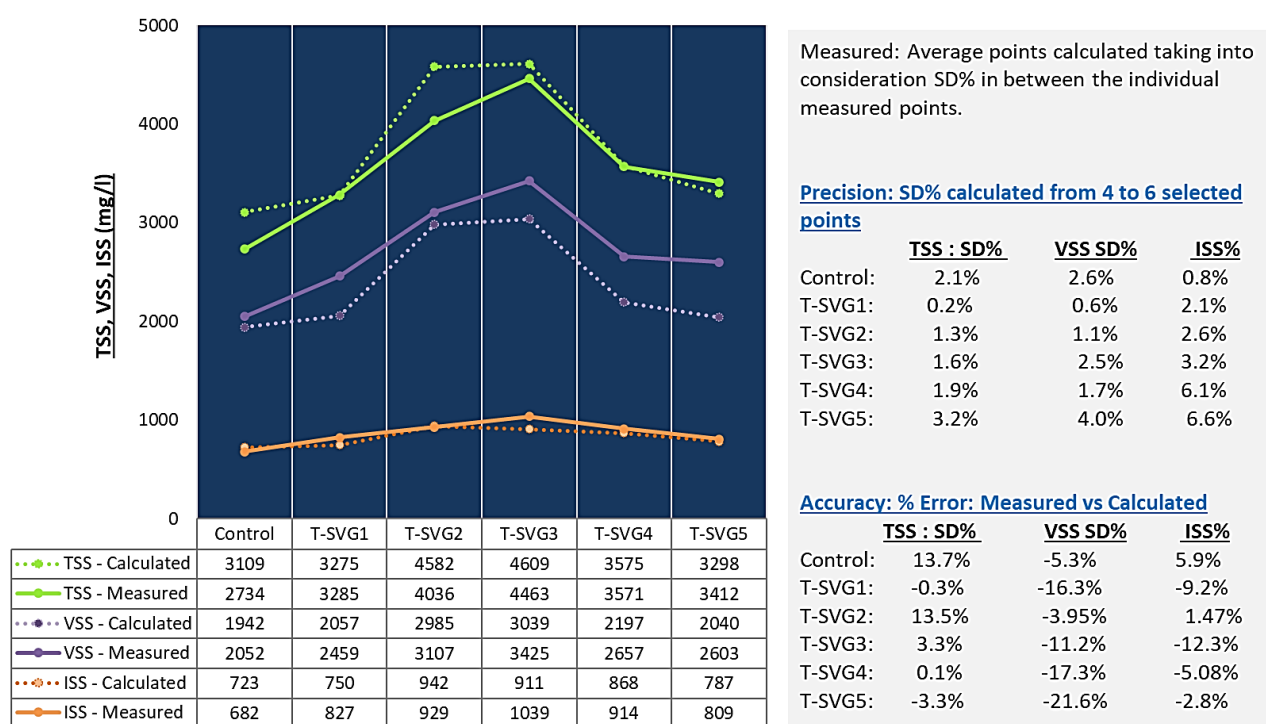


Figure 4.8: The measured versus calculated starting TSS, VSS, and ISS concentrations. The precision and accuracy in the form of SD% and % error, respectively, are shown on the right-hand side (grey shaded area).

4.4.3.2. Ending TSS, VSS, and ISS concentrations

Figure 4.9 and **Figure 4.10** present the average TSS and VSS concentration decrease, from Day 0 to Day 58, for the control and five SVGs. The VSS concentration on Day 58 is considered to be that of the unbiodegradable particulate VSS (UPOVSS). The difference between Day 0 and Day 58 VSS is considered to be that of the biodegradable particulate VSS (BPOVSS). The TSS and VSS percentage removals are presented in **Figure 4.9** and **Figure 4.10**, respectively. Similar to the COD concentrations, the TSS, VSS, and ISS concentrations, as presented in **Figure 4.9**, **Figure 4.10**, and **Figure 4.11**, respectively, did not take into consideration the dilutions. The lowest TSS and VSS removals of 15.6% and 20.5%, respectively, were observed on the control samples (removal from Day 0 to Day 58). The higher VSS removals were observed in the SVG2 (35.6%) and SVG3 (41.6%). This corresponds with the higher COD removal as presented in **Section 4.4.2.2** above. It was expected that the ISS concentration would remain constant throughout the experimentation. As illustrated in **Figure 4.11**, majority of the ISS concentrations remained in a reasonably constant range despite the “outliers”.

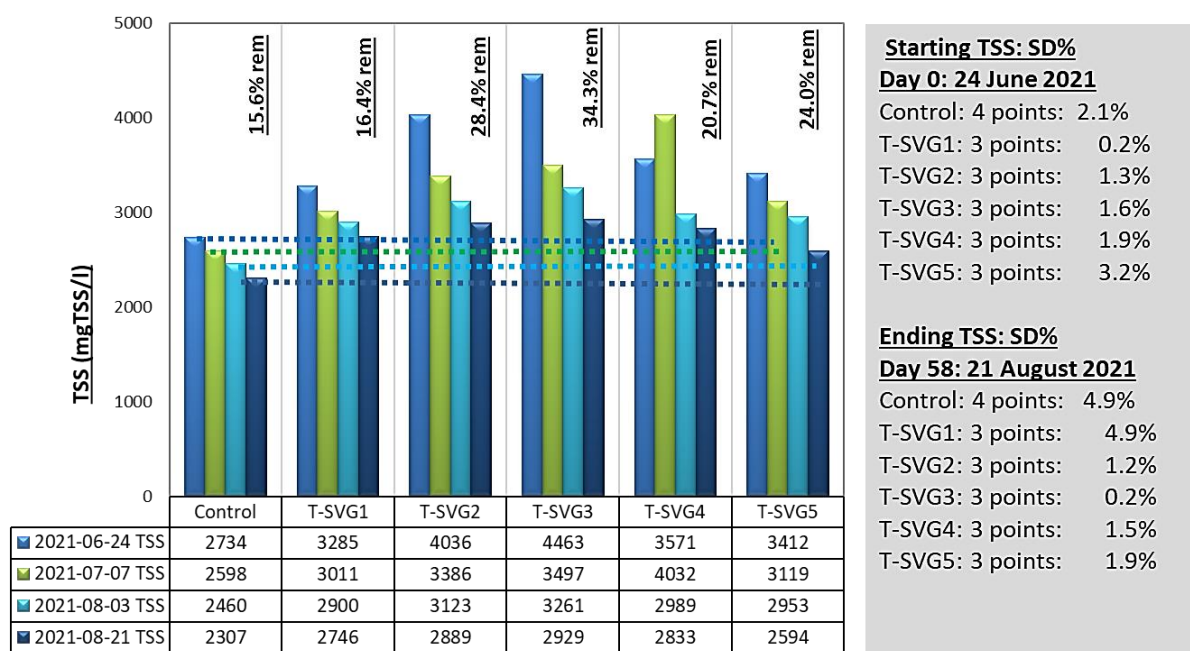


Figure 4.9: The starting and ending TSS concentrations. The SD%, as indicated on the right-hand side (grey block), is only for the starting and ending TSS concentrations. The SD% was obtained from the indicated number of the selected points. The average concentrations, as presented on the graph, were obtained from points that gave lower SD%. The percentage TSS removal (%rem) from the start to end concentrations is also indicated for the control and five SVG groups.

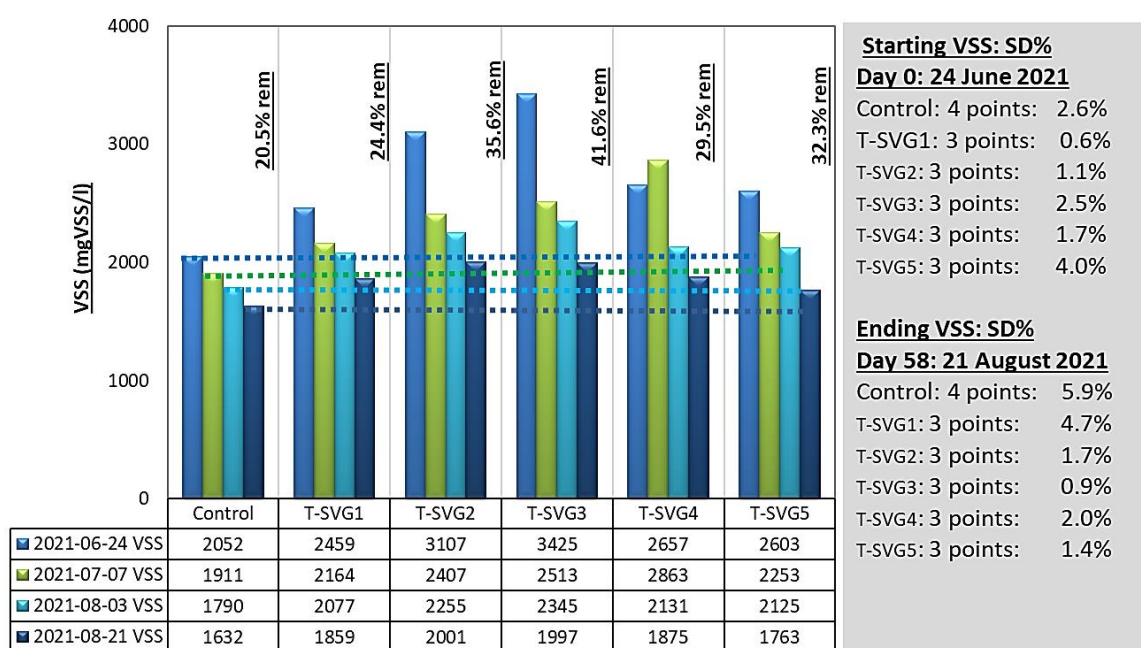


Figure 4.10: The starting and ending VSS concentrations. The SD%, as indicated on the right-hand side (grey block), is only for the starting and ending VSS concentrations. The percentage VSS removal (%rem) from the start to end concentrations is also indicated for the control and five SVG groups.

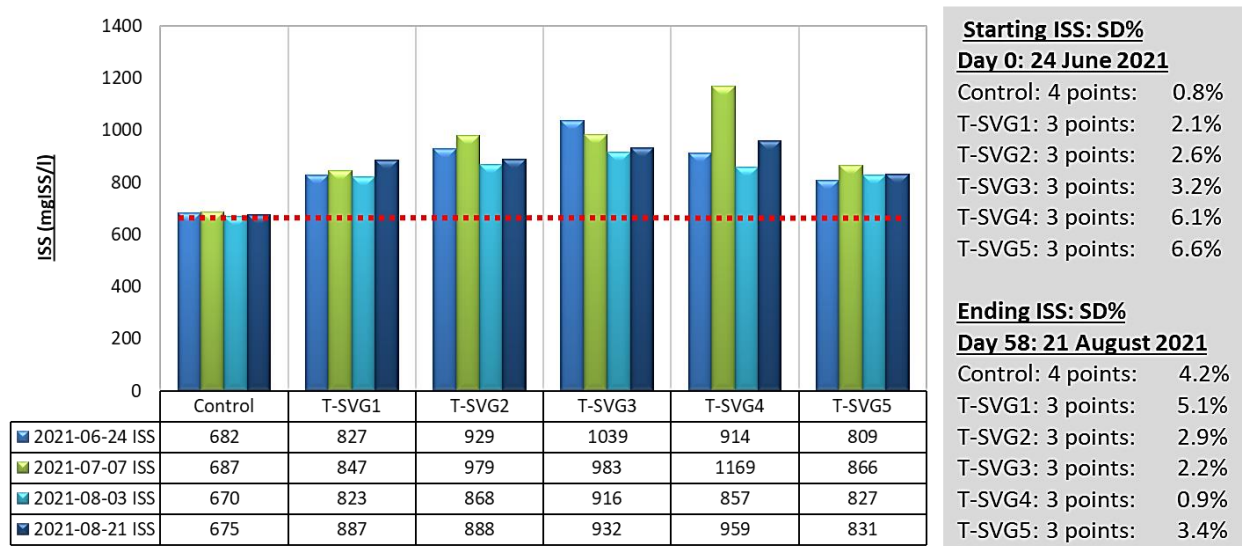


Figure 4.11: The starting and ending ISS concentrations. The SD%, as indicated on the right-hand side (grey block), is only for the starting and ending ISS concentrations.

4.4.4. AugBMP test pH, VFA and alkalinity

Figure 4.12 presents the starting and ending pH, EC, and alkalinity contents for the control and five SVG test reactors. As illustrated in the figure, the starting pH levels between 7.3–7.7 were recorded. These starting pH levels appear to be marginally higher than those observed on the main PAD system ranging between 6.8–7.2 (see **Section 3.2.5**). The high pH levels could be due to the loss of CO₂ during sample preparation when the inoculum was exposed to the atmosphere (see **Section 3.5.5** for the sampling and seeding procedures). The anaerobic digester pH levels are governed by the gaseous CO₂ partial pressure (P_{CO_2}) and HCO₃⁻ (**Equation (4.1)**) (Sötemann *et al.*, 2005a:523). As illustrated in **Figure 4.12**, from Day 1 to Day 14, a consistent drop in pH levels, to a desirable range between 6.8–7.2, was observed for all the reactors. This could be related to the release of CO₂ during the degradation of the hydrolysable organics (see **Equation (3.40)**). From Day 14 to Day 58, a gradual increase in the pH levels was observed. The gradual increase in the pH levels could imply that, by Day 14, the hydrolysable organics may have been depleted (i.e., only the biomass remained), therefore, the rate at which the CO₂ was lost (captured on the AugBMP inverted columns) was greater than the rate at which the CO₂ was released from the degradation of the biomass. As observed on the inverted column gas readings, in **Appendix B**, the dissolution of the CO₂ into the liquids was observed on the inverted columns, from approximately Day 14, for most of the reactors. The increase in the alkalinity levels was observed for all the reactors (control and SVG test reactors). The lowest alkalinity increase (112%) was observed for the control, while the highest increase was observed in the SVG3 test reactors (152%) (**Table 4.4**). There is a notable relationship between the recorded biodegradable components and alkalinity generated.

The electrical conductivity (EC) recorded also marginally increased from Day 0 to Day 58. The increase in the EC may have been exhibited by the dissociation of the degradable species during the AD, which increases the electric field strength. Similarly, the control reactors gave the lowest EC percentage increase (117%) in comparison with the SVG test reactors. This could be related to less matter being available for dissociation in the control reactors in comparison with the SVG test reactors. The HWT Water Treatment (2013) stated that the accumulation of inorganic substances (including ammonia) can increase the EC of a liquor. As compiled in **Table 4.6**, more FSA release was observed in the SVG test reactors than in the control. The relationship between the FSA release and change in the EC is a possible reason for the greater EC increase in the SVG test reactors than in the control.

$$p_{CO2} = \frac{[HCO_3^-](1 + 10^{pK'_{c1}-pH} + 10^{pH-pK'_{c2}})}{10^{-pK'_{HCO2}}(1 + 10^{pH-pK'_{c1}} + 10^{2pH-pK'_{c1}-pK'_{c2}})} \quad (4.1)$$

Where:

$[HCO_3^-]$ = Bicarbonate concentration $\sim H_2CO_3^*$

p_{CO2} = Partial pressure of carbon dioxide in the gas phase

pH = Negative $\log_{10}$ of the (H^+) activity

pK'_{HCO2} = Negative $\log_{10}$ of the apparent Henry's law constant for carbon dioxide

pK'_{c1}, pK'_{c2} = Negative $\log_{10}$ of first and second carbonate system apparent dissociation constants

Table 4.4: The EC and alkalinity percentage increase from Day 0 to Day 58 for the control and five SVGs

	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
Electrical conductivity	117.4	127.9	120.5	127.6	122.5	126.5
Alkalinity	111.7	127.9	127.8	151.5	113.6	115.3

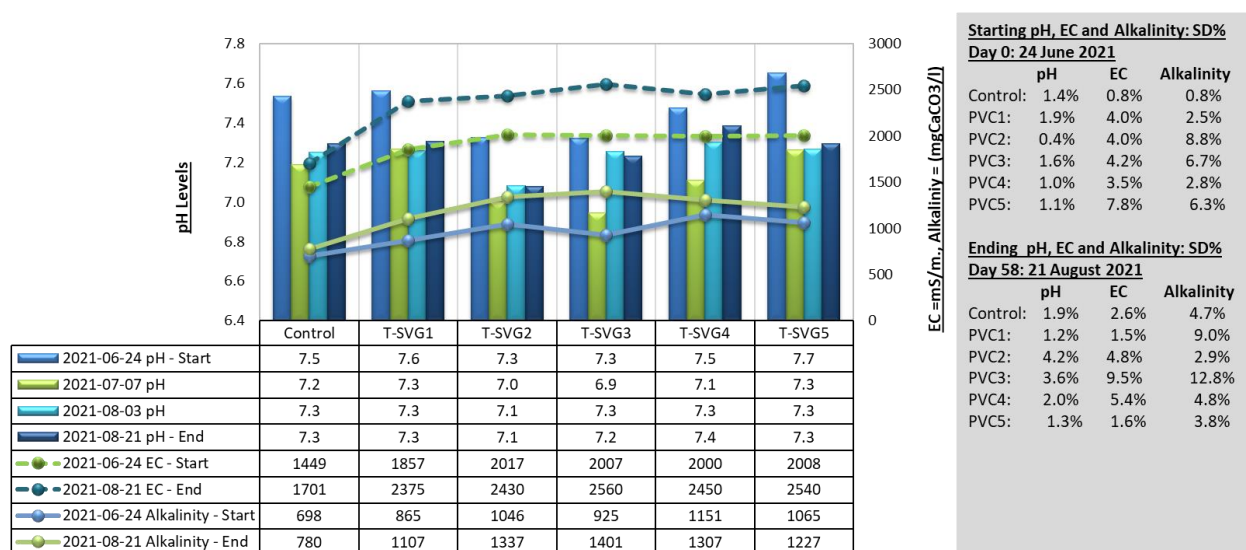


Figure 4.12: The starting and ending pH, EC, and alkalinity concentrations. The SD%, as indicated on the right-hand side (grey block), is only for the starting and ending pH, EC, and alkalinity concentrations. The exact pH, EC, and alkalinity values are shown on the table just below the graph.

4.4.5. AugBMP test FSA and TKN concentrations

4.4.5.1. Overview

The FSA and TKN concentrations were measured during the AugBMP experiment. The measurements of TKN and FSA components are particularly essential to determining the elemental composition for this study. As discussed in **Section 3.6.9**, the ΔFSA represents the N released during the degradation of the hydrolysable BPOs. Although the release of the FSA can also include the N from the BSOs (N_{obsi}), especially for the test reactors, which contains the PSS substrate, the fractions of the N_{obsi} relative to the N_{ti} ($f_{N'_{\text{obsi}}}$) in the raw and settled WW, have been reported to be significantly low, approximately 0.029 and 0.034, respectively (Wentzel & Ekama, 2006: 3.41). These fractions further decrease for the PSS. This is given that the N_{obsi} is in a dissolved form, and therefore it is not affected by the primary settling; thus, the N_{obsi} concentrations remain the same for the PSS, raw WW, and settled WW, with the $f_{N'_{\text{obsi}}}$ being governed by the respective N_{ti} concentrations (Wentzel & Ekama, 2006: 3.40). For this reason, the N-bound in the BSO and BPO will be lumped for simplification, thereby accepting that the ΔFSA is due to the BPO hydrolysis. It is important to note that the control reactor comprising the inoculum from the PAD system would rarely contain the N_{obsi} given that, at neutral pH levels, the released N in the form of NH_3 ($\text{N}_2 + 3\text{H}_2 = 2\text{NH}_3$) would react with the dissolved CO_2 to form saline ammonia ($2\text{NH}_3 + \text{H}_2\text{CO}_3 = \text{NH}_4^+ + \text{HCO}_3^-$).

The same fundamentals, as applied to the N-bound in the BPOs, apply to the N-bound in the UPOs (N_{oupi}). Essentially, the N-bound in the USO and UPO will be lumped for simplification. The South African WW $N_{\text{ousi}}/N_{\text{ti}}$ fractions for the raw WW and settled WW were reported to range between 0.00–0.04 and 0.00–0.05, respectively (Wentzel & Ekama, 2006: 3.16). These fractions further decrease for the PSS. These fractions are too low and may not cause significant difference when lumped with $f_{N'_{\text{oup}}}$. Thus, for the purpose of the present study, it is accepted that the unfiltered TKN minus the FSA on Day 58 equals the N_{oupi} . Further supporting statement to this is made by Wentzel and Ekama (2006 : 3.41) who suggested that the $f_{N'_{\text{ous}}}$ and $f_{N'_{\text{obs}}}$ fractions are associated with the $f_{S'_{\text{us}}}$ and $f_{S'_{\text{bs}}}$ COD fractions. As shown in **Table 4.5**, the $f_{S'_{\text{us}}}$ and $f_{S'_{\text{bs}}}$ for the SVGs are relatively low compared with the raw WW and settled WW. This indicates that the $f_{N'_{\text{ous}}}$ and $f_{N'_{\text{obs}}}$ for the test reactors are expected to be lower than the recorded $f_{N'_{\text{ous}}}$ and $f_{N'_{\text{obs}}}$ for the raw WW and settled WW. The below subsections describe the FSA and TKN content release during the AugBMP test. This discussion will help distinguish between the biodegradable and the unbiodegradable N in the segregated settleable matter.

Table 4.5: The relationship between the $f_{N'ous}$, $f_{N'obs}$, $f_{P'ous}$, $f_{P'obs}$, $f_{S'us}$ and $f_{S'bs}$

Testing day	Component	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5	Raw	Settled
Day 0	Total COD	3872	5178	5741	4493	4122		
Day 58	Total COD	2525	2730	2771	2611	2432		
Day 0 (Susi + Sbsi)	Filtered COD	228	310	382	326	267		
Day 58 (Susi)	Filtered COD	71	72	74	63	72		
	Sbsi = Day 0 (Susi + Sbsi) - Day 58 (Susi)	157	238	308	263	195		
	$f_{S'us}$	0.018	0.014	0.013	0.014	0.017	0.04 - 0.10	0.05 - 0.20
	$f_{S'bs}$	0.041	0.046	0.054	0.059	0.047	0.08 - 0.25	0.10 - 0.35
	$f_{N'ousi}$						0.00 - 0.04	0.00 - 0.05
	$f_{P'ousi}$						0.00 - 0.03	0.00 - 0.04
	$f_{N'obsi}$						0.029	0.034
	$f_{P'obsi}$						0.00 - 0.03	0.00 - 0.04

4.4.5.2. Starting and ending FSA and TKN concentrations

Figure 4.13 presents the changes in unfiltered TKN and FSA concentrations from Day 0 to Day 58 for the control and five SVG reactors. Theoretically, the TKN concentrations are expected to remain the same throughout the experiment given that, although there is a release of N into the bulk liquid during the anaerobic degradation of the biodegradable components (with a significantly small fraction conserved in the biomass), none of the N is lost as gas. As shown in **Figure 4.13** and **Table 4.6A**, between 126–135% FSA average increases were observed from the reactors. As shown in **Table 4.6**, although the higher percentage increase (133%) was recorded for the control, in comparison with some of the test reactors, the actual concentration released was lower for the control reactors (27 mgN/l), as compared with the test reactors (31–35mgN/l). The FSA released into the bulk liquid represents the N bound in the biodegradable organics. As illustrated in **Table 4.6**, the control reactors yielded the lowest FSA (27 mgN/l) release, while the SVG2 (45 mgN/l) and SVG3 (44 mgN/l) yielded greater releases. These releases correspond with the COD and VSS removals as presented in **Section 4.4.2.2** and **Section 4.4.3.2** above. The corresponding N_{oupi} and N_{obpi} are also presented in **Table 4.6**. Similarly, the observed control concentrations are lower than those of the test reactors. As shown in **Figure 4.13**, although few points yielded a standard deviation beyond 10%, the majority of reactors (both control and test reactors) achieved a SD% less than 10%.

Table 4.6: The unfiltered TKN, FSA, N_{obpi} and N_{oupi} concentrations from Day 0 to Day 58

Component	Source	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
Unfiltered. TKN	AugBMP test (Day 0 & Day 58 average)	238	287	364	355	316	320
FSA released (mgN/l)	$FSA_{AugBMP, DAY, 58} - FSA_{AugBMP, DAY, 0}$	27	33	45	44	31	35
% FSA Increase	$FSA_{AugBMP, DAY, 58} / FSA_{AugBMP, DAY, 0} \times 100\%$	133	127	135	133	123	126
BPO N (N_{obpi}) (mgN/l)	Assumed equal to FSA released	27	33	45	44	31	35
UPO N (N_{oupi}) (mgN/l)	Unfiltered TKN – $FSA_{AugBMP, DAY, 58}$ (Nousi lumped with Noup, see discussion in Section 4.4.5.1 above)	128	132	191	176	151	153

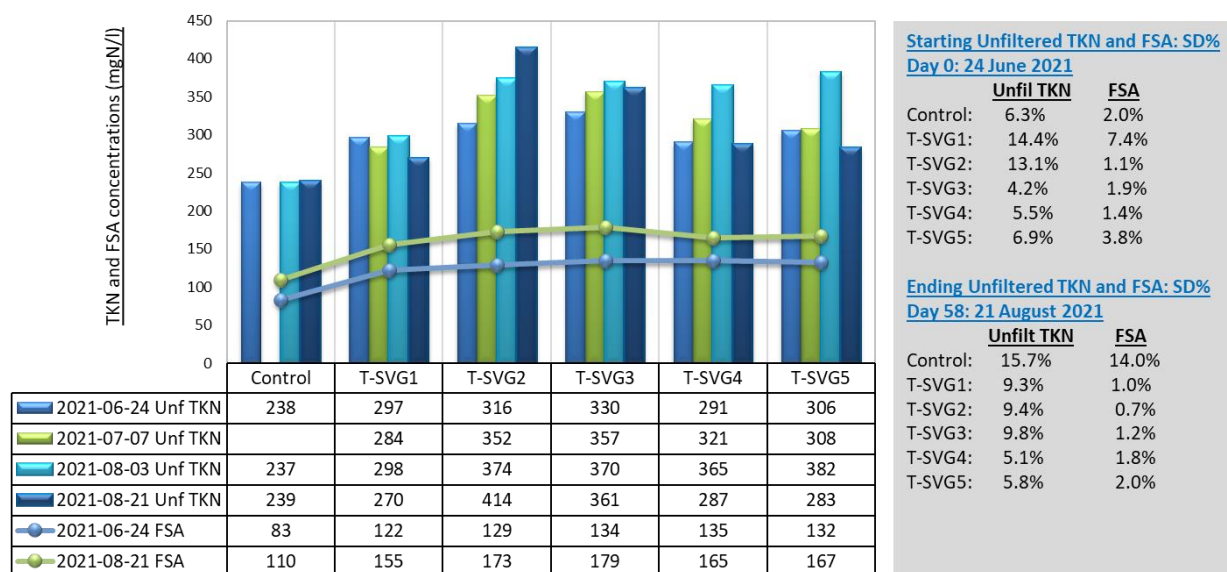


Figure 4.13: The starting and ending unfiltered TKN and FSA concentrations. The SD% as indicated on the right-hand side (grey block), is only for the starting and ending TKN and FSA concentrations. The exact TKN and FSA concentration values are shown in the table below the graph.

4.4.5.3. TKN Mass balance

Table 4.7 and **Table 4.8** present the Nitrogen MB around each of the control and test batch reactors. The steps taken to complete this MB are described in **Section 3.5.9.2.2**. While few instances indicated a MB outside the range of 80–120%, the majority of the MB points were found to be well within the 80–120% range for both the control and test reactors.

