INVESTIGATION INTO THE TECHNICAL FEASIBILITY OF BIOLOGICAL TREATMENT OF PRECIOUS METAL REFINING WASTEWATER

THESIS

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ABSTRACT

The hydrometallurgical refining of platinum group metals results in large volumes of liquid waste that requires suitable treatment before any disposal can be contemplated. The wastewater streams are characterized by extremes of pH, high inorganic ion content (such as chloride), significant residual metal loads and small amounts of entrained organic compounds. Historically these effluents were housed in evaporation reservoirs, however lack of space and growing water demands have led Anglo Platinum to consider treatment of these effluents. The aim of this study was to investigate whether biological wastewater treatment could produce water suitable for onsite reuse. Bench-scale activated sludge and anaerobic digestion for co-treatment of an acidic refinery waste stream with domestic wastewater were used to give preliminary data. Activated sludge showed better water treatment at lab scale in terms of removal efficiencies of ammonia (approximately 25%, cf. 20% in anaerobic digestion) and COD (70% cf. 43% in digestion) and greater robustness when biomass health was compared. Activated sludge was consequently selected for a pilot plant trial. The pilot plant was operated on-site and performed comparably with the bench-scale system, however challenges in the clarifier design led to losses of biomass and poor effluent quality (suspended solids washout). The pilot plant was unable to alter the pH of the feed, but a two week maturation period resulted in the pH increasing from 5.3 to 7.0. Tests on algal treatment as an alternative or follow-on unit operation to activated sludge showed it not to be a viable process. The activated sludge effluent was assessed for onsite reuse in flotation and it was found that there was no significant difference between its flotation performance and that of the process water currently used, indicating the effluent generated by the biological treatment system can be used successfully for flotation. Flotation is the method whereby minerals refining operations recover minerals of interest from ore through the addition of chemicals and aeration of the ore slurry. Target minerals adhere to the bubbles and can be removed from the process.

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LIST OF ABBREVIATIONS

AD	Anaerobic digestion
AMD	Acid mine drainage
AOP	Advanced oxidation processes
APHA	American Public Health Association
AS	Activated Sludge
AUR	Ammonium uptake rate
BOD	Biological oxygen demand
BOD_{20}	20 day Biological oxygen demand
BOD_5	5 day Biological oxygen demand
CA	Carbonic anhydrase
CFU	Colony forming units
COD	Chemical oxygen demand
CSTR	Continuously stirred tank reactor
DIC	Dissolved inorganic carbon
DO	Dissolved oxygen
DT	Distillation
DWA	Department of Water Affairs (formerly DWAF)
DWAF	Department of Water Affairs and Forestry (now DWA)
HRAP	High rate algal pond
HRT	Hydraulic retention time
ISO	International Organisation for Standardisation
IX	Ion exchange
MCRT	Mean cell retention time
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
PMR	Precious metal refinery
PSS	Primary settled sludge
RAS	Return activated sludge
RSBR	Recycle sludge bed reactor
SD	Standard deviation
SOUR	Specific oxygen uptake rate
SRT	Sludge retention time
SS	Suspended solids
SVI	Sludge volume index
SX	Solvent extraction
TN	Total nitrogen
TOC	Total organic carbon
TSS	Total suspended solids
VFA	Volatile fatty acid
VSS	Volatile suspended solids
WAS	Waste activated sludge
WSTW	Waterval sewage treatment works

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CHAPTER 1

INTRODUCTION

Given the increasing demands on limited water and energy resources in South Africa, it is important to minimise the volume of wastewater which is not reused or recycled (Zbontar and Glavic, 2000). Historically, pollution control has meant end-of-pipe treatment; however, stricter environmental legislation and the high cost and relative ineffectiveness of this option have encouraged re-evaluation of pollution prevention strategies (Cervantes and Pavlostathis, 2006). Moreover, significant evidence has demonstrated a causal relationship between the economic and environmental performance of companies, given that employing pollution reduction strategies enhances profit by increasing efficiency, decreasing compliance costs and mitigating future liabilities (King and Lenox, 2001).

Platinum group metals (PGMs) or elements (PGEs) are collective names used when referring to the six precious metal elements: platinum (Pt), palladium (Pd), rhodium (Rh), iridium (Ir), ruthenium (Ru) and osmium (Os). In the Earth's crust, the average concentration of these metals is estimated to range from 0.0001 g/t for rhodium to 0.015 g/t for palladium, with platinum, ruthenium, osmium and iridium present in equally small concentrations (Ravindra *et al*., 2004). The PGMs have unique properties of corrosion resistance, heat resistance, high melting point, high mechanical strength, good ductility and catalytic activity (Ravindra *et al*., 2004). These properties have led to their use in jewellery manufacture, automotive catalyst manufacture, and in the electronics, glass, electrical, petroleum and medical industries (Johnson-Matthey, 2002; Ravindra *et al*., 2004).

All the PGMs are generally associated with each other in the Earth's crust. However, the relative proportions of the individual metals are not constant for all PGM deposits. Platinum group metals occur naturally in nickel, copper and iron sulphide seams (Ravindra *et al*., 2004). The world's largest source of PGMs is the South African Bushveld Igneous Complex (BIC), formed around 2000 million years ago. It consists of a series of distinct layers, three of which are of economic importance as sources of PGMs. These are the Merensky Reef, the Upper Group 2 (UG2) Reef, and the Platreef. The Merensky Reef has been the principal source of PGMs since it was first worked in 1925 and now produces 50 % of all the platinum-bearing ore processed in South Africa. In 1999, the UG2 Reef increased production to yield 42 % of the country's platinum, and the Platreef only began to be exploited on a large scale in 1993 (Johnson-Matthey, 2003). Mill head grades of BIC ore (a measure of the PGM content of the ore on entering the first processing stage) are typically between 4 and

7 g.ton^{-1}. This translates to between 7 and 12 tons of ore being processed to produce a single ounce of platinum (Johnson-Matthey, 2003). An overview of the entire process involved in producing PGM product is shown in Figure 1.1.

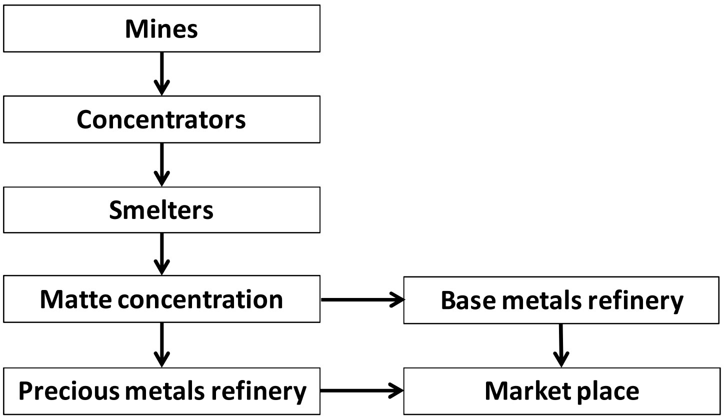


Figure 1.1 Simple overview of the PGM production process (Robinson, 2009, pers. comm).

In the concentrators, the ore is crushed and milled to reduce rock sizes and expose the minerals containing the PGMs. The rock is mixed with water and other reagents and air is pumped through this to create bubbles to which the PGM-containing particles adhere. These float to the surface and are removed as a soapy froth called concentrate. This process is known as flotation. The PGM concentration of this concentrate varies between 100 and 1000 g.ton^{-1} (Johnson-Matthey, 2003). The concentrate is dried and smelted in furnaces reaching temperatures of 1500 °C and higher. During this process a matte containing the PGMs is separated from the unwanted minerals, which form a slag and are discarded. The matte is transferred to converters, where air is blown through it in order to remove iron and sulphur. The PGM content of converter matte is in excess of 1400 g.ton^{-1} (Johnson-Matthey, 2003). The next step is to separate base metals from the PGMs. The base metals are transferred to a base metal refinery, where sulphate and metals such as cobalt, nickel and copper are refined for the marketplace. The final stage is the separation and purification of the six PGMs, plus gold, which is a by-product of the ore body. This is performed using hydrometallurgical methods such as solvent extraction and ion exchange. Figure 1.2 illustrates the order in which the precious metals are extracted from the matte. The soluble metals, gold, palladium and platinum are generally removed first. The insoluble metals are then removed; with rhodium usually last to be extracted from the concentrate (Robinson, 2009, pers. comm.).

The complex nature of the solution chemistry of PGMs contributes to the difficulty in developing methods for the separation of these metals from one another (Kramer *et al.*, 2004). There are a number of physico-chemical strategies available for the refining of precious metals, but current general trends in metal extraction of PGMs from heterogeneous solutions are ion exchange and solvent extraction. These are often used in combination, as the advantages of ion exchange (high concentrating efficiency and ease of phase separation) offset the inherent disadvantages of solvent extraction (phase separation difficulties during multiple and back-extraction and eventual flooding of the solvent with entrained contaminants) (Corvalan *et al.*, 2004).

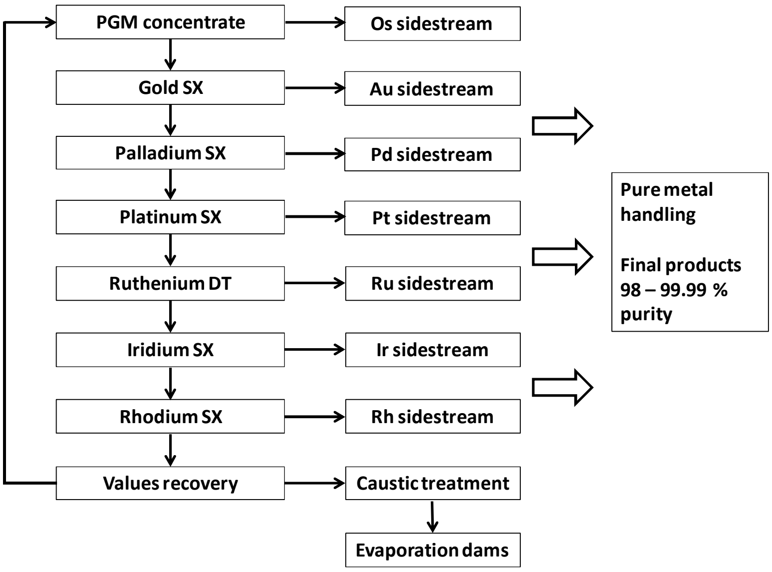


Figure 1.2 Overview of Anglo Platinum Precious Metal Refinery (PMR) flow sheet. SX: Solvent extraction, DT: Distillation, IX: Liquid ion exchange (Robinson, 2009, pers. comm.).

Solvent extraction involves extracting the metal of interest by contacting the concentrate with an organic reagent that will react with a particular metal in the concentrate and result in its conversion to a form soluble in the solvent. Usually, solvent extraction follows three steps: (1) the extraction step, where the metal ions are solubilised in the organic phase, (2) the scrubbing step, where any co-extracted metals are removed from the organic phase, and (3), the stripping step, where the isolated metal ions are removed from the organic phase (Bernardis *et al.*, 2005). The extraction of metals in this way is widely employed for selective recovery. It is one of the most common methods used for the separation of PGMs from aqueous solutions due to the simplicity of the process (Gholivand and Nozari, 2000). However, these methods are relatively expensive with elaborate equipment, high operation costs and energy requirements. At the Anglo Platinum refinery, these organic solvents include methyl-*iso*-butylketone (for gold extraction), a *beta*-hydroxyoxime (for palladium extraction), an amine (for platinum extraction) and an amide extractant (for iridium extraction) (Cole *et al.*, 2006). A major cost is the regeneration and/or disposal of the solvent liquid and the spent solvent itself, where these organic solvents, strip and scrub liquors all represent a large environmental burden in terms of disposal (Wong *et al.*, 2003). The scrub liquors are of particular interest for the current study, as they often require reprocessing due to the significant amounts of PGMs that they contain (Bernardis *et al*., 2005).

The refined PGMs usually have a purity of over 99.95 % and are produced in a number of forms, including ingots, grains or fine powders known as sponges. However, a percentage of the mined PGMs are not recovered by these techniques and remain in the wastewaters stored by the refineries in evaporation dams.

1.1 Problem statement

The refining of PGMs using hydrometallurgical processes such as solvent extraction and ion exchange results in large volumes of liquid waste that requires suitable treatment before any disposal can be contemplated. The wastewater streams are characterized by extremes of pH, high inorganic ion content (such as chloride), significant residual metal loads and small amounts of entrained organic compounds such as those mentioned previously. The composition of these wastewaters precludes any direct discharge to surrounding surface waters, and renders them untreatable by conventional domestic wastewater treatment plants. Thus, they must be managed within the refinery.

Historically, precious metal refiners have opted to store wastewaters generated during refining in favour of complete treatment or remediation, intending to extract more precious metals when recovery technologies improve. A large number of wastewaters are generated during refining, which are often combined into two, namely an acidic and a caustic stream. At the Anglo Platinum Precious Metal Refinery (PMR) in Rustenburg (Figure 1.1), the acidic stream (on average 3300 m^3 per month) is processed through a values recovery plant, which involves the addition of iron as a flocculant, followed by increasing the pH with calcium carbonate. The treated wastewater is then stored in evaporation reservoirs and precipitated metals would be sent to the head of works for reprocessing. The increasing concentration of calcium carbonate, high concentrations of other salts such as sodium chloride, the presence of large quantities of soluble base metals and ammonia and small amounts of organic solvent has resulted in generating an extremely dense wastewater which cannot easily be evaporated. Currently, Anglo Platinum is constructing a treatment plant which will incorporate an additional step following values recovery with the aim of removing calcium carbonate, decreasing the density and allowing for further evaporation and recovery of water in vacuum evaporators. The solid waste generated during evaporation will then be disposed of at a landfill and the water recovered used elsewhere in the refinery. The new process recovers residual metals in the wastewater and generates pure water for reuse; however it is extremely energy intensive and creates a recalcitrant sludge comprising mixed metals, which requires disposal as a hazardous waste. As a result the organisation continues to investigate more sustainable treatment technologies.

1.2 Rationale and hypothesis

The biological treatment of industrial wastewaters through combination with domestic wastewater has been successfully demonstrated in a number of industries. The foundation for the effective treatment of these readily degradable wastewaters is that of co-metabolism. The domestic wastewater provides the microorganisms with growth substrate while they adapt to the industrial component, before beginning to degrade recalcitrant molecules therein.

This thesis will ask the question: can this principle be employed in the biological treatment of acidic wastewater generated by the Anglo Platinum PMR? Two bench-scale treatment technologies will be investigated for their ability to improve the water quality and increase the pH of the effluent: anaerobic digestion and activated sludge. The technology which achieves superior effluent water quality and displays an enhanced robustness will be scaled up to a pilot plant. Potential alternative treatment technologies, modifications to the blended feed and possible reuse of the effluent will also be considered.

1.3 Aims and objectives

The aim of this investigation was to determine whether biological processes could successfully treat an acidic wastewater (generated during precious metal refining) to produce reusable water, by co-treatment with domestic wastewater. The objectives set to achieve this aim were the following:

- Comparison of the remediation capabilities of an anaerobic digester and activated sludge process at bench-scale.
- Design and operation of a pilot plant based on the results obtained from the bench-scale investigation.
- Examination of alternative treatment options, including algal processes and feed manipulation, for application upstream and downstream in the process train.
- Assessment of the potential for reuse of the treated effluent within Anglo Platinum's Rustenburg facility for metal refining itself, or other onsite applications according to the Department of Water Affairs (DWA, formerly Department of Water Affairs and Forestry or DWAF) industrial water reuse limits.

The research approach used to meet the objectives is summarised in Figure 1.3

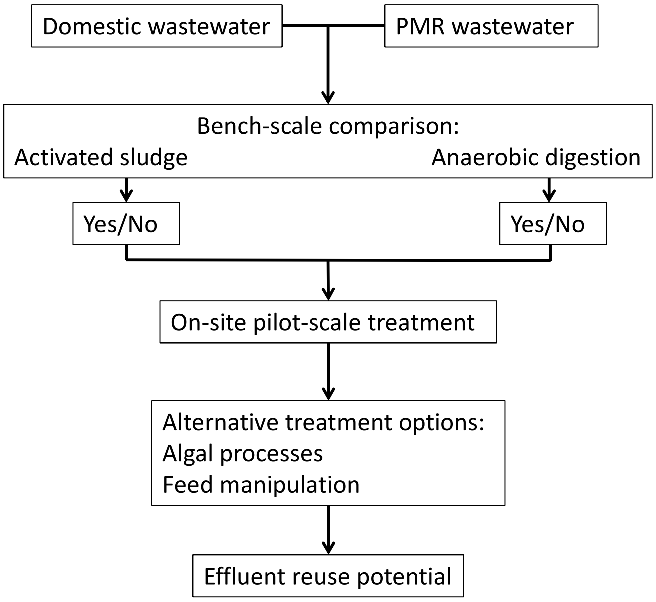


Figure 1.3 Research approach flow diagram

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

It is a well-known fact that water is a scarce resource in South Africa (Otieno and Ochieng, 2004). The mining, power generation and industrial sectors in South Africa utilise 8 % of the total water demand (DWAF, 2009) and as industrialisation and economic growth continue this figure has been projected to more than double by 2030 (Walmsley *et al.*, 1999). The drive towards sustainable development requires the industrial sector to assess its potable water needs and determine how to reduce the environmental impact of its activities.

2.1.1 Environmental consequences of industrial contaminants

The presence of essential and non-essential metals in the environment is of concern as elevated concentrations result in toxic effects on living organisms. The toxicity of metals is largely attributed to non-specific binding of metal cations to biomolecules which causes structural and functional modifications within cells (Di Giulio *et al.*, 1995). Runoff from catchments containing urban and industrial areas can contain metals in high enough concentrations to adversely affect both plants and animals populating the receiving waters. The presence of lead may lead to the mortality of gastropods and fish; copper, the normal functioning of gastropods and molluscs; and cadmium, copper, lead and zinc, the survival of crustacea. This is highlighted in the River Carnon, UK, in which the only forms of animal life are those which have developed some tolerance to the metals being released through nearby mining. Similar observations were made in the fish mortality profiles for the River Gwyddan, Wales, which receives water discharged from a steel works. The organisation installed an effluent treatment plant and its beneficial effect on the survival of fish in the river was immediately observed (Crompton, 1997).

The non-lethal effect of dietary and dissolved phases of metals is also of grave concern because bioaccumulation of metals in animals ultimately poses a threat to food safety (Wang and Rainbow, 2008). Non-lethal toxicity may manifest in a number of ways depending on the metal, metal species and the organism involved. In many instances, metals impair the reproduction of vertebrates and invertebrates. In addition, metals may affect the emergence success of eggs, activity, stress and nervous functions of vertebrates and growth of both vertebrates and invertebrates (Crompton, 1997).

Metals are by no means the only toxins released into the environment through industrial activities. Another major group of pollutants is the organic compounds used in a large variety of processes. Organic chemicals encompass an enormous array of different natural and anthropogenic molecules with a virtually infinite list of applications including pesticides, plastics, surfactants, fuels and dyes (Jiménez and Wang, 2006). Many xenobiotic molecules are recalcitrant and are often highly toxic (Eleren and Alkan, 2009).

Organic chemicals present in concentrations below their solubility limit will occur in two forms in the environment, either dissolved or sorbed. The behaviour, transport and effect of the compounds depends on the pH, temperature, suspended solids concentrations and microbial activity in the system (Lyman, 1995). Toxicity of these compounds varies greatly and includes carcinogenic and mutagenic effects and in many cases lethality. The toxic and persistent nature of the compounds renders them a major concern and investigations into their environmental and physiological effects and degradation have been underway for a number of decades.

Not all compounds released into the environment through industrial activities are intrinsically toxic. In many cases the molecules, in the form of available carbon, nitrogen and phosphorus can be utilised as nutrients. Industries releasing these compounds into the environment include food processing, pharmaceutical manufacturing, fertilizer production, solid waste disposal and petrochemical refining (Carrera *et al.*, 2003). Once these nutrients find their way into the environment the concentrations of phytoplankton and algae in the water increase rapidly, this creates eutrophication, a disruption in the functioning of the normal ecosystem and leads to hypoxic conditions that further degrade the quality of the water and functioning of the ecosystem.

2.1.2 Reduce, reuse and recycle principles for water in industry

Industrial use of water accounts for 25 % of the global water demand, and given the growing limitations surrounding the use of water, industries in developed countries have managed to reduce their water usage by a commendable 70 – 96 % in the last two decades (Lazarova, 2002). The decrease in water usage has been as a result of process optimisation, and reduction, reuse and recycling initiatives within organisations. The required levels of wastewater treatment, based on standards, legal requirements and end use, is illustrated in Figure 2.1. The final selection of treatment technologies depends on economic, technical and specific local conditions. In many cases the same level of treatment can be achieved using different conventional and innovative technologies (Lazarova, 2002).

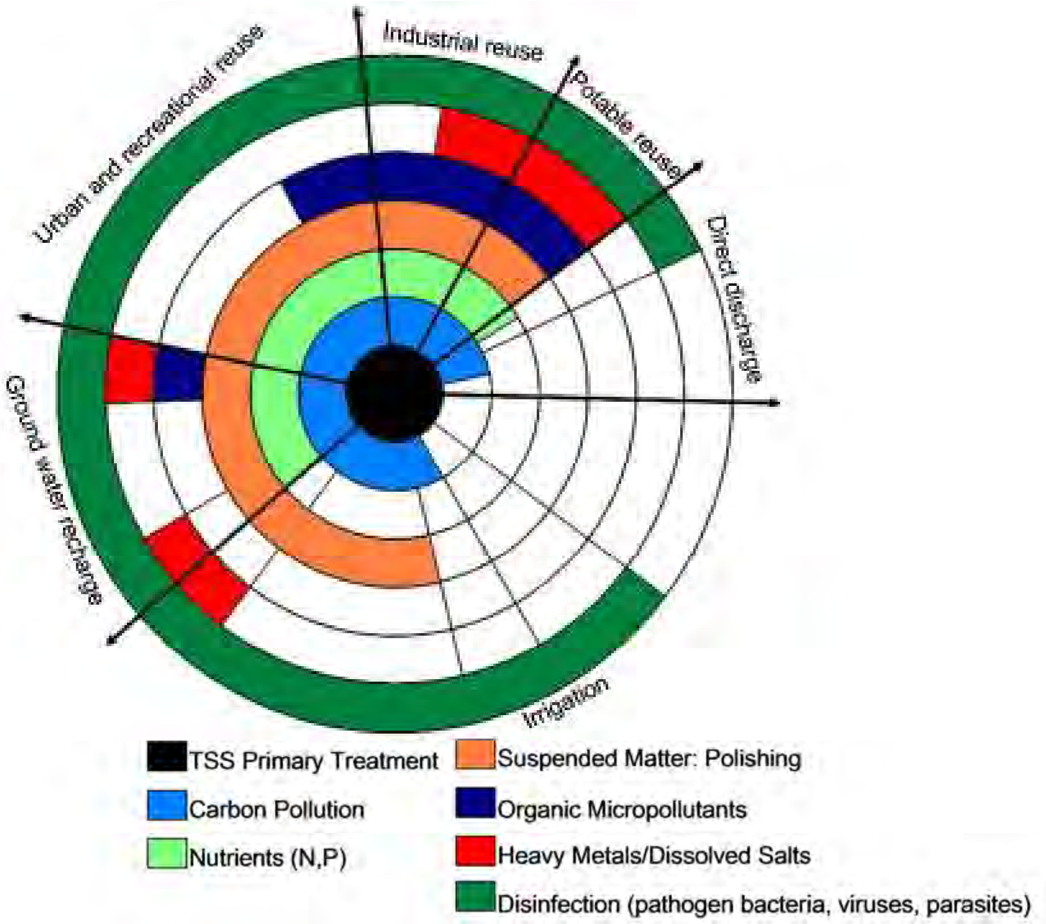


Figure 2.1 Treatment levels involved in the main reuse applications for treated wastewater, adapted from Lazarova (2002) (TSS: total suspended solids).

A number of management concepts have emerged for the minimisation of water demand, wastewater discharge and associated costs, such as water-pinch technology and advanced recycle technology. Water pinch analysis and wastewater minimisation was initially designed as a process tool for heat recovery in the 1970s and the objective of the water pinch analysis was to minimise water consumption through maximising the reuse of water (Brouckaert *et al.*, 2005).

Recycling and reuse are distinguished by the fact the recycled water may be returned to the original process, but reused water cannot be (Kuo and Smith, 1998). Direct reuse involves the use of wastewater from one process in another without any intermediate treatment steps. This can only be achieved if the contaminants from the first process have no effect on the second. The benefits of this system include the decreased use of potable water in the second process and lower wastewater discharge from the first. In all cases direct reuse should be considered first due to its low costs and simplicity (Feng and Chu, 2004) followed by indirect reuse (partial treatment) and finally recycling.

Recycling water involves the removal of some contaminants from the water, which is then returned to the same process. In many cases, this may be more difficult to achieve when compared to reuse as recycling may cause a build up of contaminants (Brouckaert *et al.*, 2005).

In some cases wastewater needs to undergo treatment before it may be reused. This is known as regeneration reuse (Brouckaert *et al.*, 2005). Two processes may be undertaken in this category. The first involves the separation of wastewaters into two streams. The stream with the lower contaminant concentration enters a regeneration plant and is treated to the quality required for another process. The stream with the higher contaminant concentrations enters a treatment plant where it undergoes treatment to meet discharge levels before being released from the site (Feng and Chu, 2004). This design requires two treatment facilities to generate reuse water and wastewater of different qualities. Alternatively, one treatment facility services all the wastewater, treating it to different levels depending on whether reuse or discharge is the ultimate purpose for the wastewater (Feng and Chu, 2004). The latter is appropriate to this study, because Anglo Platinum's PMR does not release any wastewater from its site.

The chief drawback of pinch analysis and advanced recycle technology is the difficulty of accommodating the practical constraints and characteristics of the water system. Multiple contaminants, flow rates and piping costs are just some of the variables which need to be taken into account when analysing and assessing the water usage. In addition, cost optimisation is required to determine the benefits of implementing water pinch which requires mathematical programming techniques (Brouckaert *et al.*, 2005). As a result, the theory is still developing and practical application of water pinch, particularly in South Africa, is not well established. At this point a holistic approach, combining a number of strategies and mathematical processes is needed to fully address the water usage of an individual industry and each application needs to be tailored specifically to the needs of the particular process (Alwi *et al.*, 2008).

A wide range of technologies is available for the treatment of wastewater, depending on the quality and quantity to be treated and quality of end product required. Membrane and gravity separation, adsorption, centrifugation, chemical oxidation, evaporation, filtration, electrodialysis and biotechnologies have all been utilised with success in various industrial sectors (Lazarova, 2002).

Biological processes have been identified as one of the most cost effective ways of treating a number of pollutants. In particular the co-treatment of municipal and industrial wastewaters and the use of activated sludge for the treatment of textile dye wastewater (Alinsafi *et al.*, 2006; Baban *et al.*, 2004), tannery effluents (Vidal *et al.*, 2004) and organic pollutants (Dignac *et al.*, 2000; Katsoyiannis and Samara, 2005; Zhang *et al.*, 2010) have been investigated.

2.2 Physico-chemical industrial wastewater treatment technologies

Conventional physicochemical technologies utilised for metal industry wastewater treatment include ion exchange, chemical precipitation, oxidation and reduction, evaporation and membrane filtration (Malik, 2004; Ahluwalia and Goyal, 2007). In most cases these physicochemical metal removal processes are ineffective in removing metal ions in the concentration range 1 – 100 $mg.L^{-1}$ and each is associated with significant drawbacks (Table 2.1) (Zafar *et al.*, 2007). These are summarised in the following sections.

2.2.1 Chemical precipitation

Precipitation is probably the most widely used technique for the removal of metal from solution. The pH of the solution is adjusted to >10 through the addition of strong alkalis such as calcium carbonate and sodium hydroxide (Kurniawan *et al.*, 2006). When the hydroxides, sulphites, carbonates and carbamates are added to solution, they react with the metal ions to form insoluble complexes (Eq. 2.1) which can then be recovered by sedimentation (Mauchauffée and Meux, 2007).

$$\mathrm{MCl} + \mathrm{NaOH} \rightarrow \mathrm{MOH}\downarrow + \mathrm{NaCl} \qquad 2.1$$

Chemical precipitation is often chosen as a means of metal recovery due to the ease with which it can be carried out and its low cost. Unfortunately precipitation results in a mixed metal product which is difficult to beneficiate and may pose a disposal problem. Additionally, when large volumes of wastewater are treated with precipitation, management of the pH may prove to be a challenge and precipitation may occur slowly (Kurniawan *et al.*, 2006).

Table 2.1 Conventional metal recovery technologies and their associated advantages and disadvantages.

Process and range of operation	Advantages	Disadvantages	References
Ion exchange 10 – 100 mg.L^{-1} or greater	High concentrating efficiency Ease of phase separation Resin may be regenerated to some extent No sludge Selectivity Simple and rapid	Expensive Sensitive to particles Resins eventually exhausted Pretreatment required, e.g. suspended solids removal. Limited availability of highly selective resins.	Gomes *et al.*, 2001 Ebbing and Gammon, 2002 Ahluwalia and Goyal, 2007
Chemical precipitation > 1000 mg.L^{-1}	Low capex and operational expenditure (opex). Considered the simplest and cheapest means of removing most heavy metals from solution. Sodium hydroxide introduces the smallest amount of inert material to the sludge. Simple Inexpensive Safe Convenient	Difficult metal separation. The sludge produced is heterogeneous in terms of metal content, as chemical precipitation of this nature is non-specific. Large volumes of metal-laden sludge pose disposal problem. Large volumes of wastewater to be treated often hamper precise management of the pH, leading to lower effective removal rates. Slow precipitation, poor settling and the aggregation of metal precipitates. Following precipitation, atmospheric evaporation is used. Only effective for >1 g.L^{-1} concentrations.	Kurniawan *et al*., 2006 Mauchauffée and Meux, 2007
Evaporation	Low capex and opex for atmospheric evaporation. Reusable water recovered from industrial vacuum evaporators.	Expensive Energy intensive The sludge produced is heterogeneous, as evaporation is non-specific. Atmospheric evaporation requires large amounts of space.	Cowan, 1998

Process and range of operation	Advantages	Disadvantages	References
Oxidation/reduction	Specific binding of targets can be achieved. Recovery of metals from electrodes is simple and efficient.	Additional chemicals required Climate sensitive Energy intensive Electrodes corrode over time	Chen and Lim, 2005 Kurniawan *et al.*, 2006 Barakat, 2010
Membranes < 20 $mg.L^{-1}$ or > 2000 $mg.L^{-1}$ With electrodialysis < 1000 $mg.L^{-1}$, best at < 20 $mg.L^{-1}$	Highly concentrated metal stream for recovery. Extremely specific binding.	Expensive materials High capital cost and high energy requirements. Process limited by fouling May require pretreatment to slow fouling. High maintenance cost	Kurniawan *et al.*, 2006 Sagne *et al.*, 2008
Solvent extraction	Selective Solvents can be regenerated and reused.	High chemical inputs required. Expensive, sophisticated equipment is required. Generation of waste liquors which need disposal. Reprocessing of waste liquors.	Gholivand and Nozori, 2000 Bernadis *et al.*, 2005 Cole *et al.*, 2006
Coagulation/flocculation < 100 $mg.L^{-1}$ or > 1000 $mg.L^{-1}$	Improved sludge settling and dewatering characteristics. Sludge stability Bacterial inactivation	High operating costs due to chemical consumption. High sludge volumes	Renault *et al.*, 2009
Flotation < 50 $mg.L^{-1}$ or > 150 $mg.L^{-1}$	Good removal of small particles. Short retention times. Low cost	May require pretreatment such as chemical precipitation.	Rubio *et al.*, 2002 Féris *et al.*, 2004

2.2.2 Ion exchange

Ion exchange is a process whereby one charged particle is displaced from its position on a molecule by another ion (Ebbing and Gammon, 2002). The predominant ion exchange resins are synthetic fixed ionic groups on a hydrocarbon backbone. This allows them to be tailored in terms of chemical and mechanical resistance, exchange capacity and application (Gomes *et al.*, 2001). Resins may be cationic exchangers, where the exchanging ions are positively charged, or anionic, where the ions are negatively charged (Ahluwalia and Goyal, 2007).

As more charged particles come into contact with the resin, it becomes saturated and the exchanger capacity diminishes (Figure 2.2). Resin regeneration displaces the bound ions with those from a strong solution of exchangeable active ions. Ion exchange efficiency is affected by the concentration of competing ionic species, the concentration of contaminants, interfering organic or inorganic compounds and the presence of dissolved and suspended solids. The combination of these factors limits the number of saturation-regeneration cycles the resin can withstand until it can no longer be used (Gomes *et al.*, 2001).

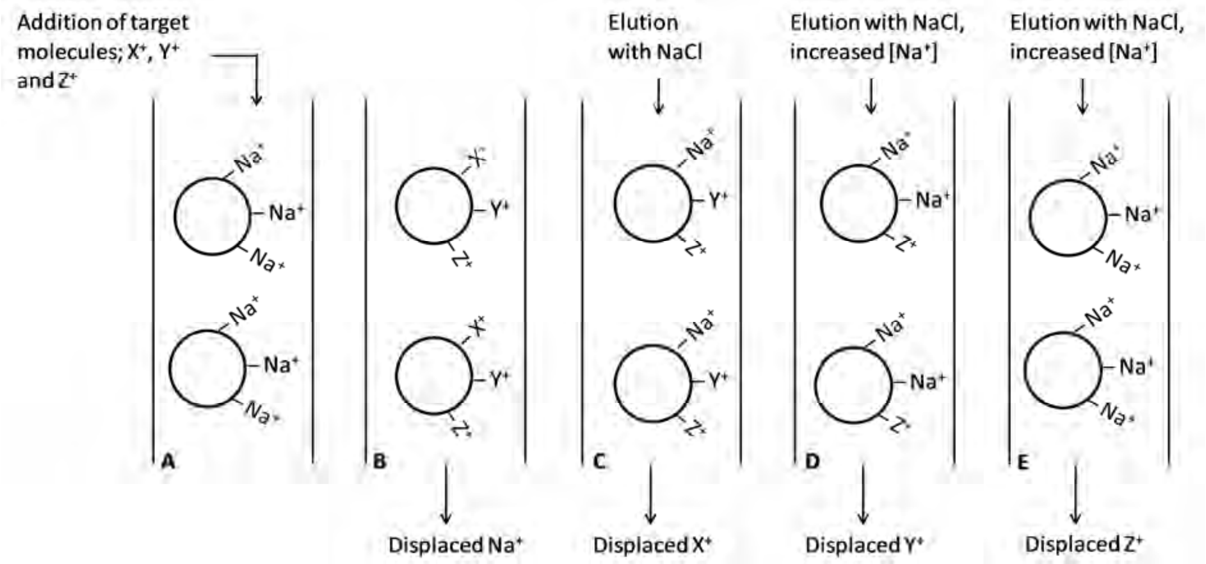


Figure 2.2 The binding, sequential elution and regeneration of a cationic exchange resin. (A) Sodium functional groups which will be displaced by target molecules (X^+, Y^+ and Z^+); (B) bound target molecules; (C), elution by NaCl of first target molecule (X^+) which is the least positively charged; (D), elution of the second target molecule (Y^+) by increasing the concentration of NaCl and finally (E) elution of the most positively charged molecule (Z^+) by further increasing the NaCl concentration.

The final flaw in using ion exchange to treat PMR wastewaters is that it is the procedure used to produce the PMGs (Figure 1.2). Hence wastewater from ion exchange contains the fraction of metals and other compounds which are not removed from solution by the ion exchange process.

2.2.3 Oxidation and reduction

Electrochemical oxidation and reduction involves a charge transfer between the electrically conductive metal and the ionic conductor, resulting in the deposition of the metal ion at the anode or cathode (Figure 2.3) (Chen and Lim, 2005). Electrochemical treatments may include electrodialysis, membrane electrolysis and electrochemical precipitation (Kurniawan *et al.*, 2006). The use of oxidation and reduction for the recovery of metals requires continuous chemical inputs and can be costly in terms of energy requirements to drive the processes. Additionally, the electrodes may become corroded and need to be continuously replaced (Barakat, 2010). However, high ion selectivity can be achieved and recovery of metals by stripping them from the electrode is simple and efficient (Chen and Lim, 2005).

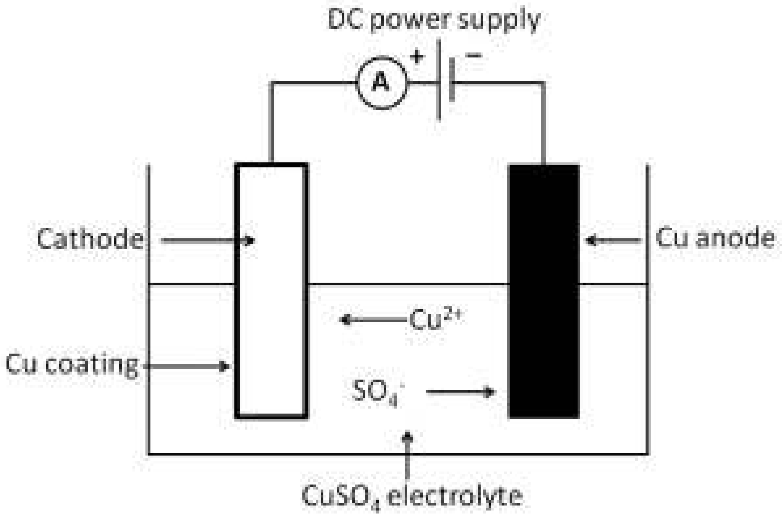
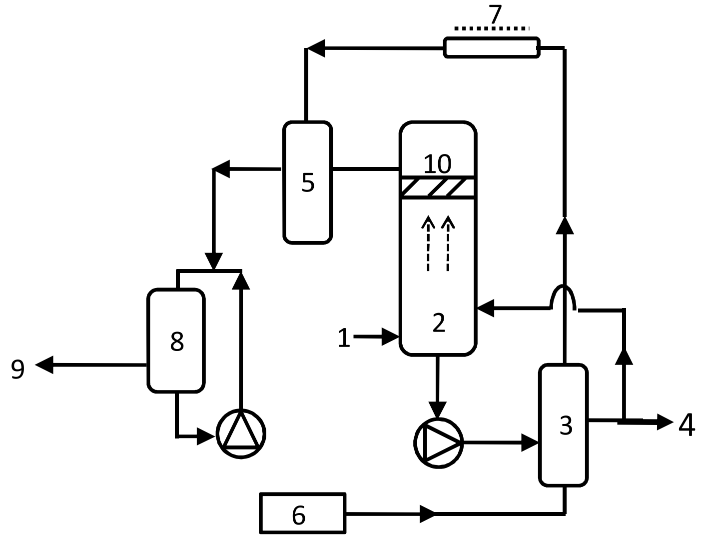


Figure 2.3 Copper electrodeposition from the copper anode onto the cathode in copper sulphate electrolyte.

Chemical oxidation is widely used to mineralise recalcitrant organic matter and render it harmless or suitable for further treatment. Advanced Oxidation Processes (AOP) have found widespread use as a co-treatment technology linked with biological treatment of wastewaters (Oller *et al.*, 2011). During AOP organic compounds such as aromatics, pesticides, complex hydrocarbons and volatile compounds are oxidised with ozone, hydrogen peroxide, oxygen and air in a precise dosage to produce stable inorganic compounds. The most significant drawback of these processes is that they consume large quantities of chemical reagents (oxidisers and catalysts) and energy (radiation, ozone, etc.).

2.2.4 Evaporation

The use of atmospheric evaporation is mainly employed in industrial settings to form a concentrated sludge. Large amounts of space are required, making this a viable option only where land is available; in addition, wastewater reservoirs or dams must be lined in order to prevent ground water contamination. The natural increase in atmospheric temperature results in water molecules being liberated from the wastewater as gas, decreasing wastewater volume; the wastewater becomes denser and forms a sludge. Evaporation may be accelerated with industrial vacuums which vaporise water at low temperatures (Figure 2.4); however this requires high capital expenditure (capex) (Cowan, 1998). Atmospheric evaporation is less expensive with the only cost incurred as a result of reservoir construction and maintenance. The use of vacuums is most often employed when accelerated evaporation is required, or when the pure water liberated during evaporation is harvested for use. The greatest disadvantage of evaporation is that it produces a single solid that contains all of the solutes in the water as a mixture, rendering the solutes very difficult or impossible to recover.



1 – Feed water
2 – Evaporator tank
3 – Evaporator heat exchanger
4 – Concentrate outlet
5 – Condenser heat exchanger
6 – Refrigerant compressor
7 – Air cooler
8 – Distillate tank
9 – Distillate
10 – Mist eliminator

Figure 2.4 Schematic representation of a low temperature vacuum evaporator.

2.2.5 Membrane filtration

In their simplest form, membrane techniques work by size exclusion. There are three main membrane filtration techniques for the removal of metal ions from solution: reverse osmosis (RO), ultrafiltration (UF) and nanofiltration (NF). Membrane treatment involves the pressure driven permeation of water through the membrane, while the metals are retained (Kurniawan *et al.*, 2006). Reverse osmosis membranes are thin film composites with a polyamine active layer and pore sizes as small as 10^{-13} m and are successfully used in water purification (Kurniawan *et al.*, 2006; Sagne *et al.*, 2008).

Ultrafiltration separates molecules from solution based on the membrane pore size (5×10^{-9} – 20×10^{-9} m) and the molecular weight of the molecules. Membrane materials include cellulose acetate, silica and alumina and polyamide (Kurniawan *et al.*, 2006).

The properties of NF membranes include steric and electrochemical mechanisms. The small pores (10^{-8} to 10^{-9} m) and surface charge of the membrane allow for charged solutes smaller than the membrane pores to be separated from the larger, neutral solutes (Kurniawan *et al.*, 2006).

2.2.6 Solvent extraction

Solvent extraction involves removing the compound of interest by contacting the concentrated wastewater with an organic reagent that will react with that particular compound in the concentrate and convert it to a form soluble in the solvent. Usually, solvent extraction follows three steps: (1) extraction, where the target compound is solubilised in the organic phase, (2) scrubbing, where any co-extracted molecules are removed from the organic phase, and (3) stripping, where the isolated target molecule is removed from the organic phase (Bernardis *et al.*, 2005). Solvent extraction is widely employed for selective recovery of one or two specified compounds in a solution or suspension and is one of the most common methods used for the separation of specific molecules from aqueous solutions due to the simplicity of the process (Gholivand and Nozari, 2000). However, solvent extraction is relatively expensive with elaborate equipment, high operation costs and energy requirements. The organic solvents used include methyl-iso-butylketone, a beta-hydroxyoxime, amines and amides (Cole *et al.*, 2006). A major cost is the regeneration and/or disposal of the solvent liquid and the spent solvent itself, where these organic solvents, strip and scrub liquors all represent a further environmental burden in terms of disposal and the scrub liquors often require reprocessing (Bernardis *et al.*, 2005). Finally, like ion exchange, solvent exchange is one of the PGM extraction processes used in metal production in the first place (recall Figure 1.2). Consequently PMR wastewater contains those ions which solvent extraction cannot recover.

2.2.7 Coagulation / flocculation

Coagulation and flocculation are common primary, secondary and tertiary treatment for the removal of dispersed particles. Chemical coagulants destabilise colloidal particles, generating micro-flocs which aggregate, thereby enhancing their removal efficiency through simple separation, such as sedimentation. Most coagulants and flocculants are mineral additives such as metal salts, polyaluminium chloride, or synthetic polymers, polyacrylamide. Barriers to the use of this technology include the expense of continuous chemical inputs and the consequent environmental drawbacks such as increasing the metal concentration of the waste, production of large volumes of toxic sludge and dispersal of acrylamide, which is hazardous. Advantages include ease of operation and effective removal of target compounds (Renault *et al.*, 2009).

2.2.8 Flotation

Flotation was initially used in ore processing for solid-solid separation, however advances in the technology have allowed it to be adapted for solid-liquid and liquid-liquid separation through the addition of carrier compounds. The process involves production of a stable froth (with or without the use of a carrier compound) to selectively separate target molecules. Solids or dispersed liquids are separated from the liquid phase via bubble attachment (Rubio *et al.*, 2002; Féris *et al.*, 2004).

The techniques described in Table 2.1 do have advantages. Ion exchange, membrane technologies and evaporation may generate pure effluent which can then be reused; chemical oxidation or reduction results in mineralisation of metal ions and precipitation is a simple and cheap process (Volesky, 2001). However, in most cases the disadvantages outweigh the advantages and the methods described are not capable of cost-effective removal of metals from dilute aqueous solutions. Most metal production methods employ ion exchange and solvent extraction, for example, and the wastewaters generated contain the metal residues not captured using those techniques. Further, problems encountered with the treatment of large volumes by the most common method (precipitation followed by evaporation) include slow precipitation, poor settling and the aggregation of metal precipitates (Kurniawan *et al.*, 2006). Following chemical precipitation of metal ions from wastewaters, atmospheric evaporation, using wastewater reservoirs known as “dams”, is used to produce a concentrated metal-bearing sludge. In the long term this “cheap” treatment becomes expensive, as large volumes of wastewater must be treated daily and a significant volume of metal-laden sludge is produced (Goyal *et al.*, 2003). For example, the hydroxide precipitation of 0.1 g Cu(II) produces as much as 1 g sludge (Peña-Castro *et al.*, 2004). This leaves a quantity of heterogeneous sludge three orders of magnitude greater than the original metal mass to be treated. In light of this, biological treatment methods have increasingly been investigated for industrial wastewater treatment (Ahluwalia and Goyal, 2007) and have found application in a number of sectors such as the treatment of tannery, textile, food processing and mine water.

2.3 Biological industrial wastewater treatment technologies

Biological processes for wastewater treatment can be roughly divided into the following categories, as outlined in Table 2.2 and expanded on in Table 2.3.

- Aerobic suspended growth
- Aerobic attached growth
- Anaerobic suspended growth
- Anaerobic attached growth
- Hybrid processes

Table 2.3 shows the major engineered unit processes used for wastewater treatment. Processes are selected for the same purpose in different wastewaters and situations according to their own advantages and disadvantages.

The range of treatment technologies and hybrid processes within the context of biological wastewater treatment is extensive and established. For the purpose of this work suspended growth systems will be more closely investigated, in particular activated sludge (AS) within aerobic treatment systems and anaerobic digestion (AD) for anaerobic wastewater treatment due to their successful application to other industrial wastewaters.

Table 2.2 Biological wastewater treatment processes.

Type	Common name	Use (additional uses in brackets)
Aerobic Processes		
Suspended growth	Activated sludge process	Carbonaceous biological oxygen demand (BOD) removal (nitrification)
	Conventional (plug-flow)	
	Complete mix	
	Step aeration	
	Pure oxygen	
	Sequencing batch reactor	
	Contact stabilization	
	Extended aeration	
	Oxidation ditch	
	Deep tank	
	Deep shaft	
	Suspended growth nitrification	Nitrification
	Aerated lagoons	BOD removal (nitrification)
	Aerobic digestion	Stabilization, BOD removal
	Conventional air	
	Pure oxygen	
Attached growth	Trickling filters	
	Low rate	
	High rate	
	Roughing filters	BOD removal
	Rotating biological contactors	BOD removal (nitrification)
	Packed bed reactors	BOD removal (nitrification)
Anaerobic processes		
Suspended growth	Anaerobic digestion	Stabilization, BOD removal
	Standard rate, single stage	
	High rate, single stage	
	Two-stage	
	Anaerobic contact process	BOD removal
	Upflow anaerobic sludge blanket	BOD removal
Attached growth	Anaerobic filter process	Stabilization, BOD removal (denitrification)
	Expanded bed	Stabilization, BOD removal
Hybrid processes	Single or multi stage processes, various proprietary processes. Attached or suspended growth or both.	BOD removal, nitrification, denitrification, phosphorus removal.

Table 2.3 Advantages and disadvantages of some biological wastewater treatment unit processes.

Process	Advantages	Disadvantages	Waste products
Activated sludge: widely used in a variety of modifications (contact stabilization, oxidation ditches, extended aeration, deep shaft etc). Vigorous aeration of flocs produces aerobic biological activity, followed by sedimentation.	Rapid purification possible at optimum settings. Good for reducing BOD and chemical oxygen demand (COD) from medium – high strength organic wastes.	Aeration and agitation rates critical. Large land areas normally required. Sludge quality critical (bulking & rising can occur). Can produce malodours.	Sludge.
Biological filtration: high rate, large surface area plastic packings promote growth of aerobic bacteria. Bed is irrigated using fixed or rotary distributor, while natural or forced air rises up through packing. “Filtration” is a bad name.	Low energy system. Widely used for high rate roughing. Flexible by virtue of packing top-up.	Susceptible to biocides and flies. Recycle may be needed to ensure packing wetted during periods of low feed.	Sludge from downstream clarifier. Odours may need treating espically in summer.
Rotating Biological Contactors (RBCs): consist of a shaft onto which are fitted large diameter plastic sheet discs or cylindrical cages containing randon or plastic media. The media is partly submerged in the effluent and the assembly is rotated slowly.	Ideal where space is at a premium and good for low and medium strength effluents.	Can suffer mechanical damage on startup due to the imbalanced loads resulting from uneven biofilm growth.	Sludge.
High rate anaerobic systems: can be upflow and downflow filters, fluidized beds, sludge blankets etc. Oxygen excluded to encourage growth of methanogenic bacteria.	Ideal for high strength organic wastes containing natural pollutants, e.g. meat processing, brewing, distillery waste and sugar / starch waste. Produces low amounts of sludge. Possible to use the methane as a fuel.	Strong foul odours.	Biogas and high strength sludge.

2.3.1 Activated sludge systems

One potential aerobic biological method for the treatment of industrial wastewaters is activated sludge (Figure 2.5), which is widely used worldwide for treatment of domestic, industrial and mixed wastewaters due to its robustness, long history and ability to be customised to suit a variety of situations.

The origins of the AS process can be traced back to the 1880s when it was determined that the aeration of wastewater resulted in increasing the rate of oxidation of organic matter. Over the decades the AS process has developed and improved and today consists of three fundamental components. The first is the aerator in which the microorganisms responsible for the wastewater treatment are maintained in suspension through vigorous aeration, the second involves solid-liquid separation, most commonly through sedimentation and the third is the recycling of solids from the sedimentation tank to the aeration tank as return activated sludge (RAS) to maintain the appropriate biomass concentration (Tchobanoglous *et al.*, 2003).

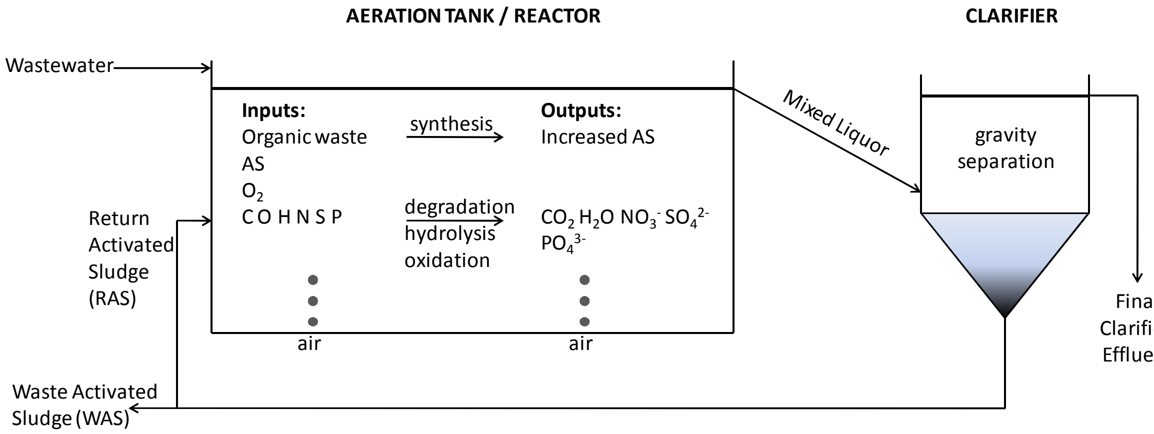


Figure 2.5 Schematic illustration of AS system showing inputs, outputs and processes in the reactors.

A number of organisms are found in healthy and functioning AS: bacteria, fungi, algae, protozoa and rotifiers. Each has an essential role to play in the treatment of wastewater. Bacteria play a significant role with regard to degradation of wastewater inputs into the system (Tchobanoglous *et al.*, 2003). Bacteria are responsible for the oxidation of carbonaceous material, the denitrification and nitrification of nitrogen species (finally liberated as N_2) and in some cases the degradation of complex and potentially toxic compounds such as petrochemicals and dyes.

Fungi are saprophytic organisms and utilise decaying biological material (including bacteria) and nutrients (C,N,P) present in wastewater as an energy source and support for growth. Many species exist in wastewater and can account for 38 % of all microorganisms present in sewage. The presence of fungi in AS can improve the settlability of the sludge, remove pathogenic organisms and degrade complex or toxic molecules (More *et al.*, 2010).

Algae have found extensive application in wastewater treatment and are important in biological treatment processes for two reasons: 1) in aerobic systems, algae have the ability to generate oxygen through photosynthesis, and 2) algae can be used to 'mop up' excess nitrogen and phosphorus that the other organisms could not utilise, thereby reducing eutrophication in receiving waters (Tchobanoglous *et al.*, 2003).

The presence of protozoa and rotifiers in AS indicate an efficiently performing system. Both types of organisms are responsible for polishing the wastewater by consuming dispersed and flocculated bacteria and small particles of organic matter (Tchobanoglous *et al.*, 2003).

2.3.2 Activated sludge performance indicators

Typically the efficiency of an AS process is monitored as a function of the removal of carbon (measured as chemical oxygen demand (COD), five day biological oxygen demand (BOD_5), twenty day biological oxygen demand (BOD_{20}) and total organic carbon (TOC)), nitrogen (ammonia, nitrite and nitrate) and phosphorus. The concentrations of these compounds in the influent determines the strength of the wastewater to be treated and affects the functioning of the AS system. In a well-functioning AS plant most of the carbon is utilised during metabolism, while the nitrogen is either assimilated by the microorganisms for cell growth or undergoes a series of oxidation reactions to eventually be released into the atmosphere as nitrogen gas. The phosphorus concentration in domestic wastewaters usually surpasses the nutritional needs of the microorganisms in the system and as a result can pose potential treatment challenges. In most cases chemical addition (such as metal salts) is required to precipitate the phosphorus in order to meet effluent quality targets.

Mixed liquor suspended solids (MLSS) concentration in the aeration tank is considered one of the fundamental indicators for AS performance and health. The MLSS approximates the concentration of micro and macro fauna (Tchobanoglous *et al*., 2003) and the majority of research undertaken on AS reports the MLSS. Additional indicators are the mixed liquor volatile suspended (MLVSS) which differentiates the biological from the inorganic fraction of the solids; the MLVSS is more useful than the MLSS when it is known that significant amounts of inorganic material is being introduced into the AS system.

The sludge volume index (SVI) is also used to monitor the health of the AS. It describes the settling characteristics of the sludge and varies depending on the MLSS concentration and sludge characteristics; as a result the SVI of two different plants cannot be compared (Tchobanoglous *et al.*, 2003).

Additional sludge health indicators include the specific oxygen uptake rate (SOUR) and ammonium uptake rate (AUR) (Madoni *et al.*, 1999), nitrification performance (You *et al.*, 2009), growth kinetics (Gikas and Romanos, 2006), changes in chemical oxygen demand (COD) (Stasinakis *et al.* 2003), and protozoan and ciliate communities (Madoni *et al.*, 1994; 1996). In situations where the AS system is required to perform in the presence of toxic compounds, the toxic effects become more acute with decreasing species diversity in the sludge (Dilek and Gökçay, 1996; Gökçay and Yetis, 1996; Madoni *et al.*, 1996; Yetis and Gökçay, 1989; Chang *et al.*, 1986; Tsuboi *et al.*, 1967).

Perhaps one of the most immediate signs that an AS system is not functioning as efficiently as it should is a change in the settling characteristics. Two important symptoms are bulking and rising sludge in the clarifier. Bulking sludge (which hangs in the water column and does not settle) occurs as a result of excess filamentous organisms within the AS or a decrease in density of the bacterial cells as a result of increased water content within the cells. Filamentous organisms can prevent the flocs from packing tightly and result in solids carry over in the clarifier effluent. The growth of filamentous organisms can be controlled, by, for example:

- Alteration of the dissolved oxygen concentration in the aeration tank
- Increasing the food to mass ratio
- Addition of major and/or trace nutrients
- Addition of chlorine or hydrogen peroxide to the return sludge

Factors affecting sludge bulking are either environmental, such as pH, nutrient content, flow, strength and the nature of the wastewater, or design limitations, such as poor mixing, clarifier design, air capacity and return sludge flow limitations (Tchobanoglous *et al.*, 2003).

Rising sludge (which floats at the top of the clarifier, leaving clarified water beneath) can occasionally be observed after short settling times, due to gas generation. Denitrification results in the conversion of the nitrites and nitrates to nitrogen gas, which forms in the sludge blanket and may reach a concentration where the buoyancy of the sludge is increased and it floats to the surface. Rising sludge may be minimised by (Tchobanoglous *et al.*, 2003):

- Increasing ratio of waste activated sludge (WAS) to RAS
- Decreasing the concentration of mixed liquor entering the clarifier

- Increase the rate of removal of solids from the clarifier

2.3.3 Anaerobic digestion systems

The manufacturing of biogas from organic matter originally gained scientific interest in the seventeenth century. The first anaerobic digester was constructed in 1859 by a leper colony in Bombay, India, after which the technology was taken to Britain where the first dual purpose tank for sludge treatment and sedimentation was installed in 1904 (Monnet, 2003).

Typically, AD has been used to stabilise sludges through the decomposition of matter in the absence of oxygen and has found application in the treatment of municipal and industrial wastewaters and sludges. Primary and biological sludges are converted to products such as methane (CH_4) and carbon dioxide (CO_2) under anaerobic conditions in either a standard or high-rate digestion process (Figure 2.6). In standard-rate processes the digester remains unheated and unmixed, while high-rate processes involve heating and mixing the digester contents. The two processes also differ in that the hydraulic retention time (HRT) used in standard-rate digestion is longer (30 – 60 days) than in high-rate (15 days or less) (Tchobanoglous *et al.*, 2003).

Three theoretical stages have been identified within AD: hydrolysis, acidogenesis and methanogenesis. Hydrolysis involves the enzymatic conversion of high-molecular mass compounds (proteins, lipids, complex carbohydrates and nucleic acids) into substrates which are better suited as a source of energy and cell carbon (amino acids, fatty acids, simple carbohydrates and purines and pyrimidines). Acidogenesis involves the conversion of these compounds into lower-molecular mass intermediates such as methanol, hydrogen gas, carbon dioxide, acetate, methylamine, succinate, lactate and other fermentation products. During methanogenesis these compounds are further metabolised into methane and carbon dioxide (Salminen and Rintala, 2002; Chen *et al.*, 2008; Mirzoyan *et al.*, 2010).

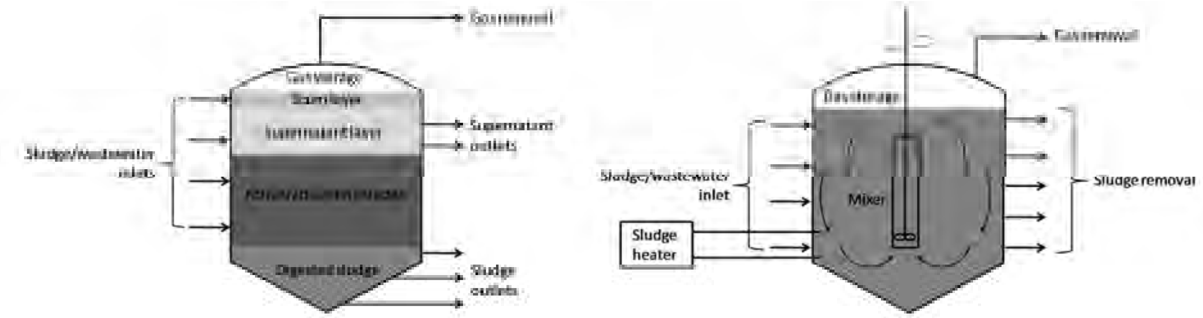


Figure 2.6 Typical anaerobic digesters, illustrating the differences between standard-rate (left) and high-rate (right) process designs (Adapted from Tchobanoglous *et al.*, 2003).

Each of these degradation steps is carried out by a separate group of microorganisms, those which are responsible for hydrolysis and acidogenesis are known as nonmethanogenic and consist of facultative and obligate anaerobic bacteria. The bacteria responsible for methonogenesis are known as 'methanogens' and are strictly anaerobic. The most important bacteria within this group are those which utilise acetic acid and hydrogen during metabolism, however they have very slow growth rates and are often the rate limiting factor in AD (Tchobanoglous *et al.*, 2003).

2.3.4 Anaerobic digester performance indicators

Performance monitoring of digesters is essential to achieve and maintain satisfactory operation. Typical parameters monitored are BOD_5, suspended solids (SS), pH, alkalinity, volatile fatty acids (VFAs) and biogas production and composition. These parameters are intimately linked and need to be carefully assessed to determine the true performance of the AD system.

Biogas is one of the most commonly used indicators as it can be measured by online sensors and provides an overview of digester performance. A drawback to the reliance on biogas production as a sole performance indicator is that a lag between process inhibition and decrease in biogas production may result in irreparable damage to the system. Biogas composition has been utilised as an indicator where increasing concentrations of CO_2 (i.e. decreasing CH_4) indicates digester failure, however the CO_2 concentration is dependent on pH. Changes in pH may affect the biogas composition without altering the CH_4 production. The prevailing pH is also commonly used as an online liquid state parameter due to the ease with which the information can be obtained. In a system with a low buffering capacity a decrease in pH may indicate an increase in the concentration of VFAs (disruption in acidogenesis), however, in a well buffered system the monitoring sensitivity of pH decreases. Monitoring the concentration of VFAs has been investigated as a suitable performance indicator, while monitoring specific VFAs yields targeted information for process diagnosis. The disadvantage of monitoring VFAs is the technical nature of the analyses: VFAs are measured either by titration, or if information with regard to individual compounds is required, gas chromatography (Boe *et al.*, 2010; Sbarciog *et al.*, 2010).

Advantages of utilising AD for wastewater treatment include low sludge production, low energy requirements (in standard-rate systems) and a high degree of waste stabilisation. However, major barriers to the industrial use of AD are poor operational stability and the technical expertise required to successfully operate the process (Chen *et al.*, 2008; Sbarciog *et al.*, 2010).

The AS and AD processes are compared in Table 2.4 with examples of the wastewaters each is capable of treating.

Table 2.4 Comparison of AS and AD wastewater treatment (Adapted from Chan *et al.*, 2009).

Characteristic	**Aerobic**	**Anaerobic**
Organic loading rate	Moderate	High
Organic removal efficiency	High	High
Nutrient requirement	High	Low
Energy requirement	High	High
Alkalinity requirement	Low	Low to moderate
Sludge production	High	Low
Temperature sensitivity	Low	High
Odour production	Less opportunity for odours	Potential odour problems
Bioenergy and nutrient	No	Yes
Start up time	2-4 weeks	2-4 months
Mode of treatment	Total (depending on influent	Essentially pretreatment
Types of wastewaters/sludges treated	Predominantly wastewaters: Tannery Textile Paper and pulp Food and beverage Agricultural	Predominantly sludges: Agricultural Food and beverage Wine distillery

2.3.5 Concluding remarks

It is rare to find a full-scale wastewater treatment plant treating industrial effluent in a single unit process. Most wastewaters require additional pre or post treatment steps in process trains to treat recalcitrant waste sufficiently. In addition to the development of process trains, many wastewaters need to be supplemented with additional nutrients or combined with wastes from other processes in an attempt to balance the nutrient load for the microorganisms treating the wastewater (Boshoff *et al.*, 2004; Neves *et al.*, 2006; Neczaj *et al.*, 2007; Buendía *et al.*, 2009; Vlyssides *et al.*, 2009; Jail *et al.*, 2010; Yu *et al.*, 2010; Senthilkumar *et al.*, 2011). In these instances both waste streams are treated concomitantly through a process widely known as co-metabolism.

Co-metabolism is a theoretical concept that evolved in the late 1950s to mid 1960s amid a certain level of controversy (Wackett, 1996). The general consensus of the definition of co-metabolism has emerged as the simultaneous oxidation of a non-growth substrate and metabolism of an utilisable energy source during microbial growth. In some instances it also describes the oxidation of non-utilisable substrates at the expense of metabolically beneficial molecules by resting cell suspensions. Co-metabolism, therefore, refers to the deliberate oxidation of any substance which is not utilised as a source of energy to support microbial growth (Horvath, 1972). Arguments against the theory of co-metabolism include the ambiguity of the definition, the inappropriate use of the term and a lack of understanding of the fundamental biochemical concepts of the oxidation of recalcitrant and/or xenobiotic compounds. Wackett (1996) protagonises that an accurate understanding of co-metabolism and its metabolic functioning has not been presented and that the concept is abused and manipulated to provide explanations for observations which have been poorly investigated and interpreted. He goes on to claim that co-metabolism is merely the function of "... broad enzyme specificity, imprecise induction specificity, and an evolutionary process that we innately expect to yield biological perfection when it is neither necessary nor, in some cases, thermodynamically feasible." (Wackett, 1996).

Despite the controversy surrounding the definition and understanding of co-metabolism the theory has been widely applied in the co-treatment of two different wastewaters where one is resistant to biological treatment while the other is readily biodegradable. Most notable is the treatment of industrial wastewaters combined with domestic sewage.

Examples of the successful aerobic and anaerobic co-treatment of industrial and domestic wastewater have been reported. Jail *et al.* (2010) investigated the possibility of treating olive-mill wastewaters combined with municipal wastewater in stabilization ponds. The authors investigated the phytotoxicity of the treated wastewater, concentrations of COD and polyphenols and the presence of faecal coliforms and faecal streptococci. The co-treatment resulted in decreasing the

COD, polyphenol and faecal bacteria concentrations, provided the upper limit of the organic loading rate was not exceeded. Furthermore, the phytotoxicity of the combined treated effluent was greatly diminished when compared to untreated olive-mill wastewater (Jail *et al.*, 2010). Neves *et al.* (2006) combined coffee waste with sewage sludge in an anaerobic co-digestion system to investigate an alternative to sending the wastes to landfill. Co-digestion achieved up to 73 % reduction in total solids, up to 80 % reduction in volatile solids and an 89 % theoretical methane potential, rendering co-treatment suitable as a replacement for landfill.

2.4 Applied co-treatment technologies

There is a paucity of public literature dealing with the biological co-treatment of metal refinery wastewaters. This may be because these wastes are stored without treatment for long periods or because treatment systems are developed in house. However, co-treatment of industrial wastewaters with domestic sewage to provide nutrients and/or ameliorate recalcitrance is a principle that has been demonstrated with other inorganic wastewaters. Aerobic and anaerobic co-treatments have been achieved with tannery wastewater and acid mine drainage (AMD), which are also high strength, inorganic wastes.