Table 4.7: The Nitrogen balance for the four control reactors

Nitrogen balance: $N_{inf} \times Vol_{inf,Liq} = (N_{rem} \times Vol_{rem,Liq}) + \text{Sum of } (N_{samp} \times Vol_{samp,Liq})_{\text{sampledFromDay,1 to DayLast}}$							
Symbol	Formular or source	Units	Control 1	Control 2	Control 3	Control 4	Average
N_{inf}	Direct measurement	mgN/l	249	242	230	231	237.8
N_{samp1}	Direct measurement	mgN/l	249	242	230	231	237.8
N_{rem1}	Direct measurement	mgN/l	249	242	230	231	237.8
N_{samp4}	Direct measurement	mgN/l	249	242	230	231	237.8
N_{rem4}	Direct measurement	mgN/l	249	242	230	231	237.8
$N_{samp14\&16}$	Direct measurement	mgN/l	270	288	249	249	263.7
$N_{rem14\&16}$	Direct measurement	mgN/l	270	288	249	249	263.7
N_{samp40}	Direct measurement	mgN/l	259	301	314	307	295.1
N_{rem40}	Direct measurement	mgN/l	259	301	314	307	295.1
$N_{sampLast58}$	Direct measurement	mgN/l	256	312	273	315	288.8
$N_{remLast58}$	Direct measurement	mgN/l	256	312	273	315	288.8
MN_{inf}	$Vol_{inf} \times N_{inf} \times 10^{-3}$	gN	1.25	1.21	0.46	0.46	0.83
MN_{samp1}	$Vol_{samp1} \times N_{samp1} \times 10^{-3}$	gN	0.03	0.02	0.02	0.02	0.83
MN_{rem1}	$Vol_{rem1} \times N_{rem1} \times 10^{-3}$	gN	1.22	1.18	0.44	0.44	0.83
MN_{samp4}	$Vol_{samp4} \times N_{samp4} \times 10^{-3}$	gN	0.02	0.03	0.02	0.02	0.83
MN_{rem4}	$Vol_{rem4} \times N_{rem4} \times 10^{-3}$	gN	1.20	1.15	0.42	0.42	0.83
$MN_{samp14\&16}$	$Vol_{samp14\&16} \times N_{samp14\&16} \times 10^{-3}$	gN	0.05	0.06	0.05	0.04	0.92
$MN_{rem14\&16}$	$Vol_{rem14\&16} \times N_{rem14\&16} \times 10^{-3}$	gN	1.25	1.32	0.41	0.41	0.92
MN_{samp40}	$Vol_{samp40} \times N_{samp40} \times 10^{-3}$	gN	0.02	0.03	0.02	0.02	1.03
MN_{rem40}	$Vol_{rem40} \times N_{rem40} \times 10^{-3}$	gN	1.18	1.35	0.49	0.49	1.03
$MN_{remLast}$	$Vol_{remLast} \times N_{remLast} \times 10^{-3}$	gN	0.04	0.04	0.04	0.04	1.01
$MN_{sampLast}$	$Vol_{sampLast} \times N_{sampLast} \times 10^{-3}$	gN	1.10	1.33	0.36	0.42	1.01
%Error - Day 14	$(N_{out} / N_{in}) \times 100$	%	107.8	118.3	107.5	107.2	110.2
%Error - Day 40	$(N_{out} / N_{in}) \times 100$	%	103.9	123.3	130.7	127.9	121.5
%Error - Day Last_58	$(N_{out} / N_{in}) \times 100$	%	100.4	124.9	110.1	121.4	114.2

Note: The volumes (Vol) used to calculate the masses are the same as those used in **Table 4.2**.

Table 4.8: The *nitrogen balance for the SVG1 to SVG5 triplicate AugBMP batch reactors. The Nitrogen balance for the SVG1 to SVG5 triplicate AugBMP batch reactors.*

Nitrogen balance: $N_{inf} \times Vol_{inf,Liq} = (N_{rem} \times Vol_{rem,Liq}) + \text{Sum of } (N_{samp} \times Vol_{samp,Liq})_{\text{sampledFromDay,1 to DayLast}}$																						
Symbol	Formular or source	Units	T- SVG1	T- SVG1D	T- SVG1T	Ave	T- SVG2	T- SVG2D	T- SVG2T	Ave	T- SVG3	T- SVG3D	T- SVG3T	Ave	T- SVG4	T- SVG4T	T- SVG4D	Ave	T- SVG5	T- SVG5D	T- SVG5T	Ave
N_{inf}	Direct measurement	mgN/l	297	277	307	294	279	330	337	316	337	330	324	330	301	280		291	296	327	294	306
N_{samp1}	Direct measurement	mgN/l	297	277	307	294	279	330	337	316	337	330	324	330	301	280		291	296	327	294	306
N_{rem1}	Direct measurement	mgN/l	297	277	307	294	279	330	337	316	337	330	324	330	301	280		291	296	327	294	306
$N_{samp14\&16}$	Direct measurement	mgN/l	291	271	291	284	318	375	365	352	364	378	329	357	316	333		324	322	296	312	310
$N_{rem14\&16}$	Direct measurement	mgN/l	291	271	291	284	318	375	365	352	364	378	329	357	316	333		324	322	296	312	310
N_{samp40}	Direct measurement	mgN/l	298	297	300	298	370	335	336	347	398	305	351	351	384	357		370	349	412	318	359
N_{rem40}	Direct measurement	mgN/l	298	297	300	298	370	335	336	347	398	305	351	351	384	357		370	349	412	318	359
$N_{sampLast58}$	Direct measurement	mgN/l	252	287	270	270	389	361	375	375	326	375	319	340	243	240		242	331	194	273	266
$N_{remLast58}$	Direct measurement	mgN/l	252	287	270	270	389	361	375	375	326	375	319	340	243	240		242	331	194	273	266
MN_{inf}	$Vol_{inf} \times N_{inf} \times 10^{-3}$	gN	1.48	1.39	0.61	1.18	1.40	1.65	0.67	1.24	1.68	1.65	0.65	1.33	1.51	1.40	LEAKED	1.5	1.48	1.63	0.59	1.22
MN_{samp1}	$Vol_{samp1} \times N_{samp1} \times 10^{-3}$	gN	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03		0.0	0.03	0.03	0.02	0.03
MN_{rem1}	$Vol_{rem1} \times N_{rem1} \times 10^{-3}$	gN	1.46	1.33	0.55	1.13	1.37	1.62	0.64	1.21	1.65	1.59	0.59	1.28	1.48	1.37		1.4	1.46	1.61	0.56	1.20
$MN_{samp14\&16}$	$Vol_{samp14\&16} \times N_{samp14\&16} \times 10^{-3}$	gN	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.03	0.04	0.03	0.03		0.0	0.03	0.03	0.03	0.03
$MN_{rem14\&16}$	$Vol_{rem14\&16} \times N_{rem14\&16} \times 10^{-3}$	gN	1.40	1.27	0.49	1.06	1.53	1.80	0.66	1.33	1.75	1.77	0.57	1.36	1.52	1.60		1.6	1.55	1.43	0.57	1.18
MN_{samp40}	$Vol_{samp40} \times N_{samp40} \times 10^{-3}$	gN	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03		0.0	0.03	0.03	0.03	0.03
MN_{rem40}	$Vol_{rem40} \times N_{rem40} \times 10^{-3}$	gN	1.44	1.40	0.52	1.12	1.75	1.58	0.58	1.31	1.88	1.40	0.57	1.28	1.82	1.69		1.8	1.65	1.95	0.55	1.34
$MN_{remLast}$	$Vol_{remLast} \times N_{remLast} \times 10^{-3}$	gN	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.05	0.04	0.06	0.05	0.05	0.03	0.03		0.0	0.05	0.03	0.04	0.04
$MN_{sampLast}$	$Vol_{sampLast} \times N_{sampLast} \times 10^{-3}$	gN	1.19	1.32	0.43	0.98	1.79	1.66	0.59	1.35	1.49	1.66	0.47	1.21	1.12	1.10		1.1	1.52	0.89	0.43	0.96
%Error - Day 14	$(N_{out} / N_{in}) * 100$	%	97.9	95.6	89.5	95.0	113.6	113.1	107.9	112.3	107.8	111.7	96.7	107.6	104.8	118.4		111.6	108.6	90.7	105.9	101.4
%Error - Day 40	$(N_{out} / N_{in}) * 100$	%	102.3	106.7	97.4	102.1	131.4	101.5	100.2	112.5	117.5	91.0	102.6	104.1	126.6	126.8		126.7	117.3	124.8	107.7	116.8
%Error - Day Last_58	$(N_{out} / N_{in}) * 100$	%	87.2	103.4	89.0	92.9	137.9	108.9	110.1	120.0	97.3	110.3	94.3	102.2	82.4	87.2		84.8	111.5	61.8	94.5	88.3

Note: The volumes (Vol) used to calculate masses are the same as those used in **Table 4.3**.

4.4.6. AugBMP test OP and TP concentrations

4.4.6.1. Starting and ending OP and TP concentrations

Figure 4.14 presents the changes in unfiltered TP and OP concentrations from Day 0 to Day 58 for both the control and five SVG test reactors. Similar to the TKN, the unfiltered TP was expected to remain constant throughout the experiment given that the organically bound P is released to the bulk liquid as OP and lost as gas. As shown in **Figure 4.14**, the gradual decrease (about 14–28% decreases) in the TP was recorded from Day 14 to Day 58. The decrease was observed in both the control and test reactors. The main cause of this decrease is unknown. As expected, the OP showed an increase in concentration from Day 0 to Day 58. Approximately 186–241% OP increases were observed for both the control and test reactors (see **Table 4.9**). The overall OP concentration for the control was significantly low, starting from 5 mgP/l on Day 0 and rising to merely 11 mgP/l on the last day. A maximum of 8 mgP/l, which subsequently increased to 16 mgP/l, was observed in the SVG3 test reactors. As shown in **Figure 4.14**, a satisfactory standard deviation of less than 10% was achieved for nearly all of the reactors.

The principles applied to N for the determination of N_{oupi} and N_{obpi} above are applied to P for the determination of P_{oupi} and P_{obpi} . The OP released into the bulk liquid represents the P-bound in the hydrolysable organics, i.e., P_{obpi} . The P-bound in the unbiodegradable organics (P_{oupi}) was determined by subtracting the total OP, at Day 58, from the unfiltered TP. As illustrated in **Table 4.9B**, the control reactors yielded the lowest OP release (6.6 mgP/l), while the SVG1 (7.0 mgP/l), SVG2 (6.8 mgP/l), and SVG3 (7.9 mgP/l) yielded greater release. The overall P release from both the control and test reactors was generally low (6.6–7.9 mgP/l OP release). As shown in **Figure 4.14**, although few points gave a standard deviation beyond 10%, the majority of reactors (both control and test reactors) achieved a SD% less than 10% for both the OP and TP measurements.

Table 4.9: The unfiltered TP, OP, P_{obpi} and P_{oupi} concentrations from Day 0 to Day 58

Component	Source/Formula	Control	SVG1	SVG2	SVG3	SVG4	SVG5
Unfiltered TP (mgP/l)	AugBMP test (Day 0 & Day 58 average)	53	56	64	65	60	58
OP released (mgN/l)	$OP_{AugBMP, DAY, 58} - OP_{AugBMP, DAY, 0}$	6.0	6.3	8.9	9.4	6.0	7.6
% OP Increase	$OP_{AugBMP, DAY, 58} / OP_{AugBMP, DAY, 0} \times 100\%$	200	184	192	212	159	207
BPO P (P_{obpi}) (mgP/l)	Assumed equal to OP released	6.0	6.3	8.9	9.4	6.0	7.6
UPO P (P_{oupi}) (mgP/l)	Unfiltered TP – $OP_{AugBMP, DAY, 58}$ (P_{ousi} lumped with P_{oupi})	41	44	49	49	47	45

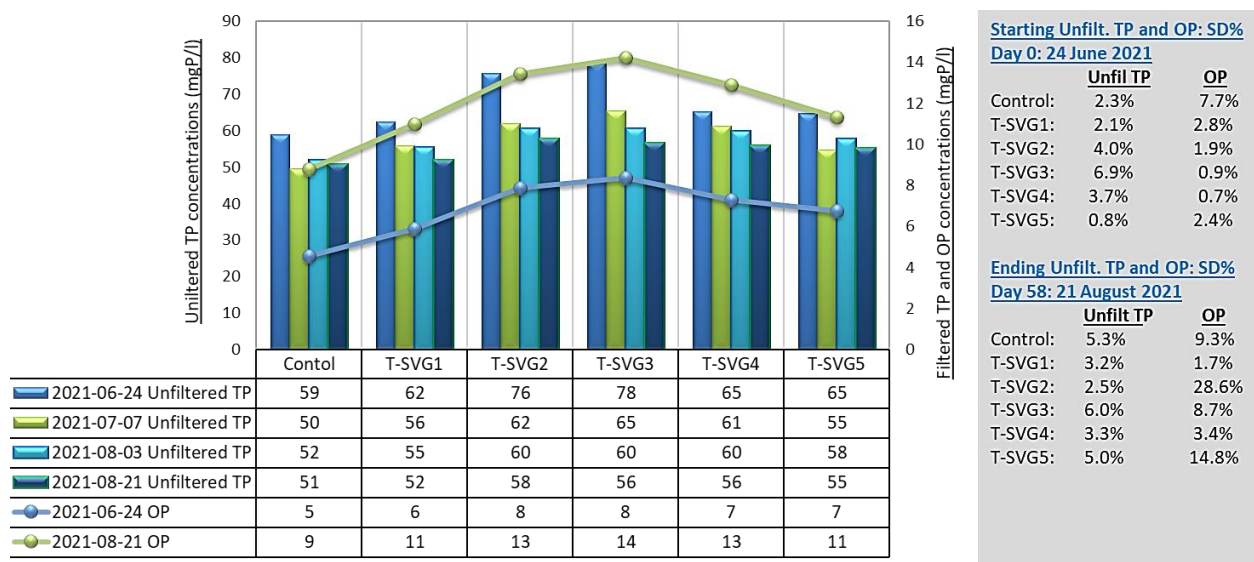


Figure 4.14: The starting and ending unfiltered TP and OP concentrations. The SD%, as indicated on the right-hand side (grey block), is only for the starting and ending unfiltered TP and OP concentrations. The exact TP and OP concentrations are shown in the table below the graph.

4.4.6.2. P mass balance

Table 4.10 and **Table 4.11** present the material MB around each of the control and test batch reactors. The steps taken to complete this MB are described in **Section 3.5.9.2.3**. The MB for the control reactors, as presented in **Table 4.10**, was found to be well within 80–120%, except for an outlier of 75.7%. For the SVG test reactors, although the majority of the MBs were within 80–120%, a continuous decrease in the MB, from Day 14 to Day 58 (last day) for the majority of the reactors, was observed. As mentioned in **Section 4.4.6.1**, the reasons behind this decrease in P are unknown.

Table 4.10: The TP mass balance for the four control reactors

P Balance: $P_{inf} \times Vol_{Inf,Liq} = (P_{rem} \times Vol_{rem,Liq}) + \text{Sum of } (P_{smp} \times Vol_{smp,Liq})_{\text{sampledFromDay,1 to DayLast}}$							
Symbol	Formular or source	Units	Control 1	Control 2	Control 3	Control 4	Ave
P_{inf}	Direct measurement	mgTP-P/l	58	60	57	60	58.9
P_{smp1}	Direct measurement	mgTP-P/l	58	60	57	60	58.9
P_{rem1}	Direct measurement	mgTP-P/l	58	60	57	60	58.9
P_{smp4}	Direct measurement	mgTP-P/l	58	60	57	60	58.9
P_{rem4}	Direct measurement	mgTP-P/l	58	60	57	60	58.9
$P_{smp14\&16}$	Direct measurement	mgTP-P/l	55	50	45	48	49.5
$P_{rem14\&16}$	Direct measurement	mgTP-P/l	55	50	45	48	49.5
P_{smp40}	Direct measurement	mgTP-P/l	54	55	51	48	51.8
P_{rem40}	Direct measurement	mgTP-P/l	54	55	51	48	51.8
$P_{smpLast58}$	Direct measurement	mgTP-P/l	52	49	54	48	50.6
$P_{remLast58}$	Direct measurement	mgTP-P/l	52	49	54	48	50.6
MP_{inf}	$Vol_{inf} \times P_{inf} \times 10^{-3}$	gP	0.29	0.30	0.11	0.12	0.21
MP_{smp1}	$Vol_{smp1} \times P_{smp1} \times 10^{-3}$	gP	0.01	0.01	0.01	0.00	0.01
MP_{rem1}	$Vol_{rem1} \times P_{rem1} \times 10^{-3}$	gP	0.28	0.29	0.11	0.12	0.20
MP_{smp4}	$Vol_{smp4} \times P_{rem1} \times 10^{-3}$	gP	0.00	0.01	0.00	0.00	0.01
MP_{rem4}	$Vol_{rem4} \times P_{rem4} \times 10^{-3}$	gP	0.28	0.29	0.10	0.11	0.20
$MP_{smp14\&16}$	$Vol_{smp14\&16} \times P_{smp14\&16} \times 10^{-3}$	gP	0.01	0.01	0.01	0.01	0.00
$MP_{rem14\&16}$	$Vol_{rem14\&16} \times P_{rem14\&16} \times 10^{-3}$	gP	0.25	0.23	0.07	0.08	0.00
MP_{smp40}	$Vol_{smp40} \times P_{smp40} \times 10^{-3}$	gP	0.00	0.01	0.00	0.00	0.00
MP_{rem40}	$Vol_{rem40} \times P_{rem40} \times 10^{-3}$	gP	0.24	0.25	0.08	0.08	0.16
$MP_{remLast}$	$Vol_{remLast} \times P_{remLast} \times 10^{-3}$	gP	0.01	0.01	0.01	0.01	0.01
$MP_{smpLast}$	$Vol_{smpLast} \times P_{smpLast} \times 10^{-3}$	gP	0.23	0.21	0.07	0.06	0.14
%Error - Day 14	$(P_{out}/P_{in}) \times 100$	%	94.5	84.4	80.7	81.5	85.3
%Error - Day 40	$(P_{out}/P_{in}) \times 100$	%	92.7	92.2	88.5	80.7	88.6
%Error - Day Last_58	$(P_{out}/P_{in}) \times 100$	%	88.4	81.2	87.1	75.7	83.1

Note: The volumes (Vol) used to calculate masses are the same as those used in **Table 4.2**.

Table 4.11: The TP balance for the SVG1 to SVG5 triplicate AugBMP batch reactors

Phosphorus balance: $P_{inf} \times Vol_{Inf,Liq} = (P_{rem} \times Vol_{rem,Liq}) + \text{Sum of } (P_{smp} \times Vol_{smp,Liq})_{\text{sampledFromDay,1 to DayLast}}$																							
Symbol	Formular or source	Units	T- SVG1	T- SVG1D	T- SVG1T	Ave	T- SVG2	T- SVG2D	T- SVG2T	Ave	T- SVG3	T- SVG3D	T- SVG3T	Ave	T- SVG4	T- SVG4T	T- SVG4D	Ave	T- SVG5	T- SVG5D	T- SVG5T	Ave	
P _{inf}	Direct measurement	mgTP-P/l	64	63	61	62	77	72	77	76	81	82	72	78	68	64	LEAKAGE	66	65	64	65	65	
P _{samp1}	Direct measurement	mgTP-P/l	64	63	61	62	77	72	77	76	81	82	72	78	68	64		66	65	64	65	65	
P _{rem1}	Direct measurement	mgTP-P/l	64	63	61	62	77	72	77	76	81	82	72	78	68	64		66	65	64	65	65	
P _{samp14&16}	Direct measurement	mgTP-P/l	50	58	60	56	64	61	61	62	65	65	66	65	64	59		61	53	59	53	55	
P _{rem14&16}	Direct measurement	mgTP-P/l	50	58	60	56	64	61	61	62	65	65	66	65	64	59		61	53	59	53	55	
P _{samp40}	Direct measurement	mgTP-P/l	57	55	54	55	61	59	61	60	64	61	56	60	59	56		58	61	56	56	58	
P _{rem40}	Direct measurement	mgTP-P/l	57	55	54	55	61	59	61	60	64	61	56	60	59	56		58	61	56	56	58	
P _{sampLast58}	Direct measurement	mgTP-P/l	51	51	54	52	57	57	59	58	57	60	53	56	57	56		57	58	55	52	55	
P _{remLast58}	Direct measurement	mgTP-P/l	51	51	54	52	57	57	59	58	57	60	53	56	57	56		57	58	55	52	55	
MP _{inf}	Vol _{inf} x P _{inf} x 10 ⁻³	gP	0.32	0.31	0.12	0.25	0.39	0.36	0.15	0.30	0.41	0.41	0.14	0.31	0.34	0.32	LEAKAGE	0.33	0.32	0.32	0.13	0.26	
MP _{samp1}	Volsamp1 x P _{samp1} x 10 ⁻³	gP	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01	
MP _{rem1}	Volrem1 x P _{rem1} x 10 ⁻³	gP	0.31	0.30	0.11	0.24	0.38	0.35	0.15	0.30	0.40	0.39	0.13	0.30	0.33	0.31		0.32	0.32	0.32	0.13	0.25	
MP _{samp14&16}	Volsamp14&16 x P _{samp14&16} x 10 ⁻³	gP	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01		0.01	0.00	0.01	0.01	0.01	
MP _{rem14&16}	Volrem14&16 x P _{rem14&16} x 10 ⁻³	gP	0.24	0.27	0.10	0.21	0.31	0.29	0.11	0.24	0.31	0.31	0.11	0.24	0.31	0.28		0.29	0.25	0.28	0.10	0.21	
MP _{samp40}	Volsamp40 x P _{samp40} x 10 ⁻³	gP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00		0.00	0.00	0.00	0.00	0.00	
MP _{rem40}	Volrem40 x P _{rem40} x 10 ⁻³	gP	0.28	0.26	0.09	0.21	0.29	0.28	0.11	0.23	0.30	0.28	0.09	0.22	0.28	0.27		0.27	0.29	0.26	0.10	0.22	
MP _{remLast}	VolremLast x P _{remLast} x 10 ⁻³	gP	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01	
MP _{sampLast}	VolsampLast x P _{sampLast} x 10 ⁻³	gP	0.24	0.24	0.09	0.19	0.26	0.26	0.09	0.21	0.26	0.26	0.08	0.20	0.26	0.26		0.26	0.26	0.27	0.25	0.08	0.20
%Error - Day 14	(P _{out} /P _{in})*100	%	79.8	90.5	92.1	88.2	83.1	84.8	79.5	82.2	79.9	78.6	87.5	82.3	94.1	92.3	LEAKAGE	93.2	82.2	91.3	81.8	85.0	
%Error - Day 40	(P _{out} /P _{in})*100	%	91.4	88.7	89.5	89.8	79.2	81.9	80.3	80.4	79.4	73.7	75.5	76.4	87.0	88.9		87.9	94.4	87.2	86.6	89.4	
%Error - Day Last_58	(P _{out} /P _{in})*100	%	81.6	82.8	89.3	84.6	74.4	79.0	77.9	76.9	71.0	71.8	72.0	71.8	85.1	88.7		86.9	89.9	86.1	81.5	85.7	

Note: The volumes (Vol) used are the same as those used in **Table 4.3**.

4.5. BPO, UPO, and ISS characterisation

4.5.1. Overview

This section characterizes the five SVG particulate TSS contents into their BPO, UPO, and ISS components. This characterization was derived from the AugBMP results (**Section 4.4**) and PE processes (**Section 3.7.2**). Before characterizing the five SVGs, the inoculum characterization into BPO, UPO, and ISS will be made to simplify the process of subtracting the inoculum components from the test reactors. After characterizing the inoculum, the substrate will be characterized in terms of BPO, UPO, and ISS settling proportions and their related elemental composition.

4.5.2. Comparison of modelled versus experimental results

Section 4.5.3 below details the characteristics of the inoculum used as seed during the AugBMP experiment. **Table 4.12** and **Table 4.13** show comparisons between the experimentally measured and PE modelled effluent concentrations. The starting concentrations used in the PE modelling were accepted to equal the experimentally measured starting concentrations. As evident from **Table 4.12** to **Table 4.13**, the COD and VSS effluent targets were reached while squared errors were observed for the effluent FSA, OP, alkalinity, and Carbon (C). The higher TSS %error, as presented in **Table 4.12**, is due to the experimental errors in the ISS concentration (the ISS is expected remain constant throughout the experiment). In the PE, the COD and VSS were given more weight relative to the FSA, OP, alkalinity, and C (see **Table 3.12**). As a result, the biodegradable COD and VSS governed the release of FSA, OP, and alkalinity. While the squared error for the FSA and OP was found to be less than 200, the squared error for the effluent C and alkalinity was found to vary in the range 12–90 816. The considerably high difference between the experimental and the PE modelled C could be linked to (i) the high level of errors associated with the gas measurement (see **Section 4.4.2.4**), and to some extent (ii) the adjustments made by the model assuming that the experimentally measured influent and effluent COD and VSS concentration are correct.. The effect of (ii), above, is that the effluent C, FSA, OP, and alkalinity were adjusted accordingly to satisfy the influent and effluent COD and VSS. **Appendix E** and **F** provide the detailed PE modelled outcomes for the control and test reactors. It is important to note that the data in **Table 4.12** and **Table 4.13** did not take into consideration the dilution factors to cater for dilutions made during the seeding process, and so are the data in **Appendices E** and **F**. All the necessary dilutions are done stepwise in **Table 4.17** of **Section 4.5.4**.

Table 4.12: The COD, VSS, ISS, TSS, FSA and OP AugBMP test modelled versus experimental ending concentrations

	COD	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
CHEMICAL OXYGEN DEMAND (COD)	Total COD Start - Experimental	3283	3872	5178	5741	4493	4122
	Total COD End - Experimental	2208	2525	2730	2771	2611	2432
	Total COD End - Modelled	2208	2525	2730	2771	2611	2432
	ΔTotal COD - Experimental	-1075	-1347	-2448	-2970	-1882	-1690
	ΔTotal COD - Modelled	-1075	-1347	-2448	-2970	-1882	-1690
	(Experimental - Modelled)/Experimental) x 100	0	0	0	0	0	0
	Filtered COD Start - Experimental	158	228	382	310	326	267
	Filtered COD End - Experimental	53	71	74	72	63	72
	Filtered COD End - Modelled	53	71	74	72	63	72
	ΔFiltered COD - Experimental	-105	-157	-308	-238	-263	-195
	Δ Filtered COD - Modelled	-105	-157	-308	-238	-263	-195
	% Error	0	0	0	0	0	0
	Particulate COD Start - Experimental	3125	3644	4796	5431	4166	3855
	Particulate COD End - Experimental	2155	2454	2656	2700	2548	2360
	Particulate COD End - Modelled	2155	2454	2656	2700	2548	2360
	Δ Particulate COD - Experimental	-971	-1190	-2140	-2732	-1619	-1494
	Δ Particulate COD - Modelled	-971	-1190	-2140	-2732	-1619	-1494
	% Error	0	0	0	0	0	0
	VSS and ISS	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
VSS, ISS AND TSS	VSS Start - Experimental	2052	2459	3107	3425	2657	2603
	VSS End - Experimental	1632	1859	2001	1997	1875	1763
	VSS End - Modelled	1631	1859	2001	2000	1875	1763
	ΔVSS - Experimental	-420	-599	-1106	-1427	-782	-840
	ΔVSS - Modelled	-421	-599	-1106	-1425	-782	-840
	% Error	0	0	0	7	0	0
	ISS Start - Experimental	682	827	929	1039	914	809
	ISS End - Experimental	675	887	888	932	959	831
	ISS End - Modelled	682	827	929	1039	914	809
	ΔISS - Experimental	-7	60	-41	-107	45	22
	ΔISS - Modelled	0	0	0	0	0	0
	% Error	42	3600	1653	11377	1995	490
	TSS Start - Experimental	2734	3285	4036	4463	3571	3412
	TSS End - Experimental	2307	2746	2889	2929	2833	2594
	TSS End - Modelled	2313	2686	2930	3039	2789	2572
	ΔTSS - Experimental	-427	-539	-1147	-1534	-737	-818
	ΔTSS - Modelled	-421	-599	-1106	-1425	-782	-840
	% Error	42	3600	1653	11377	1995	490
	FSA & OP	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
FSA AND OP	FSA Start - Experimental	83	122	129	134	135	132
	FSA End - Experimental	110	155	173	179	165	167
	FSA End - Modelled	111	158	183	191	177	174
	ΔFSA - Experimental	27	33	45	44	31	35
	ΔFSA - Modelled	29	36	54	57	42	42
	% Error	3	9	92	165	135	52
	OP Start - Experimental	5	6	8	8	7	7
	OP End - Experimental	11	13	15	16	14	13
	OP End - Modelled	12	12	14	20	17	16
	Δ OP - Experimental	7	7	7	8	7	7
	Δ OP - Modelled	7	6	6	12	10	9
	% Error	0	0	1	15	11	8

Table 4.13: The pH, alkalinity, and carbon AugBMP test modelled versus experimental ending concentrations

	Ph, Alkalinity, & Carbon	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
pH	pH Start - Experimental	7.5	7.6	7.3	7.3	7.5	7.7
	pH End - Experimental	7.3	7.3	7.1	7.2	7.4	7.3
	pH End - Modelled	7.3	7.3	7.1	7.2	7.4	7.3
	Δ pH - Experimental	0	0	0	0	0	0
	Δ pH - Modelled	0	0	0	0	0	0
	% Error	0	0	0	0	0	0
ALKALINITY	Alkalinity Start - Experimental	698	865	1046	925	1151	1065
	Alkalinity End - Experimental	780	1107	1337	1401	1307	1227
	Alkalinity End - Modelled	783	978	1226	1099	1275	1190
	Δ Alkalinity - Experimental	81	242	291	476	156	162
	Δ Alkalinity - Modelled	85	113	180	175	125	126
	% Error	12	16714	12385	90816	997	1357
CARBON	Carbon Start - Experimental	-	-	-	-	-	-
	Carbon End - Experimental	99	147	321	388	0	77
	Carbon End - Modelled	200	251	444	535	324	325
	Δ Carbon - Experimental	99	147	321	388	0	77
	Δ Carbon - Modelled	200	251	444	535	324	325
	% Error	10094	10822	15284	21505	104796	61516

4.5.3. Parent anaerobic digestion effluent characterization (Inoculum)

The characterization of the inoculum was necessary for the present study for the following reasons:

- To obtain details of the biomass (Z_{AD}) and PAD residual BPO concentrations used to inoculate the AugBMP BRs: As discussed in **Section 3.7**, the Z_{AD} required to be known to accurately model both the control and test reactors. As mentioned in **Section 3.9.2**, given that the Z_{AD} ($0.089 = 8.9\%$) and Z_{AM} ($0.024 = 2.4\%$) organism groups were found to have (i) greater yield coefficients (Y), (ii) significant impact on the effluent COD organics, and (iii) significant impact on the gas production (Sötemann *et al.*, 2005a: 512), the PAD system total biomass (which will be denoted as Z_{AD}) was accepted to have a total yield of 11.3% (i.e., from 8.9% plus 2.4%) denoted as Y_{AD} . The hydrolysable BPO from the PAD was taken as the difference between the PAD PSS influent and effluent and multiplying this difference by a dilution factor of 0.8 (i.e., from 400/500) (see **Section 3.2.3**). The endogenous respiration rate (b_{AD}) and biomass unbiodegradable fraction (f_{AD}) were allocated the literature values of 0.014/d and 0.08, respectively (Sötemann *et al.*, 2005a; Ikumi *et al.*, 2014). The system R_s (which equals the R_{hm} for the completely mixed system) was calculated, from the sludge mass harvested daily, to be 36 days.
- To simplify the process of subtracting the inoculum masses from the test reactors, thereby leaving merely the substrate concentrations.