2.4.1 Tannery wastewater treatment

Tannery wastewaters contain high concentrations of COD, salts, ammonium compounds, sulphur and total suspended solids (De Gisi *et al.*, 2009), some of which may be compared with the refining wastewaters described in Section 2.1.3. These wastewaters are extremely complex and toxic to the environment and require treatment before being released into municipal wastewater systems or water courses. A number of biological treatment methods have been investigated and include AS (Ganesh *et al.*, 2006; Munz *et al.*, 2008; De Gisi *et al.*, 2009), membrane bioreactors (Munz *et al.*, 2007; 2008) and anaerobic systems (Genschow *et al.*, 1996; Wiemann *et al.*, 1998; Song *et al.*, 2001; Lefebvre *et al.*, 2006; El-Sheikh *et al.*, 2011).

One example of a full-scale activated sludge tannery-municipal wastewater co-treatment system was investigated (Munz *et al.*, 2008). The wastewaters originated from a municipal treatment works in South Miniato, Pisa, Italy which received municipal wastewater and tannery effluent from approximately 110 vegetable tanning processes which had undergone pre-treatments including sulphide-oxidation and primary settling. The ratios of each wastewater were 55 % tannery effluent and 45 % municipal wastewater, with high organic and nitrogen concentrations, phenols, high salinity and large load variability. The treatment process was broken into three steps, namely pre-denitrification, nitrification and separation with an HRT of 70 hours, divided into 22 hours of anoxic functioning and 48 of aerobic functioning. The authors monitored TSS, volatile suspended solids (VSS), total nitrogen (TN), ammonium, sulphur and phenols. It was found that AS was able to remove 94.7 % of the ammonium from the system, however the removal was not stable and 4.4 ± 3.7 mg.L^{-1} of ammonia was detected in the effluent. The authors stated that the COD removal efficiency of 76.8 % was not as high as values reported elsewhere. The low COD removal and unstable ammonia removal were attributed to the presence of phenols (mean of 125 mg.L^{-1} in the influent), which they concluded inhibited the specific growth rate of the microorganisms and accounted for the need for an extended SRT (over 50 days).

2.4.2 Acid mine drainage treatment

Acid mine drainage (AMD) is formed when water drains through underground mine shafts, or as run-off or discharge from open pits, mine waste dumps and ore tailings where sulphide containing rocks/ores have been exposed. Typically AMD is characterised by extremely high acidity and large concentrations of metals, sulphur and salts (Mapanda *et al.*, 2007). The co-treatment of AMD with municipal waste has been successfully demonstrated at full-scale by the Rhodes University BioSURE Process (Whittington-Jones *et al.*, 2002).

The principle behind the development of the process is that primary settled sludge (PSS) may be solubilised biosulphidogenically as a carbon source to generate in excess of 30 % VFA equivalents, which may be used as an electron acceptor in sulphate reduction. The primary role of the first stage of the treatment process (Recycle Sludge Bed Reactor (RSBR)) was to solubilise the PSS to act as an electron donor for the second stage. The authors selected a baffled reactor for the second stage where sulphate reduction took place. The alkalised, sulphide-rich effluent generated from this dual-stage process fed into an AMD pre-treatment system where it was used as a neutralising agent and to precipitate heavy metals in the AMD. Additional steps investigated in the process included a reduced sulphate (S_0) removal step and High Rate Algal Ponds (HRAP) for polishing and disinfection of the final effluent (Rose, 2002b).

When the system was operated at a theoretical COD : SO_4 ratio of 0.61 : 1 (COD as acetate) the system demonstrated an increase in VFA concentration across the process of 169 %, taking into account the simultaneous consumption in sulphate reduction. In terms of process yield, the actual COD : SO_4 ratio was maintained at approximately 2 : 1 with consumption in the Baffled Reactor resulting in a final ratio of 0.65 : 1. Given the similarity between the theoretical value and actual value of COD : SO_4, it was concluded that sulphate reduction in the baffled reactor was largely driven by the VFA production during PSS hydrolysis in the RSBR. At steady state the author reported a 79 % reduction in sulphate, a 95 % decrease in COD, an increase in pH from 5.0 – 5.8 to 7.8 – 8.2 and less than 100 cfu.mL^{-1} of *Escherichia coli* (Rose, 2002b) in the final effluent.

2.5 Knowledge gap

The use of conventional physico-chemical methods for treating industrial wastewaters can often result in complex process trains that only partially treat the wastewater, especially if the wastewater contains components which persist after the application of physico-chemical processes during production. In most cases these processes generate toxic, recalcitrant by-products which either require further treatment or disposal, risking environmental contamination. An alternative is the use of biological systems to reduce toxicity, by-product generation and potentially recover usable water from industrial wastewaters. Co-treatment of industrial and municipal wastewaters has been extensively investigated and a small number of processes successfully implemented at full-scale. Given the availability of municipal wastewater and previous reports of success, co-treatment for the neutralisation, metal precipitation and polishing of refining wastewaters should be investigated. Co-treatment with municipal wastewater may potentially reduce the reliance of refineries on potable water by generating a process water of a suitable quality for reuse with the added benefit of metal recovery. This study will therefore investigate co-treatment of Anglo Platinum PMR wastewater with domestic wastewater.

In addition to bacterial treatment technologies, algal systems have been investigated to treat a number of industrial wastewaters. These include wastewaters generated during metals and mineral processing, paper and pulp wastewaters, food and beverage wastewaters and textile wastes. This study will briefly investigate the possibility of utilising algae for the treatment of the blended domestic and refinery water.

The most likely area in which water may be reused in the mining and metals processing industry is flotation. Up to 85 % of the volume of mineral pulp processed in flotation is water. Many processing plants have investigated the replacement of potable water with water recovered from tailings dams, sewage treatment works and dewatering and filtering products. The relative volumes of wastewater generated by the precious metal refinery and the local sewage works suggest that addition of the effluent to the flotation process will have little impact on process performance. This study will investigate the flotation potential of the blended wastewater to confirm whether or not it can be incorporated into Anglo’s flotation process.

CHAPTER 3

BENCH-SCALE ANAEROBIC DIGESTION TREATABILITY STUDY

3.1 Introduction

Precious metal refining generates a number of effluent streams (Figure 1.1, page 2) which contain residual concentrations of valuable metals and which cannot be released into the environment. Anglo Platinum's precious metal refinery (PMR) generates approximately 3300 m^3 of combined acid effluent a month. Accumulation of these effluents has made it necessary to consider treatment and recycling to decrease the effluent volumes and recover the metals and water. The effluent has high concentrations of chlorides (>50 $g.L^{-1}$), sodium (±15 $g.L^{-1}$), iron (±1300 $mg.L^{-1}$) and ammonia (±3250 $mg.L^{-1}$) with a pH below 0. The exact composition and volume of the acid effluent varies depending on the ore being mined at the time. Current treatment technologies are energetically and chemically expensive and generate a heterogeneous solid waste product which requires disposal at a landfill.

Anglo Platinum has access to approximately 100 000 m^3 of domestic wastewater per month from the Waterval Sewage Treatment Works (WSTW) which may be blended with the PMR acid effluent and co-treated in a biological system. As described in Chapter 2, anaerobic systems have been used to treat a number of industrial wastewaters and this chapter therefore sets out to assess the treatability of PMR acid effluent by co-metabolism and anaerobic digestion (AD).

3.2 Materials and Methods

Duplicate bench-scale anaerobic digesters were operated in parallel (Figure 3.1). The digesters were seeded with 4 L of return activated sludge (RAS) from WSTW in Rustenburg with the remaining 2.2 L working volume being made up of 2° influent from WSTW (200-500 $mg.L^{-1}$ COD and C:N:P ratio of 56:4:1).

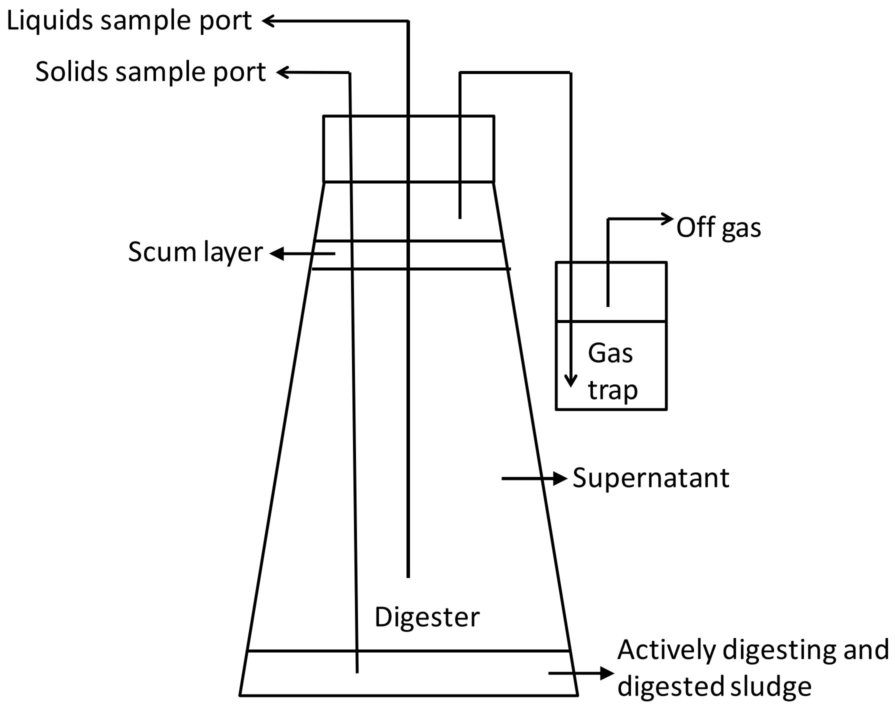


Figure 3.1 Schematic representation of one digester and sodium acetate gas trap to remove any H_2S in the off-gas (not drawn to scale).

The hydraulic retention time (HRT) of the digesters was calculated using Equation 3.1. The equation describes the average time that the wastewater resides in the digester.

$$\mathrm{HRT} = \frac{\mathrm{V}}{\mathrm{Q}} \qquad 3.1$$

where:

HRT = hydraulic retention time (d)

V = Working volume of the reactor (the volume of the round feed tank and ABR train) (m^3)

Q = Process flow rate ($m^3.d^{-1}$).

The sludge retention time (SRT) is defined as the average amount of time that the sludge remains in the digester (Equation 3.2). It can also be termed the mean cell retention time (MCRT).

$$\mathrm{SRT} = \frac{\text{Digester SS}}{\text{SS removed per day}} \qquad 3.2$$

where:

SS =suspended solids concentration ($mg.L^{-1}$)

SRT = sludge retention time (d)

Once a week 500 mL of supernatant was removed and replaced with fresh 2° influent from WSTW and 70 mL of the sludge was removed for analyses, resulting in an 87 day HRT and a 50 day SRT (given a nominal sludge volume of 500 mL). After an acclimatisation period of three SRTs (155 days), PMR wastewater was added to the feed at 2 % (v/v), rising in weekly increments to provide pH increases of 0.5 for a further 185 days. A target of 3 % PMR wastewater (v/v) in the feed was set, because the intended site for application of a successful treatment method is able to receive domestic wastewater : PMR wastewater at a volumetric ratio of 97:3.

The wastewater treatment performance was assessed using the determinands and methods shown in Table 3.1. The ammonia, COD, nitrite, nitrate and phosphate concentrations in the feed and effluents were determined with the use of Spectroquant test kits (Merck, Germany) on a Spectroquant Nova 60 (Merck, Germany) spectrophotometer. Samples were filtered through pre weighed Whatman glass fibre GF/A filters (Sigma-Aldrich, South Africa) and dried at 105 °C in an oven (Labcon, South Africa) for 72 hours to determine MLSS and TSS. The pH and conductivity were determined using either a pH meter (Eutech Instruments, Singapore) or a multiprobe (Hanna Instruments, USA). Phosphate concentrations are not reported in the results because the addition of PMR wastewater to the feed to the system interfered with the test. Data were analysed using paired t-tests with $t=1.996$ and $p=0.349$ at 95 % confidence with 67 degrees of freedom. Results from days 156 to 340 were compared to those from days 1 to 155 to assess the impact of PMR wastewater on the digesters.

Table 3.1 Parameters and analytical methods used to monitor the digester performance.

Feed	**Digester**	**Effluent**	**Analysis Method**	**Analogous Method**
Chloride	-	Chloride	Merck Test Kit (1.14897.0002)	Standard Method 4500-Cl^- E. (APHA *et al.* 1998)
COD	-	COD	Merck Test Kit (1.14538.0065 and 1.1468.0495/1.14582.0495)	Standard Method 5220D. (APHA *et al.* 1998)
NH_4^+-N	-	NH_4^+-N	Merck Test Kit (1.14752.002 and 1.00583.001)	Standard Method 4500-NH_3 D. (APHA *et al.* 1998)
NO_2^--N	-	NO_2^--N	Merck Test Kit (1.14776.0002)	Standard Method 4500-NO_2^- B. (APHA *et al.* 1998)
NO_3^--N	-	NO_3^--N	Merck Test Kit (1.009713.0002)	ISO 7890/1
pH	pH	pH	Standard Method 4500-H^+ B. (APHA *et al.* 1998)	-
Phosphate	-	Phosphate	Merck Test Kit (1.00798.001)	Standard Method 4500-P E. (APHA *et al.* 1998)
TSS	TSS	TSS	Standard Method 2450E. (APHA *et al.* 1998)	-

3.3 Results and Discussion

The aggregation of granules was observed during acclimatisation. The benefit of operating an anaerobic process with granular sludge is that much higher loading rates than those commonly used in other processes can be applied (Hulshoff Pol *et al.*, 2004), which is advantageous when treating industrial wastewaters. Figure 3.2 shows the SS concentrations of each digester during acclimatisation and after the introduction of PMR wastewater on day 155. The performance of the digesters in terms of effluent quality is summarised in Table 3.2 and detailed in Appendix A.

Table 3.2 Mean values of determinants in the feed digesters and effluents ± standard deviation (SD) (*n*=19 during acclimatisation and *n*=24 during PMR wastewater addition).

	Parameter	**Feed**	**Digester 1 effluent**	**Digester 2 effluent**
Domestic wastewater feed	Chloride (mg.L^{-1})	74 ± 33	74 ± 8	76 ± 9
	COD (mg.L^{-1})	273 ± 37	85 ± 17	83 ± 13
	NH_4^+-N (mg.L^{-1})	26.6 ± 11.4	22.2 ± 3.5	23.8 ± 3.3
	NO_2^--N (mg.L^{-1})	0.04 ± 0.01	0.00 ± 0.00	0.00 ± 0.00
	NO_3^--N (mg.L^{-1})	0.26 ± 0.24	0.1 ± 0.2	0.1 ± 0.3
	pH range	6.84 - 8.54	6.99 - 7.78	7.01 - 7.78
	Digester SS (mg.L^{-1})	-	939 ± 603	1381 ± 825
	Effluent SS (mg.L^{-1})	-	36 ± 4	36 ± 4
PMR wastewater feed (3 %)	Chloride (mg.L^{-1})	886 ± 33	703 ± 345	722 ± 338
	COD (mg.L^{-1})	267 ± 22	91 ± 19	90 ± 21
	NH_4^+-N (mg.L^{-1})	106.6 ± 18.9	86.9 ± 32.4	85.3 ± 19.0
	NO_2^--N (mg.L^{-1})	0.05 ± 0.04	0.00 ± 0.00	0.00 ± 0.00
	NO_3^--N (mg.L^{-1})	0.19 ± 0.35	0.1 ± 0.2	0.1 ± 0.2
	pH range	5.19 - 6.87	5.55 - 7.54	5.83 - 7.92
	Digester SS (mg.L^{-1})	-	1623 ± 375	1578 ± 474
	Effluent SS (mg.L^{-1})	-	43 ± 6	48 ± 5

Because pH is the negative logarithmic value of the H^+ ion concentration, the use of the arithmetic mean of

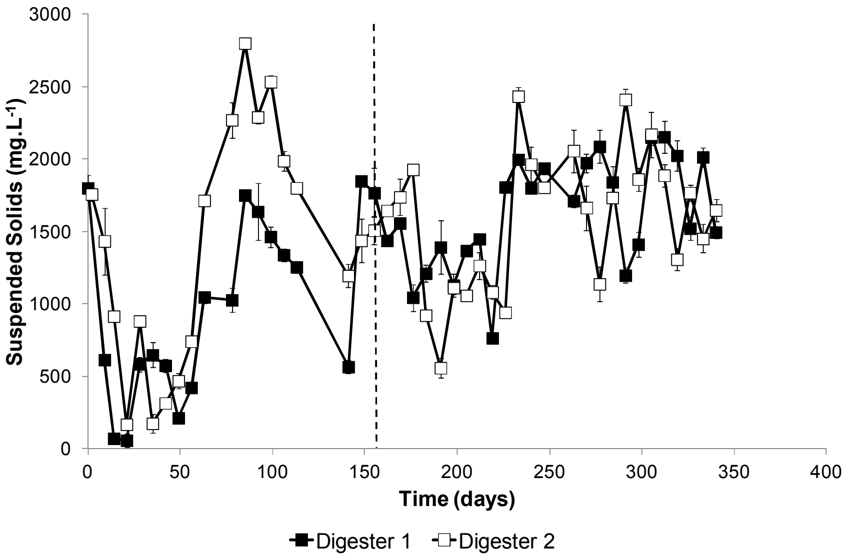


Figure 3.2 The SS concentration of the digesters during acclimatisation and addition of PMR wastewater on day 155 (dashed line). Data points are mean values and *y*-axis error bars indicate SD (*n*=3); in some cases the error bars are too small to be visible.

Erratic SS determinations were partially attributed to channelling occurring in the sludge layer at the sampling port and supernatant being withdrawn instead of biomass. There was no statistically significant difference between the two digesters during the 340 day operation. Conversely, a significant difference between the SS before and after the addition of PMR wastewater was observed in each digester. More consistent SS determinations were obtained after the addition of the PMR wastewater.

Addition of PMR wastewater to the feed was gradual with the concentration being increased from 0 % to 2 % over 34 days. This allowed acclimatisation to occur as only 500 mL of the total volume of the digester was replaced weekly. This acclimatisation period can be observed with the pH change in the digesters (Figure 3.3).

Both digesters were able to tolerate the initial changes in pH as more of the digester volume was replaced with increasing concentrations of PMR wastewater. By day 181 the digesters were being fed with 2 % PMR wastewater (v/v), however once the entire volume of the digester was replaced with 2 % PMR wastewater the pH in both decreased to slightly above that of the feed, statistically different from the previous operating pH. The initial resistance to the change in pH was attributed to the ability of anaerobic sludge to increase the alkalinity within the system (Poinapen *et al.*, 2009; Lakaniemi *et al.*, 2010). However, the presence of other inhibitory compounds or the increasing acidity of the feed resulted in an overall decrease in the digesters' ability to buffer the pH.

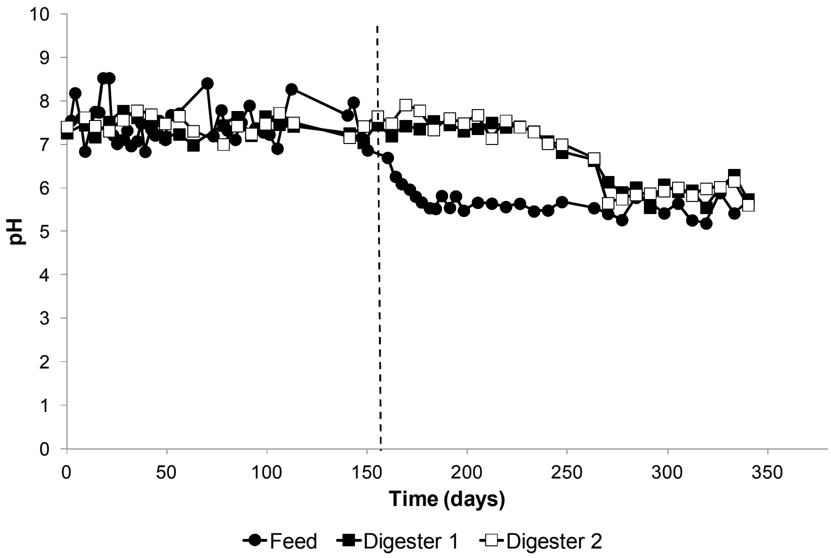


Figure 3.3 The change in pH of the digesters during acclimatisation (days 0 to 154) and addition of PMR wastewater (day 155 (dashed line) to 340). Error bars indicate SD (*n*=3) and in most cases are too small to be visible.

The most common anaerobic co-treatment of low pH wastewaters is the treatment of AMD with domestic wastewater. In this instance the biological portion of the process train does not come into contact with the acidic wastewater. The effluent generated by the anaerobic sludge contains high levels of alkalinity, which is then blended with the domestic wastewater and AMD at the beginning of the treatment process, increasing the pH of the feed to a physiologically acceptable range. During this step many of the solubilised metals precipitate, which further decreases the potential toxicity of the AMD and prevents the inhibition of normal metabolic functioning of the anaerobic bacteria (Rose *et al.*, 2002b; Poinapen *et al.*, 2009). In the present study the anaerobic bacteria came into direct contact with the acidic feed and precipitation of metal (specifically iron) occurred within the digesters. Methanogens, in particular, are sensitive to changes in pH and inhibited by high concentrations of various ions (Mara, 2003) which would have affected the pH buffering capacity of the digesters as the microbial population dynamics changed.

Ammonia removal efficiency was limited and erratic during acclimatisation (Figure 3.4) and after the third week never increased beyond 40 %. Initial ammonia removal was attributed to the presence of nitrifiers in the activated sludge seed, which continued to metabolise while the residual dissolved oxygen concentration was not limiting. The onset of anaerobic conditions resulted in denitrification of NO_2^- to NO, N_2O and N_2, followed by nitrogen fixation which liberated oxygen, produced NH_3 and caused negative ammonia removal efficiency figures (due to a net gain of ammonia). Addition of the PMR wastewater to the feed increased its ammonia concentration and negated any variations in ammonia concentrations in the domestic wastewater, resulting in an apparent stabilisation of ammonia removal. However, once the entire digester volume was replaced with 2 % PMR wastewater (v/v) nitrification rapidly decreased.

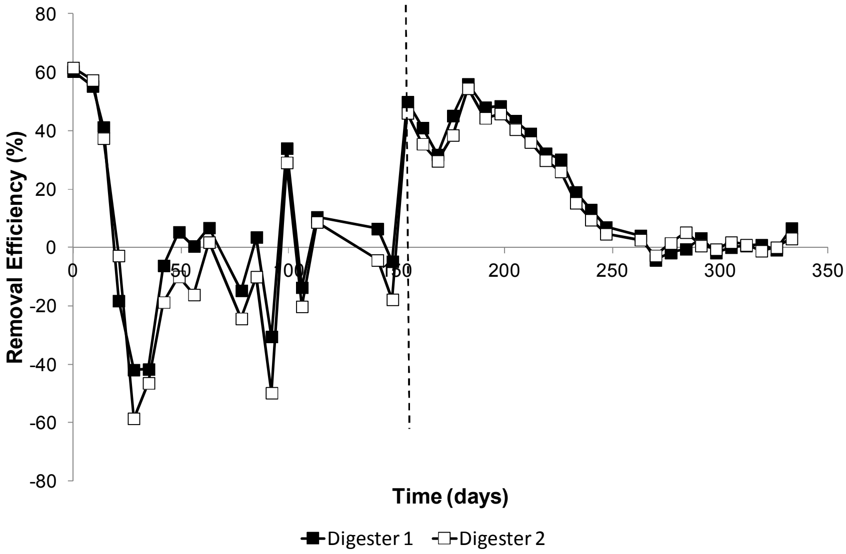


Figure 3.4 Ammonia removal efficiency during acclimatisation and addition of PMR wastewater. Error bars indicate SD (*n*=3) and are generally too small to be visible.

Ammonia oxidation is carried out almost solely by nitrifying bacteria which are obligate aerobes (Mara, 2003); as a result the poor nitrogen removal capability of the digesters was anticipated. In most cases anaerobic digestion is used in conjunction with other unit processes and is most commonly used in domestic wastewater treatment as a primary treatment step exclusively for sludge stabilisation and BOD removal (Tchobanoglous *et al.*, 2003). In cases where AD is used to treat industrial wastes with high ammonium concentrations, ammonia is first removed either by stripping (Lei *et al.*, 2007; Zhang and Jahng, 2010; Yabu *et al.*, 2011) or precipitation (Uludag-Demirer *et al,*. 2008) and in some cases ammonia oxidation may be inhibited by compounds produced during digestion (Nyber *et al.*, 2004).

Sung and Liu (2003) investigated the effects of different ammonia nitrogen concentrations on a completely mixed thermophilic digester over a pH range of 6.5 to 8.0 and reported that methanogenesis was significantly inhibited by the addition of ammonia, although acclimatisation could be achieved. Although they investigated a pH range narrower than the one used in this study, their findings suggested that increasingly acidic conditions inhibited methanogenic activity at an ammonia concentration of 1.2 g.L^{-1}. The results from day 155 onwards corroborate that conclusion (Figure 3.3). Siles *et al.* (2010) investigated the effects of ammonia and sulphate on a similar anaerobic system. They reported that a concentration of 620 mg.L^{-1} of ammonia resulted in the gradual 21 % decrease of biogas production.

The digesters were able to maintain COD removal throughout the addition of the PMR wastewater (Figure 3.5), The COD removal efficiency was 59 - 79 % while treating WSTW wastewater alone, however as the PMR wastewater concentration in the feed increased, the COD removal efficiency decreased from 79 % to 43 %. A number of compounds within the PMR wastewater may inhibit normal anaerobe functioning, including the ammonia concentration discussed above, decreasing pH, and iron precipitation which created a layer that coated the granules and may have impaired the mass transfer of substrates and products leading to localised starvation or toxicity. The carbon removal of this system operating with or without the addition of PMR wastewater was poor compared to the literature pertaining to digestion of high strength organic wastes. Khelifi *et al.* (2009) reported COD removal efficiency of 90 % when treating industrial dye effluent in an up-flow anaerobic fixed bed bioreactor; Colin *et al.* (2007) achieved removal rates of 87 % with a horizontal flow filter reactor treating cassava starch extraction wastewaters and TOC removal efficiencies as high as 91 % were reported by Bernet *et al*. (2000) when treating piggery wastewaters. In contrast, Artanto *et al.* (2009) investigated the digestion of inorganic mechanical thermal expression water and reported that after 14 days a 45 % decrease in COD concentration was observed. Digestion had to be augmented with additional chemical processing to achieve improved COD removal (Artanto *et al.*, 2009). This last wastewater was the most similar to the PMR wastewater, thus the present study is consistent with the literature.

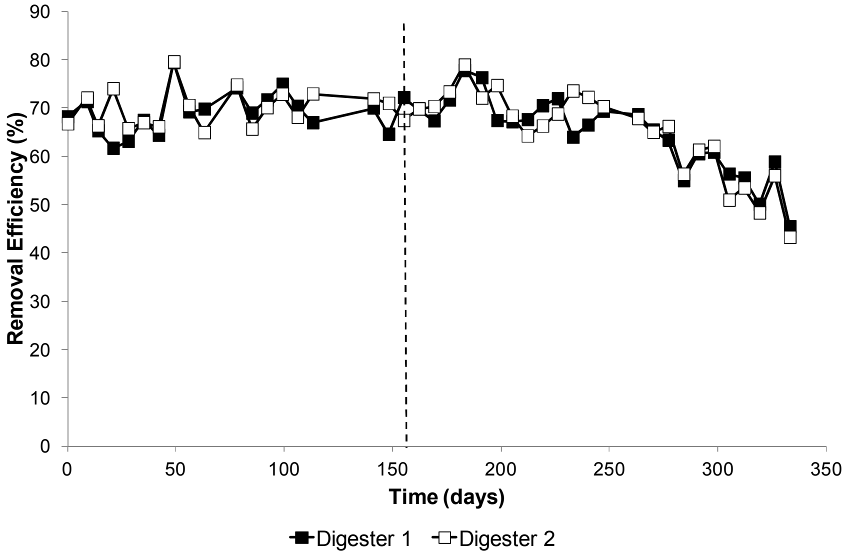


Figure 3.5 The COD removal efficiency of the digesters during acclimatisation and addition of PMR wastewater on day 155 (dashed line). Error bars indicate SD (*n*=3) and are too small to be visible.

Figure 3.6 depicts the chloride concentration in the digesters' effluent, and by extension their increasing salinity. Previous studies have applied AD to the treatment of saline wastewaters. Gebauer (2004) operated a mesophilic continuously stirred tank reactor (CSTR) with fish farm effluent containing 10 - 10.5 g.L^{-1} sodium and achieved COD stabilisation of 35 - 55 % . However, the process was strongly inhibited, an observation attributed to the high sodium concentration by the author. Diluting the wastewater with tap water resulted in stabilising and improving the efficiency of the process.

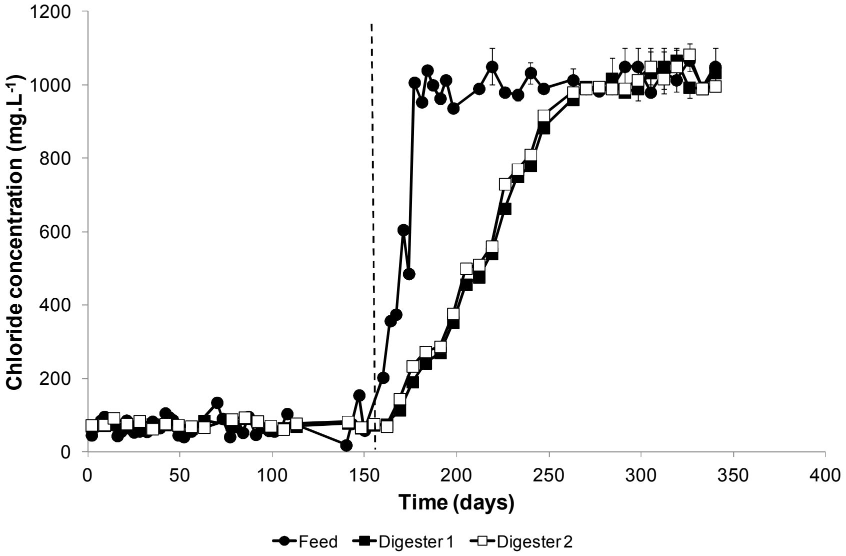


Figure 3.6 The chloride concentration in the digesters during acclimatisation and addition of PMR wastewater on day 155 (dashed line). Error bars indicate SD (*n*=3) and in some cases are too small to be visible.

The chloride concentration of the feed containing 2 % PMR wastewater was ≈1000 mg.L^{-1} and this contributed to the inhibition of the anaerobic bacteria. Anaerobic systems have successfully treated wastewaters with high salinity: Guerrero *et al.* (1997) were able to optimise an up-flow anaerobic filter reactor to maintain a COD removal efficiency of >80 % when treating wastewater from a fish meal factory containing 7.5 g.L^{-1} chloride and 2 g.L^{-1} total ammonia. Similarly, Omil *et al.* (1995) had previously adapted anaerobic sludge to treat seafood-processing industry wastewater containing a high organic content (10 – 60 g.L^{-1} COD), 5 – 12 g.L^{-1} sodium, 8 – 19 g.L^{-1} chloride and 0.6 – 2.7 g.L^{-1} sulphate. In both of these cases sufficient carbon was available to facilitate biomass growth, whereas the C:N:P ratio of the wastewater in this study was extremely unfavourable (56:4:1) and most likely contributed to the inability of the biomass to overcome the inhibitory effects of the PMR wastewater.

3.4 Conclusions

Comparing the digesters' effluents with the DWA industrial water quality targets (Table 3.3) shows that the effluents only met the target for category 4 water pH; the concentrations of chloride, COD and SS all exceeded the acceptable upper limits. The probable reason is the requirements of AD for higher carbon concentrations than were present in the mixed feed and the intolerance to the feed pH range, which rendered anaerobic treatment of the PMR wastewater without carbon supplementation unfeasible. The corollary of this conclusion was that aerobic treatment should be tested to ascertain the treatability of PMR wastewater when mixed with domestic wastewater, due to the high operating costs associated with indefinite chemical addition.

Table 3.3 Comparison of AD effluents (3 % PMR wastewater) with DWA water quality guides for industrial use (DWAF, 1996).

Parameter	**Digester 1**	**Digester 2**	**DWA Category 1**	**DWA Category 2**	**DWA Category 3**	**DWA Category 4**
Cl^- ($mg.L^{-1}$)	703 ± 345	722 ± 338	<20	<40	<100	<500
COD ($mg.L^{-1}$)	91 ± 19	90 ± 21	<10	<15	<30	<75
NH_4^+ ($mg.L^{-1}$)	86.9 ± 32.4	85.3 ± 19.0	-	-	-	-
NO_2^- ($mg.L^{-1}$)	LOD	LOD	-	-	-	-
NO_3^- ($mg.L^{-1}$)	0.1 ± 0.2	0.1 ± 0.2	-	-	-	-
pH range	5.55 - 7.54	5.83 - 7.92	7.0 - 8.0	6.5 - 8.0	6.5 - 8.0	5.0 - 10.0
TSS ($mg.L^{-1}$)	43 ± 6	48 ± 5	<3	<5	<5	<25

LOD - Limit of detection 0.00 $mg.L^{-1}$

CHAPTER 4

BENCH-SCALE ACTIVATED SLUDGE TREATABILITY STUDY

4.1 Introduction

Activated sludge (AS) is one of the most widespread treatment processes for industrial wastewaters due to its robustness, long history and ability to be customised to suit a variety of situations. Wastewaters arising from metal industries usually contain compounds that may be toxic or inhibit the growth of microorganisms. They are also often saline or exhibit extremes of pH and as such are recalcitrant to biological treatment. In Chapter 3 we saw that the low pH and high ammonium and nitrate concentrations evinced by the precious metal refinery (PMR) wastewater, which are typical characteristics of mineral and metal processing wastewaters (Koren *et al.*, 2000), inhibited anaerobic digestion and caused the digester effluent to fail to meet the water quality targets for industrial use. The digesters were unable to remove any significant amounts of nitrogenous compounds from the wastewaters, and their removal is important to the intended downstream use of the treated effluent in the concentrators used in the refinery. The nitrification process has previously been reported to be similarly inhibited in conventional municipal wastewater treatment by the addition of metal industry waste streams to the primary influent (Carrera *et al.*, 2003). However, aerobic co-treatment of mining and metal refining wastewaters has also been demonstrated to succeed in the laboratory and even at pilot and full scale (Rose *et al.*, 2002a; Whittington-Jones *et al.*, 2002). This chapter therefore sets out to assess the potential for aerobic co-treatment of the PMR wastewater with municipal wastewater in the laboratory.

4.2 Materials and Methods

Two bench-scale AS processes were operated in parallel for the treatment of PMR acid wastewater (Figure 4.1). Two 8 L aeration tanks were inoculated with AS obtained from the Johannesburg Water Northern Sewage Works (Johannesburg), covered to minimise evaporation and operated in an air-conditioned laboratory to mitigate the effects of temperature fluctuations. Mixing was achieved by sparging compressed air through the column and mixed liquor flowed under gravity to a clarifier with a volume ratio of 1:0.6.

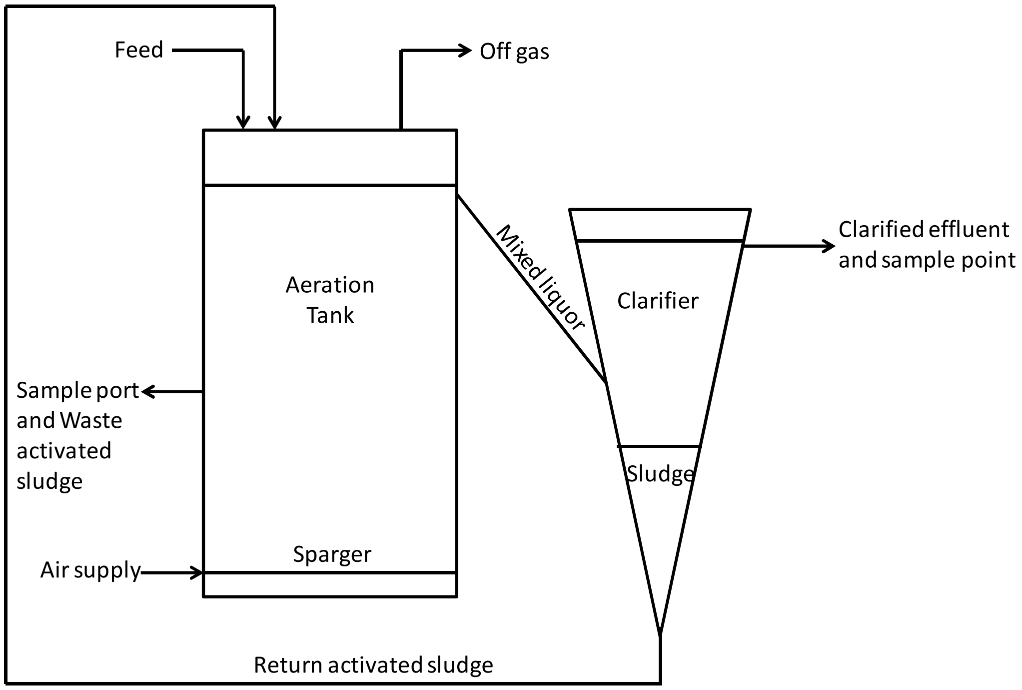


Figure 4.1 Schematic diagram of one AS unit (not drawn to scale).

Domestic wastewater used to feed the AS was obtained from Johannesburg Water's Northern Sewage Works (95 – 450 mg.L^{-1} COD and COD:N:P of 125:10:1) three times a week. The AS systems operated with sufficient airflow to provide complete mixing, a sludge retention time (SRT) of 8 days, a hydraulic retention time (HRT) of 40 hours and return activated sludge (RAS):feed ratio of 1:1, resulting in dissolved oxygen (DO) of 6 – 7 mg.L^{-1} and mixed liquor suspended solids (MLSS) concentration of 1000 – 3000 mg.L^{-1} in the aeration tanks. After a 150 day commissioning period, acidic wastewater from Anglo American Platinum's Rustenburg PMR was added to the feed in a stepwise fashion, decreasing the pH by 0.5 every SRT until a final PMR wastewater concentration of 3 % (v/v) was achieved. Waste sludge was removed from the aeration tanks at a rate designed to maintain the desired SRT.

The treatment performance of both systems was assessed using the feed and effluent pH and concentrations of chloride, COD, ammonia, nitrate, nitrite, phosphate and SS using the methods shown in Table 3.2 (page 35) and described in Section 3.2. The aeration tank MLSS and DO concentrations, settleable solids and sludge volume index (SVI) were determined according to the methods shown in Table 4.1.

Table 4.1 Parameters used to monitor the performance of the bench scale AS systems.

Feed	Aeration tank	Effluent	Analysis Method
-	Settleable solids	-	Stand Method 2710F. (APHA *et al.* , 1998)
-	SVI	-	Stand Method 2710D. (APHA *et al.* , 1998)
TSS	MLSS	TSS	Stand Method 2450E. (APHA *et al.* , 1998)

4.3 Results and Discussion

The data recorded on days 50 to 149 were compared to data from days 150 to 250 to assess the effects of PMR wastewater. The data were analysed using paired t-tests with t= 1.981 and p= 0.628 at 95 % confidence and 114 degrees of freedom. The results obtained are summarised in Table 4.2 and given in detail in Appendix B and are expanded upon in the following sections.

Table 4.2 Mean values of determinants in the feed, aeration tanks (MLSS, SVI and settleable solids) and clarified effluents ± SD (*n*=32 for the acclimatisation period and *n*=26 for the PMR feeding period).

	Parameter	Feed	Aeration tank 1 effluent	Aeration tank 2 effluent
Domestic wastewater feed	Chloride (mg.L^{-1})	28 ± 2	28 ± 3	28 ± 3
	COD (mg.L^{-1})	210 ± 83	67 ± 23	65 ± 23
	NH_4^+-N (mg.L^{-1})	21.3 ± 2.5	3.0 ± 6.2	3.2 ± 6.2
	NO_2^--N (mg.L^{-1})	0.06 ± 0.10	2.36 ± 3.99	2.81 ± 4.32
	NO_3^--N (mg.L^{-1})	0.5 ± 0.4	12.0 ± 8.2	11.5 ± 8.0
	pH range	6.93 - 7.98	6.17 - 7.42	6.44 - 7.62
	Settleable solids (ml.L^{-1}	-	47 ± 7	55 ± 20
	SVI (ml.g^{-1})	-	32 ± 10	32 ± 10
	Aeration tank SS (mg.L 1)	-	543 ± 201	549 ± 321
	Effluent SS (mg.L^{-1})	-	51 ± 6	52 ± 4
PMR wastewater feed (3 %)	Chloride (mg.L^{-1})	732 ± 369	687 ± 391	688 ± 390
	COD (mg.L^{-1})	280 ± 89	54 ± 8	52 ± 6
	NH_4^+-N (mg.L^{-1})	78.7 ± 32.6	72.5 ± 36.1	71.9 ± 36.2
	NO_2^--N (mg.L^{-1})	0.17 ± 0.17	1.05 ± 2.42	1.00 ± 2.34
	NO_3^--N (mg.L^{-1})	1.0 ± 1.0	3.4 ± 3.7	3.6 ± 3.8
	pH range	2.84 - 7.98	2.82 - 7.42	2.77 - 7.39
	Settleable solids (ml.L^{-1}	-	58 ± 17	61 ± 16
	SVI (ml.g^{-1})	-	52 ± 17	60 ± 17
	Aeration tank SS (mg.L 1)	-	1171 ± 466	995 ± 336
	Effluent SS (mg.L^{-1})	-	61 ± 5	60 ± 5

Preliminary experiments indicated that the PMR wastewater had a marked impact on the pH of the AS system, even at extremely low concentrations. Consequently, the pH of the system was decreased by 0.5 unit per SRT to allow the microbial population to acclimatise. Figure 4.2 illustrates the change in pH once the PMR wastewater was added to the feed (day 149), ultimately resulting in an operating pH of approximately 2.8.

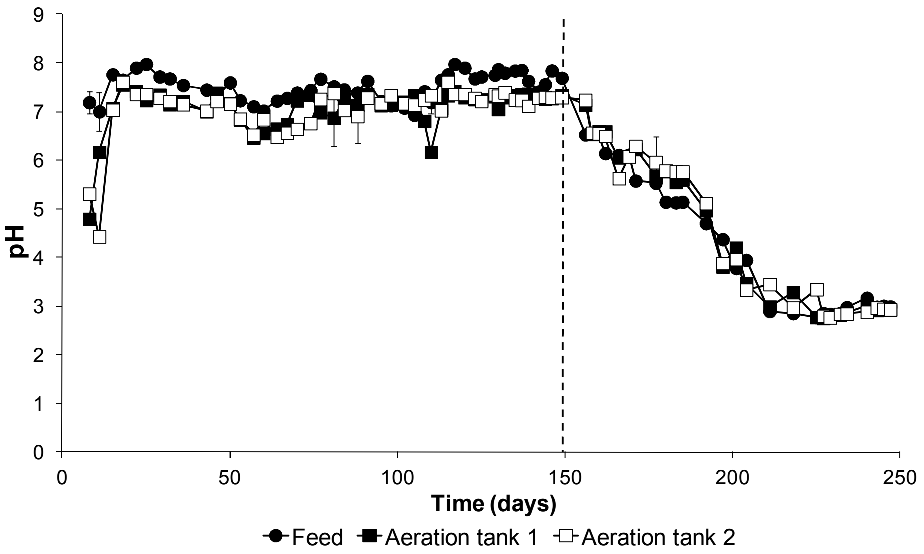


Figure 4.2 The change in aeration tank pH when PMR wastewater was added to the AS systems' feed on day 149 (dashed line), decreasing the pH by 0.5 per SRT until a final concentration of 3 % (v/v) of PMR wastewater was achieved. Error bars indicate SD (*n*=3) and in some cases are too small to be visible.

The ideal COD:N:P ratio for AS feed is 100:5:1 (Tchobanoglous *et al.*, 2003). The COD in the feed obtained from the Northern Sewage Works during the commissioning and steady state operation of the AS system never exceeded 335 mg.L^{-1} and remained below 250 mg.L^{-1} (as low as 100 mg.L^{-1} during commissioning) for the majority of the acclimatisation period. With feed ammonia concentrations of 17 – 27 mg.L^{-1}, an average COD of 450 mg.L^{-1} was required to obtain 100:5:1. The effects of the low carbon concentration in the feed were observed in the concentration of MLSS (Figure 4.3). Both aeration tanks were reseeded with RAS from the Northern Sewage Works on days 25, 36 and 53. Decreases in MLSS were observed immediately after each RAS addition, with later recovery of biomass growth. The most likely reason for the lack of sustainable biomass growth and eventually the sustained MLSS concentration of ≈1000 mg.L^{-1} is the lack of available carbon in the weak feed.

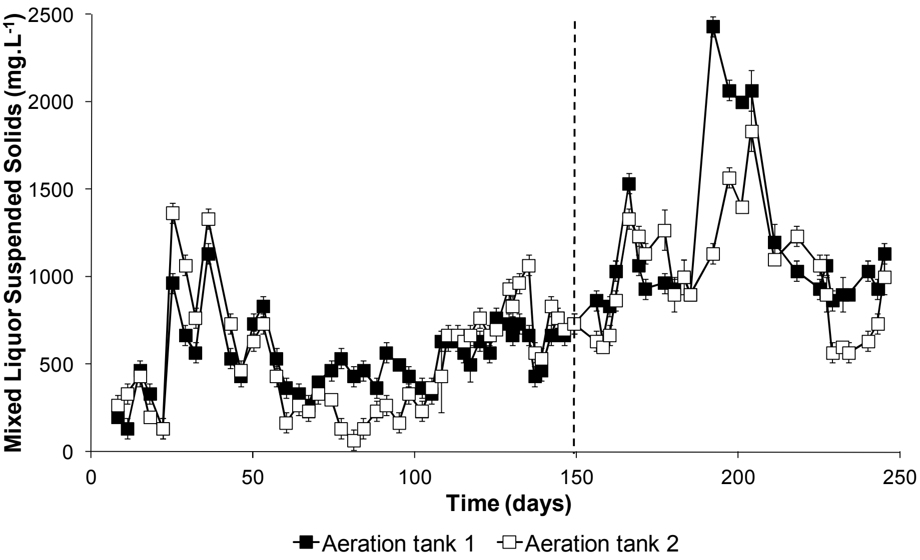


Figure 4.3 The MLSS concentration of the AS systems during steady state operation and addition of PMR wastewater on day 149 (dashed line). Error bars indicate SD (*n*=3).

Despite the difficulty in maintaining the MLSS concentrations before the addition of PMR wastewater, the MLSS concentration began to increase upon the addition of the PMR wastewater on day 149. A significant increase in MLSS concentration can be observed between days 177 and 204 in both aeration tanks, correlating to an operational pH decrease from approximately pH 6 to 3, during which time the PMR wastewater concentration increased from 1.8 to 3.0 % (v/v). Once the target PMR wastewater concentration of 3 % (v/v) was achieved, the MLSS concentration in both aeration tanks decreased, however tank 1 was able to sustain the biomass concentration more effectively than tank 2, which did begin to recover MLSS concentration towards the end of the operation of the treatment systems. While it is apparent that MLSS in aeration tank 1 was better maintained than tank 2, no statistically significant overall difference was observed in their MLSS concentrations.

The increase in MLSS upon the addition of a metallic toxin to AS has been documented previously. McCarthy (1964) proposed characterisation of the response of microorganisms to heavy metal concentrations in three zones: increasing stimulation, decreasing stimulation and toxicity (Figure 4.4) (McCarthy, 1964).

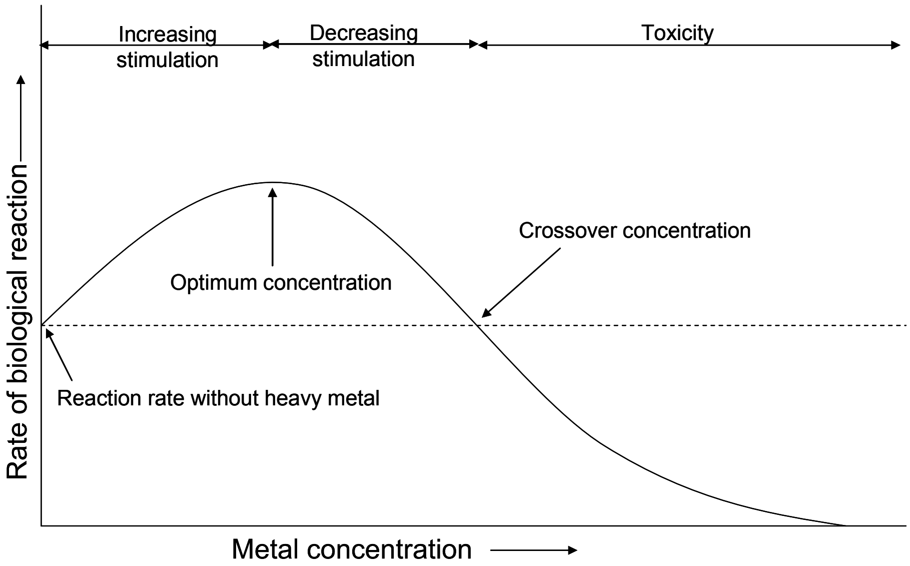


Figure 4.4 Effects of increasing heavy metal concentrations on microbial growth (adapted from McCarthy, 1964).

More recently, Valix *et al.* (2001) proposed that exposure of microorganisms to toxins has five distinct phases. The first is the lag phase after inoculation, during which very little growth takes place. During the second phase rapid growth occurs, however it is still repressed when compared to a control (a replicate subculture with no toxin added). In the third phase a decline in growth occurs, then the growth rates of the test and control organisms are similar in the fourth phase (indicative of increased tolerance of the organism). Finally, in the fifth phase, growth is rapid and often exceeds that of the control. All five phases take place within McCarthy's zone of increasing stimulation. The shapes of microbial growth curves may vary greatly depending on as the prevailing pH, other metal ions, biomass concentration, metal speciation and the presence of non-metal compounds in the system (Gikas, 2008).

Valix's five phases may be observed in the MLSS concentration after the addition of the PMR wastewater on day 149. However, in this case the first four phases appear to occur rapidly before the fifth phase of increased biomass, probably as a result of the addition of very low concentrations of PMR wastewater. A statistically significant difference between MLSS concentration before and after the addition of the PMR wastewater was observed within each aeration tank, which may be attributed either to the response of the microorganisms to toxins in the PMR wastewater, or to the increase in carbon concentration upon the addition of PMR wastewater to the feed enabling greater microbial growth, or to a combination of both factors.

The treatment of many industrial wastewaters has a negative effect on the settleability of the sludge and sludge is considered to be bulking if the SVI exceeds 150 mL.g^{-1}, while SVI <120 mL.g^{-1} is considered satisfactory (Jenkins *et al.*, 2003). Figure 4.5 shows the SVI of both aeration tanks.

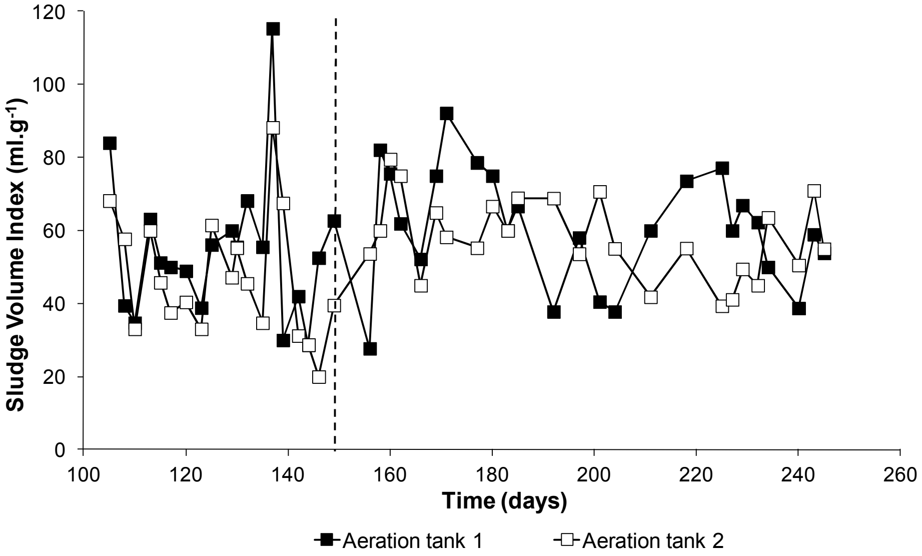


Figure 4.5 The SVI concentration of the aeration tanks during acclimatisation and after addition of PMR wastewater commenced on day 149 (dashed line).

The settleability of the sludge before and after the addition of PMR wastewater remained within the acceptable SVI range; the addition of PMR wastewater caused no bulking or rising. In contrast, upon visual comparison the sludge appeared to become thinner after the addition of the PMR wastewater than before, with decreased floc size and a change in colour from dark brown to rust orange/red. The colour change and good settleability could be attributed to the iron concentration (exceeding 30 mg.L^{-1} at 3 % (v/v)) in the PMR wastewater, added as ferric chloride during the precious metal recovery process. Precipitation of the iron occurred in the aeration tanks due to the high pH and DO.

In many instances the addition of an industrial wastewater or other potentially toxic compounds negatively affects sludge settleablity, resulting in rising or bulking sludge in the clarifier. Sludge rises as a result of the denitrification of nitrates and nitrites, leading to the formation of nitrogen gas. The gas bubbles are trapped in the sludge bed and eventually cause it to become buoyant and rise to the surface, leaving clarified effluent below the sludge blanket. The most common form of sludge bulking (when the depth of the clarifier contains an almost constant concentration of sludge which neither settles nor rises) is as a result of the over growth of filamentous organisms, or the change in morphology of organisms which can become filamentous under adverse conditions (Tchobanoglous *et al.*, 2003).

Thompson and Forster (2003) reported that changing the feed to two bench-scale AS systems treating paper mill wastewater from virgin fibre to recycled fibre resulted in an immediate and continuous loss of sludge settleablity, while Al-Mutairi (2009) developed a method of adding aerobic selectors to conventional AS systems treating slaughterhouse waste to address permanently bulking sludge. Such interventions were not necessary for this system, as the major factor was the presence of the iron salts. Iron sulphates and chlorides are effective precipitants for phosphorus removal and are used as coagulants/flocculants in water treatment. Iron (III) is generally used more but iron (II) can be used if it is first oxidised to iron (III). Clark *et al*. (2000) investigated the impact of iron (III) chloride and iron (II) sulphate on an AS pilot plant and reported poor suspended solids removal efficiency (69.5% for iron (II) and 48.0% for iron (III)) due to problems with filamentous bacteria and denitrification in the clarifiers. The flocs produced with iron (II) were larger and denser than those with iron (III), similar to the observations made in this study.

The use of ammonium chloride during precious metal refining results in high concentrations of ammonium compounds in the PMR wastewater. Figure 4.6 shows the concentrations of nitrogenous compounds in the feed, depicting the increasing ammonia concentration as the PMR wastewater in the feed was increased.

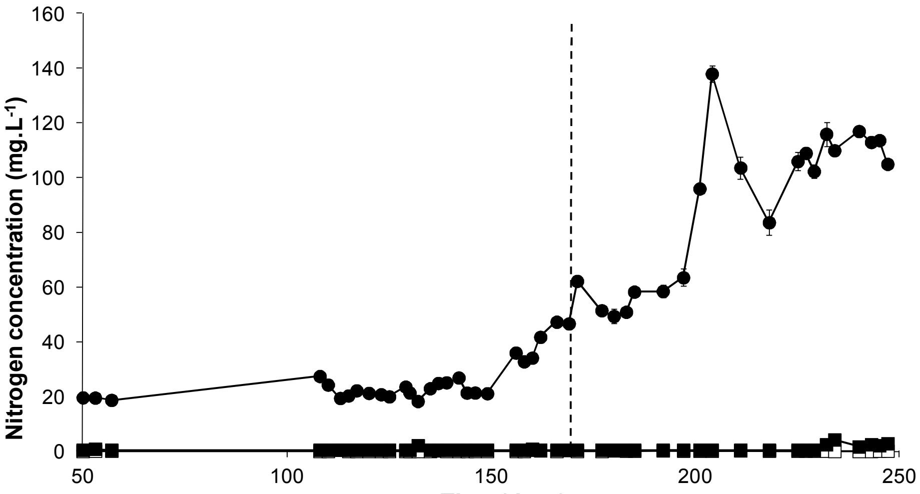


Figure 4.6 The concentration of ammonia, nitrite and nitrate in the feed of the AS systems during acclimatisation and addition of PMR wastewater after day 149 (dashed line). Error bars indicate SD (*n*=3) and at most data points are too small to be visible.

Prior to the addition of the PMR wastewater, 100 % ammonia removal was achieved in both systems. Addition of enough PMR wastewater to shift the pH from approximately 7 to 5.5 resulted in the almost complete loss of nitrification (Figure 4.7) and a statistically significant increase in the ammonia in the effluent.

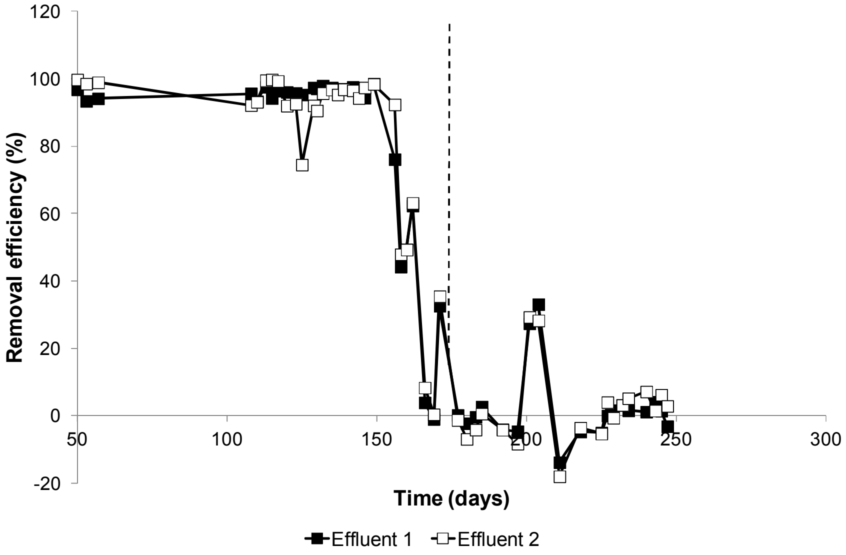


Figure 4.7 The removal efficiency of ammonia by the AS during acclimatisation and addition of PMR wastewater after day 149 (dashed line). Error bars indicate SD (*n*=3) and at most data points are too small to be visible.

When assessing the rate of ammonia removal from the wastewater, no significant difference was observed during acclimatisation (0.02 ± 0.93 mg NH_4^+-N.mg MLSS.d^{-1}) and during PMR wastewater feeding (0.02 ± 2.61 mg NH_4^+-N.mg MLSS.d^{-1}). The absence of a significant difference implies that under both conditions maximum nitrification was occurring and that further nitrification of the increased ammonia concentration was rate limited, probably by the low carbon concentration of the feed, rather than being inhibited by PMR wastewater components. This suggests that addition of a readily available carbon source to the feed may enhance nitrification in addition to supporting increased biomass concentrations for the co-treatment of domestic wastewater and PMR wastewater.

However, high concentrations of iron in AS have been reported to impede nitrification: Clark *et al.* (2000) investigating the effects of Fe^{3+} as iron (III) chloride and Fe^{2+} as iron (III) sulphate observed that nitrification was inhibited substantially more by the presence of Fe^{3+} than Fe^{2+} with removal efficiencies of 17.3 % and 88.7 %, respectively. Campos *et al.* (2002) studied the nitrification abilities of AS fed with saline wastewater with a high ammonia concentration (up to 4 g.L^{-1}) and also determined that the nitrification ability of the system depended on the concentration of salts other than the ammonium salts. Campos *et al.* (2002) found that 100 % nitrification was achieved at all salt concentrations below 13 and 8.3 g.L^{-1} of sodium chloride and sodium sulphate respectively, however nitrification ceased at higher salt concentrations.

The increased concentrations of nitrite and nitrate observed during the treatment are consistent with the absence of rising or bulking sludge, and with the laboratory conditions. The aeration tank DO (6 – 7 mg.L^{-1}) was in excess of that required for COD or BOD removal (1 – 2 mg.L^{-1}), hence excess DO was carried into the clarifiers. The aerobic/oxic conditions there prevented the reduction of NO_2^- and NO_3^- to N_2 (g) and account for the lack of denitrification.

When comparing the COD removal efficiencies, Clark *et al.* (2000) reported that removal in the presence of ferric iron, 84 %, was slightly higher than in the presence of ferrous iron, 78.6 %. Figure 4.8 illustrates the COD removal efficiency of the AS system.

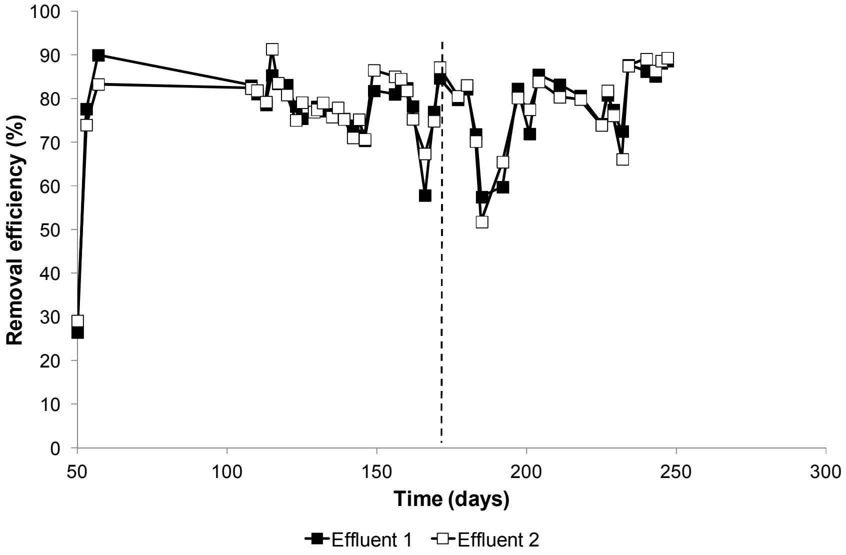


Figure 4.8 The removal efficiency of COD by the AS during steady state operation and addition of PMR wastewater on day 149 (dashed line). Error bars indicate SD (*n*=3) and are generally too small to be visible.

During operation prior to the addition of PMR wastewater a maximum COD removal efficiency of 90 % was achieved in both aeration tanks, with the removal efficiency never decreasing below 70 %. Addition of the PMR wastewater resulted in an increase in COD removal efficiencies (provided the pH remained above 5.5) due to the increased feed COD. As with the ammonia, no significant difference in COD removal rates was observed before and after the addition of the PMR wastewater. As the feed concentration of PMR wastewater increased and the pH decreased a decrease in the COD removal efficiency was discernable, however this recovered within a few SRTs with removal efficiencies >86 % being observed in both aeration tanks, similar to those reported by Clark *et al.* (2000): 84.0 % for iron (III) and 78.6 % for iron (II).

Rene *et al.* (2008) investigated the effect of the C:N ratio and salinity on the performance of sequencing batch reactors and reported similar observations as those in this study. The effects of varying the C:N ratios and salinity concentrations had a negligible impact on the removal of organics, however nitrification was hindered. In addition to containing high metal concentrations and low pH, the PMR wastewater also contained a high concentration of chloride ions largely present as ferric, ammonium and sodium chloride. Figure 4.9 depicts the increasing chloride concentrations as the PMR wastewater concentration increases.

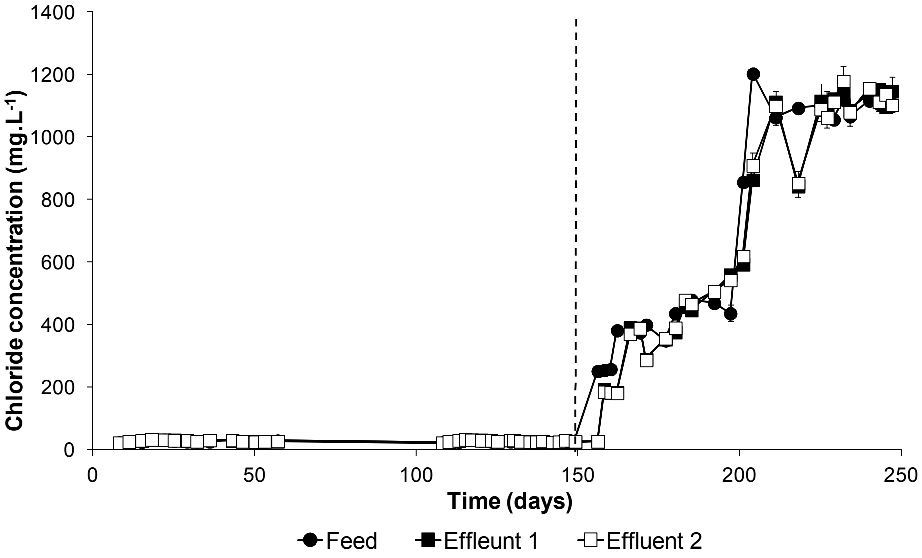


Figure 4.9 The concentration of chloride in the AS systems during acclimatisation and addition of PMR wastewater after day 149 (dashed line). Error bars indicate SD (*n*=3) and at most data points are too small to be visible.

The effects of salinity on AS have been extensively investigated. Aloui *et al.* (2009) assessed the impact of saline fish processing water and found that AS was able to acclimatise up to a sodium chloride concentration of 4 %, with COD removal efficiencies >97 %. When the NaCl concentration was >4 %, the COD and ammonium removal efficiencies deteriorated, while the most effective treatment was observed at 2 % NaCl . Similarly, a previous study carried out by Hamoda and Al-Attar (1995) demonstrated that addition of NaCl concentrations of 10 and 30 mg.L^{-1} did not result in decreased COD removal of their acclimatised bench-scale AS. The authors attributed an increase in MLSS concentration to the addition of NaCl resulting in the proliferation of salt-tolerant microorganisms (Hamoda and Al-Attar, 1995).

Abou-Elela *et al.* (2010) compared the ability of AS, AS augmented with halo-tolerant bacteria and the halo-tolerant bacteria alone to treat saline wastewater. When each system was dosed with 1 % saline, COD removal efficiencies for the three systems remained similar (80 – 90 %), however when the saline concentration was increased to 2 %, the COD removal efficiencies of the systems containing the halo-tolerant bacteria improved, while that of the AS alone decreased to 74 %. Any further increases in NaCl concentration significantly decreased the COD removal efficiency of the AS system containing no halo-tolerant microorganisms (Abou-Elela *et al.*, 2010). Their observations corroborated earlier findings by Kargi and Dincer (1997) who determined that 1 % was the salinity threshold for effective treatment of wastewater by AS and that shifts in salinity between 0.5 and 2.0 % resulted in a significant disruption in the normal functioning of the microorganisms.