The PSS FBSOs (S_{bsi}) and BPOs (S_{bpi}) concentrations of 1.208 and 30.109 gCOD/l, respectively, were fed into the PAD system described in **Section 3.2** to generate the inoculum. The UPOs and USOs of 7.542 gCOD/l and 0.186 gCOD/l, respectively, together with the ISS of 2.387 gISS/l were part of the components making up the PSS substrate fed into the PAD system. Although the UPOs may undergo degradation at a significantly slow rate, it is accepted in the present study that the UPOs, USOs, and ISS components do not undergo any biological degradation and these components flow through the system at in and out concentrations that are essentially the same.

Feeding the PAD system with a total COD concentration of 39.045 gCOD/l, comprising 30.109 gCOD/l BPOs and 1.208 gCOD/l FBSO (in addition to the UPOs and USOs), and accepting that the S_{bpe} , acidogen biomass yield (Y_{AD}), endogenous respiration rate (b_{AD}), and biomass unbiodegradable fraction (f_{AD}) are 1.146 gCOD/l, 0.113 gCOD biomass/ gCOD organics, 0.041 /d, and 0.2, respectively, the BPO hydrolysed at a R_s of 36 days was calculated to be 30.098 gCOD/l (**Table 4.14**). The BPO hydrolysed was assumed to be equal to the sum of the BPO and FBSO, i.e., 30.098 gCOD/l ($S_{bpe} = 1.146$ gCOD/l) for simplification given that the FBSO merely accounts for 3.86% (i.e., from $1.208 / 31.317 \times 100$) of the total biodegradable matter.

As shown in **Table 4.15**, the total Z_{AD} formed and used as an inoculum is 1.468 gCOD/l. The ratio of the BPO hydrolysed and conserved as biomass (E) was calculated to be 0.0545 (5.45%) gBiomassGenerated/gCODutilized. The digestion of 31.317 gCOD/l BPOs resulted in 28.529 gCOD/l methane (CH_4) production in a dissolved form, which is equivalent to the methane gas (Q_m) production of 10.718 l CH_4 /l $infl$. The CH_4 produced represents 94.6% of the total BPOs, while the balance of 5.45% is converted into biomass. As confirmed in **Table 4.15**, the MB is achieved over the system (i.e., from $18L \times [39.045 \text{ g/l}] = 18 \times [30.098 + 7.542 + 1.468 + 0.17 [Z_{ED}] + 0.186 + 1.146 = 39.045 \text{ gCOD}]$).

Table 4.14: The PSS and PAD effluent characteristics

Primary Sludge Characteristics - PAD Substrate			
S_{ti}	PSS total Inf COD: PAD Feed or Substrate measured using OFM method (see Table 3.10)	39045	mgCOD/l
S_{tsi}	PSS total filtered COD (see Table 3.10)	1395	mgCOD/l
S_{pi}	$S_{ti} - S_{tsi}$	37650	mgCOD/l
S_{upi}	(i) Particulate COD: Control _{Day58} (See Figure 4.6) x 3.5 (Dilution factor, see Section 3.5.5) (ii) Accept Z_{AD} at Day 58 is zero	7542	mgCOD/l
S_{bpi}	S_{pi} - Particulate COD for Control at Day58	30109	mgCOD/l
S_{usi}	Soluble COD: Control _{Day58} (See figure) x 3.5 (Dilution factor, see Section 3.5.5)	186	mgCOD/l
S_{bsi}	$S_{tsi} - S_{usi}$	1208	mgCOD/l
VSS	TSS test on PSS	16096	mgVSS/l
UPO VSS	VSS: Control _{Day58} (See figure) x 3.5 (Dilution factor, see Section 3.5.5) (ii) Accept Z_{AD} at Day 58 is zero	5710	mgVSS/l
BPO VSS	VSS - UPO VSS	10386	mgVSS/l
PAD Effluent Substrate			
PAD S_{upi}	Similar to PSS S_{upi}	7542	mgCOD/l
PAD S_{te}	Effluent Total COD from PAD	8947	mgCOD/l
PAD S_{tse}	Effluent Filtered COD from PAD	259	mgCOD/l
PAD S_{pe}	Effluent Particulate COD from PAD: $S_{te} - S_{tse}$	8688	mgCOD/l
PAD S_{bpe}	PAD $S_{pe} - S_{upi}$	1146	mgCOD/l
VSS	VSS: Control _{Day0} (See figure) x 3.5 (Dilution factor, see Section 3.5.5)	7182	mgVSS/l
UPO VSS	Similar to PSS UPO VSS	5710	mgVSS/l
BPO VSS	VSS - UPO VSS	1472	mgVSS/l
ISS	PAD ISS Influent (Control ISS Day ₁ x 3.5)	2387	mgVSS/l
S_{bpe} Hydrolysed in PAD	$S_{ti} - \text{PAD } S_{te}$	30098	mgCOD/l
S_{bpe} Hydrolysed in AugBMP test Control	PAD $S_{pe} - \text{PAD } S_{upi}$	1146	mgCOD/l

Table 4.15: The percentage BPO conserved in the biomass of the PAD system, control, and five SVG masses

	Formula or Source (AD Steady state equations by Sötemann <i>et al.</i> (2005a: 511–528))	Units	PAD	PAD	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5
Y_{AD}	$gCOD_{biomass}/gCOD_{organics}$	Given	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113
b_{AD}	Literature (see Section 4.5.3)	/d	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
f_{AD}	Literature (see Section 4.5.3)	-	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
R_h	Literature (see Section 4.5.3)	d	36	94	58	58	58	58	58	58
S_{bpe}	$K_s \times (b_{AD} + 1/R_h) / [(Y_{AD} \times K_m - (b_{AD} + (1/R_h))]$	gCOD/l	1.146	1.146	0.00	0.00	0.00	0.00	0.00	0.00
	$S_{bpe} \times \text{Dilution factor}$	gCOD/l	0.3276	0.3276	0.00	0.00	0.00	0.00	0.00	0.00
	$S_{bpe} \times \text{Reactor volume}$	gCOD	1.64	1.64	0.00	0.00	0.00	0.00	0.00	0.00
S_{bpe} Hydrolysed in PAD	$S_{ti} - PAD S_{te}$	gCOD/l	30.098	30.098	0.328	1.190	2.210	2.495	1.619	0.500
Z_{AD}	$Y_{AD} \times (S_{bpi} - S_{bpe}) / [1 + b_{AD} \times R_h \{1 - Y_{AD} \times (1 - f_{AD})\}]$	gCOD/l	1.468	0.766	0.012	0.043	0.080	0.090	0.058	0.018
	$Z_{AD} \times \text{Dilution factor}$	gCOD/l	0.42	0.22		0.01	0.02	0.03	0.02	0.01
	$Z_{AD} \times \text{Reactor volume}$	gCOD	2.10	1.09	0.00	0.06	0.11	0.13	0.08	0.03
Z_{ED}	$f_{AD} \times b_{AD} \times Z_{AD} \times R_h$	gCOD/l	0.17	0.24	0.002	0.008	0.015	0.017	0.011	0.003
	$Z_{ED} \times \text{Dilution factor}$	gCOD/l	0.05	0.07						
	$Z_{ED} \times \text{Reactor volume}$	gCOD	0.25	0.34	0.01	0.04	0.08	0.09	0.06	0.02
			0.71	0.71	0.02	0.03	0.04	0.04	0.03	0.02
r_h	$\{K_m \times S_{bpe} / (K_s + S_{bpe})\} \times Z_{AD}$	gCOD/l.d	0.893	0.000	0.006	0.022	0.041	0.046	0.030	0.009
r_h	$(Z_{AD}/Y_{AD}) \times [(1/R) + b_{AD}]$	gCOD/l.d	0.893	0.350	0.006	0.022	0.041	0.046	0.030	0.009
S_m (If dissolved)	$(1 - Y_{AD}) \times r_h \times R_s$	gCOD/l	28.529	29.169	0.313	1.139	2.115	2.388	1.549	0.479
R	Gas constant	l.kPa/K.mol	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314
T_{std}	Standard Temp	K	293	293	293	293	293	293	293	293
P_{std}	Standard Press	kPa	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32
Specific Gas Vol of CH_4 @20		(l/mol) _{gas}	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
CH_4 specific COD		gCOD/mol CH_4	64	64	64	64	64	64	64	64
Methane gas production	$(S_m \times \text{SpecVol}) / CH_4 \text{ COD}$	l CH_4 /l $infl$	10.718	10.958	0.118	0.428	0.795	0.897	0.582	0.180
S_{te}	$S_{upi} + Z_{AD} + Z_{ED} + S_{bpe} + S_{usi}$	gCOD/l	11	10	2.98	2.58	2.82	2.88	2.68	2.45
S_{out}	$S_{te} + S_m$	gCOD/l	39	39	3.29	4.18	5.41	5.73	4.70	3.40
COD Balance	$(COD_{in} / COD_{out}) \times 100$	%	100.00	100.00	99.77	92.55	95.73	97.20	95.62	121.19
E	$(Z_{AD} + Z_{ED}) / (S_{bpi} - S_{bpe})$	gBiomGen/gCODutilized	0.05	0.03	0.04	0.04	0.04	0.04	0.04	0.04
	Conserved in Biomass	%	5.45	3.33	4.30	4.30	4.30	4.30	4.30	4.30

Note: As illustrated on the table, there is no difference between % biomass conserved in the control and the five SVG masses even though the BPO hydrolysed is different. This is because the biomass conserved is largely dependent on the SRT. Therefore, having the same SRT of 58 days for both the control and the five SVGs implies that the % conserved will be the same across the reactors. The PS BPO hydrolysed, methane production, biomass (Z_{AD}) concentrations formed, and MB is also presented.

4.5.4. Five settling velocity groups substrate characterization into UPO, BPO, and ISS

Table 4.16 shows comparisons between the parameter estimated and experimental BPO, UPO, and ISS. While one would expect the experimental and PE modelled UPOCOD, UPOVSS, BPOCOD, and BPOVSS to be the same since, as shown in **Table 4.12**, the experimental effluent targets (COD and VSS) were achieved during modelling, this is not the case in **Table 4.16**. The BPOs from the PE appeared to be marginally higher than the experimentally measured, whereas the UPOs was found to be marginally lower than the experimentally measured. The following are possible reasons to support the differences:

- a. The experimental BPO was taken as the difference between the start and end concentrations (see **Section 3.7.3**), whereas the SS AD model took into consideration the BPO conserved in the biomass.
- b. The experimental UPO was taken as the concentration measured on the last day of AugBMP. As described in **Sections 3.9.3** and **3.7.3**, the concentrations measured on the last day may include some residual active biomass, which can be mistaken for UPO. The SS AD model takes into consideration the slow death of biomass, thus decreasing the UPO from the PE in comparison with the experimental value.
- c. The experimental concentration of the ISS was taken as the average of the start and end concentrations given that the ISS is expected to remain constant throughout the experiment. The model, however, assumed that the starting ISS equals the end ISS.

While it is possible to characterize the five SVG substrates into UPO, BPO, and ISS, using the experimental data (see **Section 3.7.3**), the possibility of errors associated with (i) the experimental measurements, and (ii) the erroneous mass balance carry over (due to experimental measurements inaccuracies) make the modelled data preferable. **Table 4.17** shows the substrate UPO, BPO, and ISS results obtained from the PE processes. As described in **Section 3.7.2**, the control and test reactor masses were modelled using the same method so that the substrate concentrations can be taken as the difference between the modelled seed (or inoculum) and test reactor concentrations. After subtracting the inoculum masses (or concentrations), the dilution factors were applied to get the exact final substrate concentrations. The substrate outcomes are presented in **Table 4.17** below. The table also presents the mass ratios, which are discussed in greater detail in **Section 4.5.5**.

Table 4.16: The comparisons between the BPO, UPO, and ISS concentrations for the control and five SVG groups

A: BPO CONCENTRATIONS												
	Control		T-SVG1		T-SVG2		T-SVG3		T-SVG4		T-SVG5	
	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.
COD (mgCOD/l)	971	1007	1190	1235	2210	2293	2495	2761	1619	1680	1494	1551
Carbon (mgC/l)	99	200	147	251	321	444	388	535	203	324	166	325
OrgN (mgN/l)	9	27	29	33	47	45	43	44	16	31	22	35
OrgP (mgP/l)	6	7	6	7	9	7	9	8	6	7	8	7
VSS (mgVSS/l)	420	436	599	619	1106	1142	1427	1468	782	809	840	865
B: UPO CONCENTRATIONS												
	Control		T-SVG1		T-SVG2		T-SVG3		T-SVG4		T-SVG5	
	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.
COD (mgCOD/l)	2155	1699	2454	1989	2658	2155	2698	2178	2548	2067	2360	1885
Carbon (mgC/l)	750	591	854	692	925	750	939	758	887	719	821	656
OrgN (mgN/l)	90	128	101	132	134	191	104	176	121	151	126	153
OrgP (mgP/l)	47	41	49	44	57	49	61	49	49	47	50	45
VSS (mgVSS/l)	1632	1434	1859	1658	2001	1783	1997	1774	1875	1666	1763	1556
C: ISS CONCENTRATIONS												
	Control		T-SVG1		T-SVG2		T-SVG3		T-SVG4		T-SVG5	
	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.
ISS (mgISS/l)	679	682	857	827	908	929	985	1039	936	914	820	809

Note: See **Appendix E** and **F** for the detailed PE modelled results. The “Exp” represents experimental data and “Mod” represent PE modelled data.

Table 4.17: The PE modelled control and five SVGs concentrations and mass fractions calculations. A: These outcomes were derived from PE modelling processes. Subscript “DnC” implies concentrations where dilutions are not considered, B: SVG substrate concentrations after subtracting inoculum concentrations, C: Dilution factors applied to SVG substrate concentrations, and D: Resulting mass fractions.

			INOCULUM			SVG1			SVG2			SVG3			SVG4			SVG5		
A: AUGBMP RAW OUTCOMES DERIVED FROM PE AND STEADY STATE AD MODEL - DILUTION FACTORS NOT CONSIDERED																				
Sample Formular or Source OR Measurement		Units	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic
COD _{DnC}	UPO and BPO COD obtained via PE	mgCOD/l	1699	1007	-	1989	1235	-	2155	2293	-	2178	2761	-	2067	1680	-	1885	1551	-
VSS _{DnC}	UPO VSS & BPO VSS obtained via PE	mgVSS/l	1434	436	-	1658	619	-	1783	1142	-	1774	1468	-	1666	809	-	1556	865	-
TSS _{DnC}	UPO TSS & BPO TSS = UPO VSS & BPO VSS	mgTSS/l	1434	436	-	1658	619	-	1783	1142	-	1774	1468	-	1666	809	-	1556	865	-
ISS _{DnC}	See Table 3.9 for ISS measurement	mgISS/l	-	-	682	-	-	827	-	-	929	-	-	1039	-	-	914	-	-	809
TKN _{DnC}	See Table 3.9 for TKN (Nti), UPO (Nousi) & BPO N (Nobpi)	mgN/l	127	29	83	129	36	122	181	54	129	163	57	134	139	42	135	145	42	132
TOC _{DnC}	C obtained from PE. See Section 3.8.2.iv	mgC/l	591	200	-	692	251	-	750	444	-	758	535	-	719	324	-	656	325	-
TP _{DnC}	See Table 3.9 for TP (Pti), UPO (Pousi) & BPO P (Pobpi)	mgP/l	41	7	5	44	6	6	50	6	8	45	12	8	43	10	7	42	9	7
OrgN _{DnC}	See Table 3.9 for total organic N, Noupai and Nobpi	mgN/l	127	29	-	129	36	-	181	54	-	163	57	-	139	42	-	145	42	-
OrgP _{DnC}	See Table 3.9 for total organic P, Poupi and Pobpi	mgP/l	41	7	-	44	6	-	50	6	-	45	12	-	43	10	-	42	9	-
Z _{AD}	See Section 4.4.2			419			419			419			419			419			419	
B: SETTLING VELOCITY GROUP 1 TO 5 SUBSTRATE CONCENTRATIONS (Inoculum concentrations removed) - DILUTION FACTORS NOT CONSIDERED																				
Substrate COD _{DnC}	COD from SVGn subtract COD from inoculum	mgCOD/l				291	227	-	456	1286	-	479	1754	-	369	672	-	186	544	-
Substrate VSS _{DnC}	VSS from SVGn subtract VSS from inoculum	mgVSS/l				224	182	-	349	706	-	341	1032	-	232	372	-	123	428	-
Substrate TSS _{DnC}	TSS from SVGn subtract TSS from inoculum	mgTSS/l				224	182	-	349	706	-	341	1032	-	232	372	-	123	428	-
Substrate ISS _{DnC}	ISS from SVGn subtract ISS from inoculum	mgISS/l				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Substrate TKN _{DnC}	TKN from SVGn subtract TKN from inoculum	mgN/l				3	7	39.3	54	25	46.1	36	28	51.7	13	13	51.9	19	13	49.8
Substrate TOC _{DnC}	TOC from SVGn subtract TOC from inoculum	mgC/l				-	52	-	-	245	-	-	335	-	-	124	-	-	125	-
Substrate TP _{DnC}	TP from SVGn subtract TP from inoculum	mgP/l				3	-1	1.31	9	-1	3.32	4	5	3.78	2	3	2.73	1	2	2.16
Substrate OrgN _{DnC}	OrgN from SVGn subtract OrgN from inoculum	mgN/l				3	7	-	54	25	-	36	28	-	13	13	-	19	13	-
Substrate OrgP _{DnC}	OrgP from SVGn subtract OrgP from inoculum	mgP/l				3	-1	-	9	-1	-	4	5	-	2	3	-	1	2	-
Z _{AD}							0			0			0			0			0	
C: SETTLING VELOCITY GROUP 1 TO 5 SUBSTRATE CONCENTRATIONS (Dilution Factors considered) - - DILUTION FACTORS CONSIDERED																				
Dilution Factor for the respective settling velocity group - CONSIDERED						4	4	4	2	2	2	2	2	2	2	2	2	2	2	2
COD	Substrate COD x Dilution Factor	mgCOD/l				1163	910	-	913	2572	-	958	3509	-	737	1345	-	372	1087	-
VSS	Substrate VSS x Dilution Factor	mgVSS/l				897	730	-	699	1412	-	681	2064	-	465	745	-	245	857	-
TSS	Substrate TSS x Dilution Factor	mgTSS/l				897	730	-	699	1412	-	681	2064	-	465	745	-	245	857	-
ISS	Substrate ISS x Dilution Factor	mgISS/l				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TKN	Substrate TKN x Dilution Factor	mgN/l				10.1	28.9	157.3	108.5	50.9	92.3	72.6	56.6	103.5	25.2	26.8	103.7	37.2	26.1	99.7
TOC	Substrate TOC x Dilution Factor	mgC/l				-	206	-	-	489	-	-	671	-	-	248	-	-	251	-
TP	Substrate TP x Dilution Factor	mgP/l				12.8	-3.0	5.2	17.8	-2	6.63	7.89	9	7.56	4.5	5.6	5.5	1.8	4.6	4.3
OrgN	Substrate OrgN x Dilution Factor	mgN/l				10	28.9	-	108	50.9	-	73	56.60	-	25	26.8	-	37	26.1	-
OrgP	Substrate OrgP x Dilution Factor	mgP/l				12.8	-3.0	-	17.8	-2.1	-	7.89	9.44	-	4.5	5.6	-	1.8	4.6	-
D: MASS RATIOS: INOCULUM AND FIVE SETTLING VELOCITY GROUPS' SUBSTRATE																				
			INOCULUM			SVG1			SVG2			SVG3			SVG4			SVG5		
		Units	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic
VSS/TSS	VSS/TSS	gVSS/gTSS				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ISS/TSS	VSS/TSS	gISS/gTSS				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
f _{cv}	COD/mass,VSS	gCOD/gVSS	1.18	2.31	-	1.30	1.25	-	1.31	1.82	-	1.41	1.70	-	1.59	1.81	-	1.52	1.27	-
f _c	TOC/mass,VSS	gC/gVSS	0.41	0.46	-	0.42	0.28	-	0.42	0.35	-	0.43	0.32	-	0.43	0.33	-	0.42	0.29	-
f _n	OrgN/mass,VSS	gN/gVSS	0.1	0.04	-	0.01	0.04	-	0.16	0.04	-	0.11	0.03	-	0.05	0.04	-	0.15	0.03	-
f _p	OrgP/mass,VSS	gP/gVSS	0.025	0.005	-	0.01	-0.004	-	0.03	0.00	-	0.01	0.005	-	0.01	0.01	-	0.01	0.01	-
f _s	OrgS/mass,VSS		0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
f _o	16/18(1-f _{co})/8-8f _c /12-12f _n /14-26/32f _s		0.39	0.31	-	0.47	0.54	-	0.31	0.44	-	0.36	0.47	-	0.39	0.45	-	0.30	0.54	-
f _h	8(4f _c /12+f _n -2f _o /16-3f _n /14)		0.08	0.18	-	0.08	0.14	-	0.09	0.18	-	0.10	0.17	-	0.11	0.18	-	0.12	0.13	-
f _c +f _n +f _p +f _h +f _o			1.00	1.00		1.00	1.00		1.00	1.00		1.00	1.00		1.00	1.00		1.00	1.00	

4.5.5. Mass ratios: Inoculum and five SVGs: f_{cv} , f_c , f_n , f_p , VSS/TSS, and ISS/TSS

Table 4.17 presents the mass ratios f_{cv} (COD/VSS), f_c (TOC/VSS), f_n (N/VSS), f_p (P/VSS), VSS/TSS, and ISS/TSS, calculated using the PE, for the inoculum and five SVG particulate matter. These mass ratios are important for determining the unknown elemental compositions. The BPO f_{cv} ratios, from the PE, for the inoculum, SVG1, SVG2, SVG3, SVG4, and SVG5 substrate were found to be 2.31, 1.25, 1.82, 1.70, 1.81, and 1.27, respectively, with an average of 1.65 gCOD/gVSS (**Table 4.18**). These BPO f_{cv} ratios are relatively close to the ones observed from the experimental results (**Appendix G**). The BPO f_{cv} of 1.65 is relatively close to the ratios reported in the literature. For instance, Gaszynski (2020:142) reported the PSS BPO f_{cv} range of 1.99–2.23 gCOD/gVSS, while Wentzel *et al.* (2003: 273) cited Izzett *et al.* (1992), Moen *et al.* (2001), Ristow *et al.* (2005), and Sötemann *et al.* (2005) indicating the BPO f_{cv} ratios of 1.627, 1.321, 1.302, and 1.568, respectively. The parameter estimated BPO f_c ratios of 0.45, 0.29, 0.35, 0.33, 0.34, and 0.30 (with an average of 0.33) were recorded for the inoculum, SVG1, SVG2, SVG3, SVG4, and SVG5, respectively. The BPOTOC to COD ratio (or f_c to f_{cv} ratio) was found to be between 0.185–0.233 (with an average of 0.205) for the five SVGs. This range is marginally lower than the UPOTOC: COD ratio of 0.348 of Ekama and Brink (2007: 5) and 0.339 of Wentzel *et al.* (2003: 273) (see **Section 3.6.6**). The ratio of 0.205 obtained in this study is, however, closer to the UPOTOC: COD ratio of 0.207 obtained by Angula (2022: 97) when treating the Bellville WWTWs primary sewage sludge. The decreased UPOTOC: COD ratio is attributed to the decreased f_c ratio (from 0.5 [Ekama and Brink, 2007: 5; Wentzel *et al.*, 2003: 273] to 0.311 [Angula, 2022: 97] or 0.33 obtained in the present study). This f_c deviation from the literature values could be traced to the source of the Bellville wastewater, which comprises domestic and industrial. As mentioned in **Section 2.2.1**, the characteristics of wastewater may vary depending on the sources. Significantly close BPO f_n and f_p ratios between 0.03–0.2 and 0.002–0.01, respectively, were recorded from both the PE and experimental data.

The UPO f_{cv} ratios of the substrate from the PE outcomes were found to range between 1.18–1.59, with an average of 1.40. These values are considerably close to the UPO f_{cv} ratios obtained from the experimentally measured data (ranging between 1.31–1.57) (**Appendix G**). This UPO f_{cv} range is also close to the ratios (1.42 and 1.481) accepted in the literature (Marais & Ekama, 1976: 167). The approximate PE modelled f_c ratios of 0.41–0.43 were recorded for the UPOs. It is important to remember that a UPOTOC to COD ratio of 0.348, from the literature, was used together with the UPO f_{cv} ratios of the present study to calculate these UPO f_c ratios (see **Section 3.6.6**). Similarly, these modelled f_c ratios are close to the values calculated from the experimentally measured data (the experimental f_c ratios range between 0.46–0.56). The UPO f_n and f_p for the inoculum and five SVGs

were found to range between 0.01–0.1 and 0.01–0.025, respectively. Overall, the BPO f_{cv} is marginally higher than that of the UPOs, indicating that the BPO mass has a marginally greater COD, in comparison with the carbon (C), N, and P concentrations of the UPOs and BPOs that are relatively lower than the VSS concentrations.

The recorded VSS/TSS fraction for the inoculum is 0.75 while those for the five SVG groups ranged between 0.74–0.81, with the remaining fraction representing the ISS/TSS ratio. This VSS/TSS ratio range is close to the South African typical range of 0.75–0.80 reported by Wentzel and Ekama (2006: 3.16). The SVG5, which contained the particulate concentrations similar to the settled WW, yielded the VSS/TSS ratio of 0.81. While Wentzel and Ekama (2006: 3.16) reported a range of 0.83–0.87 for settled WW, the value of 0.81 recorded in the present study is relatively close to this literature range.

4.6. Outcomes from PE: Stoichiometric elemental compositions

Having determined the mass ratios f_{cv} , f_c , f_n , and f_p for both the UPOs and BPOs in **Section 4.5.5** above, the UPO and BPO elemental compositions (ECs) for the inoculum and five SVG PSS substrates can now be determined. The ECs are expressed in the form $C_xH_yO_zN_aP_b$ (see **Section 2.6**). **Table 4.18** and **Table 4.19** present the BPO and UPO ECs for the control and five SVGs using the PE outcome results. The BPO ECs for the five SVGs are $C_1H_{5.56}O_{1.41}N_{0.1}P_{0.003}$, $C_1H_{5.99}O_{0.98}N_{0.06}P_{0.000}$, $C_1H_{6.19}O_{1.12}N_{0.04}P_{0.001}$, $C_1H_{6.26}O_{1.07}N_{0.02}P_{0.000}$, and $C_1H_{5.40}O_{1.40}N_{0.05}P_{0.000}$, respectively, while the UPO ECs are $C_1H_{1.87}O_{0.75}N_{0.03}P_{0.001}$, $C_1H_{2.10}O_{0.44}N_{0.34}P_{0.02}$, $C_1H_{1.80}O_{0.42}N_{0.24}P_{0.001}$, $C_1H_{1.40}O_{0.36}N_{0.15}P_{0.02}$, and $C_1H_{1.67}O_{0.25}N_{0.32}P_{0.02}$, respectively. The marginal variations in the ECs throughout the SVGs could be the result of differences in the particulate compositions as governed by the settling velocity from a settleometer. In addition, the “Y” value in $C_xH_yO_zN_aP_b$, for the BPO ECs, appear higher than reported on the literature. This could be linked to the deviations mentioned in **Section 4.5.5**.