The chloride concentration in this study would equate to 1.2 % at a final PMR wastewater concentration of 3 % (v/v). However, since the sodium concentration is approximately 400 $mg.L^{-1}$, much of the salinity is conferred by other cations. The effects of these cations within the PMR wastewater cannot be individually determined as saline toxicity is mitigated or enhanced by the presence of other compounds within the wastewater and the low pH. Nevertheless, the effects of the chloride concentration at 1.2 % may be overcome through the addition and acclimatisation of halophilic microorganisms to the AS system.

4.4 Conclusions

Consistent COD removal was maintained despite the operational pH dropping to approximately 3 at a PMR wastewater concentration of 3 %. Although nitrification decreased upon addition of the industrial wastewater, it did not cease completely, indicating that the metabolic processes of the AS were limited by carbon or phosphate availability. These two promising observations and the attribution of the low denitrification to the conditions of DO dictated by the bench scale, suggest AS as a potentially viable process for the co-treatment of PMR wastewater.

Comparing the effluent to the DWA industrial water quality targets (DWAF, 1996) shown in Table 3.3 (page 41) indicates that the AS was able to provide water which met the requirements for COD and TSS for category 4 industrial use. The effluents contained higher concentrations of iron and chloride than permissible in industrial water, and this necessitates downstream processing of the AS effluent before it can be reused.

4.5 Comparison of AS and AD Treatment

The systems were compared to determine which would be the more suitable method to trial co-treatment of the PMR wastewater with domestic wastewater in a pilot plant. Data were analysed using paired t-tests with t=2.002 and p=0.012 at 95 % confidence with 57 degrees of freedom. The treatment performances of the AS and AD fed with mixed feed containing PMR wastewater are summarised in Table 4.3, which shows that better removal of both COD and ammonia was achieved in the AS system. The difference in COD and ammonia removal efficiencies in the AS and AD units were 21 and 12 % respectively, despite the AS being operated at a higher PMR wastewater concentration. The AD units maintained a higher biomass concentration than the AS system, however the biomass turnover was much lower as a result of the longer SRT, therefore the suspended solids concentration cannot be used as an indicator of biomass health. Comparing Table 4.3 to the DWA water quality targets of <500 mg.L^{-1} chlorides, <75 mg.L^{-1} COD, <25 mg.L^{-1} TSS and pH of 5.0 – 10.0 shows that while the pH of the AS effluent did not fall within the DWA guidelines, the COD concentration and effluent TSS did. The AS effluents contained lower COD, NH_4 and TSS than the AD effluents, and the AS was able to sustain higher COD, NH_4 and NO_3 removal rates.

Table 4.3 Overview of treated effluent quality and treatment performance of bench scale systems operating at 3 % PMR wastewater (v/v) (mean values ± SD).

Parameter	Anaerobic digestion	Activated sludge
Chloride (mg.L^{-1})	724 ± 336	714 ± 370
COD (mg.L^{-1})	93 ± 21	53 ± 6
COD removal efficiency (%)	57 ± 7	78 ± 8
COD removal rate (mg.m^{-3}.day^{-1})	1 ± 10	2363 ± 29790
NH_4^+ (mg.L^{-1})	83.3 ± 33.2	72.2 ± 36.1
NH_4^+ removal efficiency (%)	0.8 ± 2.6	12.6 ± 24.4
NH_4^+ removal rate (mg.m^{-3}.day^{-1})	1.2 ± 6.4	247.5 ± 4249.1
NO_2^- (mg.L^{-1})	0 ± 0	0 ± 0
NO_3^- (mg.L^{-1})	0.04 ± 0.14	3.69 ± 4.65
pH	5.58 - 7.61	2.79 - 7.40
TSS reactor (mg.L^{-1})	1601 ± 425	1106 ± 401

While neither system was able to perform ideally when the PMR wastewater was introduced, the AS was more robust than the AD when the feed contained PMR wastewater. The requirements of AD for higher carbon concentrations than AS rendered anaerobic treatment of the PMR wastewater without carbon supplementation impracticable. Further, the digester effluent would require considerably more downstream processing to meet the water quality targets for industrial use than the AS clarified effluent would. As a result the investigation of a potential pilot-scale treatment system (Chapter 5) was carried out with an AS system rather than with anaerobic digesters.

CHAPTER 5

PILOT SCALE CO-TREATMENT OF PMR AND DOMESTIC WASTEWATER BY ACTIVATED SLUDGE

5.1 Introduction

In this chapter, biological treatment is investigated in a pilot plant using the most successful operating conditions identified in Chapters 4 and 5: an activated sludge process, fed with 2% PMR: 98% domestic wastewater. Access to additional domestic wastewater made it possible to operate the pilot-scale plant at a final PMR wastewater concentration of 2 %, which would greatly enhance the treatability of the industrial effluent.

The scale-up of biological processes proceeds through three phases: laboratory, pilot and production scale. These phases may also be referred to as bench, technical, semi-production, full, commercial and industrial-scale. Bench-scale processes (as exemplified in Chapters 4 and 5) involve basic studies and testing of the fundamental concept, after which a process which generated positive preliminary data is re-tested at pilot scale before being implemented at full scale (Ju and Chase, 1992). Four approaches to scale-up may be utilised, namely: dimensional, rules of thumb, fundamental and semi-fundamental methods, which form either dimensional or experiential analyses. The exact method used is dependent on preliminary data and process conditions. For example, when scaling up a stirred tank reactor, the important parameters in dimensional analysis include the stirring Reynolds number, terminal linear velocity of the impeller and specific-volume stirring power. Within a biological context, the stirred tank may be scaled up according to operational characteristics such as the specific-volume solubility coefficient in an aerobic system (Neba *et al.*, 2007; Wang *et al.*, 2010).

While similarity relationships form part of the fundamental process of reactor scale-up, essential similarities such as kinematic, dynamic and geometric cannot be maintained during the progression from bench to full-scale (Neba *et al.*, 2007) as they are mutually exclusive (e.g. linear and volumetric similarity cannot both be achieved). Further, biological processes are more difficult than chemical ones to scale due to the complexity of biological interactions and reactions occurring within the reactor (Anderson, 2009). Altering the scale of the unit impacts the effects of heat and mass transfer on the microorganisms, typically as a result of mixing. The larger the reactor, the longer the blend time and the greater the variation in shear rates experienced by the organisms (Oldshue, 1985).

Mixing at a bench or pilot level may be achieved within a few seconds; however, at full scale this process may take a few minutes. The overall conditions in the bioreactor at each scale remain constant but the individual cells may experience a variety of non-ideal conditions for a significant period at full scale operation. The unpredictability of scale-up is further exacerbated by the properties of the medium itself. Changes in osmotic pressure, viscosity, concentrations of substrate, product and waste, surface tension and pressure gradients as the scale is increased all contribute to the challenges of scale-up. In many cases scale-up becomes highly empirical and relies on the experience and qualifications of the engineers and scientists involved (Anderson, 2009; Wang *et al*., 2010).

Previously AS scale-up was based on empirical parameters, which included hydraulic loading, organic loading and aeration. Often the design of AS systems based on these parameters would result in operation failure. The use of kinetic parameters such as substrate utilization rate, biomass growth, food-to-mass (F/M) ratio and MCRT allows for a more accurate prediction of AS scale-up and functioning (Ibrahim, 2007). The change in AS design has occurred concurrently with a shift in the last few decades from comparison of small and larger scale units to development of scale up models (Lessard and Beck, 1993; Gernaey *et al.*, 2004; Nuhoglu *et al.*, 2005; Moral *et al.*, 2008; Le Moullec *et al.*, 2011).

5.2 Materials and Methods

The pilot plant was operated outdoors as a pair of identical AS systems, one test and one control (Figure 5.1). After cold commissioning, the aeration tanks were seeded with RAS from the Waterval Sewage Treatment Works (WSTW, in Rustenburg).

Air was used for aeration and to provide mixing, the system had an SRT of 8 days and an HRT of 40 hours, with a RAS:feed ratio of 1:1. The DO concentration remained between 6 and 7 mg.L^{-1} and the MLSS concentration between 1000 and 5000 mg.L^{-1}. The aeration tanks were fed with 2° influent from the WSTW (Section 3.2.2) from a 500 L balancing tank, refilled twice a week. The aeration tanks had a 235 L working volume and were mixed by bubble diffusion. They and the 74 L clarifiers were covered to minimise evaporation. The only operating philosophy difference between the bench scale and pilot scale AS units was that in the pilot units sludge wasting only occurred when the settleable solids exceeded 350 mg.L^{-1}, to replicate the operation of WSTW. Initially both systems were fed with domestic wastewater only.

The potential for secondment of additional domestic wastewater from other sewage treatment works arose after the completion of the laboratory work, creating the possibility of operating the process at a lower PMR wastewater concentration than the 3 % (v/v) used in Chapter 4. On day 167, PMR wastewater was blended with the domestic wastewater in the test plant feed tank, gradually increasing the concentration over fourteen days to 1.6 % (v/v) PMR wastewater. The test system was operated at this concentration for 48 days before the PMR concentration was increased to 2 % (v/v) and operated for a further 40 days. Wastewater treatment performance and plant operation were monitored by measuring influent and effluent pH, COD, NH_4^+, NO_2^-, NO_3^-, P and SS and aeration tank DO, pH, SVI, settleable solids and MLSS according to the methods used at bench-scale, described fully in Sections 3.2 and 4.2, pages 32 and 42, respectively.

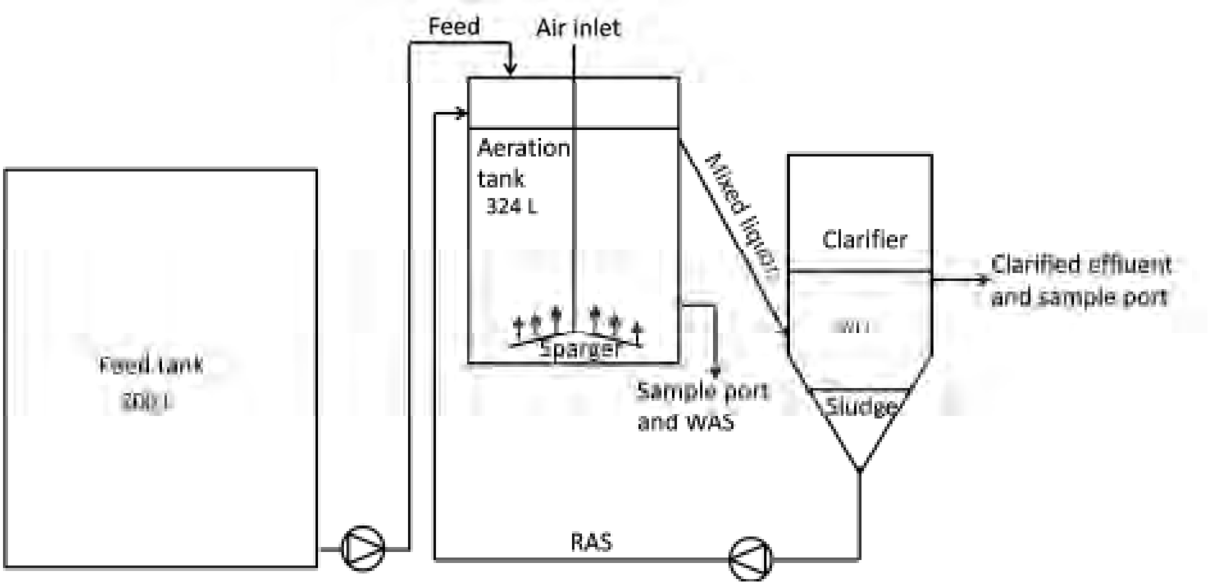


Figure 5.1 Schematic diagram of a pilot-scale AS unit (not drawn to scale).

Data were analysed using paired t-tests with t=1.976 and p=0.078 at 95 % confidence with 146 degrees of freedom.

5.3 Results and Discussion

5.3.1 Pilot plant operation

The measurements taken at the pilot plant (Appendix C) were used to calculate removal rates and removal efficiencies for COD and NH_4. The results obtained from the pilot plant are summarised in Tables 5.1 and 5.2 and expanded upon in the following sections.

Table 5.1 Mean values (± SD) of determinants in the feed and aeration tanks (MLSS, SVI and settleable solids).

Parameter		Control feed	Test feed	Control aeration tank	Test aeration tank
Domestic wastewater feed	pH range	7.11 - 8.22	7.11 - 8.22	6.71 - 7.92	6.98 - 7.88
	DO range (mg.L^{-1})	0.00 - 3.96	0.00 - 3.96	4.92 - 6.25	4.78 - 6.15
	Settleable solids (ml.L^{-1})	-	-	323 ± 179	322 ± 179
	SVI (ml.g^{-1})	-	-	147 ± 76	123 ± 51
	MLSS (mg.L^{-1})	-	-	2777 ± 629	3398 ± 1211
	SS (mg.L^{-1})	402 ± 182	421 ± 180	75 ± 26	62 ± 25
PMR wastewater feed (2 %)	pH range	7.01 - 8.58	5.11 - 7.35	7.03 - 7.67	5.17 - 7.58
	DO range (mg.L^{-1})	0.00 - 2.39	0.98 - 3.18	4.45 - 6.39	4.48 - 6.23
	Settleable solids (ml.L^{-1})	-	-	121 ± 28	156 ± 76
	SVI (ml.g^{-1})	-	-	79 ± 19	70 ± 22
	MLSS (mg.L^{-1})	-	-	2132 ± 463	2708 ± 1018
	SS (mg.L^{-1})	363 ± 114	389 ± 125	85 ± 32	68 ± 27

Table 5.2 Maximum, minimum and mean values (± SD) of the water quality analyses of the control and test feeds and effluents during commissioning and acclimatisation (days 0 – 166).

Analysis	Control feed	Test feed	Control aeration tank	Test aeration tank
Chloride (mg.L^{-1})	75 ± 28	83 ± 52	70 ± 25	70 ± 25
COD (mg.L^{-1})	281 ± 56	281 ± 55	56 ± 12	56 ± 11
COD removal efficiency (%)				
Min	-	-	66	67
Mean ± SD	-	-	80 ± 4	80 ± 4
Max	-	-	89	89
COD removal rate (mg.m^{-3}.day^{-1})				
Min	-	-	-9600	-246
Mean ± SD	-	-	-161 ± 1498	461 ± 2024
Max	-	-	1988	12425
NH$_4^+$-N (mg.L^{-1})	24.10 ± 9.18	24.55 ± 9.48	2.74 ± 3.39	3.20 ± 4.05
NH$_4^+$-N removal efficiency (%)				
Min	-	-	56.43	50.45
Mean ± SD	-	-	88.70 ± 12.72	86.39 ± 16.76
Max	-	-	100.00	99.80
NH$_4^+$-N removal rate (mg.m^{-3}.day^{-1})				
Min	-	-	-1141.6	-32.8
Mean ± SD	-	-	-27.3 ± 173.4	34.2 ± 175.3
Max	-	-	38.4	1093.1
NO$_2^-$-N (mg.L^{-1})	0.04 ± 0.04	0.04 ± 0.03	0.81 ± 1.13	0.42 ± 1.22
NO$_3^-$-N (mg.L^{-1})	0.2 ± 0.2	0.2 ± 0.3	13.8 ± 4.0	13.6 ± 4.2

Table 5.3 Maximum, minimum and mean values (± SD) of the water quality analyses of the control and test feeds and effluents during operation with 2 % PMR wastewater as a feed (days 167 – 266).

Analysis	Control feed	PMR feed	Control aeration tank	PMR aeration tank
Chloride (mg.L^{-1})	69 ± 41	867 ± 147	73 ± 26	796 ± 264
COD (mg.L^{-1})	253 ± 30	261 ± 13	55 ± 5	63 ± 12
COD removal efficiency (%)				
Min	-	-	61	51
Mean ± SD	-	-	78 ± 4	74 ± 7
Max	-	-	84	82
COD removal rate (mg.m^{-3}.day^{-1})				
Min	-	-	-1010	-417
Mean ± SD	-	-	80 ± 488	8 ± 155
Max	-	-	2300	483
NH_4^+-N (mg.L^{-1})	20.3 ± 3.0	93.8 ± 11.7	1.3 ± 1.0	73.7 ± 28.4
NH_4^+-N removal efficiency (%)				
Min	-	-	79.6	-20.7
Mean ± SD	-	-	94.0 ± 4.7	23.4 ± 26.7
Max	-	-	98	97.2
NH_4^+-N removal rate (mg.m^{-3}.day^{-1})				
Min	-	-	-95.8	-78.1
Mean ± SD	-	-	16.6 ± 56.9	-4.9 ± 21.6
Max	-	-	89.5	30.3
NO_2^--N (mg.L^{-1})	0.00 ± 0.01	0.01 ± 0.02	0.46 ± 0.78	0.17 ± 0.26
NO_3^--N (mg.L^{-1})	0.3 ± 0.3	0.2 ± 0.2	17.8 ± 2.42	9.3 ± 4.9

Mixing in both aeration tanks was achieved by sparging with air. This led to DO concentrations in the tank being higher than the concentrations usually obtained at full-scale (± 5.5 mg.L^{-1}). Denitrification requires a DO concentration of less than 1 mg.L^{-1} to occur (Tchobanoglous *et al.*, 2003) and the aeration tanks contained no anoxic zones, as a result denitrification was limited. Before the addition of PMR wastewater, nitrate concentrations in both effluents were similar (±13 mg.L^{-1}).

In bench and pilot scale systems where air diffusion is used for mixing, the DO is almost at saturation, as more air is required for mixing than for respiration. This means DO control is not possible, and any measurement of sludge handling properties that are made are not valid. To simulate full scale mixing and DO, the mixing action should be provided by means other than aeration. Mixing intensity itself affects floc structure, with consequent effects on floc ecology, sludge settling, oxygen uptake and substrate removal (Jenkins *et al.*, 1983).

After addition of PMR wastewater to the test unit feed, the effluent nitrate concentration decreased to approximately 9 mg.L^{-1}. The DO in the aeration tank remained above 5 mg.L^{-1} for the majority of the analysis period, as a result the decrease in the nitrate concentration can be attributed to inhibition of denitrificaton rather than increased nitrification. Nitrite concentrations remained negligible both before and after the addition of PMR wastewater. At full scale, and at larger pilot scale, denitrification is achieved through incorporation of anoxic zones, either through the use of a separate-stage denitrifcation system in which nitrification and denitrification occur in different reactors, or in a combined single-stage system. In this instance the reactor design facilitates the development of anoxic and aerobic zones by controlling the level of aeration and mixing occurring in each zone (Tchobanoglous *et al*., 2003).

Because a lower final PMR wastewater concentration of 2 % (v/v) was permissible for the pilot-scale study, the addition of the acidic wastewater resulted in a smaller decrease in pH of the test unit when compared to the control (Figure 5.2) than the pH decrease observed in the bench scale investigation (Figure 4.2, page 48).

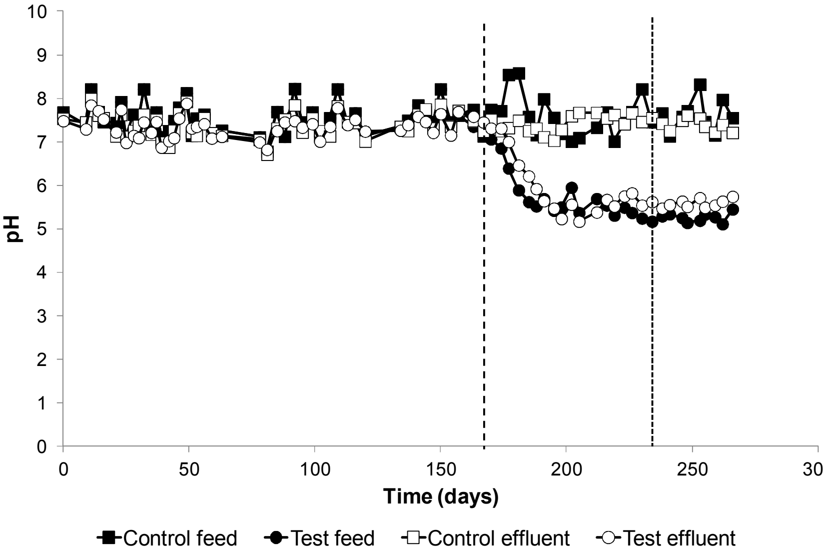


Figure 5.2 The pH of the control and test units of the pilot-scale system as PMR wastewater was added to the test unit to a concentration of 1.6 % (v/v) beginning on day 167 and 2 % (v/v) on day 234, illustrated by the dotted lines.

The test unit effluent pH remained slightly above the feed pH, however the difference is not statistically significant. Biological alterations in pH are most commonly attributed to changes in the alkalinity or proton concentrations as microorganisms attempt to regulate their environment. In an early study of the effects of temperature, pH and DO on activated sludge dewatering Sürücü and Çetín (1989) reported that operation of an AS system at pH 5.7 maintained a COD removal efficiency of 89 %, while higher a operational pH resulted in almost 100 % COD removal. Despite the effluent SS concentration being approximately four times greater than at any of the other pH values, the MLSS concentration did not appear to be impacted by the low operational pH (Sürücü and Çetín, 1989). Figure 5.3 illustrates the changes in MLSS in the present study. The feed from the WSTW had a C:N:P ratio of 56:4:1, the carbon concentration being almost half of what is ideal (Tchobanoglous *et al*., 2003). This may have contributed to difficulties in maintaining adequate biomass in both units.

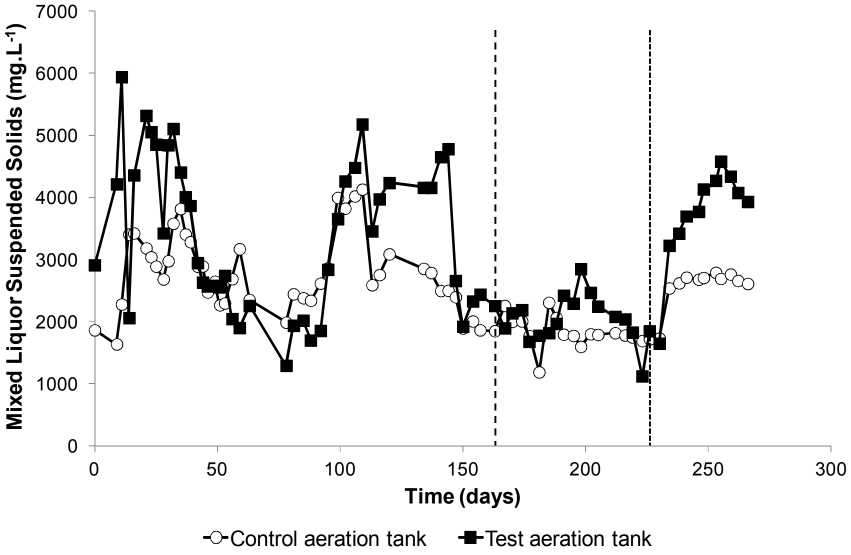


Figure 5.3 The MLSS concentration of test and control pilot plants during operation. Addition of PMR wastewater to the test unit feed in increasing concentrations to 1.6 % (v/v) beginning on day 167 and 2 % (v/v) on day 234 is illustrated by the dotted lines.

Both aeration tanks were reseeded with RAS from the WSTW on days 92 and 230. Both units were observed to undergo similar changes in MLSS concentration suggesting that the design of the AS system had a more significant impact on the MLSS concentration than the addition of PMR wastewater to the test unit. The design parameters for the clarifiers and the capacity of the RAS pump were not ideal. Sludge adhered to the clarifier walls, the sides of which were not steep enough to facilitate movement towards the bottom of the clarifier. As a result clarified effluent channelled through the sludge and was returned to the aeration tanks. The pipes returning RAS to the tanks frequently blocked, and most of the sludge remained in the clarifier for several days (until the sludge was manually returned to the aeration tanks). This resulted in localised depletion of oxygen and nutrients and a slow deterioration of the quality of the biomass. After the addition of PMR wastewater to the test feed, the MLSS in the test aeration tank increased from 1680 to 2850 mg.L^{-1} between days 177 and 198, suggesting acclimatisation of the biomass to the PMR wastewater, before gradually decreasing.

During the addition of PMR wastewater at 1.6 % (v/v), the control unit maintained a biomass concentration of 1694 – 2066 mg.L^{-1}, indicating that the increase in MLSS concentration in the test unit was a consequence of the addition of the PMR wastewater. However, whether the subsequent decrease in MLSS concentration of the test unit from 2850 to 1124 mg.L^{-1} between days 198 and 223 was a result of potential toxic effects of the PMR wastewater or poor recycling of sludge to the aeration tank cannot be determined. As discussed in Chapter 5, an increase in biomass concentration after an initial extended lag phase is often observed when toxic compounds are introduced into a biological system (Valix *et al.*, 2001).

Accumulation and subsequent degassing of the sludge in the clarifier resulted in rising sludge, which exacerbated poor sludge recycling; however the sludge was never observed to bulk. Figure 5.4 shows the SVI for both units.

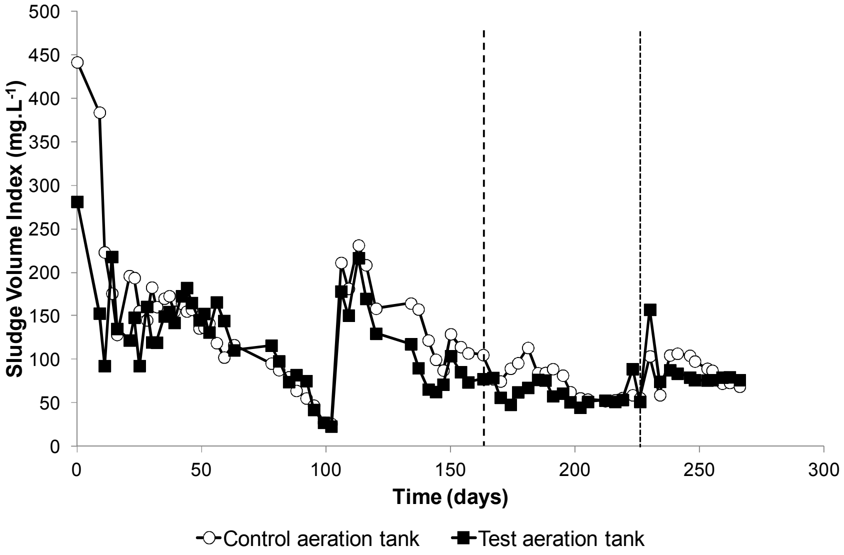


Figure 5.4 The SVI of the test and control pilot plants during acclimatisation and addition of PMR wastewater to the test unit in increasing concentrations to a final concentration of 1.6 % (v/v) beginning on day 167 and 2 % (v/v) on day 234, illustrated by the dotted lines.

Sludge is considered to be bulking if the SVI exceeds 150 mL.g^{-1} (Jenkins *et al.*, 2003), however this only occurred when the aeration tanks were seeded with fresh sludge and the MLSS increased, indicating good settling characteristics of the sludge. Bulking commonly results from imbalances in the C:N:P ratio, favouring the proliferation of filamentous microorganisms. Plants treating industrial effluent are particularly sensitive to the effects of nutritional imbalances (Pernelle *et al.*, 2001) and bulking was anticipated as a potential problem. Despite the pilot plant being operated at a lower PMR concentration than the bench-scale units, the presence of iron (approximately 25 mg.L^{-1} at 2 % (v/v)) in the wastewater had a similar effect on the biomass as reported in Chapter 4. The floc size in the test unit decreased and changed colour from brown to rust-red as a result of the precipitating iron and may have contributed to the good settleability. The observations indicate that there is potential to recover metals as valuable by-products, as well as the primary aim of producing usable water, if their fate in the wastewater treatment process can be identified.

The impact of the design of the system can be further illustrated. The slightly improved C:N:P ratio of the WSTW wastewater when compared to the Northern Sewage Works wastewater (56:4:1 and 125:10:1 respectively) and operation of the pilot plant at 2 % PMR wastewater (v/v) with the resultant increase in feed pH (approximately 5.2 vs. 2.8) was expected to result in significantly better AS functioning in the pilot plant than the bench scale unit.

While the control and test unit were both fed domestic wastewater alone there was no significant difference between their ammonia removal efficiency (Figure 5.5). Removal efficiencies of up to 100 % were observed in both, and once acclimatisation had been achieved the removal efficiency generally remained above 85 %. Similarly, there was no statistical difference in the ammonia removal rates between the two units during this time. The decrease in removal efficiency on day 141 corresponded to an unusually high concentration of ammonia in the feed, approximately 27 mg.L^{-1}.

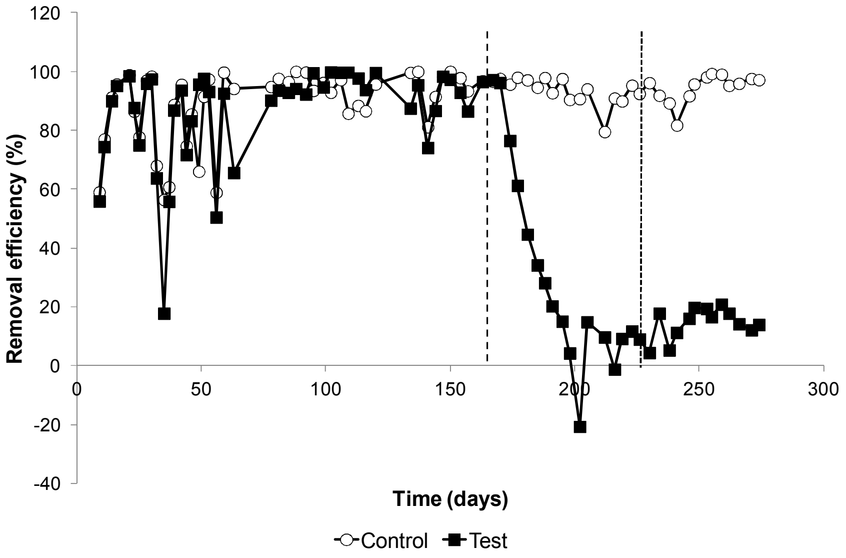


Figure 5.5 The removal efficiency of ammonia of the test and control pilot-scale units during acclimatisation and addition of PMR wastewater to the test unit in increasing concentrations to a final concentration of 1.6 % (v/v) beginning on day 167 and 2 % (v/v) on day 234.

After the introduction of PMR wastewater, a statistically significant difference between the removal efficiencies of the test and control was observed, however there was no significant difference between the removal rates. This indicates that ammonia removal was not inhibited by the PMR wastewater but was rate-limited by a lack of carbon or phosphorus (not reported as a result of inhibition of the phosphate test by the PMR wastewater), as was observed in the bench scale AS system. Similarly, the ammonia removal efficiency of the test unit decreased once the concentration of PMR wastewater was increased from 1.6 to 2 % (v/v) and a statistical difference between the test unit results before and after introduction of PMR wastewater was observed, however no statistical difference was observed in removal rates, reinforcing the theory that maximum ammonia uptake was influenced by metabolic rate-limitation, rather than the toxicity of the PMR wastewater. In contrast the inhibition of nitrification has been reported at AS pilot scale treatment of other industrial wastewaters. Chrome concentrations above 120 mg.L^{-1} in tannery wastewater (De Gisi *et al.*, 2009), VFAs (Eilersen *et al.*, 1994) and petroleum wastewater (Figuerola and Erijman, 2010) have elicited nitrification inhibition.

Figure 5.6 shows that the COD removal efficiency of both units remained between 70 and 88 % for most of the operation, and never dropped below 66 %. The decrease in removal efficiency in both units on days 174 and 181 was attributed to heavy rainfall, which diluted the wastewater from WSTW. The removal efficiency of the control unit remained within the 70-88 % range for the duration of the reactor operation. The test unit displayed no statistically significant different COD removal efficiency or removal rate from the control, before or after the addition of PMR wastewater to the test feed.

Contrary to this observation, a statistically significant difference between COD removal efficiencies in the test unit before and after the addition of PMR wastewater was observed. A statistically significant difference between the COD removal efficiency during reactor operation at 1.6 and 2 % (v/v) PMR wastewater was also observed. The COD removal efficiency decreased from 78.57 % on day 226 to 50.94 % on day 274. The decrease after the addition of the PMR wastewater and the further decrease once the PMR wastewater concentration was increased, combined with there being no statistically significant change in COD removal rates (461 ± 2024 mg.m^{3}.day^{-1} and 8 ± 155 mg.m^{3}.day^{-1} before and after PMR wastewater addition, respectively), reinforces that decreasing AS performance was more likely a result of loss of biomass due to the clarifier design than toxicity of the PMR wastewater.

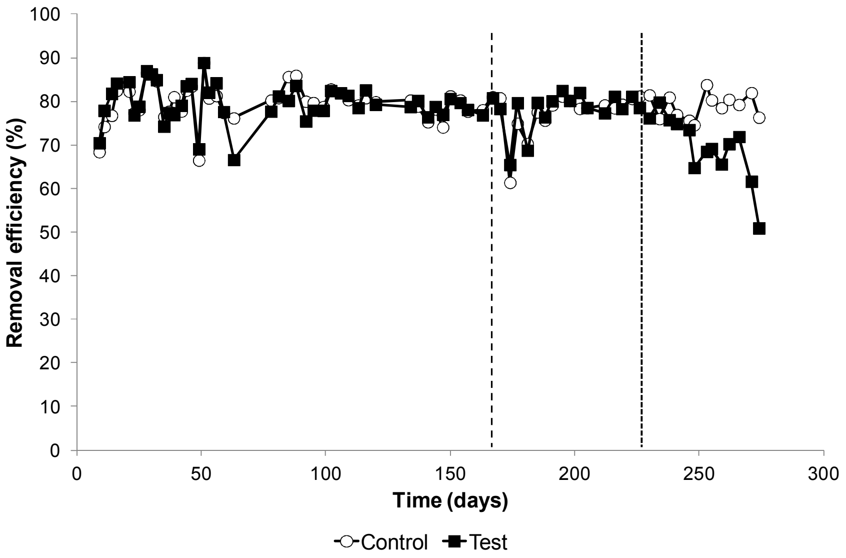


Figure 5.6 The COD removal efficiency of the test and control pilot plants during acclimatisation and addition of PMR wastewater to the test unit in increasing concentrations to a final concentration of 1.6 % (v/v) beginning on day 167 and 2 % (v/v) on day 234, illustrated by dotted lines.

The decrease in COD removal in AS systems treating industrial wastewaters at pilot and full scale has been demonstrated conclusively. The natural and synthetic tannins generated by vegetable tanning (Munz *et al.*, 2008) and the effluents produced during alcohol distilling (Satyawali and Balakrishnan, 2008) are known to suppress carbon oxidation, while the presence of industrial dyes resulted in a significant decrease in COD removal, particularly at low temperatures (Martin *et al.*, 2005). The observations in this study corroborate the literature by finding that limited COD removal can be sustained.

Figure 5.7 shows the difference in chloride concentrations in the test and control units. The chloride concentration in the test unit feed was approximately 200 mg.L^{-1} less than the feed for the bench-scale system, indicating that while the concentrations of the molecules contributing to the pH were different in each system, the concentrations of the remaining cations contributing to salinity were similar.

The effects of the cations on the AS functioning of the test unit may have been altered as a result of the increased pH. The bioavailability of the cations may have increased or decreased, and interactions with the biomass surface, cellular contents and other molecules within the system would have impacted the health of the AS. Unfortunately, determination of the effects of the cations at an increased pH is impossible; however they may have contributed to the increased MLSS observed in the test unit when compared with the control. If this is the case, it may be possible to acclimatise or augment to confer halo-tolerance to the AS a mechanism of further increasing the pH of the feed can be found. A number of authors have demonstrated the possibility of developing halo-tolerant AS, either through slow acclimatisation or augmentation of halo-tolerant microorganisms (Hamoda and Al-Attar, 1995; Aloui *et al.*, 2009; Abou-Elela *et al.*, 2010).

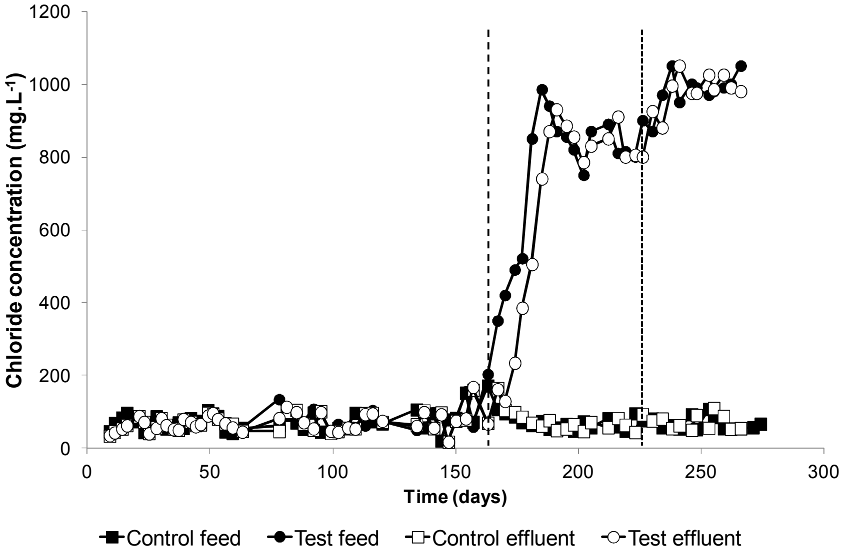


Figure 5.7 The chloride concentration of the test and control pilot-scale units during acclimatisation and addition of PMR wastewater to the test unit at 1.6 % (v/v) beginning on day 167 and 2 % (v/v) on day 234, illustrated by the dotted lines.

Sustainable biomass growth and nutrient removal would most probably be achieved by improving the clarifier design and providing augmentation to develop halo-tolerant AS. Furthermore, upstream removal of iron through precipitation by inserting an aeration process (Hove *et al.*, 2008) before the feed enters the aeration tank may also assist in increasing nitrification and COD removal in the test unit by limiting the effects of the PMR wastewater on floc size and health.

5.3.2 Comparison of bench-scale and pilot-scale test unit

The ammonia removal efficiency and removal rates of the bench and test pilot-scale systems before the addition of PMR wastewater showed no significant statistical difference despite the two units being operated with different domestic feed. However, when assessing the removal efficiency of both systems operating at steady state, there was a statistically significant difference between the systems. The pilot-scale test unit maintained an average removal efficiency of 15.45 % while being operated at 2 % PMR wastewater (v/v), while the removal efficiency of the bench-scale unit never exceeded 4.13 %.

The bench scale activated sludge process was scaled up according to the volumetric ratios of the unit, hence the geometric ratios of the aeration tanks and clarifiers could not be maintained. The bench scale system exhibited good sludge recycling and no rising sludge in the clarifiers, which ensured that the AS had a consistent supply of oxygen and nutrients and resulted in suitable biomass turn over. In contrast, the design of the pilot-scale clarifiers compared to the bench scale clarifiers (Figure 5.8) resulted in a loss of biomass as the AS became trapped in the clarifier without an oxygen supply and fresh feed for more than a day at a time. Clarifier design is concerned with efficient removal of SS from the effluent. The hydraulic characteristics of full scale plants cannot be simulated at bench scale owing to typical hydraulic overflow rates and solids loading rates, but even so some aspects of design are worth considering. The base of the clarifier should be conical to a flat bottom to minimise short-circuiting of RAS as it is drawn to the aeration basin. Protrusion of the RAS intake up into the clarifier, or the use of a conical bottom, promote sludge accumulation at the very bottom of the clarifier and leads to rising sludge (Jenkins *et al*., 1983), as observed in the pilot plant.

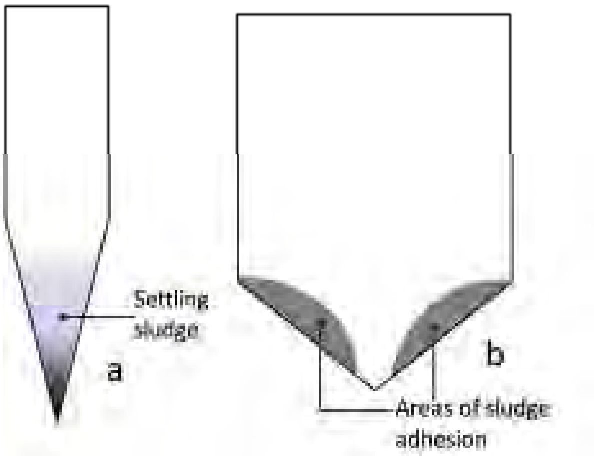


Figure 5.8 Schematic comparison of the bench (a) and pilot scale (b) clarifiers. Not drawn to scale.

Despite the effects of localised deoxygenation and nutrient starvation on the biomass, the pilot scale unit was able to continue nitrification in the presence of the PMR wastewater. This suggests that nitrification in the bench scale unit may have been affected more by the operational pH than the toxicity of the PMR wastewater. If the feed pH could be increased further, acclimatised AS may nitrify more of the ammonia present in the wastewater. This may be augmented with carbon and phosphorus addition to sustain biomass growth and ensure that low nutrient concentrations are not responsible for limiting metabolic function. The observation also suggests that the clarifier design problems which caused short-circuiting may also have allowed anaerobic zones to develop, thus facilitating nitrification-denitrification to begin inside the clarifier.

In contrast to the ammonia removal, COD removal in the pilot-scale unit was observed to be lower than that of the bench-scale units, despite the lower PMR wastewater concentration. Since autotrophic organisms are more sensitive to environmental changes than heterotrophs, it would be anticipated that the improved ammonia removal of the pilot-scale unit would correlate with a similar improvement in COD removal when compared to the bench-scale units. The fact that this was not observed further highlights the potential negative effects of the design of the pilot-scale system.

5.4 Conclusions

One of the most significant factors influencing the functioning of the pilot-scale system was the inappropriate clarifier shape. Biomass was lost in both test and control units and this exacerbated the effects of the PMR wastewater on the test unit. Despite this, the test unit was able to maintain better nutrient removal than the bench-scale AS units as a result of the increased operational pH at the lower PMR wastewater concentration. The use of aeration to provide mixing in the aeration tanks and the lack of an anoxic zone precluded full nitrification-denitrification. Modification of the pilot plant to insert either impellers (and decrease the aeration rate) or baffles to pre-contact the RAS and the feed in an unaerated zone could considerably improve nitrogen cycling. This indicates that improved AS functioning may be achieved by optimising the process design.

CHAPTER 6

MATURATION OF WASTEWATER PRIOR TO BENCH SCALE AS, ALGAL AND COMBINED TREATMENT PROCESSES

6.1 Introduction

Within the context of domestic wastewater treatment, algae have been utilised to treat both raw and settled wastewater in primary or secondary facultative ponds or as high rate-algal ponds (HRAPs) (Mara, 2003). The main function of the algae in facultative ponds is removal of BOD, nitrogen and phosphorus. The advantages of using algae in an effluent polishing step are the low cost of operation, discharge of oxygenated effluent into the receiving water and nutrient removal (Aslan and Kapdan, 2006). Furthermore, algal processes may be applied to wastewaters containing low concentrations of carbon as algae utilise carbon dioxide, carbonates and bicarbonates as dissolved inorganic carbon sources (Antunes *et al.*, 2003).

Algal technology has been applied to the direct treatment of agro-industrial wastewaters (Ogbanna *et al.*, 2000; An *et al.*, 2003; Olguín *et al.*, 2003; Mulbry *et al.*, 2008), paper and pulp wastewaters (Dilek *et al.*, 1999; Tarlan *et al.*, 2002) and indirectly by blending effluents for the treatment of acid mine drainage (AMD) (Whittington-Jones *et al.*, 2006). The use of algae for removal of industrial contaminants such as heavy metals, hydrocarbons, surfactants and biocides has been widely investigated; however, while the studies demonstrate the capacity of algal technologies to treat these compounds, actual potential for application has yet to be realised (de-Bashan and Bashan, 2010).

6.1.1 Rationale

During operation of the pilot plant it was noted that algae grew on the clarifier walls. Further, sludge with some apparent anaerobic activity accumulated at the bottom of the pilot plant test-unit feed tank, and the pH of the bulk liquid feed increased slightly during intervals between each fresh feed supply. A simple flask test was carried out to determine whether sludge extracted from the feed tank could increase the pH of fresh feed. Three 1 L flasks of mixed feed were inoculated with 100 ml of sludge from the pilot-scale test unit feed tank and topped up with the domestic and PMR wastewater blend. An identical control flask was filled with the domestic/PMR wastewater blend, without sludge inoculation. The flasks were covered to minimise evaporation and the pH was monitored twice a week for three weeks with a pH electrode (Hanna Instruments, USA). Figure 6.1

shows the change in pH of the test flasks compared to the control (appendix D). By the end of the second week the pH in the test flasks had increased from 5.32 to 6.84, while the pH of the control flask remained the same. Very little change in pH was observed in the test flasks beyond two weeks, with a final pH of 6.89 being observed. This observation suggested that allowing blended feed to mature in a balancing tank prior to AS treatment had the potential to confer advantages to the stability of the AS and the quality of the treated effluent.

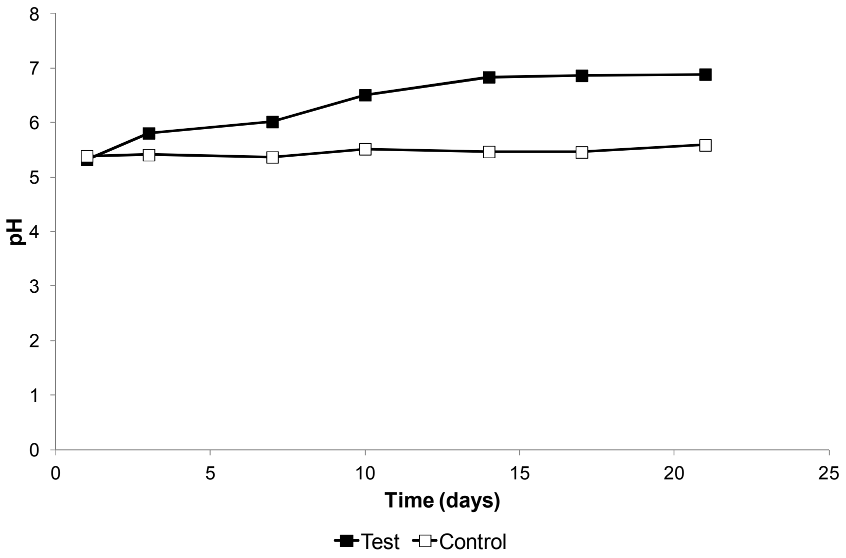


Figure 6.1 Change in pH of flasks inoculated with anaerobic sludge and fed with a domestic-PMR wastewater blend (*n=3*) compared with an uninoculated control over a period of 3 weeks. Error bars are too small to be seen.

These preliminary observations prompted an investigation into the potential for algal treatment (either after AS or instead of it) and feed maturation in the laboratory.

6.2 Materials and Methods

Three bench scale treatment processes were used: AS, algal treatment and a combined process of AS followed by algal treatment, as shown in Figure 6.2. Based on the preliminary results from blending the two wastewaters, 120 L balancing tanks were seeded with 20 L of sludge collected from the test pilot plant feed tank, topped up with the wastewater blend and allowed to mature for two weeks before being used as feed for all three processes.

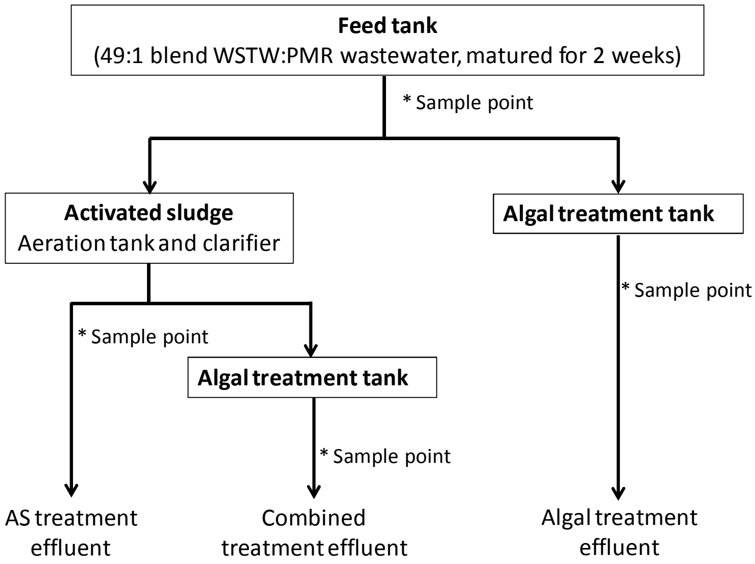


Figure 6.2 Flow diagram depicting the matured feed, three treatment processes, generation of three effluents and corresponding sample points.

6.2.1 Activated sludge treatment

The two identical bench-scale AS systems used in Chapter 5 were operated under the conditions described in Section 4.2.1 (page 42) with domestic wastewater from WSTW, Rustenburg (Section 3.2.2, page 32). Both systems received feed from the matured feed holding tanks and were operated with the same HRT. The AS systems were restarted by seeding with RAS from WSTW and operated at an MLSS of 4000 – 6000 mg.L^{-1}, without wasting, to emulate operations at WSTW. The AS was fed immediately with the wastewater blend and was not acclimatised to the PMR wastewater. Samples of the feed, aeration tank mixed liquor and effluent were taken twice a week. The sample analyses included the determination of TSS, COD, NH_4^+, MLSS, pH and alkalinity (Standard Method 2320B, APHA *et al.*, 1998) according to the methods described in Sections 3.2 and 4.2.

6.2.2 Algal treatment

Two algal tanks (Figure 6.3) were set up and operated as batch units under plant growth lights with a 16:8 hour light-dark cycle without continuous mixing. Each was seeded with a litre of algae harvested from the walls of the clarifier of the pilot-scale test unit. One was fed with the blended, matured feed and the other with the AS unit effluent, according to Figure 6.2. The algal tanks had a volume of 6.75 L, half of which was replaced with fresh feed twice a week, providing an HRT of 1.04 days, during which time the contents of the tanks were completely mixed. No algal biomass was removed during operation and changes in biomass concentration were noted as a visual observation. Samples of feed and effluent were taken twice a week and the pH and concentrations of TSS, COD, NH_4^+ and alkalinity (Standard Method 2320B, APHA *et al.*, 1998) were measured as described in Section 6.2.1.

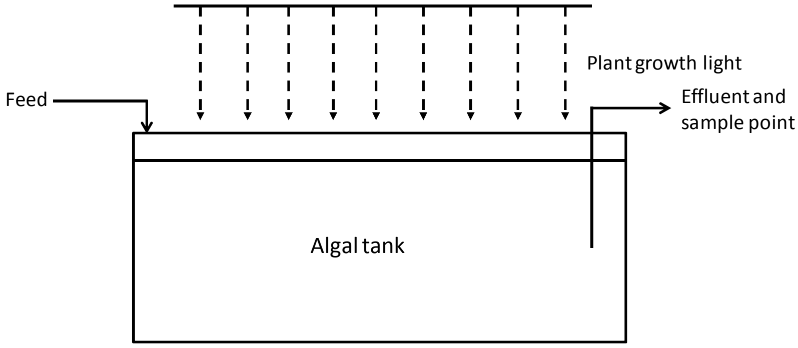


Figure 6.3 Schematic representation of the algal tanks (not drawn to scale). One fed with blended, matured WSTW and PMR wastewater and the other with effluent from the AS system.

6.2.3 Combined process: activated sludge and algal treatment in series

As shown in Figure 6.2, effluent from the bench scale AS was used to feed an algal polishing tank. The operating conditions of the AS stage were as described in Section 6.2.1 and of the algal treatment stage as in Section 6.2.2. Samples were taken from the feed, AS effluent and algal tank effluent twice a week. The pH and concentrations of TSS, COD, NH_4^+ and alkalinity were measured as described in Sections 6.2.1 and 6.2.2.

6.2.4 Metals analysis

To obtain a preliminary assessment of the fate of metals during treatment, liquid samples were taken twice a week from the sample points illustrated in Figure 6.2 for metals analysis. Spot samples of the PMR and WSTW wastewaters were analysed to determine the metal contributions of each wastewater to the feed. At the end of the experiments, solid samples were extracted from the feed tank, aeration tanks and algal tanks and analysed to measure the amounts of sorbed and precipitated metals. Metals concentrations were determined using atomic absorption spectrophotometry and inductively-coupled plasma optical emission spectrophotometry at Anglo Research Centre, using South African National Accreditation System (SANAS) accredited methods. The aim was to determine whether metals in the feed reported to the solid or liquid products of treatment.

6.3 Results and Discussion

6.3.1 Reactor performance and water quality

The bench scale AS system fed with the matured feed evinced a more variable pH (4.9 – 7.3) than that of the feed itself (Figure 6.4), which was 6.1 – 7.3 (Appendix D). The decrease in pH in the aeration units could be attributed to ferric iron hydrolysis reactions (De Gregorio *et al.*, 2010) or release of cellular contents during cell lysis.

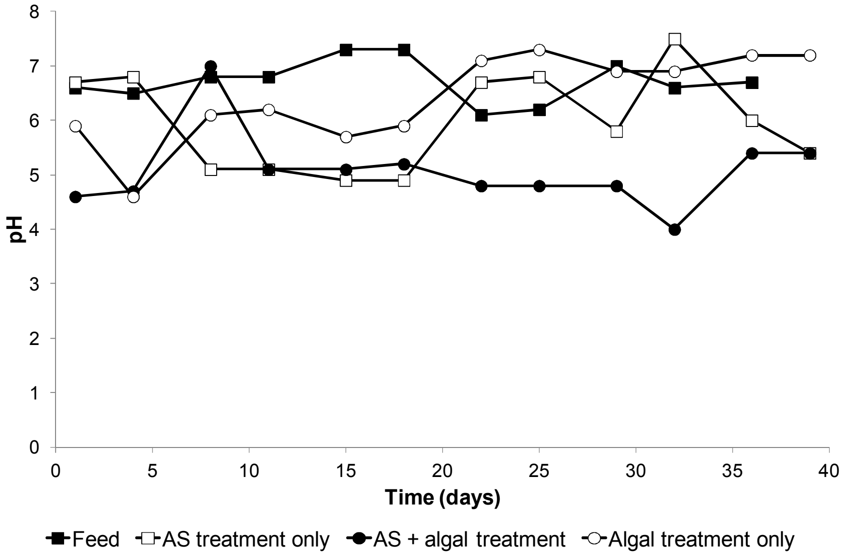


Figure 6.4 Change in pH of the blended, matured feed and the effluents of the three bench scale treatment processes during the 39 day operation (*n=3*). Error bars are too small to be seen.

The pH in both algal tanks decreased (Figure 6.4), with the pH in the algal tank with no AS treatment increasing on day 19 as a result of anaerobic bacteria contaminating the algal tank and gradually replacing the algal biomass. The experiment demonstrated that algal treatment of the feed without prior AS treatment was not a viable option, and should not be further investigated as the algae could not compete with bacteria present in the feed.

The pH of the combined AS plus algal process effluent remained below 5.4 for most of the time, contrary to the expectation that the production of bicarbonates by the algae would increase the alkalinity, thereby increasing the pH.

While alkalinity and pH are related, they should not be confused. The pH of a sample refers specifically to the relationship between hydroxide and hydrogen ions, while alkalinity refers to the relationship between carbon dioxide, carbonate and bicarbonate concentrations. The alkalinity affects the pH of the system by providing molecules which have the ability to buffer additions of acidic or basic compounds. At a pH between 5 and 9, bicarbonate alkalinity dominates. Figure 6.5 shows the alkalinity of each of the process units investigated in this section.

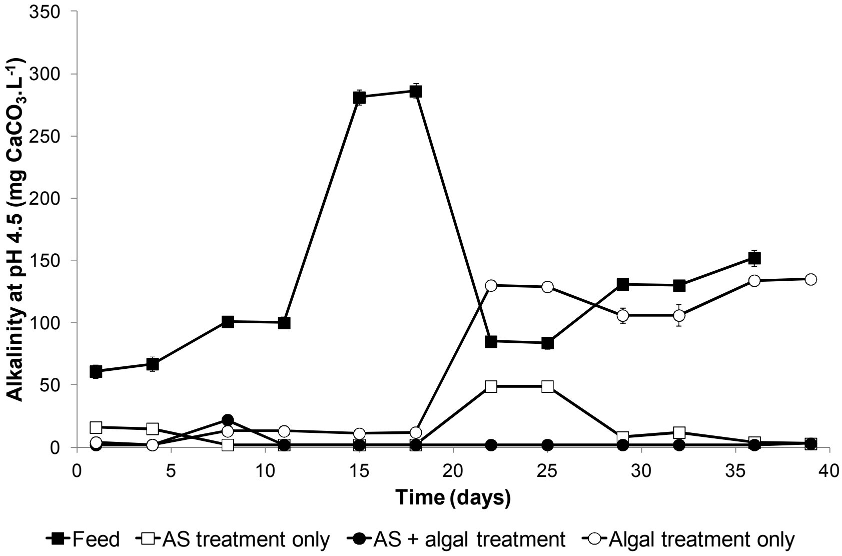


Figure 6.5 Alkalinity concentrations of the matured feed and each of the treatment process effluents (*n=3*). Error bars may be too small to be seen.

The alkalinity of the feed increased from 61 mg $CaCO_3.L^{-1}$ on day 1 to 152 mg $CaCO_3.L^{-1}$ on day 39, with a concentration above 280 mg $CaCO_3.L^{-1}$ in the third week of operation. This may indicate that when the anaerobic bacteria proliferated in the feed tank, their capacity to generate alkalinity and increase the pH also increased. The capacity of the anaerobic sludge to alter the alkalinity of the wastewater was further illustrated when the algal tank receiving feed without AS treatment became contaminated with anaerobic biomass on day 19, resulting in an increase in alkalinity and pH of the effluent.

In Equations 6.1 – 6.8, Remoudaki *et al.* (2003) described the process of metabolically increasing the pH of a liquid medium through biological generation of alkalinity using acetate as the carbon substrate in both aerobic and anaerobic systems. They achieved this by formulating the overall metabolic reaction based on microbial metabolism stoichiometry centred on three semi-reactions: carbon source oxidation, cell material synthesis and electron acceptor reduction.

Equation 6.1 is the electron donor half-reaction for the oxidation of acetate under aerobic conditions:

$$\frac{1}{8}CH_3COO^- + \frac{3}{8}H_2O \rightarrow \frac{1}{8}CO_2 + \frac{1}{8}HCO_3^- + H^+ + e^- \qquad 6.1$$

Equation 6.2 is the reaction of cell synthesis (assuming typical cell biomass formula is $C_5H_7O_2N$) and ammonium as the nitrogen source:

$$\frac{1}{5}CO_2 + \frac{1}{20}HCO_3^- + \frac{1}{20}NH_4^+ + H^+ + e^- \rightarrow \frac{1}{20}C_5H_7O_2N + \frac{9}{20}H_2O \qquad 6.2$$

Under aerobic conditions, the reduction of oxygen half-reaction is given by Equation 6.3:

$$\frac{1}{4}O_2 + H^+ + e^- \rightarrow \frac{1}{2}H_2O \qquad 6.3$$

The overall reaction for acetate with an indicative yield of $Y_{\frac{x}{s}}$ = 0.42 g biomass.g^{-1} acetate is given in Equation 6.4:

$$CH_3COO^- + 0.914O_2 + 0.217NH_4^+ \rightarrow 0.217C_5H_7O_2N + 0.131CO_2 + 0.783H_2O + 0.783HCO_3^- \qquad 6.4$$

The metabolism of one mole of acetate produces 0.783 moles of HCO_3, resulting in a progressive increase in the pH of the medium as more acetate is consumed. The production of CO_2 in the aerobic system results in the generation of carbonates and bicarbonates as a result of increased CO_2 solubility in alkaline conditions.

Under anoxic conditions, the electron capture reaction proceeds with nitrate as an electron acceptor, as represented in Equation 6.5:

$$\frac{1}{5}NO_3 + \frac{6}{5}H^+ + e^- \rightarrow \frac{1}{10}N_2 + \frac{3}{5}H_2O \qquad 6.5$$

Assuming an indicative yield of 0.2 g biomass.g^{-1} acetate, the overall metabolic reaction rate with a HCO_3^- yield of 1.478 mol per mol of acetate is described by Equation 6.6:

$$CH_3COO^- + 1.182NO_3^- + 0.104NH_4^+ + 0.600H^+ \rightarrow 0.104C_5H_7O_2N + 0.896H_2O + 1.478HCO_3^- + 0.591N_2 \qquad 6.6$$

As nitrates are consumed, a favourable environment for sulphate reducing conditions is established and sulphate acts as a terminal electron acceptor producing HS^- (Equation 6.7):

$$\frac{1}{8}SO_4^{2-} + \frac{9}{8}H^+ + e^- \rightarrow \frac{1}{8}HS^- + \frac{1}{2}H_2O \qquad 6.7$$

Equation 6.8 describes the overall metabolic reaction for acetate under sulphate reducing conditions, assuming an indicative yield of 0.1 g biomass.g^{-1} acetate, resulting in the production of 1.739 moles HCO_3^- per mole of acetate:

$$CH_3COO^- + 0.869SO_4^{2-} + 0.052NH_4^+ + 0.078H^+ \rightarrow 0.052C_5H_7O_2N + 0.869HS^- + 1.739HCO_3^- + 0.157H_2O \qquad 6.8$$

Under both aerobic and anaerobic conditions, using acetate as a model carbon source, reactions 6.4, 6.6 and 6.8 illustrate that the pH of the medium is increased due to H^+ consumption and production of carbonates in the presence of different terminal electron acceptors (Remoudaki *et al.*, 2003). Such illustrations led to the expectation that bacterial generation of alkalinity would be observed.

The alkalinity of the effluent from the AS-algal treatment process remained unexpectedly low. Nitrifying bacteria are known to utilise bicarbonates as a form of inorganic carbon (Carrera *et al.*, 2004), however, it was anticipated that the algal biomass would generate additional alkalinity. Alkalization and dissolved inorganic carbon (DIC) accumulation are two processes connected with photosynthetic CO_2 fixation. At pH <5, where the DIC is predominantly CO_2, alkalization does not occur (Shiraiwa *et al.*, 1993). Furthermore, the function of carbonic anhydrase (CA, the enzyme responsible for catalysis of carbonate and bicarbonate) is suppressed at pH < 8.3 and completely repressed at pH 5.0 (Antunes *et al.*, 2003). The pH in the feed to the algal tank in both algal systems in this study did not exceed 7.5 and in most instances the feed for the combined AS-algal treatment remained below 5.8, indicating that the alkalization ability of the algae was impeded by the feed pH.

The alkalinity of both algal tank effluents (before day 19) showed a decrease. At the pH of the feed for both algal tanks the source of DIC was CO_2 (dissolved and atmospheric) and HCO_3^- (dissolved and already present in the domestic wastewater), both of which are known to act as an algal carbon source (Yamano and Fukuzawa, 2009; Chi *et al.*, 2011).

Sigg *et al.* (1991) investigated the generation of alkalinity in a seasonally anoxic lake and observed that when anoxic conditions prevailed there was an increase in alkalinity, approximately 66 % of which was linked to nitrate reduction in the water column. Nitrate concentrations of 4 - 11 $mg.L^{-1}$ were detected in the final effluent from the combined AS-algal treatment system, indicating that nitrates may be functioning as terminal electron acceptors for the anaerobic production of bicarbonates in the feed tank. However, significant production of bicarbonates only occurs if nitrate is the predominant form of available nitrogen. If ammonia concentrations are higher, acidity is produced (Das *et al.*, 2000).

The ammonia removal efficiency for the majority of the treatment period never exceeded 10 % within any of the treatment units and large fluctuations in ammonia removal efficiency were observed (Figure 6.6). The removal efficiency of the AS treatment remained the most consistent, as a result of its high biomass concentration and aerobic conditions. However a gradual decline in removal efficiency was observed over time, consistent with observations made in the pilot plant and earlier bench scale units (Chapters 6 and 5, respectively) and probably exacerbated as a result of the biomass being unacclimatised to the PMR wastewater. The combined AS and algal treatment process was more variable in its ammonia removal, and the least removal was obtained by the algal treatment process, which deteriorated notably once the algal biomass was contaminated by anaerobic bacteria. After this occurred, the algal process demonstrated a net gain in ammonia, probably due to denitrification proceeding in the tank.

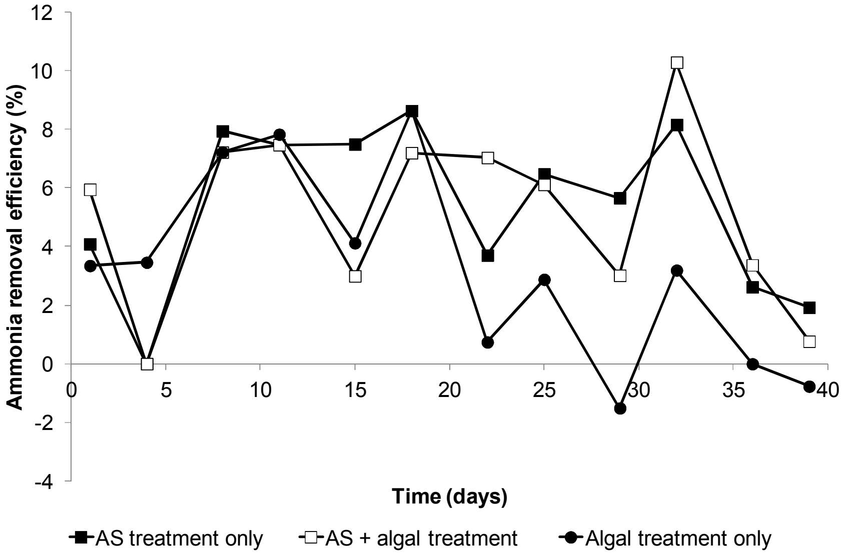


Figure 6.6 Ammonium removal efficiency at each stage of the treatment process during the 39 day operation.

Despite the low alkalinity and pH in the combined AS and algal treatment process, it showed the greatest potential for COD removal. Its COD removal efficiency was 71 - 78 % for the duration of the treatment period (Figure 6.7).

In contrast, the COD removal efficiency of the algal treatment only was low: 26 to 17 %. This is attributed to the autotrophic nature of the algae, which do not use as much organic carbon as bacterial heterotrophs, as they utilise CO_2 in the light-dependent reactions of photosynthesis. The slower growth of anaerobic bacteria when compared to aerobic systems (Tchobanoglous *et al.*, 2003) explains the lower COD removal efficiency observed in the algal treatment process after the bacterial contamination than in the AS treatment. While it was concluded that two weeks was sufficient time to increase the pH of the feed from approximately 5.3 to 7.3, biomass regeneration of the feed tank sludge was slower. This is further illustrated by the fact that the alkalinity (Figure 6.5) gradually increased as the biomass in the feed maturation tank aged, since no wasting occurred. As a result, it may be possible to improve the feed balancing tanks to generate higher biomass concentrations, and therefore high alkalinity, in addition to COD removal during maturation of the feed. This possibility is worthy of investigation, because it partly contradicts Chapter 4, in which acclimatised anaerobic bacteria were not able to maintain high pH or remove much COD.