Table 4.18: The SVG1 to SVG5 BPO elemental compositions

	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5	Test reactor subtract control = Substrate					
							S-SVG1	S-SVG2	S-SVG3	S-SVG4	S-SVG5	Ave.
COD	1007	1235	2293	2761	1680	1551	227	1286	1754	672	544	897
Carbon	200	251	444	535	324	325	52	245	335	124	125	176
OrgN	27	33	45	44	31	35	6	18	17	3	8	10
OrgP	7	7	7	8	7	7	0	0	1	0	0	0
VSS	436	619	1142	1468	809	865	182	706	1032	372	428	544
fcv	2.31	1.99	2.01	1.88	2.08	1.79	1.25	1.82	1.70	1.81	1.27	1.65
fc	0.46	0.41	0.39	0.36	0.40	0.38	0.28	0.35	0.32	0.33	0.29	0.32
fn	0.06	0.05	0.04	0.03	0.04	0.04	0.03	0.02	0.02	0.01	0.02	0.02
fp	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.001
fo	0.28	0.36	0.39	0.43	0.37	0.42	0.55	0.45	0.49	0.48	0.56	0.49
fh	0.18	0.17	0.18	0.17	0.18	0.16	0.14	0.17	0.17	0.18	0.13	0.16
X (Cn)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Y (Ha)	4.78	4.99	5.47	5.69	5.39	5.06	5.81	6.04	6.23	6.37	5.50	6.07
Z (Ob)	0.46	0.67	0.75	0.88	0.70	0.83	1.45	0.98	1.13	1.08	1.42	1.14
A (N)	0.12	0.11	0.09	0.07	0.08	0.09	0.10	0.06	0.04	0.02	0.05	0.05
B (P)	0.01	0.01	0.01	0.01	0.01	0.01	0.003	0.000	0.001	0.000	0.000	0.00
gVSS/mol	26	30	31	33	30	32	42	35	37	36	41	37
EDC	8	7	8	8	8	7	7	8	8	8	7	8
gCOD/mol	61	59	62	62	62	57	53	63	63	65	52	61
fc+ fh + fo + fn+ fp	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
							BPO: Elemental compositions					
							SVG1	C ₁ H _{5.56} O _{1.41} N _{0.1} P _{0.003}				
							SVG2	C ₁ H _{5.99} O _{0.98} N _{0.06} P _{0.000}				
							SVG3	C ₁ H _{6.19} O _{1.12} N _{0.04} P _{0.001}				
							SVG4	C ₁ H _{6.26} O _{1.07} N _{0.02} P _{0.000}				
							SVG5	C ₁ H _{5.40} O _{1.40} N _{0.05} P _{0.000}				
							Average	C ₁ H _{5.99} O _{1.13} N _{0.05} P _{0.000}				

Note: T-SVG1, T-SVG2, T-SVG3, T-SVG4, and T-SVG5 represent the test reactor concentrations for the respective SVGs. S-SVG1, S-SVG2, S-SVG3, S-SVG4, and S-SVG5 represent the substrate concentrations for the respective SVGs.

Table 4.19: The SVG1 to SVG5 UPO elemental compositions

	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5	Test reactor subtract control = Substrate					
							S-SVG1	S-SVG2	S-SVG3	S-SVG4	S-SVG5	Ave.
COD	1699	1989	2155	2178	2067	1885	291	456	479	369	186	356
Carbon	591	692	750	758	719	656	101	159	167	128	65	124
OrgN	128	132	191	176	151	153	4	62	47	23	24	32
OrgP	41	44	49	49	47	45	2	8	7	5	3	5
VSS	1434	1658	1783	1774	1666	1556	224	349	341	232	123	254
fcv	1.18	1.20	1.21	1.23	1.24	1.21	1.30	1.31	1.41	1.59	1.52	1.403
fc	0.41	0.42	0.42	0.43	0.43	0.42	0.45	0.45	0.49	0.55	0.53	0.49
fn	0.09	0.08	0.11	0.10	0.09	0.10	0.02	0.18	0.14	0.10	0.20	0.13
fp	0.03	0.03	0.03	0.03	0.03	0.03	0.01	0.02	0.02	0.02	0.03	0.0202
fo	0.39	0.40	0.37	0.37	0.38	0.38	0.45	0.27	0.28	0.26	0.18	0.29
fh	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.08	0.07	0.06	0.07	0.07
X (Cn)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Y (Ha)	2.17	2.13	2.15	2.09	2.03	2.12	1.87	2.10	1.80	1.40	1.67	1.79
Z (Ob)	0.72	0.72	0.66	0.65	0.65	0.67	0.75	0.44	0.42	0.36	0.25	0.45
A (N)	0.19	0.16	0.22	0.20	0.18	0.20	0.03	0.34	0.24	0.15	0.32	0.22
B (P)	0.03	0.02	0.03	0.02	0.03	0.03	0.01	0.02	0.02	0.02	0.02	0.02
gVSS/mol	29.10	28.74	28.53	28.10	27.79	28.48	26.59	26.40	24.52	21.73	22.74	7
EDC	4.17	4.19	4.18	4.19	4.19	4.18	4.27	4.22	4.22	4.23	4.21	4
gCOD/mol	34.48	34.48	34.48	34.48	34.48	34.48	34.48	34.48	34.48	34.48	34.48	10
fc+ fh + fo + fn+ fp	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
fs'up							0.494	0.241	0.195	0.305	0.222	
							SVG1	C ₁ H _{1.87} O _{0.75} N _{0.03} P _{0.001}				
							SVG2	C ₁ H _{2.10} O _{0.44} N _{0.34} P _{0.02}				
							SVG3	C ₁ H _{1.80} O _{0.42} N _{0.24} P _{0.001}				
							SVG4	C ₁ H _{1.40} O _{0.36} N _{0.15} P _{0.02}				
							SVG5	C ₁ H _{1.67} O _{0.25} N _{0.32} P _{0.02}				
							Average	C ₁ H _{1.79} O _{0.45} N _{0.22} P _{0.02}				

Note: T-SVG1, T-SVG2, T-SVG3, T-SVG4, and T-SVG5 represent the test reactor concentrations for the respective SVGs. S-SVG1, S-SVG2, S-SVG3, S-SVG4, and S-SVG5 represent the substrate concentrations for the respective SVGs.

4.7. BPO, UPO, and ISS proportions from parameter estimation: Substrate settleables

Table 4.20 and **Figure 4.15** provide the final BPO, UPO, and ISS settleable fractions collected from the 5C-settleometer. The stepwise process followed to obtain these fractions is shown **Table 4.20** (in addition to the discussion given in **Section 3.9**). As shown in **Figure 4.15A**, the maximum BPO proportions of 0.23 and 0.38 were collected in the PVC2 and PVC3 columns, respectively. The PVC2 and PVC3 correspond with the V_{up} of 0.214 and 0.115 m/min, respectively. On the other hand, greater proportions of UPO and ISS were removed in the PVC1 (corresponding with the V_{up} of 0.429 m/min) in comparison with the PCV5 (corresponding with 0.064 m/min). The UPO proportion of 0.31 was collected in the PVC1 while only 0.08 was removed in the PVC5. The ISS proportion of 0.23 was removed in the PVC1, with only 0.10 in the PVC5. This particle size distribution indicates that the ISS and UPO particles from the Bellville WWTWs had higher particle settling velocities in comparison with the BPOs. As illustrated in **Table 4.21**, the reported fs'_{up} is higher in PVC1 and decreases towards PVC5, indicating that UPOs are associated with higher settling velocities relative to BPOs.

Table 4.20: The concentrations and masses for the control and five SVGs derived from the PE modelled data

A. Control and the five SVG concentrations: BPO is the difference between the starting and the ending concentrations. UPO is the concentration on the last day of the experiment. ISS was taken as an average between the starting and the ending concentrations (ISS do not change throughout the experimentation)							
	Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5	Units
Volume	5	5	5	5	5	5	Litre
BPOVSS	436	619	1142	1468	809	865	mgVSS/l
UPOVSS	1434	1658	1783	1774	1666	1556	mgVSS/l
ISS	682	827	929	1039	914	809	mgISS/l
B. Control and the five SVGs masses: Concentrations in A multiplied by the respective volume.							
BPOVSS	2182	3095	5712	7342	4044	4324	mgVSS
UPOVSS	7169	8290	8916	8872	8331	7781	mgVSS
ISS	3410	4133	4643	5193	4570	4046	mgISS
C. Control concentrations subtracted from the test batch reactors for the five SVG reactors							
	Control	S-SVG1	S-SVG2	S-SVG3	S-SVG4	S-SVG5	Sum
BPOVSS	0	182	706	1032	372	428	2721
UPOVSS	0	224	349	341	232	123	1269
ISS	0	145	247	357	232	127	1107
D. Concentrations of the five SVGs taking into consideration the dilution factors.							
	Control	S-SVG1	S-SVG2	S-SVG3	S-SVG4	S-SVG5	Units
Volume		4	2	2	2	2	-
BPOVSS		730	1412	2064	745	857	5807
UPOVSS		897	699	681	465	245	2987
ISS		579	493	713	464	254	2504
E. Five SVGs settleable fractions: See Section 3.9.2, 3.9.3, and 3.9.4 for BPO, UPO, and ISS fractionations calculation steps							
	S-SVG1	S-SVG2	S-SVG3	S-SVG4	S-SVG5	Sum	Units
BPOVSS	0.10	0.27	0.37	0.14	0.12	1.00	-
UPOVSS	0.28	0.22	0.23	0.18	0.09	1.00	-
ISS	0.23	0.20	0.28	0.19	0.10	1.00	-
TSS	0.10	0.27	0.37	0.14	0.12	1.00	-
Cumulative TSS mass retained							
	0.20	0.43	0.73	0.88	1.00		

Note: T-SVG1, T-SVG2, T-SVG3, T-SVG4, and T-SVG5 represent the test reactor concentrations for the respective SVGs, and S-SVG1, S-SVG2, S-SVG3, S-SVG4, and S-SVG5 represent the substrate concentrations for the respective SVGs.

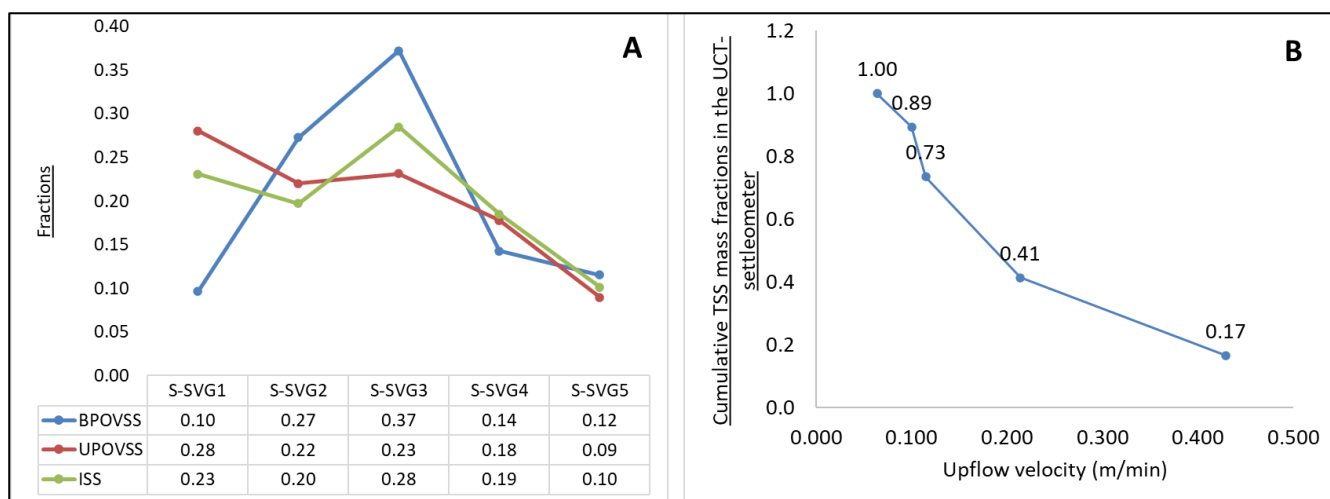


Figure 4.15: The BPO, UPO, and ISS settling proportions. A: the BPO, UPO, and ISS particulate segregation between the five SVGs. B: the TSS particulate accumulation between the five SVGs.

Table 4.21: The $f_{S^{UP}}$ fractions for the five SVG substrate

Components concentrations from the parameter estimation outcomes								Control subtracted from SVG1 to SVG5 test reactors					
		Control	T-SVG1	T-SVG2	T-SVG3	T-SVG4	T-SVG5	Control	S-SVG1	S-SVG2	S-SVG3	S-SVG4	S-SVG5
S_{ti}	Total COD	3283	3872	5178	5741	4493	4122	0	589	1894	2458	1210	838
S_{upi}	Total unbiodegradable particulate COD	1699	1989	2155	2178	2067	1885	0	291	456	479	369	186
$f_{S^{UP}}$	S_{upi}/S_{ti}								0.494	0.241	0.195	0.305	0.222

4.8. Summary

This chapter presented (i) the FS-PST diurnal influent, effluent, and underflow data of the Bellville WWTWs, (ii) the settleometer test run output data, and (iii) the supporting AugBMP experimental data, which was further supported by the PE data to reconcile the potential errors between the experimentally measured data. These results were presented in terms of COD, UPO, BPO, TSS, VSS, ISS, UPO, TKN, TP, FSA, OP, pH, and alkalinity. The related outcomes took into consideration data evaluation processes which includes standard deviations, percentage errors, and mass balances. The overall outcome from these results is (i) the five SVGs characterised in terms of BPOset, UPOset, and ISetS settling proportions and their corresponding elemental compositions, (ii) the comprehensively characterized FS-PST diurnal influent, effluent, and underflow characteristics, and (iii) the general WW characteristics in terms of the buffering capacities and behaviour during anaerobic digestion. In the next chapter, these results will be applied to the DDPST model to facilitate the necessary evaluations.

CHAPTER 5:

DATA-DRIVEN PST

MODEL EVALUATION

Chapter 5: Data-driven PST model evaluation

5.1. Overview

As introduced in **Chapter 1**, the main goal of the present study is to evaluate the recently developed DDPST model, which requires the parameters generated by the 5C-settleometer. The 5C-settleometer was operated onsite, at the Bellville WWTWs, and was fed the same influent WW as the influent of the full-scale primary settling tank (FS-PST). The solids that accumulated in the settleometer columns were processed further to obtain their BPO, UPO, and ISS characteristics. The processing included running the AugBMP experiments and analysing the data using the parameter estimation tools. Measurements were also taken over the FS-PST to obtain the diurnal data on the same period as that of the main 5C-settleometer test runs. This section evaluates the data from the FS-PST outputs, their comparison with the 5C-settleometer outputs, and subsequently comparison with the DDPST model outputs. As previously mentioned, the DDPST model relies on the 5C-settleometer data to make predictions that can be compared with the FS-PST data to confirm whether the virtual PST satisfactorily represents the real PST.

5.2. Full-scale PST influent, overflow, and removals

Table 5.1 presents the BPO, UPO, and ISS summaries for the raw WW (influent), settled WW (effluent), and PSS derived from the FWAs in **Table 4.1**. As mentioned in **Section 3.4.3**, the raw WW and settled WW UPO fractions ($f_{s'up}$), from a lab-scale Modified Ludzack-Ettinger (MLE) system treating the raw WW and settled WW from the Bellville WWTWs (Ikumi *et al.*, 2022 in progress), are used for characterization. Using the $f_{s'up}$ fractions of 0.1259 and 0.0418 to calculate the raw WW and settled WW UPOCOD and assuming 100% MB around the PST, the PSS $f_{s'up}$ was calculated to be 0.289 (**Table 5.1**). The PSS $f_{s'up}$ of 0.289 is significantly close to the PSS $f_{s'up}$ of 0.334 obtained from the PSS AugBMP experimental test procedure of Angula (2022: 97). After calculating the UPOCOD (S_{upi}) (**Table 5.1A** and **Equation (3.12)** to **Equation (3.14)**), the corresponding BPOCOD (S_{bpi}) was obtained by subtracting the S_{upi} from the total particulate COD (S_{tpi}).

The UPO and BPO f_{cv} fractions ($f_{cv,upo}$ and $f_{cv,bpo}$) were required to convert the UPOCOD and BPOCOD to UPOVSS (VSS_{upi}) and BPOVSS (VSS_{bpi}). The UPOVSS and BPOVSS are required especially for the generation of the influent file required for the DDPST model in the WEST[®] platform. The average $f_{cv,upo}$ and $f_{cv,bpo}$ of 1.48 and 1.61 (Ikumi *et al.*, 2022 in progress), respectively, were accepted and used for the raw WW and settled WW characterization. The average $f_{cv,upo}$ and $f_{cv,bpo}$ of 1.48 and 1.61 are significantly close to 1.403 and 1.648, respectively, obtained from the AugBMP test experiment of this present study (see **Section 4.6**). Similar to the PSS $f_{s'up}$, the $f_{cv,upo}$ and $f_{cv,bpo}$ of 1.48 and 1.61,

respectively, are close to the values of 1.432 ($f_{cv,upo}$) and 1.50 ($f_{cv,bpo}$) obtained from the Bellville WWTWs PSS study by Angula (2022: 97). As stated by Ikumi (2011:394), the raw WW, settled WW, and PSS UPO (and BPO) are expected to have the same composition given that they represent the same compound tracked at different unit operations of the WWTW.

The BPO, UPO, and ISS removals of 39.7%, 78.1%, and 76.7%, respectively, which correspond with the respective COD and TSS removals of 34% and 56.7% were recorded for the FS-PST. These removals are significantly close to the percentage removal ranges reported by Ikumi (2011: 16) (citing Marais and Ekama [1976]). The UPO and ISS were removed in greater proportions than the BPO, with the overall TSS being removed in marginally greater proportions than the COD, as observed in the literature (Ikumi *et al.*, 2014). These FS-PST removals are significantly important as they will be used for comparison with the 5C-settleometer outcomes, and eventually, the DDPST model.

Table 5.1: The FS-PST raw influent, effluent, and PSS UPOCOD, UPOVSS, BPOCOD, BPOVSS, and ISS

Components	Total COD	VFA	FSA	OP	TSS	ISS	VSS	f _{S'up}	f _{cv,upo}	f _{cv,bpo}
Units	mgCOD/l	mg/l	mgN/l	mgP/l	mgTSS/l	mgISS/l	mgVSS/l			
Unfiltered (Raw WW)	1012	-	-	-	549	98	450	0.126	1.4800	1.6100
Supernatant (Settled WW)	671	-	-	-	239	23	216	0.023	1.4800	1.6100
Filtered (0.45um Filtrate)	272	98	58	8	-	-	-			
			PSS	f _{S'up}	0.289					
			PSS	f _{cv'upo}	1.480					
			PSS	f _{cv'bpo}	1.610					
			Concentrations			Fluxes			%Removals	Expected %Removals
			Raw	Settled	PSS	Raw	Settled	PSS	PSS Flux/Inf flux	
A	UPOCOD	Total COD x f _{S'up}	127	28	19908	3494	765	2729	78.1%	70 - 80%
B	BPOCOD	Total COD - Filt COD - UPOCOD	613	371	48723	16800	10122	6678	39.7%	40 - 60%
C	UPOVSS	UPOCOD/f _{cv,upo}	86	19	13451	2361	517	1844	78.1%	70 - 80%
D	BPOVSS	Total VSS - UPOVSS	381	231	30263	10435	6287	4148	39.7%	40 - 60%
E	ISS		98	23	15104	2699	629	2070	76.7%	80 - 90%
F	TSS		549	239	62226	15036	6508	8529	56.7%	45%
G	COD		1012	671	68903	27751	18307	9444	34.0%	40%
H	Flow rate in ML/d					27.412	27.275	0.13706		

5.3. 5C-settleometer outputs and full-scale PST outputs comparison

This section compares the 5C-settleometer and FS-PST BPO, UPO, and ISS underflows and overflows. This comparison is carried out using the same methods as presented in **Section 3.5.1**. While **Section 3.5.1** compared the 5C-settleometer and FS-PST influent and effluent, this section largely focuses on the settleable particulates removed (as PSS). This comparison does not take into consideration the settling velocity values, mainly settling proportions. Essentially, it was possible to calculate the respective underflow masses given that the volumes used to run the AugBMP test were recorded for each of the SVGs (regarded underflow volumes). The calculation was done as follows:

- a. As shown in **Figure 5.1**, the BPOVSS, UPOVSS, and ISS concentrations obtained in **Table 4.20D** were multiplied by the respective volumes used for the AugBMP test procedure (see **Table 3.9**).
- b. The total effluent volume is the difference between the total influent volume (5C-settleometer influent) and volumes used for the AugBMP test procedure.
- c. Once the masses for each of the SVGs, influent, and effluent were determined, the masses from the five SVGs were summed and considered as total settleable masses ($MSVG_{set}$).
- d. The $MSVG_{set}$ was divided by the influent mass and multiplied by 100% to yield the %removal by the 5C-settleometer.

As shown in **Figure 5.1**, the BPO, UPO, and ISS percentage removals from the 5C-settleometer are within 15% of the FS-PST removals. Similar to the FS-PST, the ISS and UPO appeared to be removed in higher proportions than the BPO. For this specific scenario, the 5C-settleometer and FS-PST removals are expected to be almost the same given that the actual 5C-settleometer test run was able to achieve the effluent concentrations close enough to those of the FS-PST.

It is important to note that while the FS-PST underflow was accepted to be 0.5% of the influent flow (see **Section 3.4.4**), the total PSS volume for the 5C-settleometer was found to be 17.3%. This difference in the volume removed could be one of the reasons behind the %removal differences. This is given that, considering the theoretical underflow of 0.5%, the higher underflow of 17.3% from the 5C-settleometer, as obtained in the present study, clearly consists of volumes of WW that should form part of the settled WW, thus adding WW dilutions to the removals. For future studies, a close enough FS-PST underflow volume, to 0.5% of the influent flow, should be targeted. This way, there will be more confidence in comparing the percentage removals from the two systems. Given the possible challenge to achieve the concentrated settleable solids from the 5C-settleometer to undergo the AugBMP test (considering the potential blockages on the settleometer due to the accumulation of particles), multiple settleometer runs can be made. Thereafter, the accumulated solids, from the respective columns, can be combined to run the biodegradability test. When considering the multiple settleometer runs, it is essential that all runs have the same flow rate, and preferably that they are done on the same day.

As discussed in **Section 3.5.1**, a flow rate between 0.6–0.8 resulted in a reasonable particle segregation (**Figure 3.17**). In terms of the percentage removals, one can consider the difference between the 5C-

settlemeter and actual PST removals as not being too high (being within 15%), despite the removals not being 100% accurate. This proves that the 5C-settlemeter can be used to represent the FS-PST reasonably well.

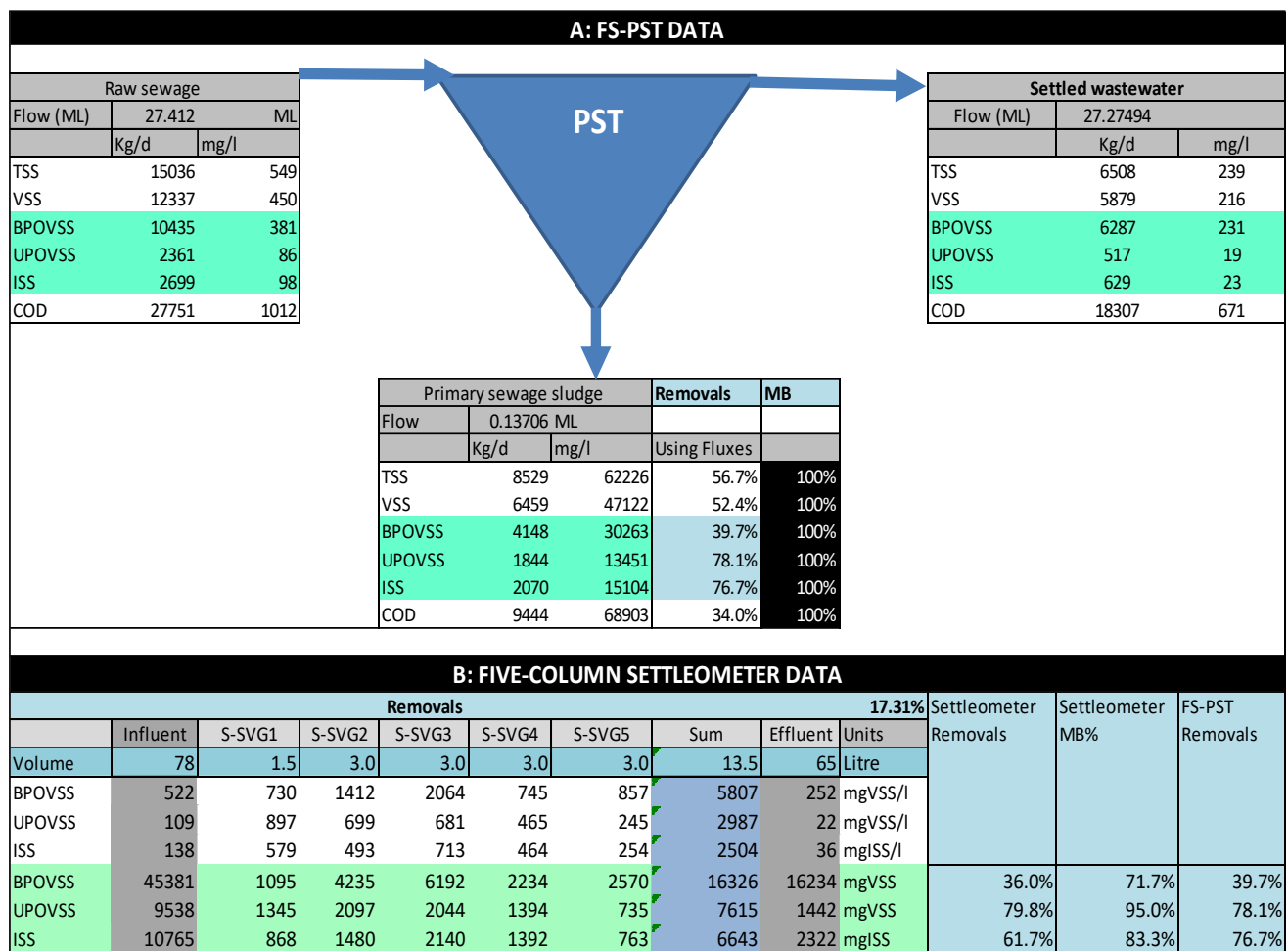


Figure 5.1: The comparisons between the FS-PST and 5C-settlemeter percentage removals overflow, and mass balances

5.4. Data-driven PST model predictions and comparison with the full-scale PST data

5.4.1. Overview

Prior to the actual DDPST simulations, the trial simulations were carried out using the verified data to check whether desirable outcomes can be obtained. The (i) settling proportions (fractions), (ii) settling velocities recorded in meter/day (m/d) (Polorigni, 2020: 5–2), (iii) PST influent masses recorded in kilograms/day (Kg/d), and (iv) PST dimensions (area and height in m² and m, respectively) used by Polorigni (2020) during the development of the model were used for these trial simulations. **Figure 5.2** depicts a data-driven PST model interface within the WEST platform used in the present study. From the trial simulations, all the desirable outcomes, as tabulated by Polorigni *et al.* (2021: 6), were obtained.

5.4.2. Data-driven PST model predictions outcomes

5.4.2.1. DDPST model predictions: Scenario 1

The settling velocities in m/d (see **Table 3.4** in **Section 3.3.6.1** for velocities in m/hr), settling proportions as fractions, PST influent masses in Kg/d, and PST dimensions (area and height in m² and m), as tabulated in **Figure 5.3**, were used as the input parameters to run the DDPST model. The outputs from the DDPST model from these input parameters were recorded (**Figure 5.3**). In comparison with the FS-PST outputs, the model resulted in approximately 100% removal of BPO, UPO, and ISetS. This is different from the full-scale outcomes where only 78.1%, 76.7%, and 39.7% of ISS, UPO and BPO, respectively, were removed. From this scenario, it is evident that upflow velocities collected from the settleometer TeR1 (in m/d) (to reflect settling velocities), were too high to allow accurate model predictions. This is because, relative to overflow rate of 28.76 m/d of the FS-PST (i.e., from 27412 m³/d divided by 962.1 m²), the settleometer column V_{up} (which reflect V_s) are 540, 236, 160, 101, and 62.6 m/d. These settleometer velocities are much higher than the real FS-PST overflow rate. As a result, all the particles are easily moved via the underflow in response to a low PST overflow rate.

5.4.2.2. DDPST model predictions: Scenario 2

A different scenario was created where all the settleable solids were assigned to the lowest particle settling velocity group (**Figure 5.4**). Similar to the Scenario 1 (**Figure 5.3**), the complete removal of solids was observed for the UPOset, BPOset, and ISetS. This confirmed that the measured velocities, using the settleometer (in m/d), were too high. Further discussion on the impact of the settling velocities, together with the settling proportion differences, is given in **Section 5.4.3**.