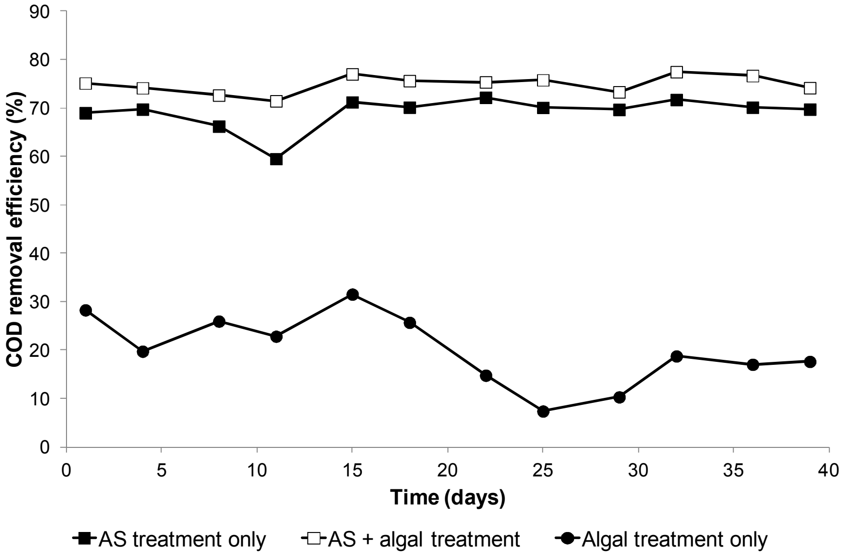


Figure 6.7 Removal efficiency of COD of the AS, algal and combined processes over the treatment period.

6.3.2 Distribution of metals

The metal concentrations in the effluents were monitored throughout the treatment process, while the solid fraction was analysed for metal precipitation and accumulation only at the completion of the 39 day treatment period because the analytical procedure destroyed the sludge. Table 6.1 lists the metal concentrations in each wastewater comprising the feed, and the blended feed.

Table 6.1 shows that the measurements of metals in the mixed feed correlated poorly with the calculations, based on a 49:1 mixture of domestic:PMR wastewaters. The measured concentrations of aluminium, boron, barium, calcium, cobalt, copper, iron, magnesium, manganese, nickel, phosphorus, silica and sodium were lower than the predictions. This may be attributed to reactions taking place during mixing of the feed (e.g. precipitation of some components) or to adsorption of some metals onto the sludge in the feed tank. Many of the elements listed above sorb readily to AS (Aragón *et al.*, 2010; Laurent *et al.*, 2010; Park *et al.*, 2010; Suzuki *et al.*, 2010; Wang and Waite, 2010; Benaïssa and Elouchdi, 2011 ; Li *et al.*, 2011; Ochoa-Herrera *et al.*, 2011; Peeters *et al.*, 2011).

The difference between expected and observed values cannot all be thus explained. Antimony and potassium appear to exceed the calculated values. In the case of antimony, the contradiction is probably due to the measurement in domestic wastewater being so close to the limit of detection that it is not entirely reliable (especially as the result was obtained from a spot sample). The potassium apparent discrepancy can be accounted for by the SD of the measured concentration in the mixed feed; 15 ± 5 mg.L^{-1} is in agreement with the predicted value of 14 mg.L^{-1}.

Table 6.1 Mean concentrations of metals in each wastewater, calculated mixed feed concentration and observed mixed feed concentration at 2 % PMR wastewater.

Metal (mg.L^{-1})	Domestic wastewater	PMR wastewater	Calculated mixed feed concentration	Measured mixed feed concentration
Aluminium	0.08	24.00	0.56	0.09 ± 0.13
Antimony	0.05	83.00	1.71	7.39 ± 2.55
Boron	0.55	1.07	0.56	0.18 ± 0.11
Barium	1.23	0.97	1.22	0.97 ± 0.37
Calcium	40	54	40	24 ± 3
Cobalt	0.01	1.00	0.03	0.02 ± 0.02
Copper	0.06	10.24	0.26	0.10 ± 0.00
Iron	0.25	1297.93	26.20	7.08 ± 9.50
Magnesium	11	19	11	9 ± 1
Manganese	0.05	24.79	0.54	0.31 ± 0.18
Nickel	0.20	283.53	5.87	2.50 ± 2.37
Phosphorus	7.89	3.41	7.80	1.93 ± 2.81
Potassium	14	9	14	15 ± 5
Silica	7.9	55.7	8.9	7.4 ± 2.6
Sodium	67	14725	360	224 ± 64
Zinc	0.30	8.27	0.46	0.33 ± 0.25

The possibility of interference as a result of increasing chemical complexity of the wastewater is raised by the fact the effluent concentrations of calcium, magnesium, nickel and sodium for each treatment process (Table 6.2) correlated better with the calculated feed concentrations than the measured feed concentrations. If the calculated feed concentrations are compared to the effluent concentrations of each treatment process of the other metals it is apparent that the decreases in concentration observed for aluminium and boron are within the SD of the mean, and hence are not significant.

Table 6.2 Metals concentrations in each of the treatment units at 2 % PMR wastewater.

Metal (mg.L^{-1})	**AS treatment process effluent**			**AS + algal treatment process effluent**			**Algal treatment process effluent**		
	Min	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
Aluminium	0.01	0.23 ± 0.25	0.89	0.01	0.13 ± 0.15	0.37	0.01	0.05 ± 0.05	0.13
Antimony	0.05	8.29 ± 0.83	2.9	0.15	6.30 ± 0.71	2.16	0.05	4.88 ± 1.89	2.5
Boron	0.06	0.18 ± 0.08	0.29	0.32	0.38 ± 0.12	0.48	0.1	0.22 ± 0.08	0.33
Barium	0.15	0.81 ± 0.35	1.21	0.29	0.74 ± 0.24	0.89	0.14	0.83 ± 0.37	1.29
Calcium	28	35 ± 4	40	33	40 ± 5	44	25	32 ± 8	49
Cobalt	0.02	0.06 ± 0.02	0.07	0.04	0.06 ± 0.01	0.07	0.01	0.07 ± 0.14	0.05
Copper	0.05	0.17 ± 0.15	0.24	0.11	0.17 ± 0.04	0.21	0.01	0.05 ± 0.07	0.19
Iron	0.10	0.23 ± 0.10	0.33	0.08	0.14 ± 0.05	0.21	0.04	5.45 ± 9.07	21
Magnesium	10	11 ± 1	13	11	13 ± 2	16	9	11 ± 2	15
Manganese	0.44	0.86 ± 0.27	1.13	0.57	0.80 ± 0.10	0.91	0.06	0.48 ± 0.20	0.79
Nickel	0.81	7.42 ± 3.85	13	0.61	6.74 ± 3.19	9.45	0.35	3.98 ± 3.50	8.3
Phosphorus	0.04	0.12 ± 0.09	0.31	0.03	0.07 ± 0.03	0.1	0.02	0.13 ± 0.10	0.31
Potassium	12	15 ± 4	22	13	15 ± 2	18	9	13 ± 3	17
Silica	7.0	8.29 ± 0.83	9.4	5.4	6.30 ± 0.71	7.7	1	4.88 ± 1.89	7.5
Sodium	332	371 ± 23	412	314	364 ± 26	398	243	288 ± 49	397
Zinc	0.41	0.82 ± 0.36	1.4	0.53	0.97 ± 0.30	1.43	0.05	0.50 ± 0.35	0.96

The concentrations of the metals moving through the system in most instances were determined to be close to the 0.01 mg.L^{-1} detection limit of the analytical method. In some cases it appeared that metals were accumulating in the various processes, however the units were operated as a continuous or semi-batch system and metal accumulation in the liquid fraction would have been impossible. The concentrations of sodium, calcium, magnesium and nickel were most notable in their apparent accumulation; however sodium, calcium and magnesium were all detected using an atomic adsorption spectrophotometer, which has a narrower detection range and accuracy than inductively-coupled plasma spectrophotometry. In addition, samples were filtered before acidification, hence if precipitation of sodium, calcium or magnesium occurred during sample collection, transport or preparation the reported metal concentration in the liquid fraction would have been lower than the actual concentration prior to sampling.

A major drawback to the use of spectroscopy is interference by anions or cations present in the sample. Spectral interferences are caused by the presence of atoms which have absorption lines very close to that of the target analyte, or by fine rotational lines of the molecular absorption band, resulting in either a positive or negative error in the measurement. For example, the presence of iron, magnesium, nickel and copper in the same sample were reported to yield much larger atomic fractions in the flame than the sample (El-Gohary, 2002). In addition many chloride and sulphate compounds are known to exhibit suppressive effects (Akman and Ince Tekgül, 1999).

Common methods to overcome the effect of interference include calibration of the instrument by standard addition, matching standard solutions to the sample or chemically removing known interfering compounds. Unfortunately each of these techniques has its own drawbacks which may also result in analytical errors and require additional efforts, time, sample and reagents (Kościelniak and Kozak, 2001).

Even at a 2 % concentration of PMR wastewater, the concentrations of calcium, iron, magnesium and sodium were orders of magnitude higher than the other metals detected in the sample. Given that the limit of detection of the analysis method was reported to be 0.01 mg.L^{-1} and that most of the metals at each stage of the treatment process were determined to have concentrations lower than 1 mg.L^{-1} (Tables 6.1 and 6.2), it is likely that there was significant interference by the cations and anions present at higher concentrations, resulting in either a positive or negative error in the results obtained.

The concentrations of antimony, barium, copper, manganese, silica and zinc either remained the same throughout the treatment process when compared to both the calculated and measured feed concentrations, or were within one SD of the mean, or decreased in concentration. The only metal to result in an increased concentration in each process was cobalt; however the concentration was determined to be so close to the limit of detection of the analysis method that given the complexity of the wastewater, it cannot be a reliable representation. Iron and phosphate were the only elements determined to significantly decrease in concentration during treatment.

Iron removal in the AS and combined treatment processes can be attributed to the aeration of the AS. The decrease in the iron concentration in the effluent from the AS and combined treatment processes was between 20 and 50 fold that of the effluent from the algal treatment process (Figure 6.8) and as high as 99 % in some cases. Upon visual inspection it was concluded that the iron precipitated was most likely ferric hydroxide, which readily precipitates when aerated and is dependent on the presence of DO (Hove *et al*., 2008).

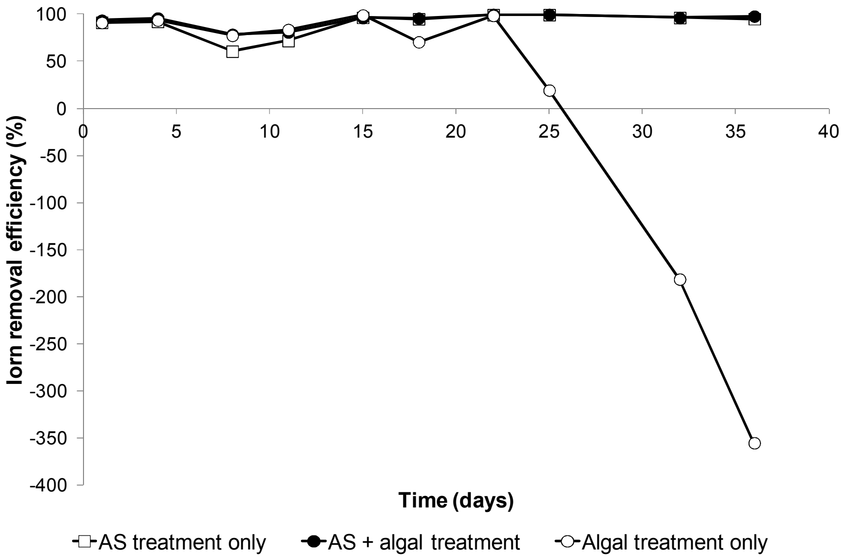


Figure 6.8 Iron removal efficiency of the three treatment systems.

This result supports the suggestion advanced on page 68 that WAS extracted from the AS process may yield useful, recoverable metals.

The phosphorus concentration also decreased during treatment (Figure 6.9). While a portion of phosphorus removal might be attributed to precipitation (Table 6.3), phosphorus removal increased steadily to >98 % in each treatment process, indicating that phosphorus was being biochemically utilised and was likely to be metabolically limiting, and hence was a significant contributing factor in the low ammonia removal efficiencies observed at the bench and pilot-scale. The decrease in removal efficiency on day 32 was attributed to low phosphorus concentrations being detected in the feed, however the removal efficiency increased again to above 97 % in all three processes. This trend is consistent with the observations made in earlier chapters regarding the C:N:P imbalance in the feed. As soon as one of the three nutrients has been used up, the uptake of the other two all but ceases.

Table 6.3 lists the concentration of detectable metals in the solids extracted from the treatment process units at the completion of the experiment. Effluent from the AS units was stored in a 100 L tank before being added to the algal tank as feed. While the effluent remained in the tank, formation of a precipitate was observed, which was included in the solids metal analyses.

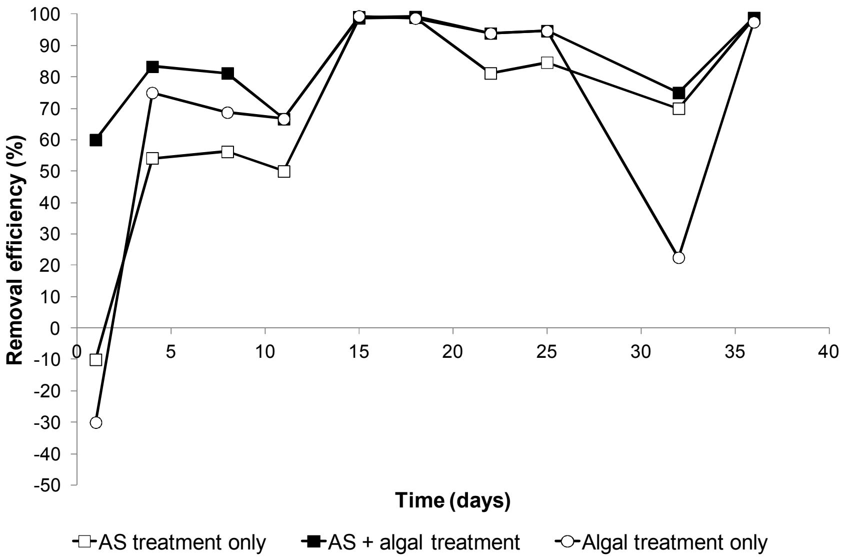


Figure 6.9 Phosphorus removal efficiency of the three treatment systems.

Table 6.3 Metals present in solids in the treatment systems at the end of the 39 day treatment cycle at a PMR wastewater concentration of 2 %.

Metals (mg.g^{-1})	Maturation tank sludge	AS aeration tank sludge	Algal biomass (AS + algal treatment)	Algal biomass (algal treatment only)	AS effluent tank sludge
Aluminium	19.7	13.9	11.6	< 0.05	15.4
Barium	0.0	0.0	2.7	< 0.05	9.0
Calcium	12.5	8.8	7.8	0.3	9.0
Chromium	8.5	2.3	3.9	< 0.05	2.8
Copper	10.4	2.9	1.0	< 0.05	3.9
Iron	47.6	102.0	48.6	< 0.05	108.0
Magnesium	15.2	7.4	18.3	< 0.05	8.4
Nickel	17.1	2.1	1.4	< 0.05	2.8
Phosphorus	4.0	23.0	8.5	< 0.05	22.9
Silica	54.2	37.6	77.3	< 0.05	37.9
Titanium	1.2	0.9	0.8	< 0.05	1.0
Zinc	2.6	0.0	1.6	< 0.05	1.1

Most metals achieved maximum precipitation in the maturation tank, except for iron, which precipitated more readily after aeration in the AS units. The iron concentrations in the aeration tank sludge and effluent tank sludge were similar (102 and 108 mg.L^{-1}, respectively) and iron continued to precipitate in the algal tank receiving AS effluent. The improved precipitation in the maturation tank can be attributed to the prevailing pH. Metal solubility decreases with increasing pH, and the decrease in pH of the AS and algal units would have aided solubility of metals as they entered each system. No metals, except for 0.3 mg.L^{-1} of calcium, could be detected in the solid fraction of the algal tank receiving matured feed, this is a result of algal die off as the anaerobic bacteria proliferated in the tank and the final biomass concentration being extremely low.

The presence of metals has a varied effect on microorganisms within wastewater treatment operations. Metals in high enough concentrations may impair growth rates (Gikas and Romanos, 2006), disrupt COD and ammonia removal (Stasinakis *et al.*, 2002) and change the population dynamics of the sludge (Nicolau *et al.*, 2005). Other than the high concentrations of sodium, calcium and iron, it is unlikely that the metals in the PMR wastewater were present at high enough concentrations to exert any inhibitory effect on the biomass function in isolation. However, as part of a complex wastewater their effects may be mitigated or enhanced in a manner which is impossible to determine at this time.

Tables 6.1, 6.2 and 6.3 indicate that most of the dissolved metals removed from the wastewater reported to the sludge by-products. This presents the possibility of recovering the metals, which would prevent them from being lost to the environment and defray the cost of water treatment.

The sludge is mainly carbon-based; smelters use carbon as a reductant, so to add sludge to the smelter is not expected to have any negative effects (Slatter, 2012, pers. comm.). The base and PG metals of the sludge would report to the matte, which is the product used in refining (Figure 1.1, page 2). The iron in the sludge would mainly report to the slag, thereby removing it from the process. The sludge would need to be dried and fed to the smelter with the concentrate produced from flotation because, except for being organic (which the concentrate is not), it has similar properties (e.g. handling characteristics, rheology, particle size).

Dewatered sludges from wastewater treatment are fed to the smelters at Yak Tunnel (Montana, USA) and Port Pirie (Australia) after thickening and filtration (Zinck, 2005). Yak Tunnel disposes of all of the 1425 tonnes of sludge produced per annum by reprocessing via its smelter (Zinck, 2005).

6.4 Conclusions

Blending the PMR and domestic wastewaters and inoculating them with acclimatised anaerobic sludge allows the pH of the mixed wastewater to increase from approximately 5.3 to 7.0. This process could be improved to increase the pH through the generation of higher biomass concentrations. The increased pH could contribute to improved metal removal through precipitation and once the microbial population is sustained these metals may be recovered through wasting of the biomass. The higher pH and lower metals concentration of the feed may enable more stable AS operation and improve its effluent quality.

The bench scale treatment processes indicated that AS was the most appropriate of the three methods tested (AS, algal treatment and a combined process of AS followed by algal treatment). The use of algae as a polishing step after the AS treatment, or as a substitute for AS treatment was not successful, further supporting the decision at the end of Chapter 5 to investigate AS at pilot scale, and considering it to be the most promising candidate treatment process for the PMR wastewater. The failure of the algal treatment to biologically generate alkalinity can be accounted for by the high concentrations of organic carbon in the wastewater preventing the algae from being the dominant flora in the algal tanks and the suppression of CA function at the prevailing low pH. A possible alternative to generate alkalinity and increase the pH of the final effluent could be to cultivate the algae in domestic wastewater alone and blend the effluents of each process.

The metals analyses showed that the majority of the metals entering the treatment processes reported to the sludge, which confers two advantages. Firstly, the metals are entrapped in the solids and are therefore relatively easy to handle and recover either through acidification and the return of the eluent to the metal refining process or by smelting the solids. Secondly, the treated effluents do not contain significant concentrations of metals, which allows for a choice of routes for reuse of the water. This topic will be inspected in more detail in the following chapter.

CHAPTER 7

EFFLUENT REUSE

7.1 Introduction

Three pollution prevention strategies exist: traditional end-of-pipe waste treatment, cleaner production and industrial ecology. While end-of-pipe treatment is the most common, it often results in the waste problem being moved from one place to another; it does not address the efficient use of limited resources and it often results in more capital requirements than treatment of the waste at source. Industry needs to move away from end-of-pipe technologies in favour of a more holistic intra- and inter-industrial approach to waste minimisation and pollution control. Cleaner production assesses the use of limited resources in a particular process and attempts to minimise resource usage. In addition, recovery, recycling and reuse of materials is emphasised. Industrial ecology stresses redesigning industrial systems to ensure the waste products from one process serve as the raw materials for another. Ideally, different industries need to communicate and meet each other's needs through large scale knowledge and resource sharing. Industrial ecology is obviously a long term solution to the pollution problem but has a few challenges of its own: there is a risk that confidential information may become public; the supply chain could break down, resulting in a collapse of the system; the quality of the raw materials may not be guaranteed; and recycling does not completely exclude the production of other hazardous by-products (Cervantes and Pavlostathis, 2006).

Any individual or company that produces wastewater in South Africa is legally bound to render it harmless, except when wastewater is discharged following legal consent. Discharge licences are granted as numeric targets which can be measured and therefore enforced. In some cases it may be more feasible to reuse water which does not meet these targets within another process. The DWA has published guidelines for water quality to be used in secondary processes (Table 7.1) which are categorised according to their water quality requirements. Some of these limits are considerably more lenient than those for discharge, hence partial treatment of recalcitrant wastewaters may render them suitable for use in another area of operation.

Table 7.1 The DWA water quality guidelines for industrial use (DWAF, 1996)

Parameter	Category 1	Category 2	Category 3	Category 4
Category information (quoted from guidelines)	*"Processes that require a high quality water with relatively tight to stringent specifications of limits for most or all the relevant water quality constituents. Standard or specialised technology is essential to provide water conforming to the required quality specifications. Consequently, costs of inhouse treatment to provide such water are a major consideration in the economy of the process."*	*"Processes that require water of a quality intermediate between the high quality required for Category 1 processes and domestic water quality (Category 3 processes). Specifications for some water quality constituents are somewhat tighter or more stringent than required for domestic water quality. Standard technology is usually sufficient to reach the required water quality criteria.*	*"Processes for which domestic water quality is the baseline minimum standard. Water of this quality may be used in the process without further treatment, or minimum treatment using low to standard technology may be necessary to reach the specifications laid down for a desired water quality. Costs of further inhouse treatment are not significant in the economy of the process."*	*"Processes that within certain limitations can use water of more or less any quality for their purposes without creating any problems. No additional treatment is usually required and there is therefore no further cost."*
$CaCO_3$ ($mg.L^{-1}$)	<50	<120	<300	<1200
COD ($mg.L^{-1}$)	<10	<15	<30	<75
Chlorides ($mg\ Cl.L^{-1}$)	<20	<40	<100	<500
Iron ($mg\ Fe.L^{-1}$)	<0.1	<0.2	<0.3	<10.0
Manganese ($mg\ Mn.L^{-1}$)	<0.05	<0.1	<0.2	<10.0
pH	7.0 - 8.0	6.5 - 8.0	6.5 - 8.0	5.0 - 10.0
Silica ($mg\ Si.L^{-1}$)	<5	<10	<20	<150
Sulphate ($mg\ SO_4.L^{-1}$)	<30	<80	<200	<500
TDS ($mg.L^{-1}$)	<100	<200	<450	<1600
TDS as EC ($mS.m^{-1}$)	<15	<30	<70	<250
TSS ($mg.L^{-1}$)	<3	<5	<5	<25
Total hardness ($mg\ CaCO_3.L^{-1}$)	<50	<100	<250	<1000
Examples of processes and products where water may be used	• Evaporative cooling • Boilers • Phase separation • Washing without residuals (e.g. electronic parts)	• Solution cooling • Water heating • Humidification • Gas cleaning • Solvent agent • Beverages • Dairy products	• Once-through evaporative cooling • Mould cooling • Dilution agent • Descaling • Gas scrubbing • Surface washing • Domestic use (i.e. treated to potable quality)	• Ash quenching • Dust suppression • Fire fighting • Rough washing • Transport water

The Anglo Platinum facilities at Rustenburg include base and precious metal extraction (recall Figure 1.2, page 3). The preferred route for water reuse is the Retrofit Concentrator, because flotation uses vast volumes of water. This water demand means that a reticulation system already exists to deliver reusable and recyclable water to the concentrator. Before a new water source can be connected to the concentrator, the effect the new water would have on its process must be determined.

Experiments were conducted to determine whether it would be possible to incorporate the treated water from the biological treatment processes into the concentrator make-up water, or whether the effluents would have a detrimental effect on flotation. Flotation is the process whereby minerals present in a slurry containing value and gangue minerals encounter an air bubble swarm. The addition of various reagents facilitates the adhesion of the target minerals to the bubbles, which are then separated from the slurry and further processed to produce the final metal product (Rubio *et al.*, 2002; Féris *et al.*, 2004; Yianatos, 2007).

The suitability of the effluents generated in Chapter 7 for reuse in the concentrator was investigated, specifically in reference to minerals flotation. Finally, the effluents were compared with the DWA guidelines for water quality for industrial uses to judge whether the treated water might be used in applications other than flotation.

7.2 Materials and Methods

7.2.1 Flotation analysis

The effluents generated by the three treatment processes described in Chapter 7 (page 71), namely AS treatment only, AS and algal treatment and algal treatment only, were investigated for their suitability for use in flotation and compared to the process water currently used for flotation at Anglo Platinum's Retrofit Concentrator, Rustenburg. Process water is the standard water used for flotation at the Retrofit Concentrator. Flotation experiments were performed according to standard Anglo Research (Johannesburg) laboratory flotation procedures. All flotation tests were carried out in 100 % of each of the test waters on a Merensky ore sample obtained from the Retrofit Concentrator. Results were reported as grade recovery curves. The curves were compared with one another and specifically to the curve obtained using the process water as this is the standard water to assess the impact the effluents would have on routine operation. Base metal grades are reported as percentages, while precious metal grades are reported as g.ton^{-1}.

7.3 Results and Discussion

7.3.1 Reuse of treated effluent for flotation

A good grade recovery curve is characterised by high recovery of a high grade product. However, these two are mutually exclusive and the most desirable trade-off is represented by a curve in which the final grade datum point (at the right hand end of the data series) is as far right on the x-axis and as high on the y-axis as possible. High recovery is more important than high grade, because poor recovery of the metal cannot be rectified, but low grade product can be further refined.

Figure 7.1 shows the grade recovery curve for sulphur flotation in each test water. The process water generated the highest grade of 7.78 %, but the lowest recovery at 88 % compared with the 92 % observed with the biological process effluents. The process water and the test water of algal effluent without AS treatment demonstrated lower flotation rates than the AS effluent test water and the test water of effluent from the algal tank receiving AS treated feed. The lower flotation rate is attributed to the differences in pH of each of the waters. The process water and algal effluent without AS treated feed had pH values of 7.09 and 6.39 respectively, while the pH of the AS effluent and effluent from the other algal unit was 4.65 and 4.89 respectively. The flotation rate increases at lower pH due to surface cleaning of the mineral (Malysiak, 2011, pers. comm.). However, the lower pH waters pose a risk to equipment due to corrosion.

When nickel flotation was investigated it was observed that the final recoveries produced from flotation in each of the waters were similar at 73 % (Figure 7.2. The final grade produced by process water was 3.18 %, while the effluent from the AS units generated a final grade of 2.84 % and the test waters from each of the algal units gave a final grade of 2.67 %.

The flotation results for copper were found to be similar to those for nickel (Figure 7.3). All the waters produced a final recovery of 90 %, however the process water generated the highest grade of 1.44 %, while the biological effluents all generated similar grades of 1.24 %.

The final recovery for platinum in all four wastewaters was 94 % as illustrated in Figure 7.4. Once again the process water produced the highest final grade of 70 g.ton^{-1}. The effluent from the AS units, effluent from the algal tank fed with AS effluent and the water from the other algal unit produced final grades of 58, 60 and 62.5 g.ton^{-1} respectively.

Flotation of palladium (Figure 7.5) showed that all four waters generated 91 % final recovery. The process water generated the highest grade at 27.4 g.ton^{-1}, while all three biological effluents produced a final palladium grade of 23.5 g.ton^{-1}.

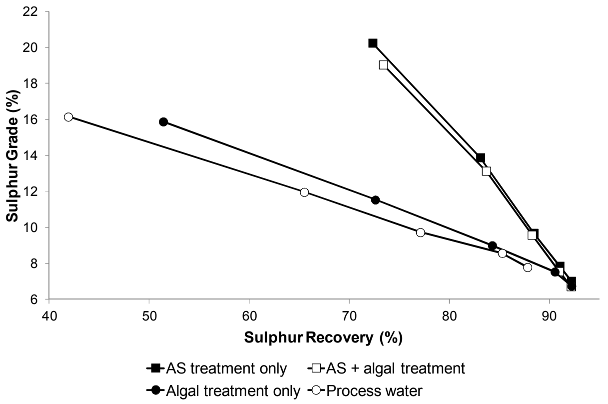


Figure 7.1 Sulphur grade recovery curves for the four test waters.

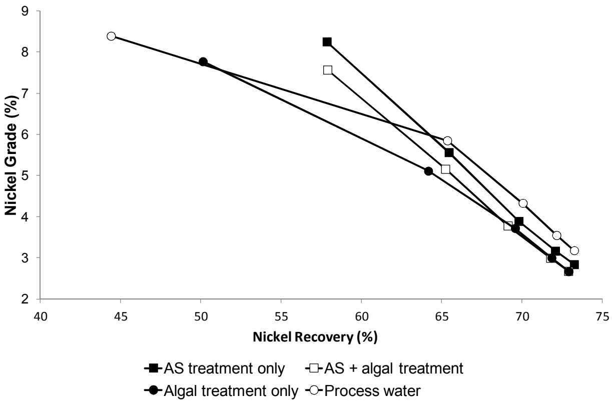


Figure 7.2 Nickel grade recovery curves for the four test waters.

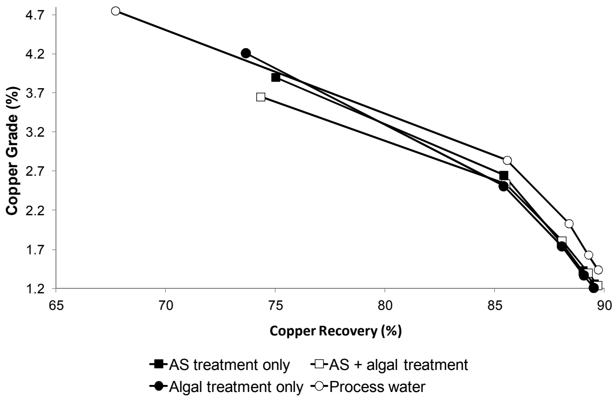


Figure 7.3 Copper grade recovery curves for the four test waters.

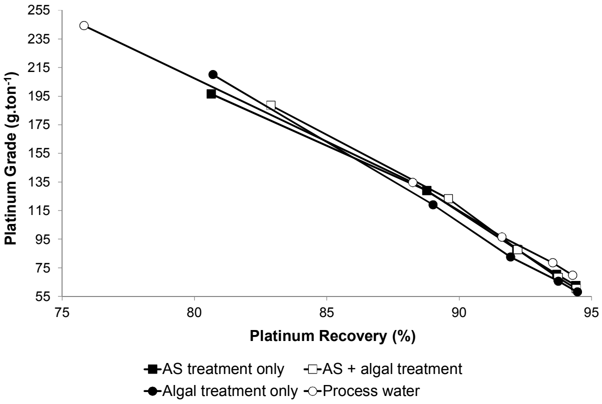


Figure 7.4 Platinum grade recovery curves for the four test waters.

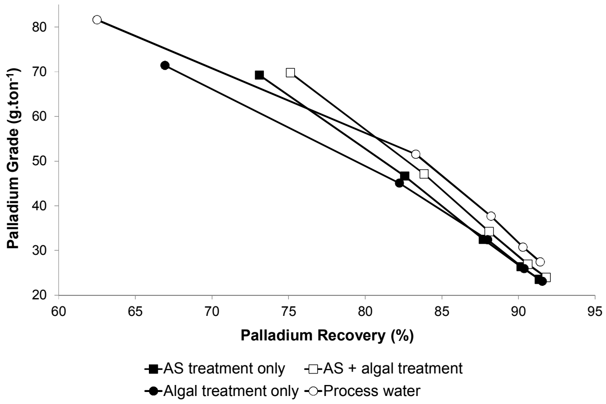


Figure 7.5 Palladium grade recovery curves for the four test waters.

The grade recovery curves show that the recoveries of the products were unchanged or improved (in the case of sulphur) and the final grades were slightly lower in all cases. However, flotation of Merensky ore in the various biological effluents was not statistically significantly different from the flotation results observed for the process water. As a result it was concluded (in consultation with

Anglo Platinum) that none of the biological effluent waters would impact negatively on flotation if they were used at the Retrofit Concentrator without further treatment. Effluent from the AS units demonstrated slightly better flotation performance than the effluents from the algal tanks.

Currently the treated WSTW domestic wastewater is returned as a make-up water to the Anglo Platinum Retrofit Concentrator. In volumetric ratios, the domestic wastewater comprises approximately 1 % of the water used for flotation. Integrating the effluent volumes produced by co-treatment of the PMR wastewater with the WSTW wastewater into the system would have no effect on flotation performance.

7.3.2 Additional uses

The qualities of the effluents produced by the treatment units described in Chapters 4 and 5 were compared to the DWA Category 4 Process Water Quality Guidelines to determine if they may be used in any other processes. Table 7.2 lists the DWA guidelines and the corresponding water quality values in each effluent.

Table 7.2 Comparison of biologically treated PMR wastewater with Category 4 water quality guidelines.