5.4.2.3. Data-driven PST model predictions mass balance

In addition to the outcomes of the solids removal, **Figure 5.3** and **Figure 5.4** show the MB outcomes for each of the DDPST model simulations. It is important to note that the overall removals, achieved in both scenarios presented above, were achieved under steady-state conditions where the mass in and out of the system were equal. Essentially, as shown in **Figure 5.3** and **Figure 5.4**, the MB is generally poor during the first couple of days but improves towards 100% as the system approaches steady state. The MB for the BPO, UPO, and ISS were achieved for all the two scenarios (**Figure 5.3** and **Figure 5.4**).

5.4.3. Discussion of data-driven PST model prediction outcomes

5.4.3.1. Impact of settling velocities

Sections 5.4.2.1 and **5.4.2.2** above discussed two scenarios which proved the impact of the settling velocities on the overall BPO, UPO, and ISS removals. There is a distinct gap between the settleometer

design and DDPST data modelling process. While the model may well represent the real FS-PST, the settleometer relationship with the DDPST model requires to be revised to ensure that the settleometer, as a lab-scale PST, is well represented in the model. From the settleometer and AugBMP outcomes, the BPO, UPO, and ISS concentrations in the PST overflow and underflow can be calculated, and as discussed in **Section 5.3**, it is possible to obtain some level of output data comparable with the FS-PST model. This proves that the problem is more related to the actual DDPST model when the settleometer upflow velocities (V_{UP}) are applied.

5.4.3.2. Possible reasons for percentage removal differences

As shown in **Figure 3.17**, the 5C-settleometer has shown its ability to segregate the settleable particles into different SVGs. While this is the case, a number of factors may have affected the particle segregation. This can be briefly explained as follows:

- a. **The manner of flow of the raw WW into the settleometer:** The inflow into the 5C-settleometer is via the bottom (**Figure 5.5**). While this method does not affect the particle settling velocities, the accumulation of particles in a column during the settleometer run has a potential to affect the incoming raw WW particles through the interparticle forces. Various studies have indicated the decrease in the particle movement in the presence of nearby particles (Kumbhakar *et al.*, 2017; Zhu *et al.*, 2019). These occurrences can result in a poor particle movement leading to a poor particle segregation. The DDPST model adopted the principles of the Takacs *et al.* (1991) model where the influent is through the middle layer (layer 5). The inflow through the middle layer allows particles to flow freely. The current design of a settleometer implies that the interparticle forces should be accounted for in the DDPST model to ensure the accurate model predictions.
- b. **Particle misplacement:** During the settleometer sampling (see **Section 3.3.5**), all the masses from the columns are sent for the TSS analysis. It is possible for the masses in the PCV1, PVC2, PVC3, and PVC4 to contain the PCV2, PVC3, PVC4, and PVC5 particles, respectively, which had not yet reached the respective columns when the settleometer stops. For instance, considering that 100 L influent are pumped into the settleometer before it stops, 63 L would reach the effluent, whereas the balance of 37 L would not. Of this 37 L are:
 - The PVC1 1.8 L mass that may contain the PCV2, PVC3, PVC4, and PVC5 BPO, UPO, and ISS proportions.

- The PVC2 4.5 L mass that may contain the PVC3, PVC4, and PVC5 BPO, UPO, and ISS proportions.
- The PVC3 6.2 L mass that may contain the PVC4 and PVC5 BPO, UPO, and ISS proportions.
- The PVC4 9.5 L mass that may contain the PVC5 BPO, UPO, and ISS proportions.

From the above discussion, it can be deduced that the particles that have not reached the correct PVC columns will be considered as misplaced in the wrong columns. While this contribution to the SVG settling proportions (relative to the accumulated masses) may be regarded negligible, it is important to have this accounted for in the model environment to ensure that the model predictions are as accurate as possible.

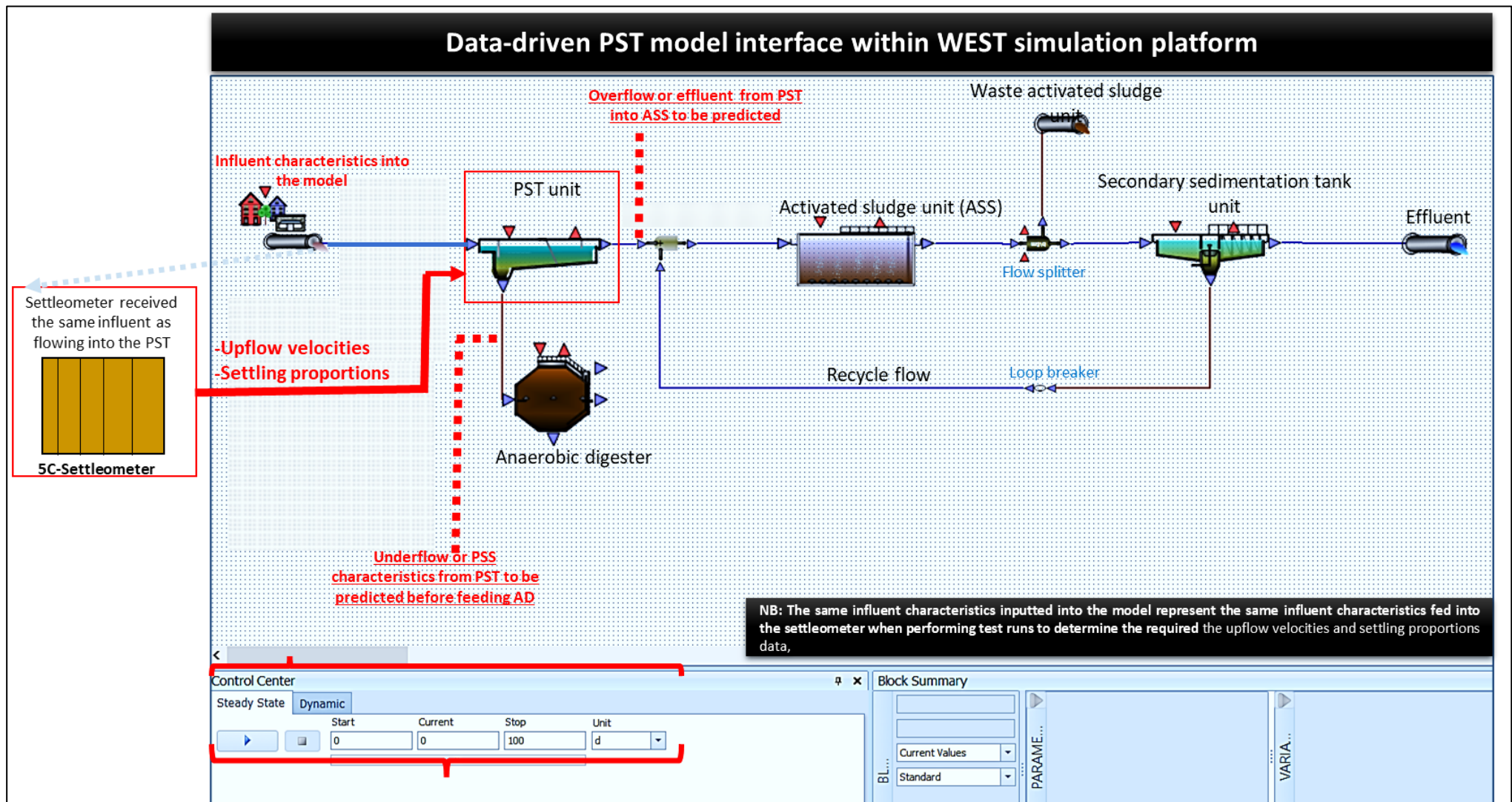


Figure 5.2: The data-driven model outputs from the settleometer TeR1 (see Section 4.2 to 4.6). (A) Scenario 1, and (B) mass balance scenario during the DDPST modelling.

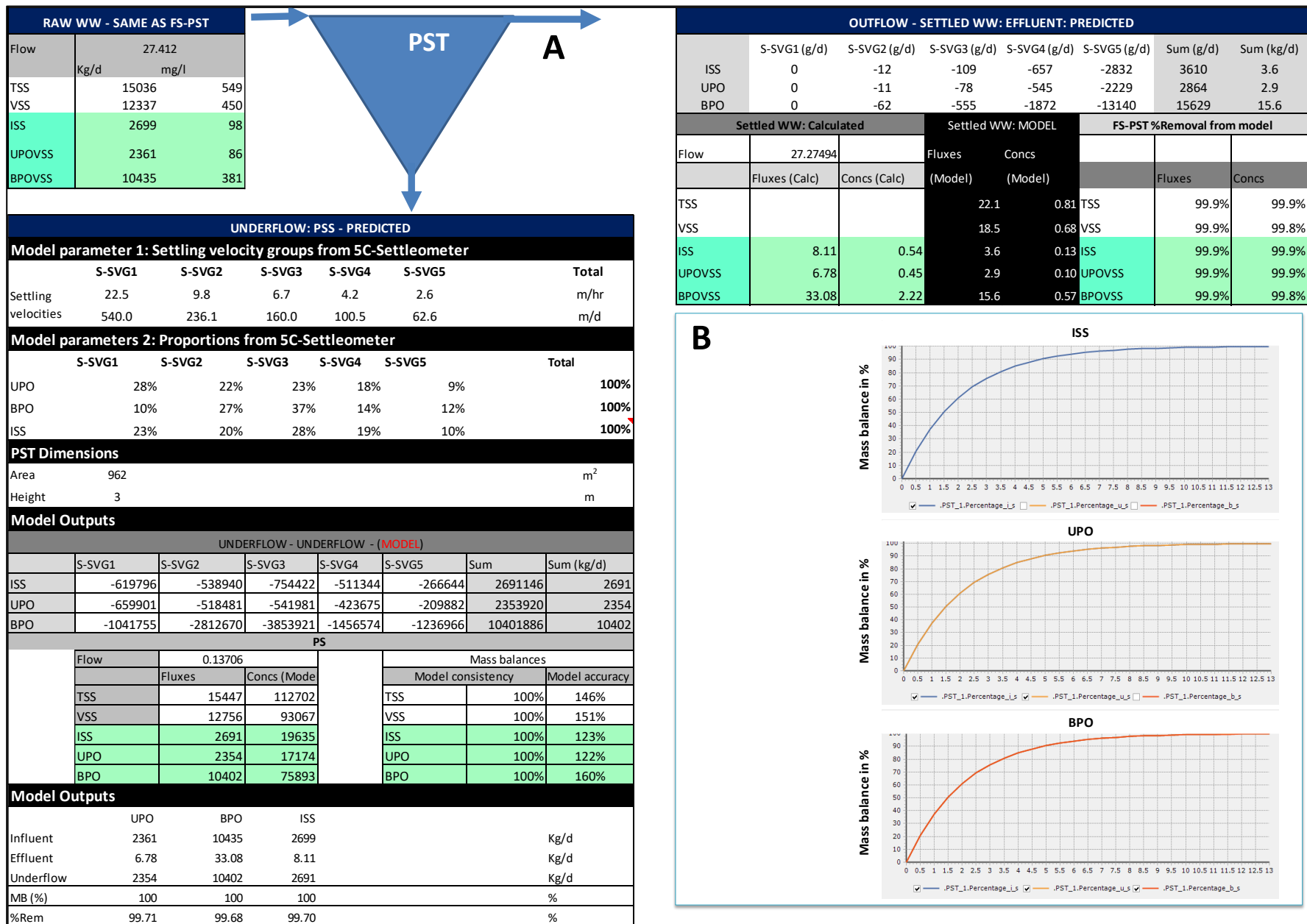


Figure 5.3: The data-driven model outputs from the settleometer TeR1 (see Section 4.2 to 4.6). (A) Scenario 1, and (B) mass balance scenario during the DDPST modelling.

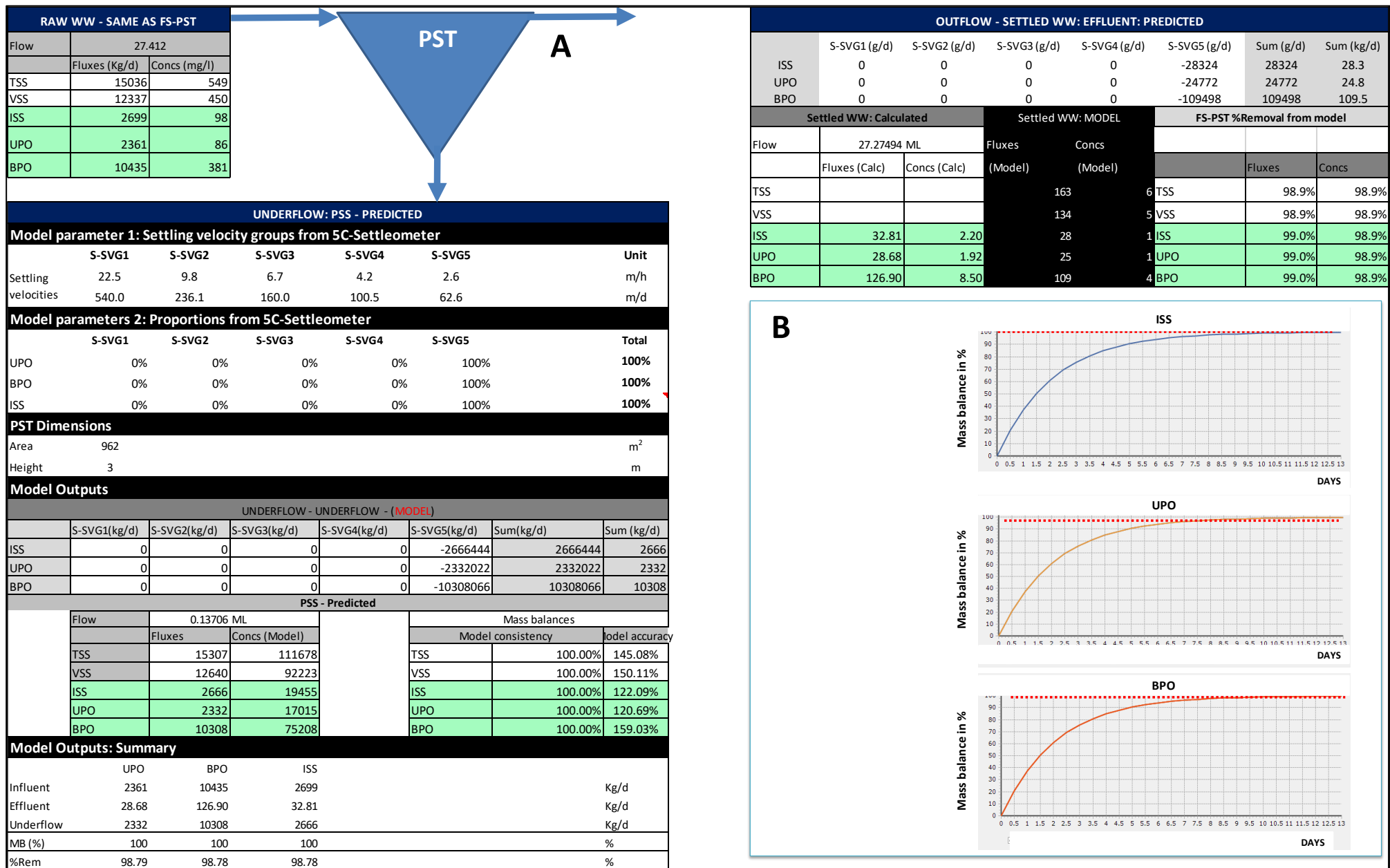


Figure 5.4: The data-driven model outputs from the settleometer TeR1 (see Section 4.2 to 4.6). (A) Scenario 2, and (B) MB scenario during the DDPST modelling.

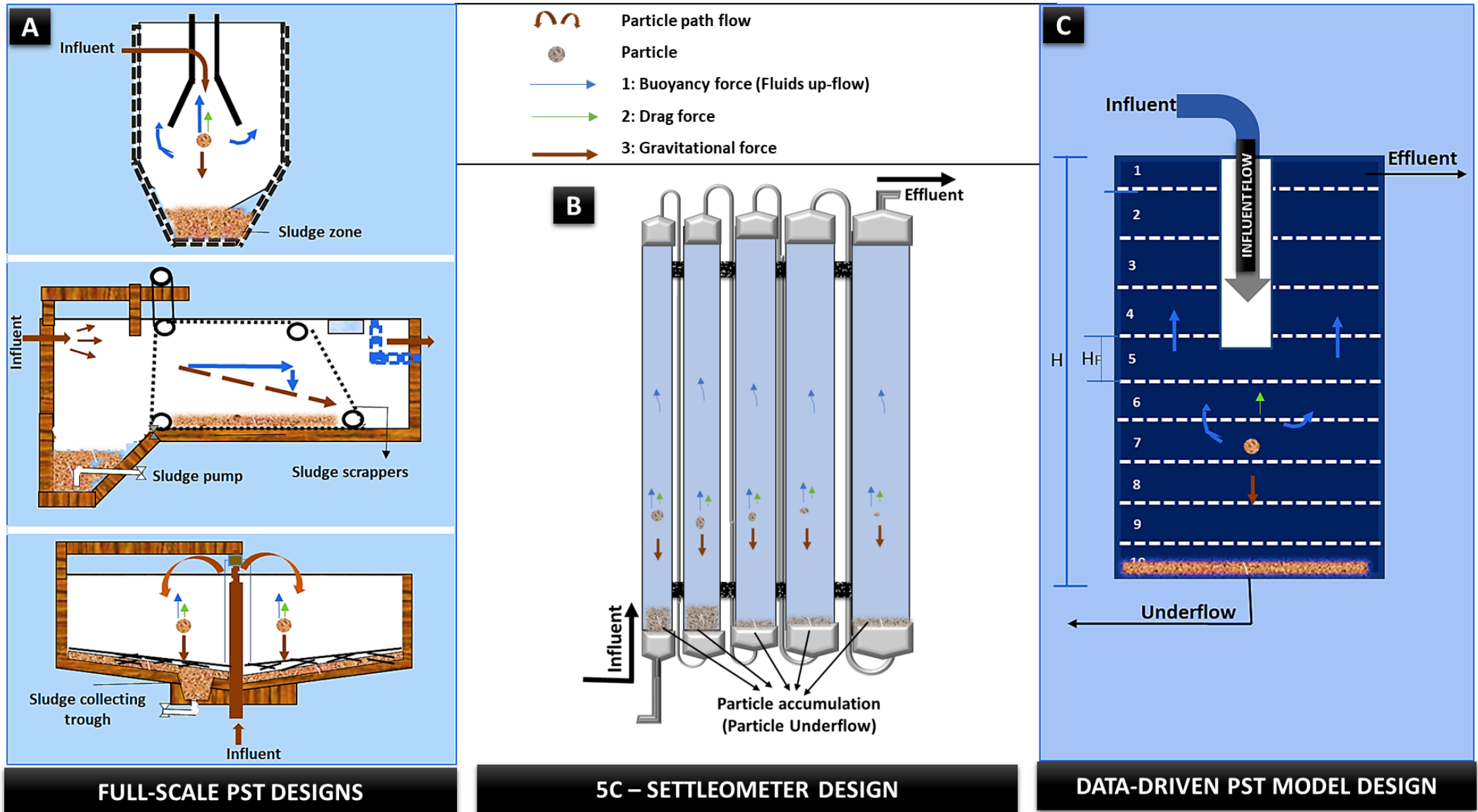


Figure 5.5: The influent flow patterns for: (A) the FS-PST, (B) the 5C-settleometer, and (C) the DDPST model.

CHAPTER 6:

CONCLUSIONS AND

RECOMMENDATIONS

Chapter 6: Conclusions and recommendations

6.1. Overview

The aim of this research project was to evaluate the DDPST model by verifying the accuracy of the 5C-settleometer to mimic the settleability patterns of a FS-PST unit. The 5C-settleometer has previously been described as an instrument capable of segregating particles into five different SVGs. Along with the AugBMP test procedure, each of the five SVGs can be characterized into BPO, UPO, and ISS proportions. A Microsoft Excel SS AD model, together with a solver function, was used to minimise the errors between the experimentally measured data by estimating the critical parameters for use in both the elemental compositions and settling proportion determinations. The settling velocities and settling proportions from the 5C-settleometer serve as parameters to allow the DDPST model predictions.

The FS-PST 24-hour diurnal samples were collected in parallel with the settleometer main test runs. The DDPST model ability to make accurate predictions is reflected by how comparable the model outputs are to the FS-PST in terms of the PST BPO, UPO, and ISS removals and overflow characteristics. From the settleometer trial and test runs, a particle segregation trend, between the columns, was observed. Flow rates less than 0.4 l/min resulted in most particles accumulating in the first two columns corresponding with the V_{UP} between 5–13m/hr. A shift in columns recording maximum particle accumulation was observed when increasing the flow rates. For instance, increasing the flow rates to 0.6–0.8 l/min shifts the maximum particle accumulation to the PVC2 and PVC3, corresponding with the V_{UP} between 5–12m/hr. Similarly, increasing the flow rate, beyond 1.2 l/min, shifts the maximum settling towards the PVC3 to PVC5. This trend indicates that the raw WW is primarily characterized by particles with similar settling velocity range. In terms of the overall particle distribution, flow rates between 0.6–0.8 l/min led to better particle distribution than lower flow rates between 0.4–0.6 l/min. Overall, the ISS and UPO components appeared to be removed in greater proportions than the BPO. The BPO and UPO 5C-settleometer average compositions of $C_1H_{5.99}O_{1.13}N_{0.05}P_{0.00}$ and $C_1H_{1.79}O_{0.45}N_{0.22}P_{0.02}$, respectively, were obtained. The source of the WW governs the corresponding elemental composition.

6.2. Five-column settleometer design and operation

While it was possible to run a settleometer test necessary for characterising the settleable solids into the five SVGs, two main challenges were encountered. These are summarised as follows:

a. **Decreasing flow rate:** A constant pump frequency resulted in a flow rate decrease across the 5C-settleometer PVC columns, and subsequently, an overflow. This gradual decrease in the flow rate might have been caused by (i) the presence of sharp bends on the 5C-settleometer design, and (ii) the particle accumulation in the PVC columns, which obstructs the particle flow.

- The settleometer is designed in such a way that tubes are used to interconnect the respective columns. The tubes bend from the top of the first column down to the bottom of the second column, bend again from the top of the second column down to the bottom of the third column, and so forth. This design implies that the inflow into the columns is subject to bending forces which causes pressure losses, thus decreasing the flow movements. The bends, rises, and falls on the 5C-settleometer are inherent parts of its design. A recommendation on how the 5C-settleometer design can be improved is given in **Section 6.5.2**.

b. **Low flow rates:** Achieving the low flow rates of less than 0.4 l/min was a challenge. This is given that the lowest flow rates required setting the pump to a significantly low frequency of less than 4Hz. Unfortunately, such low frequency appeared to be below the pump capacity to operate efficiently. Frequent pump vibrations and regular pump stopping, during the system operation, prevailed. A different approach, involving the use of a two-way valve, was adopted to remediate the problem. The approach involved splitting the inflow, from the inlet towards the settleometer, into two directions, that is, a specified inflow towards the settleometer and the other reverted to the influent. The two-way valve method allowed the pump to be operated at its optimum rate while allowing only a small fraction of the influent to flow into the settleometer.

6.3. Five-column settleometer representation of full-scale PST

This study has shown the settleometer ability to represent the FS-PST in terms of the overall BPO, UPO, and ISS removals. The principle is to ensure that the settleometer effluent characteristics equal those of the FS-PST, provided that both systems are fed the same influent characteristics. While it may also be advised to aim for the same hydraulic retention time (HRT) for both the settleometer and FS-PST, this study has shown that the settleometer dimensions may not result in desirable outcomes. This is given that setting the settleometer HRT to be equal to the FS-PST HRT may require the flow rate to be set at its lowest. Considering the effects of the low flow rates, as discussed in **Sections 3.3.4.4** and **6.5.2.2**, it may remain ideal to target an HRT that leads to the settleometer effluent characteristics to be similar to those of the FS-PST while maintaining reasonable particle segregation.

6.4. Five-column settleometer effectiveness in DDPST model evaluations

While the settleometer instrumentation has proven the ability to segregate particles to a certain level, its use (together with the AugBMP test) towards evaluating the data-driven PST model may require to be reassessed. It became evident from the model simulations in the present study that the upflow velocities from the settleometer were too high to allow accurate predictions. Higher particle settling velocities result in all particles being removed via the underflow. This shows a need to review the relationship between the settleometer instrumentation (together with its outcomes) and DDPST model to ensure that the exact settleometer dimensions are correctly modelled.

Another aspect that needs to be investigated is the accuracy of the settling proportions in the five settleometer columns. As highlighted in **Section 6.2**, the effect of prominent inter-particle forces that occurs in a settleometer, possibly due to extended HRT, cannot be underestimated. This is given that the interparticle forces represent a source of flocculation which changes the character of individual particles, and subsequently, lead to particles accumulation in incorrect columns. The accurate settling proportions can only be confirmed through outputs representativeness between the DDPST model predictions and real PST.

6.5. Recommendations for future work

6.5.1. Lab-scale PST (i.e., settleometer) replica onto DDPST model

The current DDPST model requires to be corrected to reflect the settleometer operational dimensions. This includes correctly linking the settleometer upflow velocities and allowing the model to account for the particle distribution inevitable errors associated with the settleometer design. This study has shown the settleometer potential to account for the overall removals. Therefore, if the model equations can be designed in such a way that the settleometer typical scenario is translated to fit the representable PST solids removal and overflow, the model can make accurate predictions.

6.5.2. Five-column settleometer flow rates

6.5.2.1. 5C-Settleometer constant flow rates

Given that it may be challenging to represent sharp bends making up the settleometer dimensions on the DDPST model, it remains important to adjust the pump frequency consistently across the 5C-settleometer columns to maintain a constant flow rate. It is important to ensure that the adjustment of the pump controller is as smooth as possible to prevent the formation of bubbles which may affect the particle settling or cause issues related to the shooting of particles from one column into the other.

6.5.2.2. Achieving 5C-Settleometer low flow rates

As discussed in **Section 3.3.4.4**, a two-way valve method can be adapted to allow the settleometer operation at low flow rates. Although running the settleometer at a significantly low flow rate may result in low upflow velocities, this may negatively impact the particle distribution. A lower V_{up} facilitated by a lower flow rate allows for an increased HRT in each column, thus, giving particles more time to accumulate. The disadvantage of this is that more particles tend to accumulate in the leading PVC columns. This particle accumulation interferes with the particle movement of the incoming flow from one column into the other (via the pressure drop that increases the flow resistance). This was more evident during the experimentation when operating the settleometer at a low flow rate resulted in prevalent interparticle actions and greater particle accumulation in the PVC1 and PVC2 than in the PVC3, PVC4, and PVC5. It is, therefore, recommended to opt for a high enough flow rate targeting (i) a flow rate that allows a satisfactory particle distribution, and (ii) a flow rate that yields the settleometer effluent characteristics that are comparable to the FS-PST. In the present study, a flow rate between 0.6–0.8 l/min yielded satisfactory results. It is also advised to stop the settleometer operation as soon as evidence of pipe blockages occur, particularly when sufficient effluent mass (e.g., say 30 L) has been collected.

6.5.2.3. Higher capacity pump investment

While the current 5C-settleometer pump can still be used, taking into consideration the points discussed above (**Sections 6.5.2.1** and **6.5.2.2**), options to invest in a higher capacity pump should be explored. This will particularly make the settleometer operation at low flow rates (lower than 0.4 l/min) achievable.

6.5.2.4. Five-column settleometer flow meter investment

To monitor the influent flow rate across the 5C-settleometer columns (in their current design) during operation, one requires to manually measure the flow rate as discussed in **Section 3.3.4.1**. The shortfall of this method is that it is associated with a high level of errors (i.e., human errors in taking the measurements as the flow progresses). Investing in a flow meter that can be installed in close proximity of the 5C-settleometer first column would add a benefit to this process by simplifying the process of controlling the influent flow.

6.5.3. Combination of high and low flow rates to perform a set of 5C-settleometer test run

From the discussions above, it is evident that running the 5C-settleometer at high flow rates (say >1.2 l/min) result in escape of particles into the effluent (see **Section 3.3.4.3**). On the other hand, running the 5C-settleometer at low flow rates (say <0.4 l/min) result in prominent inter-particle force actions in the leading PVC columns which affects both individual particle movement and particle distribution (see **Section 6.5.2.2**). To overcome this, one way that can be explored is (i) running the settleometer at a high flow rate (say 1.2 l/min) and collect sufficient effluent (of say 50 L). As previously mentioned, such high flow rate may result in solids escaping into the effluent. To account for the escaped solids, (ii) re-run the settleometer using the effluent (not the raw WW) at a low flow rate to accumulate the initially escaped solids. Before re-running the settleometer, it is important to ensure that the first high flow rate accumulations are all emptied from the settleometer and the corresponding upflow velocities are recorded. This way, interparticle forces will be minimised given that the second low flow rate run (with effluent) would not consist as many particles as the raw WW. Again, for the second run, the corresponding upflow velocities require to be recorded. Thereafter, the recorded sets of upflow velocities can be grouped into five SVGs.

6.5.4. Five-column settleometer BPO, UPO, and ISS experimental component determinations

It is possible that the settleometer settleable solids, collected from an operation with only 60 L influent, may not be sufficient to run the AugBMP test (for the five SVGs), especially when conducting the tests in triplicates. Therefore, instead of using a single settleometer operation output, two or three settleometer operation outputs can be used. From the multiple settleometer outputs, the segregated particles, from each respective column, could be mixed to run an AugBMP test. This would give an opportunity to use the settling proportions at various times of the day, in the same way the FS-PST samples are collected throughout the day and obtain the FWAs. When opting for this method, it is important that the multiple settleometer runs are performed at the same flow rate. Multiple settleometer outputs would also be beneficial for the AugBMP test given that, during the experimental set-up of the present study, it was observed that a high substrate mass is required to run the AugBMP test to maintain satisfactory substrate representation.

6.5.5. Standard process development for DDPST model simulations

While this study detailed all the steps followed to generate the required parameters to allow the application of the DDPST model, areas which can be improved on have also been identified. Once all the necessary modifications have been implemented, and the 5C-settleometer, together the DDPST model, has proven to yield more accurate results, a finalised standard process that can serve as a guide

to using the DDPST model should be developed. This standard process will, with no doubt, lessen the probability of omitting steps or making errors that may affect the quality of the output results.

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Appendices

Appendix A: Wastewater sources

Appendix B: Biogas release per reactor

Appendix C: BPO, UPO, and ISS characterisation block diagrams for the five SVGs substrate

Appendix D: AugBMP test modelled results for both the control and test reactors

Appendix E: Parameter estimation summary tables

A. Appendix: Wastewater sources

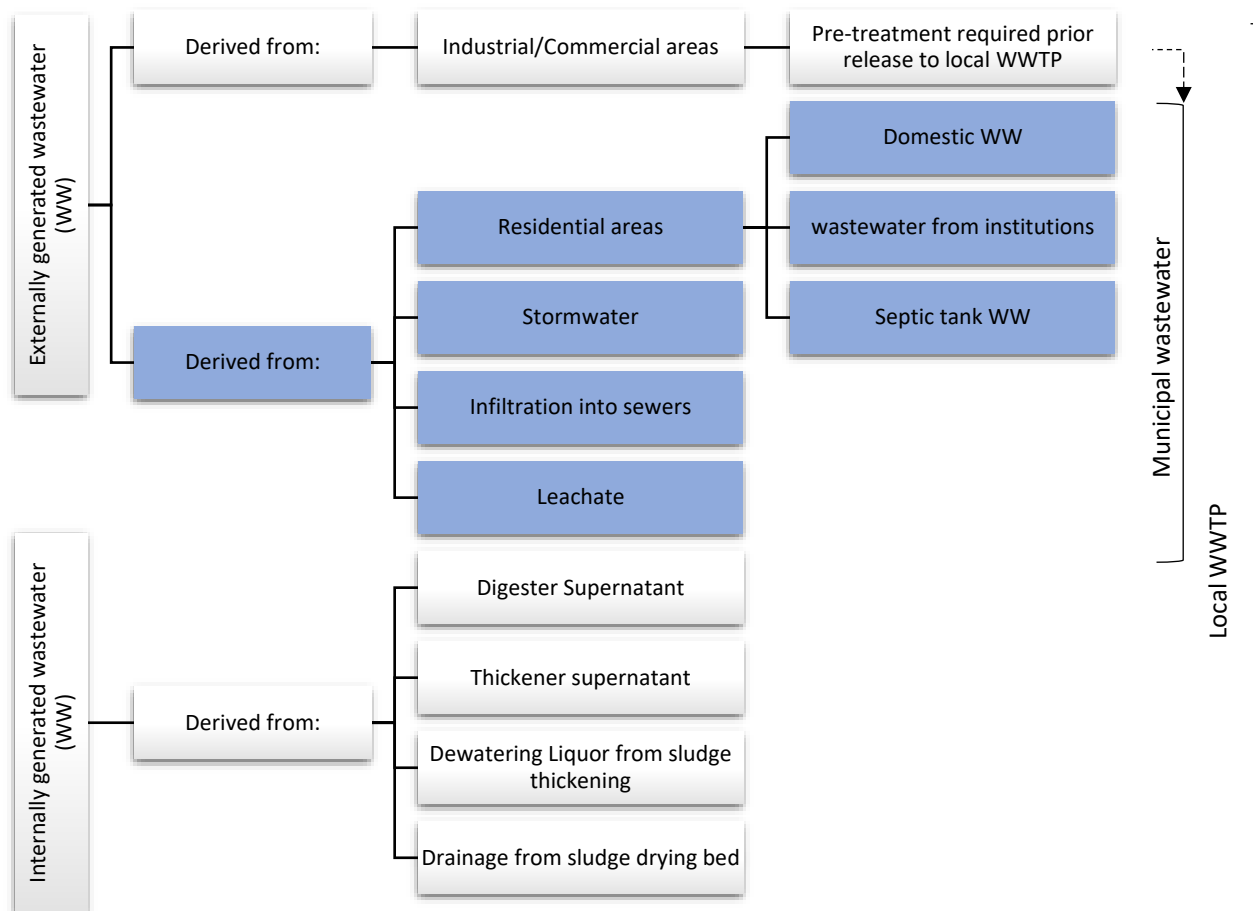


Figure 8.1: The different types of wastewaters entering a local WWTP. Adapted from Henze and Comeau (2008).

B. Appendix: Biogas release per reactor

Table 8.1: The Control, PVC1 and PVC2 daily biogas cumulative release

			CONTROLS				CONTROLS				PVC1						PVC2					
			Inverted column water displacement				Biogas volume accumulation				Inverted column water displacement			Biogas volume accumulation			Inverted column water displacement			Biogas volume accumulation		
Day	Hours	Date	Control 1	Control 2	Control 3	Control 4	Control 1 (5L)	Control 2 (5L)	Control 3 (2L)	Control 4 (2L)	PVC1	PVC1D	PVC1T	PVC1 (5L)	PVC1D (5L)	PVC1T (2L)	PVC2	PVC2D	PVC2T	PVC2 (5L)	PVC2D (5L)	PVC2T (2L)
1	0	2021/06/24	163	159	120	155	0	0	0	0	1953	1954	1961	0	0	0	1966	1962	1965	0	0	0
2	24	2021/06/25	235	159	175	175	72	0	55	20	1953	1931	1920	0	65	116	1760	1650	1960	582	882	14
3	48	2021/06/26	275	159	199	189	112	0	79	34	1953	1921	1910	0	93	144	1562	1410	1872	1142	1561	263
4	72	2021/06/27	295	250	219	219	132	91	99	64	1940	1911	1897	37	122	181	1460	1295	1872	1431	1886	263
5	96	2021/06/28	302	272	222	219	139	113	102	64	1931	1906	1884	62	136	218	1378	1223	1870	1663	2089	269
6	120	2021/06/29	321	294	223	220	158	135	103	65	1921	1904	1889	90	141	204	1390	1240	1872	1629	2041	263
7	144	2021/06/30	320	301	230	218	157	142	110	63	1911	1902	1882	119	147	223	1318	1220	1872	1832	2098	263
8	168	2021/07/01	320	325	235	216	157	166	115	61	1903	1890	1882	141	181	223	1308	1210	1848	1860	2126	331
9	192	2021/07/02	320	355	240	215	157	196	120	60	1896	1880	1882	161	209	223	1272	1197	1811	1962	2163	435
10	216	2021/07/03	320	375	242	218	157	216	122	63	1888	1861	1882	184	263	223	1259	1183	1810	1999	2203	438
11	240	2021/07/04	314	381	249	213	151	222	129	58	1856	1855	1885	274	280	215	1267	1192	1810	1976	2177	438
12	264	2021/07/05	312	388	249	212	149	229	129	57	1846	1847	1883	303	303	221	1244	1162	1811	2041	2262	435
13	288	2021/07/06	315	385	245	210	152	226	125	55	1841	1837	1883	317	331	221	1227	1154	1812	2089	2285	433
14	312	2021/07/07	320	392	252	215	157	233	132	60	1837	1827	1883	328	359	221	1197	1140	1811	2174	2324	435
15	336	2021/07/08	322	401	253	221	159	242	133	66	1833	1820	1882	339	379	223	1184	1120	1811	2211	2381	435
16	360	2021/07/09	315	403	250	215	152	244	130	60	1825	1812	1882	362	401	223	1174	1115	1811	2239	2395	435
17	384	2021/07/10	316	405	252	215	153	246	132	60	1820	1810	1882	376	407	223	1170	1111	1811	2251	2406	435
18	408	2021/07/11	317	407	253	215	154	248	133	60	1815	1808	1882	390	413	223	1168	1109	1811	2256	2412	435
19	432	2021/07/12	320	409	255	215	157	250	135	60	1810	1806	1880	404	418	229	1164	1107	1811	2268	2417	435
20	456	2021/07/13	312	410	252	212	149	251	132	57	1805	1803	1886	418	427	212	1182	1123	1818	2217	2372	416
21	480	2021/07/14	320	415	255	210	157	256	135	55	1800	1801	1886	433	433	212	1177	1111	1814	2231	2406	427
22	504	2021/07/15	312	420	255	210	149	261	135	55	1799	1800	1886	435	435	212	1180	1110	1818	2222	2409	416
23	528	2021/07/16	315	425	252	211	152	266	132	56	1800	1795	1885	433	450	215	1176	1100	1816	2234	2437	421
24	552	2021/07/17	317	437	255	215	154	278	135	60	1798	1788	1884	438	469	218	1156	1100	1816	2290	2437	421
25	576	2021/07/18	318	441	255	215	155	282	135	60	1798	1784	1883	438	481	221	1150	1100	1816	2307	2437	421
26	600	2021/07/19	319	445	255	215	156	286	135	60	1798	1782	1882	438	486	223	1138	1100	1816	2341	2437	421
27	624	2021/07/20	320	445	253	215	157	286	133	60	1800	1780	1882	433	492	223	1145	1088	1819	2321	2471	413
28	648	2021/07/21	315	442	252	211	361	672	314	133	1800	1782	1885	433	486	215	1146	1083	1819	2318	2485	413
29	672	2021/07/23	312	435	250	211	354	656	309	133	1800	1780	1884	433	492	218	1153	1092	1820	2299	2460	410
30	696	2021/07/27	320	480	255	215	373	763	321	143	1795	1766	1882	447	532	223	1133	1048	1814	2355	2584	427
31	720	2021/07/30	315	475	252	212	361	751	314	135	1800	1771	1886	433	517	212	1112	1062	1825	2415	2545	396
32	744	2021/08/01	315	475	255	212	361	751	321	135	1800	1771	1886	433	517	212	1112	1053	1823	2415	2570	401
33	768	2021/08/10	325	475	255	211	385	751	321	133	1800	1764	1884	433	537	218	1092	1048	1830	2471	2584	382

Table 8.2: PVC3, PVC4 and PVC5 daily biogas cumulative release

			PVC3			PVC3						PVC4			PVC4						PVC5			PVC5		
			Inverted column water displacement			Biogas volume accumulation						Inverted column water displacement			Biogas volume accumulation						Water displacement levels on inverted column			Biogas volume accumulation in inverted column		
Day	Hours	Date	PVC3	PVC3D	PVC3T	PVC3 (5L)	PVC3D (5L)	PVC3T (2L)				PVC4	PVC4T	PVC4D	PVC4 (5L)	PVC4D (5L)	PVC4T (2L)				PVC5	PVC5D	PVC5T	PVC5 (5L)	PVC5D (5L)	PVC5T (2L)
1	0	2021/06/24	1964	1965	1961	0	0	0				1956	1930	1965	0	0	0				1963	1940	1955	0	0	0
2	24	2021/06/25	1664	1620	1930	848	975	88				1674	1854	1800	797	215	467				1963	1930	1930	277	28	71
3	48	2021/06/26	1342	1323	1883	1759	1815	221				1630	1821	1688	922	308	783				1900	1910	1922	376	85	93
4	72	2021/06/27	1170	1168	1863	2245	2253	277				1580	1806	1688	1063	351	783				1865	1877	1905	418	178	141
5	96	2021/06/28	1090	1092	1858	2471	2468	291				1544	1785	1662	1165	410	857				1799	1849	1892	464	257	178
6	120	2021/06/29	1097	1105	1862	2451	2432	280				1549	1784	1662	1151	413	857				1722	1840	1898	546	283	161
7	144	2021/06/30	1067	1073	1856	2536	2522	297				1526	1792	1660	1216	390	862				1688	1818	1892	597	345	178
8	168	2021/07/01	1057	1070	1859	2564	2531	288				1526	1792	1668	1216	390	840				1615	1800	1892	670	396	178
9	192	2021/07/02	1033	1050	1859	2632	2587	288				1506	1792	1667	1272	390	843				1615	1788	1886	729	430	195
10	216	2021/07/03	1035	1062	1858	2627	2553	291				1502	1792	1665	1284	390	848				1615	1786	1881	746	435	209
11	240	2021/07/04	1026	1050	1862	2652	2587	280				1502	1792	1660	1284	390	862				1611	1771	1879	803	478	215
12	264	2021/07/05	1026	1050	1861	2652	2587	283				1502	1792	1650	1284	390	891				1601	1760	1875	865	509	226
13	288	2021/07/06	1030	1053	1862	2641	2579	280				1503	1792	1650	1281	390	891				1603	1760	1874	964	509	229
14	312	2021/07/07	1044	1020	1862	2601	2672	280				1498	1792	1657	1295	390	871				1601	1760	1869	975	509	243
15	336	2021/07/08	1031	1008	1861	2638	2706	283				1490	1790	1652	1318	396	885				1611	1758	1866	1004	515	252
16	360	2021/07/09	1031	1053	1863	2638	2579	277				1502	1790	1650	1284	396	891				1602	1760	1866	1001	509	252
17	384	2021/07/10	1030	1052	1862	2641	2581	280				1501	1790	1650	1286	396	891				1603	1760	1865	1004	509	254
18	408	2021/07/11	1029	1050	1862	2644	2587	280				1501	1790	1648	1286	396	896				1601	1760	1864	1024	509	257
19	432	2021/07/12	1027	1047	1862	2649	2596	280				1500	1790	1646	1289	396	902				1601	1760	1864	1024	509	257
20	456	2021/07/13	1048	1070	1862	2590	2531	280				1512	1796	1654	1255	379	879				1608	1765	1870	1004	495	240
21	480	2021/07/14	1042	1063	1868	2607	2550	263				1508	1792	1651	1267	390	888				1608	1762	1869	1004	503	243
22	504	2021/07/15	1042	1063	1862	2607	2550	280				1508	1792	1651	1267	390	888				1609	1762	1869	1001	503	243
23	528	2021/07/16	1038	1063	1851	2618	2550	311				1509	1794	1653	1264	385	882				1611	1765	1870	995	495	240
24	552	2021/07/17	1037	1063	1824	2621	2550	387				1508	1793	1651	1267	387	888				1612	1762	1868	992	503	246
25	576	2021/07/18	1034	1063	1818	2630	2550	404				1508	1793	1651	1267	387	888				1611	1762	1868	995	503	246
26	600	2021/07/19	1034	1061	1814	2630	2556	416				1508	1794	1650	1267	385	891				1609	1762	1868	1001	503	246
27	624	2021/07/20	1042	1068	1799	2607	2536	458				1510	1798	1653	1261	373	882				1611	1766	1868	995	492	246
28	648	2021/07/21	1043	1069	1799	2604	2533	458				1511	1758	1653	1258	486	882				1609	1846	1869	1001	266	243
29	672	2021/07/23	1049	1073	1800	2587	2522	455				1516	1760	1653	1244	481	882				1608	1846	1870	1004	266	240
30	696	2021/07/27	1028	1053	1797	2646	2579	464				1505	1755	1602	1275	495	1026				1609	1845	1867	1001	269	249
31	720	2021/07/30	1043	1068	1803	2604	2536	447				1514	1763	1610	1250	472	1004				1612	1850	1871	992	254	238
32	744	2021/08/01	1045	1070	1803	2598	2531	447				1512	1762	1612	1255	475	998				1610	1850	1870	998	254	240
33	768	2021/08/10	1026	1070	1808	2652	2531	433				1517	1767	1600	1241	461	1032				1609	1852	1874	1001	249	229

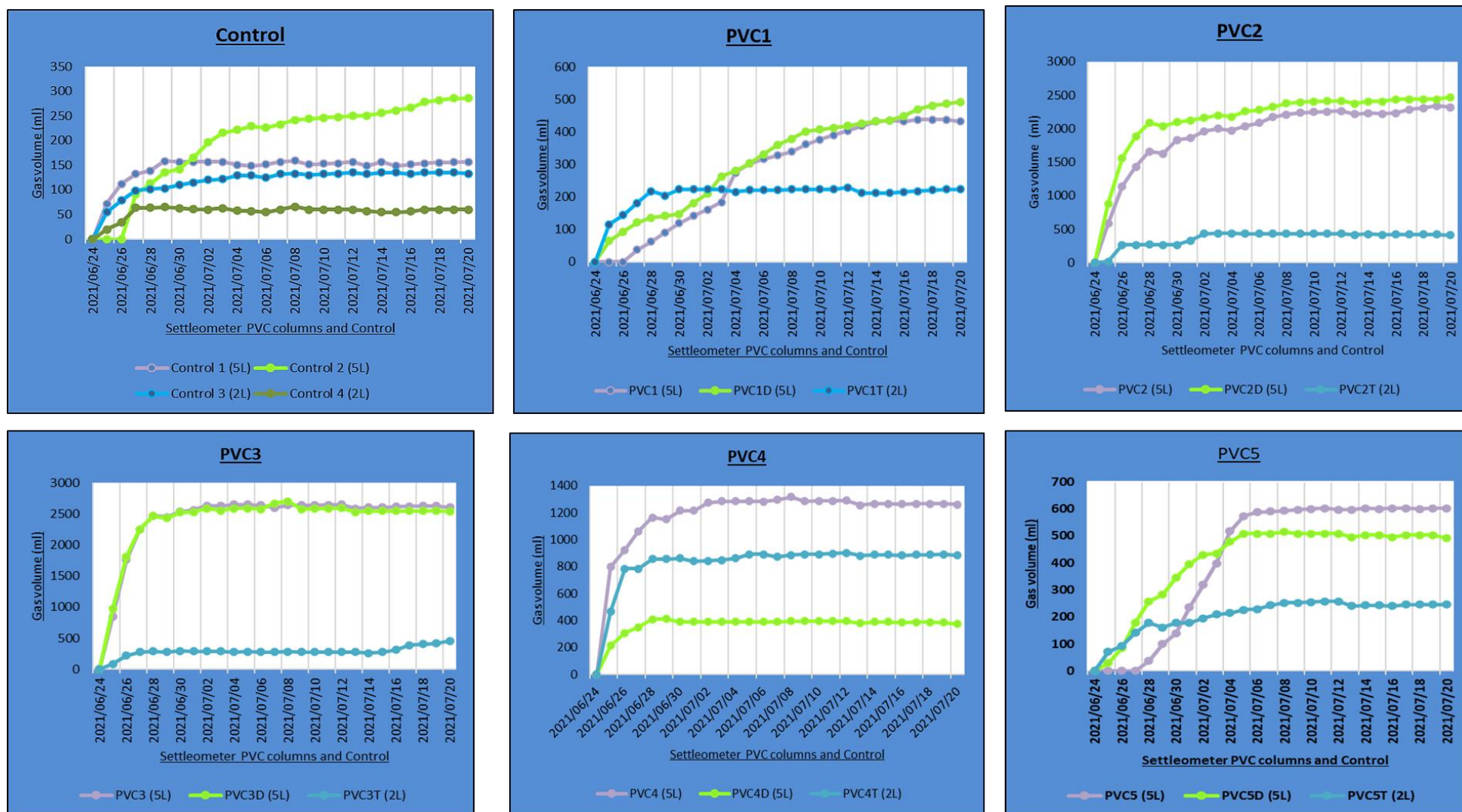


Figure 8.2: Daily recorded biogas production from each reactor of the control and SVG test reactors

C. Appendix: CH₄ COD calculation steps for control and test samples

	Formula or source	Control 1	Control 2	Control 3	Control 4	PVC1	PVC1D	PVC1T	PVC2	PVC2D	PVC2T	PVC3	PVC3D	PVC3T	PVC4	PVC4D	PVC4T	PVC5	PVC5D	PVC5T	Units
Starting batch reactor vol.	Direct measurement	5	5	2	2	5	5	2	5	5	2	5	5	2	5	5	2	5	5	2	Litre
Biomass Dilution factor	Directly applied	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	
Headspace	Direct measurement	300	300	460	460	300	300	460	300	300	460	300	300	460	300	300	460	300	300	460	ml
Total sampled gas vol.	Direct measurement	92	116	106	106	112	99	150	145	112	115	130	123	113	155	45	101	119	114	106	ml
Total vol produced	Inverted columns direct reading	477	879	427	249	747	837	689	2771	2884	898	2952	3006	924	1618	795	1492	1324	815	717	ml
CH ₄ percentage	Gas chromatography	51.4%				43.5%			41.0%			52.7%			49.7%			35.6%			
CH ₄ gas volume	%CH ₄ x Total vol produced	245	452	219	128	325	430	354	1424	1483	462	1517	1545	475	831	409	767	680	419	369	ml
CO ₂ gas volume	Total vol produced - CH ₄ gas vol	232	427	207	121	422	407	335	1347	1402	437	1435	1461	449	786	386	725	643	396	349	ml
R	Gas constant	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	8.314	l.kPa/K.mol
T _{std}	Standard Temperature	293	293	293	293	293	293	293	293	293	293	293	293	293	293	293	293	293	293	293	K
P _{std}	Standard Press	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	101.32	kPa
CH ₄ moles	PV = nRT (n = PV/RT)	0.010	0.019	0.009	0.005	0.014	0.018	0.015	0.059	0.062	0.019	0.0631	0.0643	0.0197	0.0346	0.0170	0.0319	0.0283	0.0174	0.0153	mol
CO ₂ moles	PV = nRT (n = PV/RT)	0.010	0.018	0.009	0.005	0.018	0.017	0.014	0.056	0.058	0.018	0.0597	0.0608	0.0187	0.0327	0.0161	0.0302	0.0268	0.0165	0.0145	mol
Total gas moles	CH ₄ moles + CO ₂ moles	0.02	0.04	0.02	0.01	0.03	0.03	0.03	0.12	0.12	0.04	0.12	0.13	0.04	0.07	0.03	0.06	0.06	0.03	0.03	mol
CH ₄ COD mass	64000n	652	1202	584	340	865	1146	943	3792	3946	1229	4039	4113	1264	2213	1087	2041	1811	1115	981	mgCOD
Total C in CH ₄ (Mass)	12gC/mol x CH ₄ moles	122	226	110	64	162	215	177	712	741	231	758	772	237	415	204	383	340	209	184	mgC
Total C in CO ₂ (Mass)	12gC/mol x CO ₂ moles	116	213	104	60	211	203	167	672	700	218	716	729	224	392	193	362	321	198	174	mgC
Total C in CH ₄ Gas (Conc)	C in CH ₄ Gas Mass/Starting vol	24.5	45.1	21.9	12.8	32.5	43.0	35.4	142.3	148.1	46.1	151.6	154.4	47.4	83.1	40.8	76.6	68.0	41.8	36.8	mgC/l
Part. C in CO ₂ Gas (Conc)	C in CO ₂ Gas Mass/Starting vol	23.1	42.6	20.7	12.1	42.1	40.6	33.4	134.4	139.9	43.6	143.2	145.8	44.8	78.5	38.6	72.4	64.2	39.5	34.8	mgC/l
Part. C in CH ₄ Gas (Conc)	C _{CH₄} - (C _{CH₄} * % S _{bsl})	21.6	39.0	19.7	11.5	28.5	38.1	31.4	129.9	133.1	41.4	134.8	137.8	42.1	70.3	35.8	65.6	60.5	36.3	33.0	mgC/l
Part. C in CO ₂ Gas (Conc)	C _{CO₂} - (C _{CO₂} * % S _{bsl})	20.4	36.8	18.6	10.9	36.9	36.0	29.6	122.7	125.7	39.1	127.3	130.2	39.8	66.4	33.8	62.0	57.2	34.2	31.2	mgC/l
Tot. biod. COD conc	S _{bi}	864	787	931	1162	1325	1267	1450	2467	2362	2515	2765	2774	2870	1862	1939	1843	1766	1642	1661	mgCOD/l
Tot. Sol. Biod. COD conc	S _{bsl}	102	108	96	113	163	144	165	215	240	259	307	298	321	286	238	265	194	219	173	mgCOD/l
Tot. biod. COD mass	MS _{bi}	4320	3936	1862	2323	6624	6336	2899	12336	11808	5030	13824	13872	5741	9312	9696	3686	8832	8208	3322	mgCOD
Tot. Sol. Biod. COD mass	MS _{bsl}	509	538	192	227	816	720	330	1075	1200	518	1536	1488	641	1430	1190	530	970	1094	346	mgCOD
Tot. part. biod. COD mass	MS _{bpi}	3811	3398	1670	2097	5808	5616	2569	11261	10608	4512	12288	12384	5100	7882	8506	3156	7862	7114	2976	mgCOD
% Biodegradable solubles	%S _{bsl}	11.8	13.7	10.3	9.8	12.3	11.4	11.4	8.7	10.2	10.3	11.1	10.7	11.2	15.4	12.3	14.4	11.0	13.3	10.4	%
Total volume	5L Equivalent	477	879	1067	621	747	837	1723	2771	2884	2246	2952	3006	2309	1618	795	3730	1324	815	1793	Litre

D. Appendix: BPO, UPO, and ISS characterization block diagrams for the 5 SVGs' substrates

Figure 8.3, Figure 8.4, Figure 8.5, Figure 8.6, and Figure 8.7 present complete COD block diagrams for the five settling velocity groups' substrates. Although it is possible to generate the COD, N, and P characterization block diagram using data presented in **Table 4.17**, this project focus on COD (and VSS) which brings emphasis on VSS (both UPO VSS and BPO VSS). For this reason, only COD (and VSS) block diagrams will be presented. Accompanying the block diagrams are the respective mass ratios as calculated in **Table 4.17**.

SVG1 (Inoculum concentrations removed and dilution factors considered)									
Sti				2355 mgCOD/l					
Sbsi	S _t i - S _{use}	211	mgCOD/l	S _{use}	(FiltSolEff _{SVG1} - FiltSolEff _{control}) x 4	71.04	mgCOD/l		
f _{S'} bsi	S _{bsi} /S _t i	0.090	mgCOD/mgCOD	f _{S'} usi	S _{usi} /S _t i	0.030	mgCOD/mgCOD		
Stsi				(S _{COD,Start,SVG1} - S _{COD,Start,Control}) x 4				282	mgCOD/l
								0.1198	
Total biodegradable particulates - Substrate				Total unbiodegradable particulates - Substrate					
S _{bpi}	See Table 4.21C	910	mgCOD/l	S _{upi}	See Table 4.21C	1163	mgCOD/l		
BPO _{VSS}	See Table 4.21C	730	mgVSS/l	UPO _{VSS}	See Table 4.21C	897	mgVSS/l		
f _{cv}	S _{bpi} /BPO _{VSS}	1.25	mgCOD/mgVSS	X _{ii}	S _{upi} /f _{cv}	897	mgVSS/l		
f _{S'} bpi	S _{bpi} /S _t i	0.386	mgCOD/mgCOD	f _{cv}	S _{upi} /UPO _{VSS}	1.297	mgCOD/mgVSS		
				f _{S'} upi	S _{upi} /S _t i	0.494	mgCOD/mgCOD		
S _{tpi}				S _t i - S _t si				2073	
S _{bi}	S _{bsi} + S _{bpi}	1121	mgCOD/l	S _{ui}	S _{usi} + S _{upi}	1234	mgCOD/l	f _{check}	1.0

Figure 8.3: SVG1 COD and VSS block diagram

SVG2 (Inoculum concentrations removed and dilution factors considered)										
Sti					1178 mgCOD/l					
Sbsi	Stsi - Suse	106	mgCOD/l		Usi	(FiltSolEffSVG1 - FiltSolEffcontrol) x 4		35.52	mgCOD/l	
fS'bsi	Sbsi/Sti	0.090 mgCOD/mgCOD			fS'usi	Usi/Sti		0.030 mgCOD/mgVSS		
Stsi					(SCOD,Start,SVG1 - SCOD,Start,Control) x 2				141 mgCOD/l	0.1198
Total biodegradable particulates - Substrate					Total unbiodegradable particulates - Substrate					
Sbpi	See Table 4.21C	2572	mgCOD/l		Supi	See Table 4.21C	913	mgCOD/l		
BPOVSS	See Table 4.21C	1412	mgVSS/l		UPOVSS	See Table 4.21C	699	mgVSS/l		
fcv	Sbpi/BPOVSS	1.82 mgCOD/mgVSS			Xii	Supi/fcv	699 mgVSS/l			
fS'bpi	Sbpi/Sti	2.184 mgCOD/mgCOD			fcv	Supi/UPOVSS	1.306 mgCOD/mgVSS			
					fS'upi	Supi/Sti	0.775 mgCOD/mgCOD			
Stpi					Sti - Stsi				1036 mgCOD/l	
Sbi	Sbsi + Sbpi	2678 mgCOD/l			Sui	Usi + Supi		948 mgCOD/l	fcheck 3.1	

Figure 8.4: SVG2 COD and VSS block diagram

SVG3 (Inoculum concentrations removed and dilution factors considered)									
Sti				4915 mgCOD/l					
Sbsi	S _{tSi} - S _{use}	408	mgCOD/l	S _{usi}		(FiltSolEff _{,SVG1} - FiltSolEff _{,control}) x 4		40.64	mgCOD/l
f _{S'bsi}	S _{bsi} /S _{ti}	0.083	mgCOD/mgCOD	f _{S,usi}		S _{usi} /S _{ti}		0.008	mgCOD/mgVSS
Stsi		(S _{COD,Start,SVG1} - S _{COD,Start,Control}) x 4				448 mgCOD/l		0.0912	
Total biodegradable particulates - Substrate				Total unbiodegradable particulates - Substrate					
S _{bpi}	See Table 4.21C	3509	mgCOD/l	S _{upi}		See Table 4.21C	958	mgCOD/l	
BPO _{VSS}	See Table 4.21C	2064	mgVSS/l	UPO _{VSS}		See Table 4.21C	681	mgVSS/l	
f _{cv}	S _{bpi} /BPO _{VSS}	1.70	mgCOD/mgVSS	X _{ii}		S _{upi} /f _{cv}	681	mgVSS/l	
f _{S'bpi}	S _{bpi} /S _{ti}	0.714	mgCOD/mgCOD	f _{cv}		S _{upi} /UPO _{VSS}	1.406	mgCOD/mgVSS	
				f _{S'upi}		S _{upi} /S _{ti}	0.195	mgCOD/mgCOD	
S _{tpi}		S _{ti} - S _{tSi}				4467 mgCOD/l			
S _{bi}	S _{bsi} + S _{bpi}	3916	mgCOD/l	S _{ui}		S _{usi} + S _{upi}		999	mgCOD/l
				f _{check}		1.0			

Figure 8.5: SVG3 COD and VSS block diagram

SVG4 (Inoculum concentrations removed and dilution factors considered)									
Sti				2419 mgCOD/l					
Sbsi	Stsi - Suse	317	mgCOD/l						
fS'bsi	Sbsi/Sti	0.131 mgCOD/mgCOD		Usi	(FiltSoleffSVG1 - FiltSoleffcontrol) x			20.16	mgCOD/l
				fS,usi	Usi/Sti			0.008 mgCOD/mgVSS	
Stsi				(SCOD,Start,SVG1 - SCOD,Start,Control) x 4				337 mgCOD/l	
				0.139					
Total biodegradable particulates - Substrate				Total unbiodegradable particulates - Substrate					
Sbpi	See Table 4.21C	1345	mgCOD/l	Supi	See Table 4.21C	737	mgCOD/l		
BPOVSS	See Table 4.21C	745	mgVSS/l	UPOVSS	See Table 4.21C	465	mgVSS/l		
fcv	Sbpi/BPOVSS	1.81 mgCOD/mgVSS		Xii	Supi/fcv	465	mgVSS/l		
fS'bp	Sbpi/Sti	0.556 mgCOD/mgCOD		fcv	Supi/UPOVSS			1.587 mgCOD/mgVSS	
				fS'upi	Supi/Sti			0.305 mgCOD/mgCOD	
Stpi				Sti - Stsi				2082 mgCOD/l	
Sbi	Sbsi + Sbpi	1662 mgCOD/l		Sui	Susi + Supi			757 mgCOD/l	
				fcheck 1.0					

Figure 8.6: SVG4 COD and VSS block diagram

SVG5 (Inoculum concentrations removed and dilution factors considered)									
Sti				1677 mgCOD/l					
Sbsi	S _t si - S _{use}	181	mgCOD/l						
f _{S'} bsi	Sbsi/S _{ti}	0.108 mgCOD/mgCOD							

Figure 8.7: SVG5 COD and VSS block diagram

E. Appendix: AugBMP test modelled results for both the control and test reactors

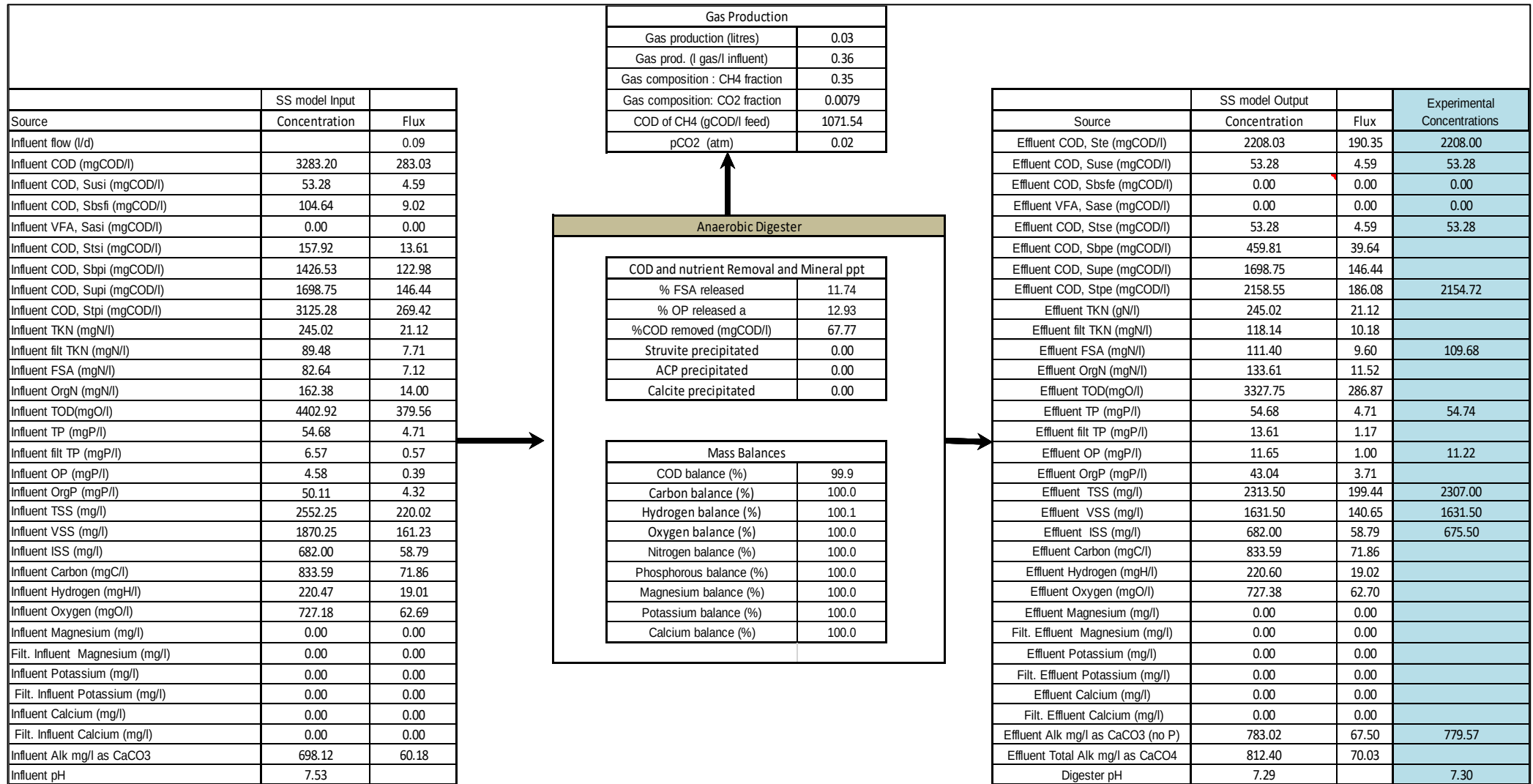


Figure 8.8: Steady-state simulations for the control reactor (AugBMP test modelled results). Experimental effluent concentrations on the last column (in blue).

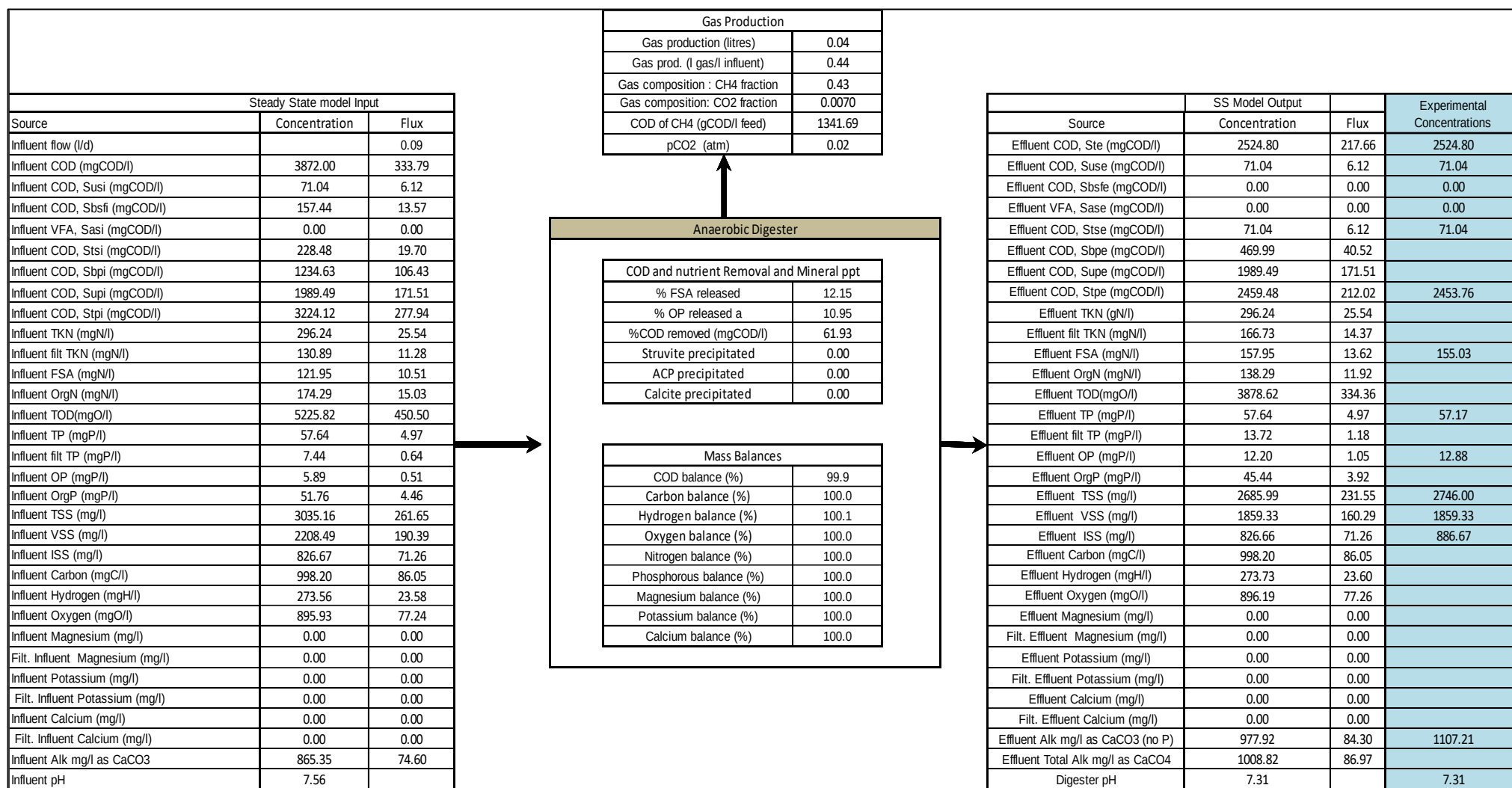


Figure 8.9: Steady-state simulations for SVG1 reactor (AugBMP test modelled results). Experimental effluent concentrations on the last column (in blue).

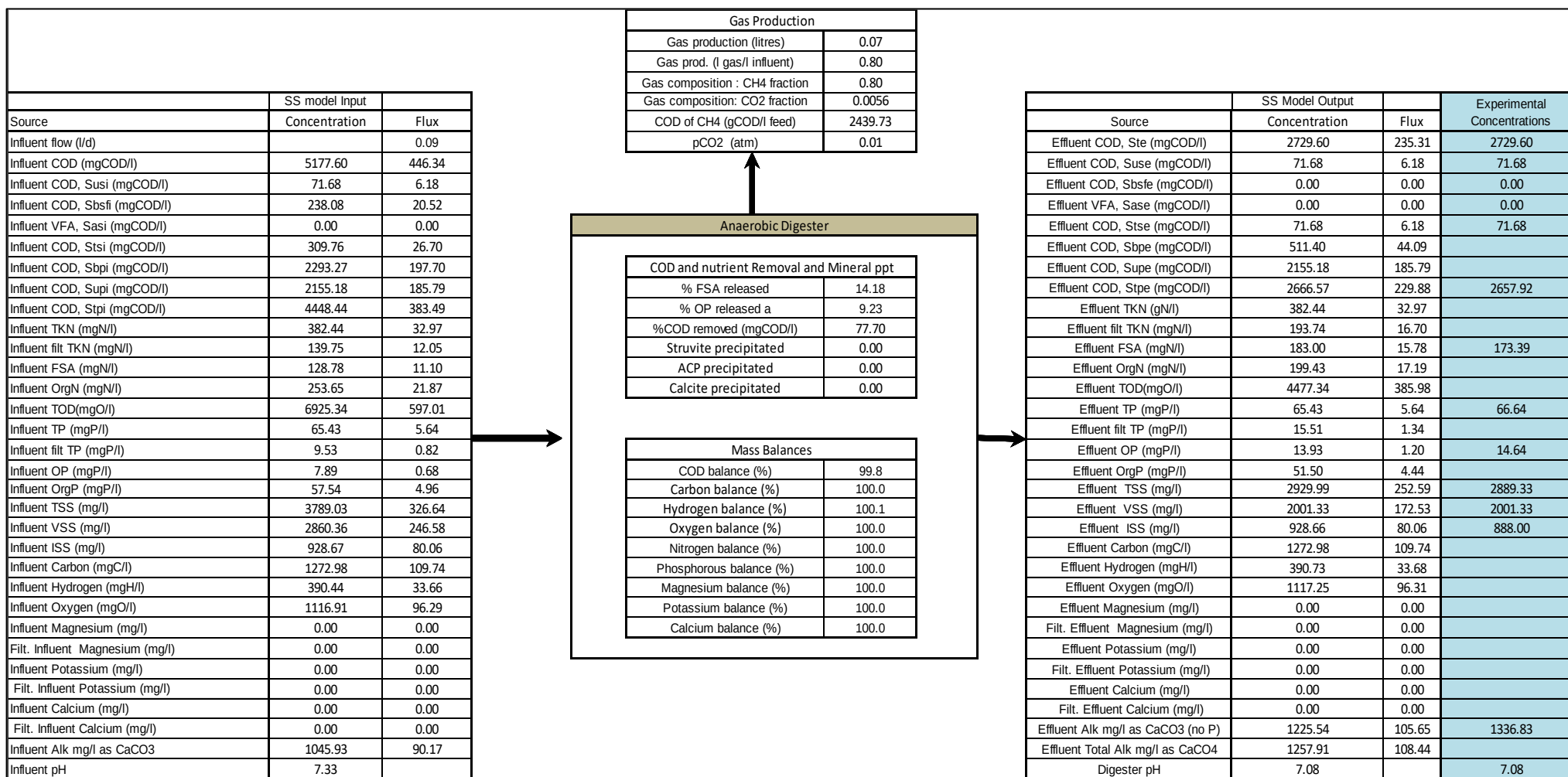


Figure 8.10: Steady-state simulations for SVG2 reactor (AugBMP test modelled results). Experimental effluent concentrations on the last column (in blue).

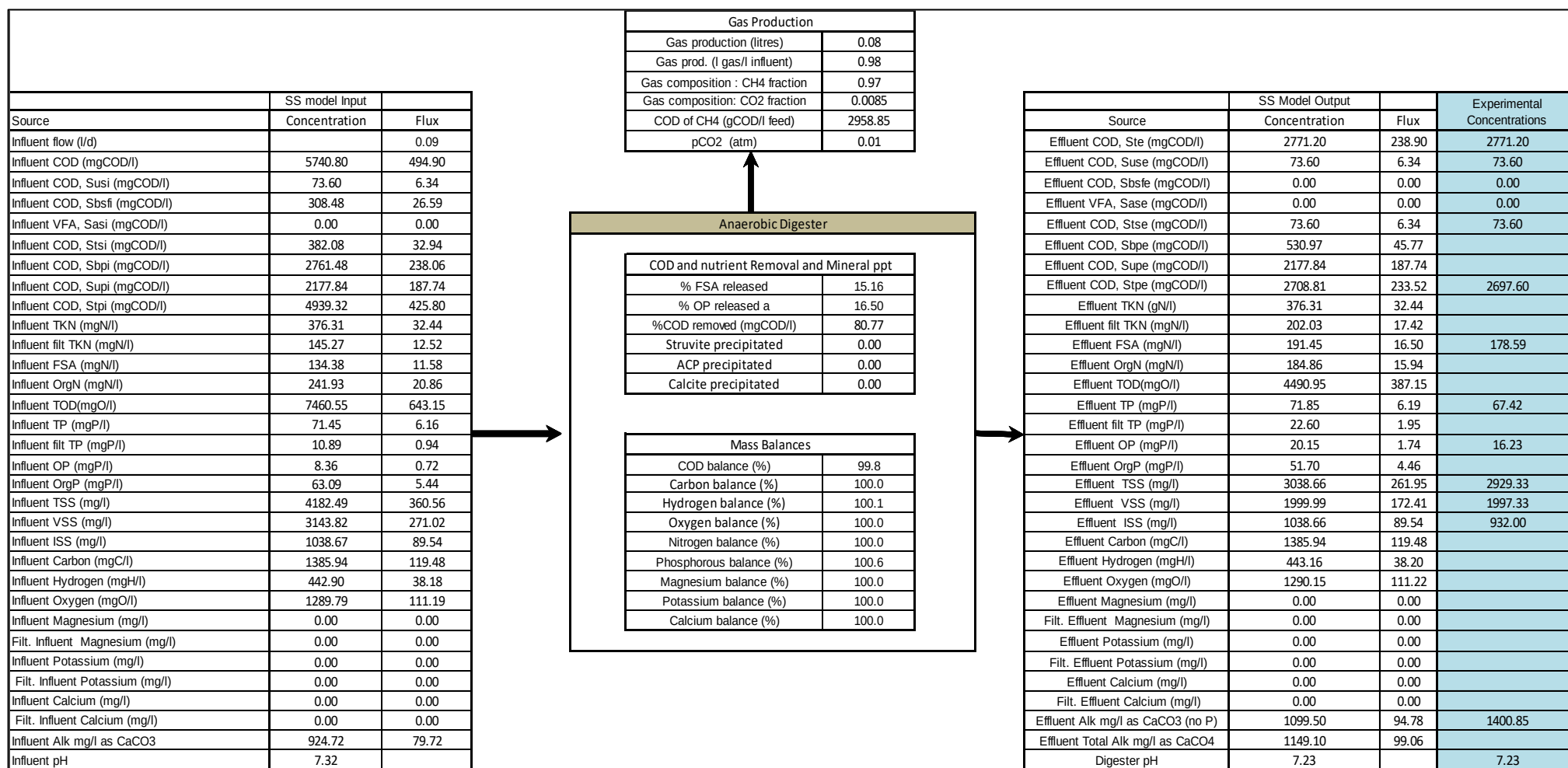


Figure 8.11: Steady-state simulations for SVG3 reactor (AugBMP test modelled results). Experimental effluent concentrations on the last column (in blue).

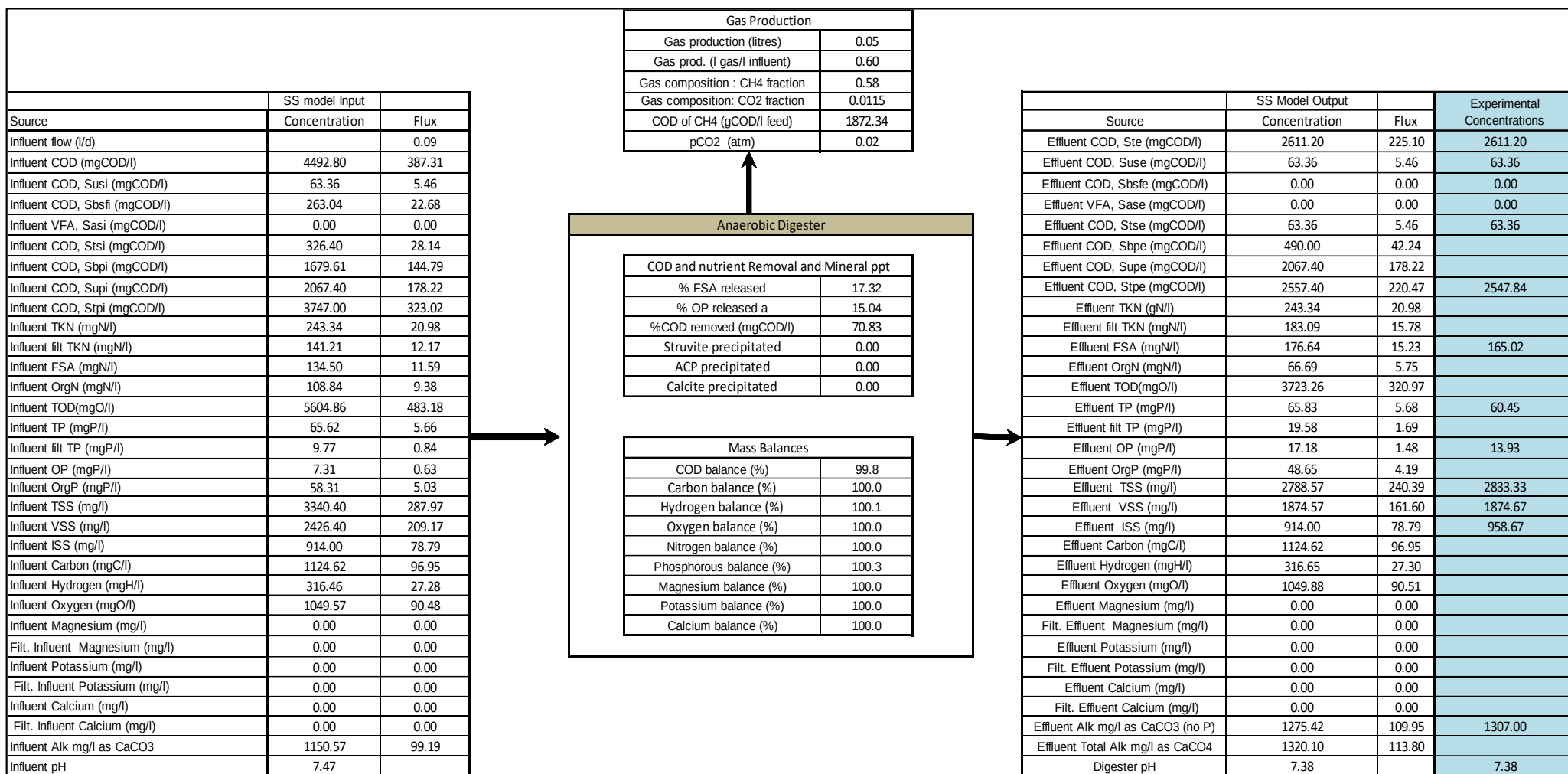


Figure 8.12: Steady-state simulations for SVG4 reactor (AugBMP test modelled results). Experimental effluent concentrations on the last column (in blue).

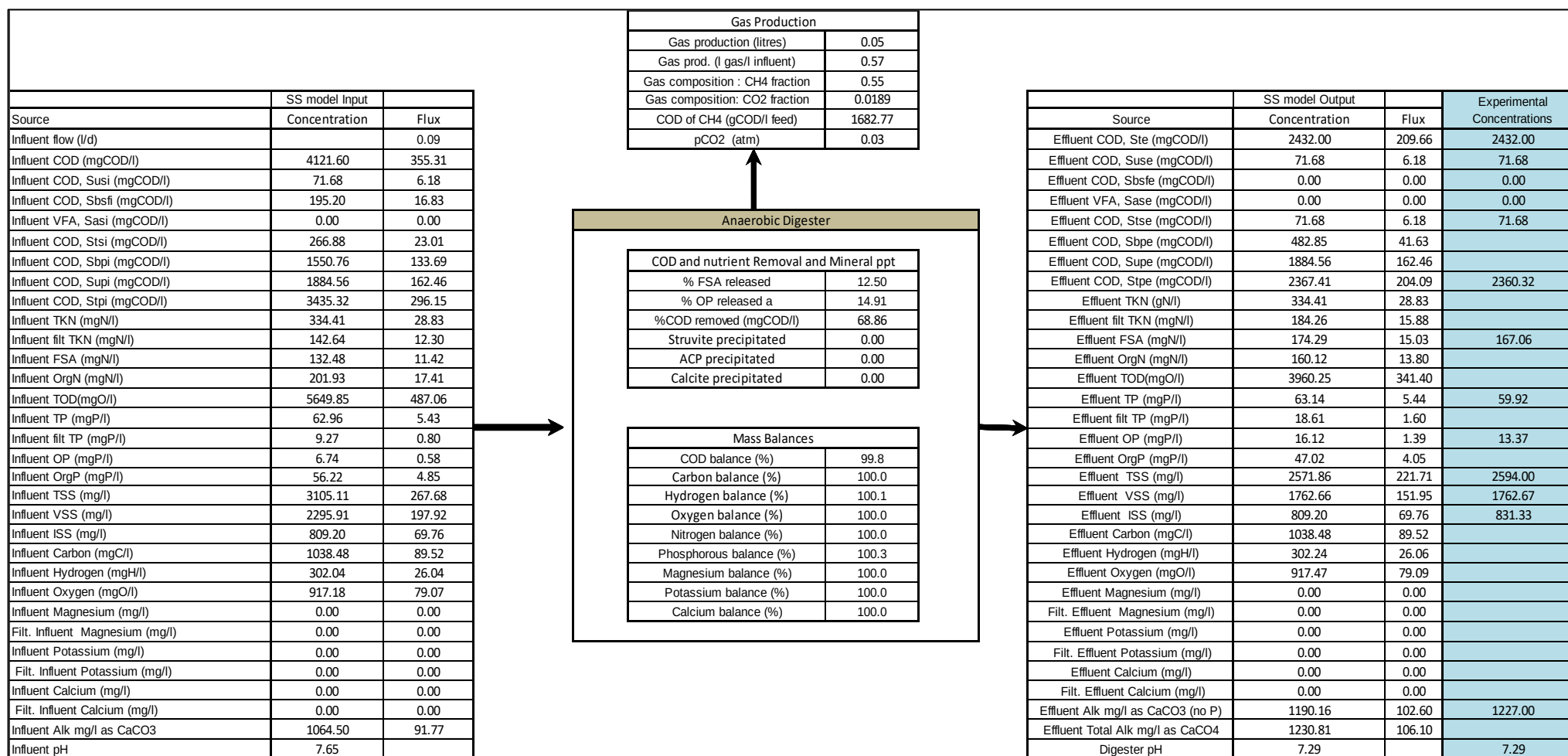


Figure 8.13: Steady-state simulations for SVG5 reactor (AugBMP test modelled results). Experimental effluent concentrations on the last column (in blue).

F. Appendix: Parameter estimation summary tables

The parameter estimation summary tables below include the experimental and modelled BPOCOD, UPOCOD, BPOVSS, UPOVSS and ISS concentrations. The corresponding mass fractions and elemental compositions are also presented. Accompanying these are related errors evaluations as discussed in **Section 3.7.2.3**.

	WAS	Seed - Start	Seed - End	Seed - End (Predicted)	Biomass	UPO & ER Seed	BPO Seed
Total COD		3283.2	2208.00	2208.03			
Filt COD		157.9	53.28	53.28			
Particulate COD		3125.28	2154.72	2154.75			
ZAD COD		419.4	230.55	267.16			
Total VSS		2052.0	1631.50	1631.50			
FSA, t=0		82.6	109.68	111.40			
OP, t=0		4.6	11.22	11.65			
Alk in		698.1	779.57	783.02			
pH in		7.5	7.30	7.30			
p_{CO_2} (atm)		0.00	0.01	0.01			
Total C		0.00	99.19	199.66			
ISS		682.0	675.50	682.00			
Ca		0.00	0.00	0.00			
Mg		0.00	0.00	0.00			
K		0.00	0.00	0.00			
TP		58.87	50.61				
TKN		237.83	239.40				
UPO COD		1699					
BPO COD		1007					
UPO VSS		1434					
BPO VSS		436					
f _S up							0.517
f _{cv} biomass init					2.31	1.185	2.307
f _c biomass init					0.46	0.412	0.457
f _n biomass init					0.06	0.090	0.062
f _p biomass init					0.02	0.029	0.015
f _s					0.00	0.00	0.00
f _o					0.28	0.39	0.28
f _h					0.18	0.0745	0.18
f _c + f _h + f _o + f _n + f _p + f _s					1.00	1.00	1.00
UPO	0.00	10.00	0.00	At Molar Mass e⁻ 12.0114 1.00791 15.999-2 14.007-3 30.9745			
BPO f _{cv}	0	10.00	0.01				
BPO f _n	3.0	1.00	2.97				
BPO f _p	0.18	1.00	0.18				
BPO f _c	11.94	1.00	11.94				
P _{co2}	0.00	1.00	0.00				
pH	0.00	1.00	0.00				
pH Adjustment	0.00						
	0.44						
		Mean error	0.60	32.07			
					Biomass	UPO &ER	BPO Seed
X (Cn)					0.038	0.034	0.038
Y (Ha)					0.1807	0.0739	0.1807
Z (Ob)					0.018	0.025	0.018
A (N)					0.004	0.006	0.004
B (P)					0.000	0.001	0.000
.i_H_Org_mol_perC					4.7	2.154	4.7
.i_O_Org_mol_perC					0.5	0.719	0.5
.i_N_Org_mol_perC					0.1	0.186	0.1
.i_P_Org_mol_perC					0.0	0.027	0.0

Figure 8.14: Control: PE summary table and the corresponding BPOCOD, UPOCOD, BPOVSS, and UPOVSS

	PS - Start	PS - End	Seed - Start	Seed - End	Total (test)	Total (test)	Predicted	Biomass	UPO &ER	BPO _{substrate}	BPO _{TEST}
Total COD	588.8	316.80	3283.2	2208.0	3872.0	2524.80	2524.80				
Filt COD	70.56	17.76	157.92	53.28	228.48	71.04	71.04				
Particulate COD	518	299	3125.28	2154.72	3644	2454	2453.76				
ZAD COD	0.00	42.94	419.40	230.55	419.4	273.5	263.6433				
Total VSS	406.67	227.83	2052.00	1631.50	2458.7	1859.3	1859.3				
FSA, t=0	39.31	45.35	82.64	109.68	122.0	155.0	157.9				
OP, t=0	1.31	1.66	4.58	11.22	5.9	12.9	12.2				
Alk	167.23	327.64	698.12	779.57	865.3	1107.2	977.9				
Ph	7.56	7.31	7.53	7.30	7.56	7.31	7.31				
pCO ₂ (atm)	0.00	0.00	0.00	0.01	0.00	0.01	0.00				
Total C	0.00	51.54	0.00	199.66	0.00	147.17	251.20				
ISS	144.67	211.17	682.00	675.50	826.7	886.7	826.7				
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
TP	3.51	1.34	58.87	50.61	62.38	51.95					
TKN	59.26	30.10	237.83	239.40	297.08	269.50	13.72				
UPO COD	290.7		1698.74		1989.49						
BPO COD	227.5		1007.14		1234.63						
UPO VSS	224.2		1433.78		1657.98						
BPO VSS	182.5		436.46		618.93						
fup (VSS)			0.67								0.51
fcv biomass init			2.31					2.31	1.20	1.25	1.99
fc biomass init			0.46					0.46	0.418	0.28	0.41
fn biomass init			0.06					0.06	0.08	0.03	0.05
fp biomass init			0.02					0.02	0.03	0.00	0.01
fs			0.00					0.00	0.00	0.00	0.00
fo			0.28					0.28	0.40	0.55	0.36
fh			0.18					0.18	0.07	0.14	0.17
fc+ fh + fo + fn+ fp + fs			1.00					1.00	1.00	1.00	1.00
UPO	0.00	Total COD End		10.00	0.00						
BPO fcv	0.0	VSS End		10.00	0.00						
BPO fn	8.5	FSA End		1.00	8.51						
BPO fp	0.46	OP End		1.00	0.46						
BPO fc	0.00	Alkalinity End		1.00	0.00						
P _{co2}	0.00	P _{co2}		1.00	0.00						
pH	0.00	pH		1.00	0.00						
pH Adjustment	0.00			1.00	0.00						
	0.43										
MEAN ERROR					0.34						
								Biomass	UPO &ER	BPO _{substrate}	BPO _{TEST}
X (Cn)			0.038					0.038	0.035	0.024	0.034
Y (Ha)			0.1807					0.181	0.073	0.136	0.167
Z (Ob)			0.018					0.018	0.025	0.034	0.023
A (N)			0.004					0.004	0.006	0.002	0.004
B (P)			0.000					0.000	0.001	0.000	0.000
C (S)			0.000					0.000	0.000	0.000	0.000
X			1.0					1.00	1.000	1.0	1.0
.i_H_Org_mol_perC			4.8					4.75	2.110	5.8	5.0
.i_O_Org_mol_perC			0.5					0.46	0.720	1.5	0.7
.i_N_Org_mol_perC			0.1					0.12	0.160	0.1	0.1
.i_P_Org_mol_perC			0.0					0.01	0.020	0.0	0.0
gVSS/mol			0.91					0.91	0.21	0.86	0.88
EDC			7.52					7.52	4.29	6.57	7.34
gCOD/mol			0.06					0.06	0.02	0.03	0.05

Figure 8.15: Test reactor 1: PE summary table and the corresponding BPOCOD, UPOCOD, BPOVSS, and UPOVSS

	PS - Start	PS - End	Seed	Seed	Total (test)	Total (test)	Predicted	Biomass	UPO &ER	BPO _{substrate}	BPO _{TEST}
Total COD	1894.4	521.60	3283.2	2208.0	5177.6	2729.60	2729.60				
Filt COD	151.84	18.40	157.92	53.28	309.76	71.68	71.68				
Particulate COD	1743	503	3125.28	2154.72	4868	2658	2657.92				
ZAD COD	0.00	79.76	419.40	230.55	419.4	310.3	393.6600				
Total VSS	1055.33	369.83	2052.00	1631.50	3107.3	2001.3	2001.3				
FSA, t=0	46.15	63.71	82.64	109.68	128.8	173.4	183.0				
OP, t=0	3.32	3.42	4.58	11.22	7.9	14.6	13.9				
Alk	347.81	557.26	698.12	779.57	1045.9	1336.8	1225.5				
Ph	7.33	7.08	7.53	7.30	7.33	7.08	7.08				
pCO ₂ (atm)	0.00	0.01	0.00	0.01	0.00	0.02	0.00				
Total C	0.00	244.51	0.00	199.66	0.00	320.55	444.18				
ISS	246.67	212.50	682.00	675.50	928.7	888.0	928.7				
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
TP	16.77	7.03	58.87	50.61	75.63	57.64					
TKN	77.70	175.00	237.83	239.40	315.53	414.40					
UPO COD	456.4		1698.74		2155.17						
BPO COD	1286.1		1007.14		2293.27						
UPO VSS	349.5		1433.78		1783.23						
BPO VSS	705.9		436.46		1142.35						
fup (VSS)			0.67								0.42
fcv biomass init			2.31					2.31	1.21	1.82	2.01
fc biomass init			0.46					0.46	0.421	0.35	0.39
fn biomass init			0.06					0.06	0.11	0.02	0.04
fp biomass init			0.02					0.02	0.03	0.00	0.01
fs	0.00		0.00					0.00	0.00	0.00	0.00
fo	0.89		0.28					0.28	0.37	0.45	0.39
fh	0.11		0.18					0.18	0.08	0.17	0.18
fc+ fh + fo + fn+ fp +	1.00		1.00					1.00	1.00	1.00	1.00
UPO	0.00	10.00	0.00								
BPO fcv	0.0	10.00	0.00								
BPO fn	92.4	1.00	92.39								
BPO fp	0.51	1.00	0.51								
BPO fc	0.00	1.00	0.00								
P _{co2}	0.00	1.00	0.00	At Molar Mass	e ⁻						
pH check	0.00	1.00	0.00	12.01	4.00						
P _{co2} check	0.00	1.00	0.00	1.01	1.00						
	0.00	1.00	0.00	16.00	-2.00						
	0.00	1.00	0.00	14.01	-3.00						
				30.97	5.00						
MEAN ERROR			3.44	32.07							
X (Cn)			0.0381					Biomass	UPO &ER	BPO	BPO
Y (Ha)			0.181					0.038	0.035	0.029	0.032
Z (Ob)			0.018					0.181	0.075	0.173	0.176
A (N)			0.004					0.018	0.023	0.028	0.024
B (P)			0.000					0.004	0.008	0.002	0.003
C (S)			0.0					0.000	0.001	0.000	0.000
X			1.0					0.00	0.000	0.0	0.0
.i_H_Org_mol_perC			4.8					1.00	1.000	1.0	1.0
.i_O_Org_mol_perC			0.5					4.75	2.140	6.0	5.4
.i_N_Org_mol_perC			0.1					0.46	0.660	1.0	0.8
.i_P_Org_mol_perC			0.01					0.12	0.220	0.1	0.1
gVSS/mol			0.91					0.01	0.03	0.00	0.01
EDC			7.52					0.91	0.21	0.87	0.96
								7.52	4.31	7.86	7.72

Figure 8.16: Test reactor 2: PE summary table and the corresponding BPOCOD, UPOCOD, BPOVSS, and UPOVSS

	PS - Start	PS - End	Seed	Seed	Total (test)	Total (test)	Predicted	Biomass	UPO &ER	BPO _{substrate}	BPO _{TEST}
Total COD	2457.6	563.20	3283.2	2208.0	5740.8	2771.20	2771.20				
Filt COD	224.16	20.32	157.92	53.28	382.08	73.60	73.60				
Particulate COD	2233	543	3125.28	2154.72	5359	2698	2697.60				
ZAD COD	0.00	0.00	419.40	230.55	419.4	230.6	330.9132				
Total VSS	1372.67	365.83	2052.00	1631.50	3424.7	1997.3	2000.0				
FSA, t=0	51.75	68.91	82.64	109.68	134.4	178.6	191.4				
OP, t=0	3.78	5.01	4.58	11.22	8.4	16.2	20.1				
Alk	226.60	621.29	698.12	779.57	924.7	1400.9	1099.5				
Ph	7.32	7.23	7.53	7.30	7.32	7.23	7.23				
pCO ₂ (atm)	0.00	0.01	0.00	0.01	0.00	0.01	0.00				
Total C	0.00	335.32	0.00	199.66	0.00	388.33	534.98				
ISS	356.67	256.50	682.00	675.50	1038.7	932.0	1038.7				
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
TP	19.54	5.81	58.87	50.61	78.41	56.42					
TKN	92.58	121.80	237.83	239.40	330.40	361.20					
UPO COD	479.1		1698.74		2177.84						
BPO COD	1754.3		1007.14		2761.48						
UPO VSS	340.7		1433.78		1774.45	1874.73					
BPO VSS	1032.0		436.46		1468.46						
fup (VSS)			0.67								0.38
fcv biomass init			2.31					2.31	1.23	1.70	1.88
fc biomass init			0.46					0.46	0.427	0.32	0.36
fn biomass init			0.06					0.06	0.10	0.02	0.03
fp biomass init			0.02					0.02	0.03	0.00	0.01
fs	0.00		0.00					0.00	0.00	0.00	0.00
fo	0.89		0.28					0.28	0.37	0.49	0.43
fh	0.11		0.18					0.18	0.07	0.17	0.17
fc+ fh + fo + fn+ fp +	1.00		1.00					1.00	1.00	1.00	1.00
UPO	0.00	10.00	0.00								
BPO fcv	7.1	0.00	0.00								
BPO fn	165.4	1.00	165.43								
BPO fp	15.36	1.00	15.36								
BPO fc	0.00	1.00	0.00								
P _{CO2}	0.00	1.00	0.00	At Molar Mass	e ⁻						
pH check	0.00	1.00	0.00	12.01	4.00						
P _{CO2} check	0.00	1.00	0.00	1.01	1.00						
	0.00			16.00	-2.00						
				14.01	-3.00						
				30.97	5.00						
MEAN ERROR			11.30	32.07							
X (Cn)			0.0381					Biomass	UPO &ER	BPO	BPO
Y (Ha)			0.181					0.038	0.036	0.027	0.030
Z (Ob)			0.018					0.181	0.074	0.167	0.171
A (N)			0.004					0.018	0.023	0.031	0.027
B (P)			0.000					0.004	0.007	0.001	0.002
C (S)			0.0					0.000	0.001	0.000	0.000
X			1.0					0.00	0.000	0.0	0.0
.i_H_Org_mol_perC			4.8					1.00	1.000	1.0	1.0
.i_O_Org_mol_perC			0.5					4.75	2.070	6.2	5.7
.i_N_Org_mol_perC			0.1					0.46	0.650	1.1	0.9
.i_P_Org_mol_perC			0.01					0.12	0.200	0.0	0.1
gVSS/mol			0.91					0.01	0.03	0.00	0.01
EDC			7.52					0.91	0.20	0.90	1.00
								7.52	4.32	7.80	7.73

Figure 8.17: Test reactor 3: PE summary table and the corresponding BPOCOD, UPOCOD, BPOVSS, and UPOVSS

	PS - Start	PS - End	Seed	Seed	Total (test)	Total (test)	Predicted	Biomass	UPO &ER	BPO _{substrate}	BPO _{TEST}
Total COD	1209.6	403.20	3283.2	2208.0	4492.8	2611.20	2611.20				
Filt COD	168.48	10.08	157.92	53.28	326.40	63.36	63.36				
Particulate COD	1041	393	3125.28	2154.72	4166	2548	2547.84				
ZAD COD	0.00	58.42	419.40	230.55	419.4	289.0	350.0138				
Total VSS	604.67	243.17	2052.00	1631.50	2656.7	1874.7	1874.6				
FSA, t=0	51.86	55.34	82.64	109.68	134.5	165.0	176.6				
OP, t=0	2.73	2.71	4.58	11.22	7.3	13.9	17.2				
Alk	452.46	527.43	698.12	779.57	1150.6	1307.0	1275.4				
Ph	7.47	7.38	7.53	7.30	7.47	7.38	7.38				
pCO ₂ (atm)	0.00	0.00	0.00	0.01	0.00	0.01	0.01				
Total C	0.00	124.06	0.00	199.66	0.00	0.00	323.72				
ISS	232.00	283.17	682.00	675.50	914.0	958.7	914.0				
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
TP	6.21	5.20	58.87	50.61	65.08	55.81					
TKN	53.10	47.60	237.83	239.40	290.92	287.00					
UPO COD	368.7		1698.74		2067.40						
BPO COD	672.5		1007.14		1679.60						
UPO VSS	232.3		1433.78		1666.12	1749.43					
BPO VSS	372.3		436.46		808.79						
fup (VSS)			0.67								0.46
fcv biomass init			2.31					2.31	1.24	1.81	2.08
fc biomass init			0.46					0.46	0.432	0.33	0.40
fn biomass init			0.06					0.06	0.04	0.01	0.04
fp biomass init			0.02					0.02	0.03	0.00	0.01
fs	0.00		0.00					0.00	0.00	0.00	0.00
fo	0.89		0.28					0.28	0.43	0.48	0.37
fh	0.11		0.18					0.18	0.07	0.18	0.18
fc+ fh + fo + fn+ fp +	1.00		1.00					1.00	1.00	1.00	1.00
UPO	0.00	10.00	0.00								
BPO fcv	0.0	10.00	0.08								
BPO fn	135.1	1.00	135.13								
BPO fp	10.54	1.00	10.54								
BPO fc	0.00	1.00	0.00	At Molar Mass	e ⁻						
P _{CO2}	0.00	1.00	0.00	12.01	4.00						
pH check	0.00	1.00	0.00	1.01	1.00						
P _{CO2} check	0.00	1.00	0.00	16.00	-2.00						
	0.00			14.01	-3.00						
				30.97	5.00						
MEAN ERROR			5.61	32.07							
X (Cn)			0.0381					Biomass	UPO &ER	BPO	BPO
Y (Ha)			0.181					0.038	0.036	0.028	0.033
Z (Ob)			0.018					0.181	0.068	0.175	0.178
A (N)			0.004					0.018	0.027	0.030	0.023
B (P)			0.000					0.004	0.003	0.001	0.003
C (S)			0.0					0.000	0.001	0.000	0.000
X			1.0					0.00	0.000	0.0	0.0
.i_H_Org_mol_perC			4.8					1.00	1.010	1.0	1.1
.i_O_Org_mol_perC			0.5					4.75	1.920	6.5	5.9
.i_N_Org_mol_perC			0.1					0.46	0.760	1.1	0.8
.i_P_Org_mol_perC			0.01					0.12	0.080	0.0	0.1
gVSS/mol			0.91					0.01	0.03	0.00	0.01
EDC			7.52					0.91	0.20	0.94	1.04
								7.52	4.35	8.32	8.52

Figure 8.18: Test reactor 4: PE summary table and the corresponding BPOCOD, UPOCOD, BPOVSS, and UPOVSS

	PS - Start	PS - End	Seed	Seed	Total (test)	Total (test)	Predicted	Biomass	UPO &ER	BPO _{substrate}	BPO _{TEST}
Total COD	838.4	224.00	3283.2	2208.0	4121.6	2432.00	2432.00				
Filt COD	108.96	18.40	157.92	53.28	266.88	71.68	71.68				
Particulate COD	729	206	3125.28	2154.72	3855	2360	2360.32				
ZAD COD	0.00	218.72	419.40	230.55	419.4	449.3	475.7594				
Total VSS	550.80	131.17	2052.00	1631.50	2602.8	1762.7	1762.7				
FSA, t=0	49.85	57.38	82.64	109.68	132.5	167.1	174.3				
OP, t=0	2.16	2.15	4.58	11.22	6.7	13.4	16.1				
Alk	366.38	447.43	698.12	779.57	1064.5	1227.0	1190.2				
Ph	7.65	7.29	7.53	7.30	7.65	7.29	7.29				
pCO ₂ (atm)	0.00	0.00	0.00	0.01	0.00	0.01	0.02				
Total C	0.00	125.45	0.00	199.66	0.00	77.09	325.11				
ISS	127.20	155.83	682.00	675.50	809.2	831.3	809.2				
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
TP	5.81	4.55	58.87	50.61	64.68	55.16					
TKN	67.84	43.40	237.83	239.40	305.67	282.80					
UPO COD	185.8	19.79	1698.74		1884.56						
BPO COD	543.6		1007.14		1550.76						
UPO VSS	122.5		1433.78		1556.30						
BPO VSS	428.3		436.46		864.75						
f _{up} (VSS)			0.67								0.46
f _{cv} biomass init			2.31					2.31	1.21	1.27	1.79
f _c biomass init			0.46					0.46	0.421	0.29	0.38
f _n biomass init			0.06					0.06	0.10	0.02	0.04
f _p biomass init			0.02					0.02	0.03	0.00	0.01
f _s			0.00					0.00	0.00	0.00	0.00
f _o			0.28					0.28	0.38	0.56	0.42
f _h			0.18					0.18	0.07	0.13	0.16
f _c + f _h + f _o + f _n + f _p + f _s			1.00					1.00	1.00	1.00	1.00
UPO	0.00	10.00	0.00								
BPO f _{cv}	0.0	0.00	0.00								
BPO f _n	52.3	1.00	52.35								
BPO f _p	7.59	1.00	7.59								
BPO f _c	0.00	1.00	0.00	At Molar Mass	e ⁻						
P _{CO₂}	0.00	1.00	0.00		12.01	4.00					
pH check	0.00	1.00	0.00		1.01	1.00					
P _{CO₂} check	0.00	1.00	0.00		16.00	-2.00					
	0.00	1.00	0.00		14.01	-3.00					
					30.97	5.00					
MEAN ERROR			3.53	32.07							
X (Cn)			0.0381					Biomass	UPO &ER	BPO	BPO
Y (Ha)			0.181					0.038	0.035	0.024	0.031
Z (Ob)			0.018					0.181	0.074	0.133	0.157
A (N)			0.004					0.018	0.024	0.035	0.026
B (P)			0.000					0.004	0.007	0.001	0.003
C (S)			0.0					0.000	0.001	0.000	0.000
X			1.0					0.00	0.000	0.0	0.0
.i_H_Org_mol_perC			4.8					1.00	1.000	1.0	1.0
.i_O_Org_mol_perC			0.5					4.75	2.110	5.5	5.0
.i_N_Org_mol_perC			0.1					0.46	0.670	1.4	0.8
.i_P_Org_mol_perC			0.01					0.12	0.200	0.1	0.1
gVSS/mol			0.91					0.01	0.03	0.00	0.01
EDC			7.52					0.91	0.21	0.81	0.89
								7.52	4.32	6.47	7.14

Figure 8.19: Test reactor 5: PE summary table and the corresponding BPOCOD, UPOCOD, BPOVSS, and UPOVSS

G. Appendix: Experimental control and five settling velocity groups concentrations and mass fractions

These outcomes were derived from **Table 4.12** and **Table 4.13** above. Subscript “DnC” next to COD, VSS, TSS, and so forth means concentrations where dilutions are not considered, B: SVG substrate concentrations after subtracting inoculum concentrations, C: Dilution factors applied to SVG substrate concentrations, and D: Resulting mass fractions.

			INOCULUM			SVG1			SVG2			SVG3			SVG4			SVG5		
A: AUGBMP RAW OUTCOMES DERIVED FROM TABLE 4.13 ABOVE - DILUTION FACTORS NOT CONSIDERED																				
	Sample Formular or Source OR Measurement	Units	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic
COD _{DnC}	See Table 3.9 for total UPO and BPO COD	mgCOD/l	2155	971	-	2454	1190	-	2658	2210	-	2698	2495	-	2548	1619	-	2360	1494	-
VSS _{DnC}	See Table 3.9 for VSS, UPO VSS & BPO VSS	mgVSS/l	1632	420	-	1859	599	-	2001	1106	-	2000	1425	-	1874	783	-	1763	840	-
TSS _{DnC}	See Table 3.9 for TSS, UPO TSS & BPO TSS	mgTSS/l	1632	420	-	1859	599	-	2001	1106	-	2000	1425	-	1874	783	-	1763	840	-
ISS _{DnC}	See Table 3.9 for ISS measurement	mgISS/l	-	-	682	-	-	827	-	-	929	-	-	1039	-	-	914	-	-	809
TKN _{DnC}	See Table 3.9 for TKN (Nti), UPO (Nousi) & BPO N (Nobpi)	mgN/l	128	27	83	132	33	122	191	45	129	176	44	134	151	31	135	153	35	132
TOC _{DnC}	See Section 3.6.6 for C calculations	mgC/l	750	99	-	854	147	-	925	321	-	939	388	-	887	203	-	821	166	-
TP _{DnC}	See Table 3.9 for TP (Pti), UPO (Pousi) & BPO P (Pobpi)	mgP/l	41	7	5	44	7	6	49	7	8	49	8	8	47	7	7	45	7	7
OrgN _{DnC}	See Table 3.9 for total organic N, Noupj and Nobpi	mgN/l	128	27	-	132	33	-	191	45	-	176	44	-	151	31	-	153	35	-
OrgP _{DnC}	See Table 3.9 for total organic P, Poupi and Pobpi	mgP/l	41	7	-	44	7	-	49	7	-	49	8	-	47	7	-	45	7	-
B: SETTLING VELOCITY GROUP 1 TO 5 SUBSTRATE CONCENTRATIONS (Inoculum concentrations removed) - DILUTION FACTORS NOT CONSIDERED																				
Substrate COD _{DnC}	COD from SVGn subtract COD from inoculum	mgCOD/l				299	219	-	503	1239	-	543	1524	-	393	648	-	206	523	-
Substrate VSS _{DnC}	VSS from SVGn subtract VSS from inoculum	mgVSS/l				228	179	-	370	686	-	368	1004	-	243	362	-	131	420	-
Substrate TSS _{DnC}	TSS from SVGn subtract TSS from inoculum	mgTSS/l				228	179	-	370	686	-	368	1004	-	243	362	-	131	420	-
Substrate ISS _{DnC}	ISS from SVGn subtract ISS from inoculum	mgISS/l				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Substrate TKN _{DnC}	TKN from SVGn subtract TKN from inoculum	mgN/l				4	6	39.3	62	18	46.1	47	17	51.7	23	3	51.9	24	8	49.8
Substrate TOC _{DnC}	TOC from SVGn subtract TOC from inoculum	mgC/l				104	48	-	175	221	-	189	289	-	137	103	-	72	67	-
Substrate TP _{DnC}	TP from SVGn subtract TP from inoculum	mgP/l				2	0	1.31	8	0	3.32	7	1	3.78	5	0	2.73	3	0	2.16
Substrate OrgN _{DnC}	OrgN from SVGn subtract OrgN from inoculum	mgN/l				4	6	-	62	18	-	47	17	-	23	3	-	24	8	-
Substrate OrgP _{DnC}	OrgP from SVGn subtract OrgP from inoculum	mgP/l				2	0	-	8	0	-	7	1	-	5	0	-	3	0	-
C: SETTLING VELOCITY GROUP 1 TO 5 SUBSTRATE CONCENTRATIONS (Dilution Factors considered) -- DILUTION FACTORS CONSIDERED																				
Dilution Factor for the respective settling velocity group - CONSIDERED						4	4	4	2	2	2	2	2	2	2	2	2	2	2	2
COD	Substrate COD x Dilution Factor	mgCOD/l				1196	875	-	1006	2478	-	1086	3047	-	786	1295	-	411	1047	-
VSS	Substrate VSS x Dilution Factor	mgVSS/l				911	715	-	740	1371	-	737	2008	-	485	724	-	262	839	-
TSS	Substrate TSS x Dilution Factor	mgTSS/l				911	715	-	740	1371	-	737	2008	-	485	724	-	262	839	-
ISS	Substrate ISS x Dilution Factor	mgISS/l				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TKN	Substrate TKN x Dilution Factor	mgN/l				14.9	24.2	157.3	124.3	35.1	92.3	94.9	34.3	103.5	45.0	7.0	103.7	48.2	15.1	99.7
TOC	Substrate TOC x Dilution Factor	mgC/l				416	192	-	350	443	-	378	578	-	274	207	-	143	134	-
TP	Substrate TP x Dilution Factor	mgP/l				8.3	1.4	5.2	15.6	0	6.63	14.88	2	7.56	10.2	0.0	5.5	6.5	0.0	4.3
OrgN	Substrate OrgN x Dilution Factor	mgN/l				15	24.2	-	124	35.1	-	95	34.33	-	45	7.0	-	48	15.1	-
OrgP	Substrate OrgP x Dilution Factor	mgP/l				8.3	1.4	-	15.6	0.2	-	14.88	2.45	-	10.2	0.0	-	6.5	0.0	-
D: MASS RATIOS: INOCULUM AND FIVE SETTLING VELOCITY GROUPS' SUBSTRATE																				
		Units	INOCULUM			SVG1			SVG2			SVG3			SVG4			SVG5		
			UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic	UPO	BPO	Inorganic
VSS/TSS	VSS/TSS	gVSS/gTSS				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ISS/TSS	VSS/TSS	gISS/gTSS				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
f _{cv}	COD/mass,VSS	gCOD/gVSS	1.32	2.31	-	1.31	1.22	-	1.36	1.81	-	1.47	1.52	-	1.62	1.79	-	1.57	1.25	-
f _c	TOC/mass,VSS	gC/gVSS	0.46	0.24	-	0.46	0.27	-	0.47	0.32	-	0.51	0.29	-	0.56	0.29	-	0.55	0.16	-
f _n	OrgN/mass,VSS	gN/gVSS	0.1	0.04	-	0.02	0.03	-	0.17	0.03	-	0.13	0.02	-	0.09	0.01	-	0.18	0.02	-
f _p	OrgP/mass,VSS	gP/gVSS	0.025	0.005	-	0.01	0.002	-	0.02	0.00	-	0.02	0.001	-	0.02	0.00	-	0.02	0.00	-
f _s	OrgS/mass,VSS		0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
f _o	16/18(1-f _o)/8-8f _c /12-17f _n /14-26/32f _s		0.34	0.45	-	0.45	0.56	-	0.26	0.47	-	0.27	0.53	-	0.26	0.51	-	0.17	0.64	-
f _h	8(4f _c /12+f _n -2f _c /16-3f _n /14)		0.07	0.27	-	0.07	0.14	-	0.08	0.18	-	0.07	0.16	-	0.06	0.19	-	0.07	0.19	-
f _c +f _n +f _p +f _h +f _o			1.00	1.00	-	1.00	1.00	-	1.00	1.00	-	1.00	1.00	-	1.00	1.00	-	1.00	1.00	-