Parameter	**Category 4** (DWAF, 1996)	**Feed**	**AS effluent**	**Algal tank effluent (with AS treatment)**	**Algal tank effluent**
$CaCO_3$ (mg.L^{-1})	< 1200	134.36	13.67	3.83	66.25
COD (mg.L^{-1})	< 75	175.56	54.00	43.97	140.58
Chloride (mg.L^{-1})	< 500	539.81	856.67	903.00	712.50
Iron (mg Fe.L^{-1})	< 10	7.08	0.23	0.14	5.45
Manganese (mg Mn.L^{-1})	< 10	0.31	0.86	0.80	0.48
pH	5.00 - 10.00	6.5 - 7.3	4.9 - 7.5	4.0 - 7.0	4.6 - 7.3
Silica (mg Si.L^{-1})	< 150	7.39	8.29	6.30	4.88
Sulphate (mg SO_4.L^{-1})	< 500	34.27	57.92	67.67	45.58
TDS (mg.L^{-1})	< 1600	777.81	1234	1249.83	989.67
TDS as EC (mS.m^{-1})	< 250	220.55	359.25	357.75	281.67
TSS (mg.L^{-1})	< 25	258.79	371.42	57.91	84.33
Total hardness ($CaCO_3$.L^{-1})	< 1000	90.09	133.83	152.25	126.83

The matured, blended feed from the holding tank m*et* all of the DWA guidelines except for the COD, chloride and TSS concentrations. The COD in the feed was approximately 100 mg.L^{-1} too high, while the chloride and TSS exceeded the recommendations by 40 and 200 mg.L^{-1} respectively. The effluent from the AS units and algal effluent (fed with AS effluent) did not meet the DWAF criteria in terms of chloride concentration, pH, TDS and TSS, while the algal tank receiving feed from the holding tank met the least of the requirements. The TSS values for each of the units may be improved through vigorous aeration and long settling times. The algal unit fed with AS effluent had the lowest TSS (57.91 mg.L^{-1}) as a result of being fed from the AS effluent tank in which iron precipitation occurred over a longer period of time after aeration.

Based on the observations and conclusions in Chapters 5 and 6, providing an AS process with matured feed and improving the clarifier design can reasonably be expected to bring the pH, TDS and TSS of the effluent within the DWA guideline ranges.

7.4 Conclusions

All of the treated wastewaters were suitable for use in flotation of sulphur, nickel, copper, platinum or palladium even if 100 % effluent was used in the concentrator. If AS effluent is used for flotation at full-scale it will only make up 1 % of the water utilised, which further confirms its suitability for reuse in this process.

The AS only process was the best of the three in terms of effluent quality as compared with DWAF (1996) guidelines. Since the pH is one concern, maturation of the feed alone would improve the AS effluent. The AS system was dogged by poor sludge settling owing to the shallow angle of the clarifier cone, hence improving the clarifier could be expected to bring the TDS and TSS to within range. Furthermore, aeration for the removal of iron would significantly decrease the TSS of the water. Such improvements may be unnecessary, however, considering the suitability of the AS effluent for its preferred purpose of flotation in the Retrofit Concentrator.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

One of the major impediments to reusing Anglo Platinum's PMR acid effluent without treatment is its extremely low pH. Current treatment of this wastewater involves the addition of lime, which adds to its salinity and does not produce reusable water (additional processing is required). The process is both financially and energetically expensive, prompting Anglo Platinum to consider biological treatment options. The aim of this investigation was therefore to determine whether biological co-treatment with domestic wastewater could successfully remediate the acidic wastewater and generate reusable water as a product. To date there has been no report on the biological treatment of precious metal refinery wastewaters and this study is the first attempt a treatment of these wastewaters aerobically, anaerobically, bacteriologically or by employment of an algal system.

8.1.1 Comparison of the remediation capabilities of an anaerobic digester and activated sludge treatment unit at bench-scale

The main function of the biological co-treatment of the PMR wastewater was to increase the pH. Since undiluted PMR wastewater was not suitable as a nutrient source it was blended with domestic wastewater in order to facilitate co-metabolism of both wastewaters. Two bench-scale systems were investigated in Chapters 4 and 5 for their ability to increase the pH and improve the quality of the wastewaters. It was clear from preliminary results that AS was more robust than AD in this context. Anaerobic processes are more effective in treating high-strength organic wastewaters and carbon supplementation would have been required to achieve satisfactory effluent in this instance, owing to the inorganic nature of the wastewater. In contrast, AS was able to generate an effluent which met more of the DWA industrial water guidelines, predicting simpler downstream processing for AS effluent than the AD effluent. The ammonia concentration of the domestic : PMR wastewater blend was significantly higher than most normal domestic wastewaters and its removal in both systems was limited.

Neither AS nor AD had any effect on the chloride concentration of the wastewater. While this was anticipated, downstream processing will be required to render the effluent suitable for reuse within chloride-sensitive industrial processes.

Aeration of the AS resulted in precipitation of iron as a hydroxide which is not bioavailable, negating some of its toxic effects. Based on the better effluent quality and the more stable operation, AS operated at a 2 % PMR wastewater concentration was selected as a more suitable treatment process than AD.

8.1.2 Design and operation of a pilot plant based on the results obtained from the bench-scale investigation

The AS pilot plant operation reported in Chapter 6 was based on the bench-scale units, although some of the design parameters could not be duplicated at the larger scale, notably the clarifier dimensions. Sludge in the pilot plant clarifiers adhered to the side walls and clarified effluent was channelled through the biomass and returned to the aeration tank. This led to poor MLSS maintenance and higher and more variable effluent TSS (41 – 178 mg.L^{-1} compared to 55 – 66 mg.L^{-1}) than in the laboratory tests.

Despite the challenges in maintaining adequate biomass at the pilot-scale, the test unit was able to achieve effluent quality similar to, and in many aspects, better than the bench-scale AS effluent. Ammonia and COD removal were improved at pilot-scale, probably as a result of the higher feed pH, which demonstrated the potential for developing halo-tolerant AS. Thinning of the sludge and reduced floc size due to the presence of iron were also observed and this may be mitigated by introducing an aeration step prior to the feed entering the aeration tank for iron precipitation.

8.1.3 Examination of alternative treatment options, including algal processes and feed manipulation

It was discovered that blending the feed, inoculating it with acclimatised anaerobic sludge and providing a fourteen day maturation period resulted in a significant increase in the feed pH upstream of any secondary biological treatment.

The alkalinity of the blended feed increased during maturation, correlating to the increase in pH, furthermore, it increased over the duration of the treatment period as more biomass was generated in the feed tanks. As a result, the potential to optimise the maturation tank to maintain higher biomass concentrations and to achieve a higher final pH is a possibility. Unfortunately, the alkalinity was removed by AS and algal treatment, which decreased the pH to below that of the unmatured blended feed. The AS was never acclimatised to the PMR wastewater, and this needs to be done to circumvent the short term biological response to the toxicity of the PMR wastewater which may have contributed to decreasing the pH of the AS effluent.

Algae found growing on the side walls of the pilot-plant test clarifier prompted a short term study on algal treatment, both subsequent to AS and as a solo treatment unit operation. It was anticipated that algal treatment would generate alkalinity and have a positive effect on effluent pH, however, at the low feed pH the ability of the algae to generate bicarbonates was impeded and instead bicarbonates were utilised as a carbon source. Algal treatment of PMR wastewater is therefore not recommended. It may be more feasible to cultivate algae in domestic wastewater to generate an effluent containing a high alkalinity and pH to be blended with the PMR wastewater without exposing the algal biomass to the industrial wastewater.

The concentrations of iron and phosphorus were decreased by biological treatment. The phosphorus was metabolised as a nutrient source, while the iron precipitated in the aeration tank or sorbed onto the sludge. Iron precipitation upstream of AS would decrease the impact of the PMR wastewater and could greatly enhance the AS process.

The majority of the metal mass entering the AS process reported to the solid by-product (the WAS). The fate of the metals as a stable solid may present an opportunity to reclaim them via digestion, elution or smelting.

8.1.4 Assessment of the potential for reuse of the treated effluent within Anglo Platinum for metal refining itself, or other onsite applications

All three effluent waters were tested to predict their effects on flotation and compare them to the process water normally utilised. The difference in the grade and recovery of sulphur, copper, nickel, platinum and palladium by the effluents was not statistically significant, indicating that each biological process effluent water was suitable for use in flotation.

The feed and effluents from the short process modification study were compared with DWA Category 4 water. None of the samples managed met all the criteria for Category 4 water and downstream processing would need to be added specifically for chloride and TSS removal if these waters were to be used undiluted. The water which met the most criteria was that of the matured feed. Optimisation of the maturation process to support increased biomass growth may render the mature wastewater a Category 4 water.

Overall, it can be concluded that objective 1 has been achieved, that objectives 2 and 3 were achieved but that recommendations for improvements can be made, and objective 4 was met in full by the flotation results alone.

8.2 Recommendations for Further Work

Experimental work that would improve on the completion of objectives 2 and 3, and that would address the additional research questions raised in this study are described below.

8.2.1. Investigation of wastewater maturation

It is possible that modification of the maturation process described in Chapter 7 may result in consistently increasing the pH of the feed to approximately 7.5 and lowering the metal load entering the AS aeration tank. This could be achieved through investigations into the efficacy of batch, semi-continuous and continuous holding/balancing tank systems for maintaining high biomass turnover and elevated pH. Increased biomass concentrations may assist in improving other water quality parameters; hence the length of maturation time and its impacts on AS robustness and effluent quality should be investigated.

8.2.2. Increased iron removal

The use of aeration to remove iron through precipitation is postulated and should be pursued as a primary process, particularly if the matured wastewater is to be used as a feed for a secondary biological process. Removal of the iron could reduce the toxicity of the wastewater and improve biomass health as well as allowing recovery of the metal. Insertion of a feed aeration tank and sludge recovery could be tested, and the effects of aerating the holding tank on AS operation, effluent quality and recoverable metals be examined.

8.2.3. Optimisation of AS functioning and determination of carbon limitations

A pilot AS plant fed with matured, aerated feed may suitably treat the PMR-domestic wastewater blend to DWAF Category 4 wastewater if the clarifier is redesigned and adequate RAS is achieved. The effluent quality may further be enhanced by obtaining organic-rich wastes from local industries, such as dairies or breweries, to mitigate the effects of the low carbon and phosphorus concentrations in the WSTW 2° influent and increasing the acclimatisation period to each new component in the feed. The simplest and therefore initial approach would be to repeat the pilot plant trial using PSS from WSTW, if 1° influent is found to contain more carbon and phosphorus than the 2° influent.

8.2.4. Generation of high alkalinity effluent

The effluent generated by algae cultivated on domestic wastewater has been shown to neutralise AMD. The possibility of applying this knowledge for the treatment of PMR wastewater should be explored as an alternative to AS and feed maturation. The process train employed by the BioSURE process could be adapted to local raw materials (i.e. PMR wastewater instead of AMD and WSTW influent and sludge in place of PSS), and its efficacy tested first in the laboratory and if the preliminary results are positive, at pilot scale.

8.2.5. Process improvement through carbon supplementation

Various carbon substrates need to be investigated to potentially improve the process performance, particularly with respect to ammonia removal.

8.2.6. The suitability of the WAS for metal recovery

Samples of WAS from the pilot plant envisaged in Section 8.2.3 should be dewatered, dried and tested to ascertain whether metals within the WAS can be economically recovered, or at least the WAS disposal problem can be solved. The available options are to elute the metals with hydrochloric acid and return them to the refining process, to digest the sludge in *aqua regia* for return to the refinery, or to input the whole dry sludge at the smelting stage. The practicability and benefits of each option need to be determined and compared to identify which course(s) of action would be viable.

APPENDIX A

PRIMARY DATA FOR THE ANAEROBIC BENCH SCALE INVESTIGATION

Table A1 Digester SS concentration before and after PMR wastewater additions

Day	Digester 1 ($mg.L^{-1}$)				Digester 2 ($mg.L^{-1}$)			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
0	1900	1770	1730	1800 ± 89	1800	1760	1710	1756 ± 45
9	630	590	620	613 ± 21	1630	1490	1180	1433 ± 230
14	70	70	70	70 ± 0	880	940	920	913 ± 31
21	110	20	40	57 ± 47	200	150	150	167 ± 29
28	640	560	550	583 ± 49	880	840	920	880 ± 40
35	720	670	550	647 ± 573	230	100	190	173 ± 67
42	600	600	520	573 ± 46	310	320	310	313 ± 6
49	220	180	230	210 ± 26	460	520	420	467 ± 50
56	410	410	440	420 ± 17	740	740	740	740 ± 0
63	1010	1090	1040	1047 ± 40	1700	1750	1690	1713 ± 32
78	1120	980	980	1027 ± 81	2380	2290	2140	2270 ± 121
85	1770	1720	1760	1750 ± 26	2760	2830	2810	2800 ± 36
92	1860	1520	1530	1637 ± 193	2280	2340	2250	2290 ± 46
99	1470	1390	1530	1463 ± 70	2580	2510	2510	2533 ± 40
106	1290	1340	1380	1336 ± 45	1920	1990	2050	1987 ± 65
113	1210	1270	1280	1253 ± 38	1770	1820	1810	1800 ± 26
141	510	590	590	563 ± 46	1100	1230	1250	1193 ± 81
148	1840	1860	1840	1846 ± 11	1340	1360	1610	1437 ± 150
155	1950	1620	1730	1767 ± 168	1400	1530	1590	1507 ± 97
162	1430	1430	1450	1437 ± 12	1630	1670	1630	1643 ± 23
169	1550	1550	1570	1557 ± 12	1870	1720	1620	1737 ± 126
176	1070	1120	940	1043 ± 93	1920	1960	1900	1927 ± 31
183	1280	1180	1170	1210 ± 61	890	910	960	920 ± 36
191	1460	1530	1180	1390 ± 185	480	600	590	557 ± 67
198	1120	1210	1050	1127 ± 80	1080	1090	1160	1110 ± 44
205	1350	1370	1380	1367 ± 15	1080	1050	1040	1057 ± 21
212	1460	1410	1470	1447 ± 32	1250	1360	1180	1263 ± 91
219	780	790	720	763 ± 38	1130	1040	1070	1080 ± 46
226	1830	1760	1830	1807 ± 40	970	910	940	940 ± 30
233	1980	2030	1980	1997± 29	2440	2370	2490	2433 ± 60
240	1780	1790	1830	1800 ± 26	1840	1970	2080	1963 ± 120
247	1980	1930	1900	1937 ± 40	1820	1820	1770	1803 ± 289
263	1690	1680	1760	1710 ± 44	2170	2110	1890	2057 ± 147
270	1900	2020	2000	1973 ± 64	1840	1560	1590	1663 ± 154
277	1960	2120	2180	2087 ± 114	1270	1110	1030	1137 ± 122
284	1730	1840	1950	1840 ± 110	1700	1750	1750	1733 ± 29
291	1150	1250	1190	1196 ± 50	2430	2330	2470	2410 ± 72
298	1400	1500	1330	1410 ± 85	1830	1950	1800	1860 ± 79
305	2170	2090	2190	2150 ± 53	2340	2140	2030	2170 ± 157
312	2260	2160	2040	2153 ± 110	1970	1870	1820	1887 ± 76
319	2040	1910	2120	2023 ± 106	1220	1370	1330	1307 ± 78
326	1430	1540	1590	1520 ± 82	1830	1750	1720	1767 ± 57
333	2090	1990	1960	2013 ± 68	1370	1420	1560	1450 ± 98
Before PMR addition	**Min**			70				740
	Mean ± SD			939 ± 603				1381 ± 825
	Max			1847				2800
After PMR addition	**Min**			763				940
	Mean ± SD			1624 ± 375				1578 ± 474
	Max			2153				2170

Table A2 Digester effluent SS concentration before and after PMR wastewater additions.

Day	Digester 1 effluent (mg.L^{-1})				Digester 2 effluent (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
0	35	40	42	39 ± 4	34	38	29	34 ± 5
9	31	35	36	34 ± 3	38	30	37	35 ± 4
14	36	32	31	33 ± 3	42	39	32	38 ± 5
21	40	43	37	40 ± 3	31	35	40	35 ± 5
28	33	35	39	36 ± 3	36	35	42	38 ± 4
35	35	39	33	36 ± 3	37	30	35	34 ± 4
42	35	31	34	33 ± 2	40	30	35	35 ± 5
49	42	34	31	36 ± 6	35	33	40	36 ± 4
56	37	39	32	36 ± 4	32	39	41	37 ± 5
63	38	41	35	38 ± 3	36	31	39	35 ± 4
78	42	31	37	37 ± 6	32	38	35	35 ± 3
85	38	30	35	34 ± 4	41	34	43	39 ± 5
92	35	31	39	35 ± 4	39	42	34	38 ± 4
99	36	30	29	32 ± 4	34	43	39	39 ± 5
106	37	30	40	36 ± 5	35	30	39	35 ± 5
113	31	39	42	37 ± 6	30	36	31	32 ± 3
141	29	34	37	33 ± 4	33	36	29	33 ± 4
148	34	38	33	35 ± 3	42	37	45	41 ± 4
155	34	35	30	33 ± 3	40	43	49	44 ± 5
162	36	30	37	34 ± 4	41	37	45	41 ± 4
169	39	34	30	34 ± 5	41	49	47	46 ± 4
176	43	34	31	36 ± 6	37	45	48	43 ± 6
183	45	38	41	41 ± 4	47	41	52	47 ± 6
191	41	33	45	40 ± 6	43	49	53	48 ± 5
198	39	32	46	39 ± 7	39	46	50	45 ± 6
205	47	36	40	41 ± 6	42	39	45	42 ± 3
212	46	40	44	43 ± 3	46	49	40	45 ± 5
219	48	42	44	45 ± 3	49	56	50	52 ± 4
226	50	53	47	50 ± 3	51	54	56	54 ± 3
233	49	53	41	48 ± 6	47	57	49	51 ± 5
240	44	49	40	44 ± 5	57	44	47	49 ± 7
247	47	43	45	45 ± 2	49	54	45	49 ± 5
263	45	40	49	45 ± 5	42	55	52	50 ± 7
270	39	46	51	45 ± 6	46	50	53	50 ± 4
277	41	45	39	42 ± 3	50	58	47	52 ± 6
284	48	45	50	48 ± 3	44	49	52	48 ± 4
291	47	53	53	51 ± 3	49	56	47	51 ± 5
298	45	50	54	50 ± 5	50	49	53	51 ± 2
305	39	49	32	40 ± 9	50	56	47	51 ± 5
312	38	44	49	44 ± 6	53	47	45	48 ± 4
319	46	52	40	46 ± 6	54	51	46	50 ± 4
326	47	56	42	48 ± 7	55	50	53	53 ± 2
333	44	55	40	46 ± 8	45	56	44	48 ± 7
Before PMR addition	**Min**			32.00				32.00
	Mean ± SD			36 ± 4				36 ± 4
	Max			40				41
After PMR addition	**Min**			33				41
	Mean ± SD			43 ± 7				48 ± 5
	Max			51				54

Table A3 Ammonia concentration primary and secondary data collected before and after PMR wastewater additions.

Day	Feed (mg.L^{-1})				Digester 1 effluent (mg.L^{-1})						Digester 2 effluent (mg.L^{-1})					
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})	1	2	3	Mean ± SD	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})
0	56	53	55	54.7 ± 1.5	23	21	21	21.7 ± 1.2	60.4	0.6	20	22	21	21.0 ± 1.0	61.6	2.2
9	47	48	48	47.7 ± 0.6	20	22	22	21.3 ± 1.2	55.2	3.1	21	21	19	20.3 ± 1.2	57.3	4.2
14	42	44	45	43.7 ± 1.5	25	27	25	25.7 ± 1.2	41.2	239.3	28	28	26	27.3 ± 1.2	37.4	3.3
21	25	22	24	23.7 ± 1.5	28	28	28	28.0 ± 0.0	-18.3	-1.0	25	24	24	24.3 ± 0.6	-2.8	-2.1
28	19.1	18.9	19.5	19.2 ± 0.3	27.1	27.2	27.3	27.2 ± 0.1	-41.9	-1.8	30	30.4	30.8	30.4 ± 0.4	-58.6	-0.3
35	22	21	20.5	21.1 ± 0.8	29	31	30	30.0 ± 1.0	-41.7	-14.7	30	31	32	31.0 ± 1.0	-46.5	6.1
42	21	20.5	19.8	20.4 ± 0.6	21	22.4	21.7	21.7 ± 0.7	-6.2	-0.9	23.4	24.5	24.9	24.3 ± 0.8	-18.8	1.7
49	19.2	20.1	20.8	20.0 ± 0.8	18.5	18.9	19.5	19.0 ± 0.5	5.3	-0.7	21.4	22.3	22.4	22.0 ± 0.6	-10.0	-0.5
56	18.1	18.9	18.1	18.4 ± 0.5	17.95	18.2	18.7	18.3 ± 0.4	0.5	0.3	20.9	21.7	21.4	21.3 ± 0.4	-16.2	0.5
63	20.1	20.1	20.4	20.2 ± 0.2	19.2	18.9	18.4	18.8 ± 0.4	6.8	14.1	19.2	19.9	20.4	19.8 ± 0.6	1.8	-0.6
78	19.6	19.3	19.4	19.4 ± 0.2	22.3	21.7	22.9	22.3 ± 0.6	-14.8	0.7	23.7	24.2	24.6	24.2 ± 0.5	-24.4	0.8
85	18.9	18.8	19	18.9 ± 0.1	18.4	18.7	17.6	18.2 ± 0.6	3.5	8.0	20.4	20.9	21.1	20.8 ± 0.4	-10.1	2.1
92	18.4	18.8	18.4	18.5 ± 0.2	24.6	24.1	23.9	24.2 ± 0.4	-30.6	-12.7	27.4	27.8	28.1	27.8 ± 0.4	-49.8	10.3
99	28.7	28.2	29	28.6 ± 0.4	17.5	17.2	17.9	17.5 ± 0.4	33.9	14.2	19.8	20.4	20.7	20.3 ± 0.5	29.1	3.3
106	20.4	20.8	21.1	20.8 ± 0.4	21.8	22.3	22.7	22.3 ± 0.5	-13.7	-9.7	24.4	24.9	25.6	25.0 ± 0.6	-20.2	-5.0
113	26.3	26.7	26.8	26.6 ± 0.3	23.4	22.9	23.7	23.3 ± 0.4	10.5	0.1	23.9	24.3	24.7	24.3 ± 0.4	8.6	0.2
141	22.1	22.5	22.3	22.3 ± 0.2	21.7	21.9	20.7	21.4 ± 0.6	6.4	-0.3	22.1	23.1	22.7	22.6 ± 0.5	-4.3	-1.4
148	19.1	19	18.5	18.9 ± 0.3	20.6	20.8	21.2	20.9 ± 0.3	-4.8	-39.5	22.7	23.7	23.4	23.3 ± 0.5	-17.8	46.8
155	42.5	42.3	42.7	42.5 ± 0.2	19.8	19.4	20.1	19.8 ± 0.4	49.9	1.7	21.5	22.5	22.7	22.2 ± 0.6	46.0	-4.9
162	41.7	41.8	42	41.8 ± 0.2	21.3	21.9	20.7	21.3 ± 0.6	41.0	2.5	22.3	23.4	23.1	22.9 ± 0.6	35.5	4.8
169	60.4	61.1	60.7	60.7 ± 0.4	24.2	25.2	24.6	24.7 ± 0.5	31.8	-4.7	26.4	27.5	27.1	27.0 ± 0.6	29.6	9.7
176	79.5	81.3	79.7	80.1 ± 1.0	41.1	41.7	41.5	41.4 ± 0.3	45.1	21.0	42.5	43.1	42.7	42.8 ± 0.3	38.5	-4.0
183	107	110	108	108.3 ± 1.5	44	44	44	44.0 ± 0.0	56.0	-8.8	51	48	49	49.3 ± 1.5	54.5	5.0
191	110	92	98	100.00± 9.2	48	47	48	47.7 ± 0.6	48.0	-4.5	49	50	49	49.3 ± 0.6	44.3	2.3
198	114	118	117	116.3 ± 2.1	52	53	51	52.0 ± 1.0	48.4	-4.2	55	56	56	55.7 ± 0.6	45.8	19.6
205	116	113	112	113.7 ± 2.1	61	59	60	60.0 ± 1.0	43.4	-9.5	62	63	64	63.0 ± 1.0	40.5	-3.7
212	112	115	111	112.7 ± 2.1	64	65	64	64.3 ± 0.6	39.1	1.8	67	69	67	67.7 ± 1.2	36.1	6.2
219	110	107	112	109.7 ± 2.5	68	69	69	68.7 ± 0.6	32.2	-0.2	72	71	73	72.0 ± 1.0	29.8	3.7
226	111	114	110	111.7 ± 2.1	75	74	74	74.3 ± 0.6	30.1	-8.8	76	78	77	77.0 ± 1.0	26.0	-1.1
233	117	116	114	115.7 ± 1.5	78	79	77	78.0 ± 1.0	19.0	5.1	82	83	83	82.7 ± 0.6	15.3	2.0
240	115	118	115	116.0 ± 1.7	94	93	94	93.7 ± 0.6	12.9	-7.3	97	99	98	98.0 ± 1.0	9.5	5.1
247	117	116	113	115.3 ± 2.1	102	101	100	101.0 ± 1.0	6.9	0.9	105	106	104	105.0 ± 1.0	4.6	-0.6
263	113	117	115	115.0 ± 2.0	108	107	107	107.3 ± 0.6	4.1	-5.1	110	109	111	110.0 ± 1.0	2.6	2.2
270	110	107	108	108.3 ± 1.5	110	111	110	110.3 ± 0.6	-4.3	3.4	111	112	113	112.0 ± 1.0	-2.8	-1.3
277	109	113	114	112.0 ± 2.7	114	113	112	113.0 ± 1.0	-1.8	-0.8	113	110	111	111.3 ± 1.5	1.5	1.0
284	116	118	115	116.3 ± 1.5	113	115	114	114.0 ± 1.0	-0.6	-1.0	109	110	112	110.3 ± 1.5	5.2	-1.1
291	113	117	111	113.7 ± 3.1	117	118	116	117.0 ± 1.0	3.2	-3.8	111	110	110	110.3 ± 0.6	0.6	0.3
298	111	107	110	109.3 ± 2.1	110	109	111	110.0 ± 1.0	-1.8	0.4	113	114	112	113.0 ± 1.0	-0.6	1.2
305	115	114	113	114.0 ± 1.0	111	112	111	111.3 ± 0.6	0.0	28.6	109	110	111	110.0 ± 1.0	1.8	0.5
312	114	117	115	115.3 ± 1.5	115	114	113	114.0 ± 1.0	0.6	-0.4	112	111	113	112.0 ± 1.0	0.9	0.6
319	116	114	117	115.7 ± 1.5	114	114	116	114.7 ± 1.2	0.9	0.6	115	114	114	114.3 ± 0.6	-1.2	0.4
326	118	114	112	114.7 ± 3.1	115	115	114	114.7 ± 0.6	-0.9	2.6	116	118	117	117.0 ± 1.0	0.0	-1.7
333	121	119	123	121.0 ± 2.0	117	116	114	115.7 ± 1.5			113	115	116	114.7 ± 1.5		
Before PMR addition	**Min**			18.4				17.5	-41.9	-39.5				20.3	-49.8	-1.4
	Mean ± SD			26.6 ± 11.4				22.2 ± 3.5	5.4 ± 30.7	11.1 ± 58.2				23.8 ± 3.3	-2.0 ± 34.7	4.0 ± 11.2
	Max			54.7				30.0	60.4	239.3				31.0	61.6	46.8
After PMR addition	**Min**			41.8				19.8	-4.3	-9.5				22.2	-1.2	-4.9
	Mean ± SD			106.6 ± 18.9				83.9 ± 32.4	19.7 ± 20.9	0.4 ± 8.6				85.3 ± 19.0	18.2 ± 19.0	1.9 ± 5.1
	Max			121.0				115.7	49.9	28.6				114.7	46.0	19.6

Table A4 Nitrite primary and secondary data collected before and after PMR wastewater additions.

Day	**Feed (mg.L^{-1})**				**Digester 1 effluent (mg.L^{-1})**				**Digester 2 effluent (mg.L^{-1})**			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
0	0.03	0.03	0.03	0.03 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
9	0.03	0.03	0.03	0.03 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
14	0.05	0.04	0.04	0.04 ± 0.01	0.01	0.01	0.01	0.00 ± 0.00	0.01	0.01	0.01	0.00 ± 0.00
21	0.04	0.04	0.03	0.04 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
28	0.04	0.03	0.03	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
35	0.02	0.02	0.02	0.02 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
42	0.03	0.04	0.03	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
49	0.05	0.05	0.04	0.05 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
56	0.04	0.04	0.04	0.04 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
63	0.05	0.04	0.05	0.05 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
78	0.03	0.03	0.04	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
85	0.03	0.03	0.02	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
92	0.02	0.03	0.02	0.02 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
99	0.05	0.04	0.04	0.04 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
106	0.05	0.05	0.05	0.05 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
113	0.03	0.04	0.03	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
141	0.02	0.03	0.02	0.02 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
148	0.05	0.05	0.05	0.05 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
155	0.05	0.04	0.04	0.04 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
162	0.05	0.05	0.05	0.05 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
169	0.03	0.04	0.04	0.04 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
176	0.04	0.03	0.03	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
183	0.06	0.05	0.05	0.05 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
191	0.05	0.05	0.05	0.05 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
198	0.03	0.02	0.03	0.03 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
205	0.02	0.02	0.02	0.02 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
212	0.04	0.04	0.05	0.04 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
219	0.12	0.13	0.12	0.12 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
226	0.05	0.05	0.05	0.05 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
233	0.01	0.01	0.01	0.01 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
240	0.13	0.13	0.14	0.13 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
247	0.04	0.04	0.04	0.04 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
263	0.07	0.07	0.06	0.07 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
270	0.02	0.02	0.02	0.02 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
277	0.02	0.02	0.02	0.02 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
284	0.05	0.05	0.06	0.05 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
291	0.11	0.1	0.1	0.10 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
298	0.03	0.03	0.03	0.03 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
305	0.03	0.03	0.03	0.03 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
312	0.19	0.19	0.18	0.19 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
319	0.03	0.03	0.03	0.03 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
326	0.05	0.05	0.06	0.05 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
333	0.03	0.03	0.03	0.03 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
Before PMR addition	**Min**			0.02				0.00				0.00
	Mean ± SD			0.04 ± 0.01				0.00 ± 0.00				0.00 ± 0.00
	Max			0.05				0.00				0.00
After PMR addition	**Min**			0.01				0.00				0.00
	Mean ± SD			0.05 ± 0.04				0.00 ± 0.00				0.00 ± 0.00
	Max			0.13				0.00				0.00

Table A5 Nitrate primary and secondary data collected before and after PMR additions.

Day		Feed (mg.L^{-1})				Digester 1 effluent (mg.L^{-1})				Digester 2 effluent (mg.L^{-1})			
		1	2	3	Mean ± SD	1	2	3	Mean ± SD	1	2	3	Mean ± SD
0		0.40	0.30	0.40	0.37 ± 0.06	0.02	0.02	0.01	0.02 ± 0.01	0.01	0.02	0.01	0.01 ± 0.01
9		0.40	0.50	0.40	0.43 ± 0.06	0.05	0.07	0.05	0.06 ± 0.01	0.02	0.03	0.02	0.02 ± 0.01
14		0.40	0.50	0.40	0.43 ± 0.06	0.04	0.05	0.04	0.04 ± 0.01	0.02	0.01	0.01	0.01 ± 0.01
21		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
28		0.00	0.00	0.00	0.00 ± 0.00	0.06	0.05	0.04	0.05 ± 0.01	0.02	0.03	0.01	0.02 ± 0.01
35		0.50	0.50	0.40	0.47 ± 0.06	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
42		0.40	0.30	0.30	0.33 ± 0.06	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
49		0.50	0.50	0.50	0.50 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
56		0.01	0.00	0.00	0.00 ± 0.01	0.00	0.00	0.00	0.00 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00
63		0.40	0.40	0.40	0.40 ± 0.00	0.50	0.60	0.50	0.53 ± 0.06	0.80	0.70	0.70	0.73 ± 0.06
78		0.00	0.00	0.00	0.00 ± 0.00	0.70	0.70	0.70	0.70 ± 0.00	0.60	0.70	0.70	0.67 ± 0.06
85		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
92		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
99		0.50	0.60	0.40	0.50 ± 0.01	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
106		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
113		0.40	0.40	0.50	0.43 ± 0.06	0.80	0.70	0.80	0.77 ± 0.06	0.50	0.60	0.70	0.60 ± 0.10
141		0.70	0.50	0.60	0.60 ± 0.10	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
148		0.50	0.50	0.50	0.50 ± .00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
155		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
162		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
169		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
176		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
183		0.80	0.70	0.60	0.70 ± 0.10	0.50	0.60	0.50	0.53 ± 0.06	0.70	0.60	0.70	0.67 ± 0.06
191		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
198		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
205		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
212		0.00	0.00	0.00	0.00 ± 0.00	0.50	0.50	0.50	0.50 ± 0.00	0.60	0.60	0.70	0.63 ± 0.06
219		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
226		0.50	0.60	0.50	0.53 ± 0.06	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
233		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
240		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
247		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
263		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
270		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
277		0.80	0.90	0.80	0.83 ± 0.06	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
284		0.20	0.30	0.30	0.27 ± 0.06	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
291		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
298		0.80	0.50	0.80	0.70 ± 0.17	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
305		0.00	0.00	0.00	0.00 ± 0.00	0.70	0.80	0.80	0.77 ± 0.06	0.50	0.60	0.50	0.53 ± 0.06
312		1.10	1.40	1.30	1.27 ± 0.15	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
319		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
326		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
333		0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00	0.00 ± 0.00
Before PMR addition	**Min**				0.00				0.00				0.00
	Mean ± SD				0.26 ± 0.24				0.11 ± 0.25				0.11 ± 0.25
	Max				0.60				0.77				0.73
After PMR addition	**Min**				0.00				0.00				0.00
	Mean ± SD				0.18 ± 0.35				0.08 ± 0.21				0.08 ± 0.21
	Max				1.27				0.77				0.67

Table A6 COD primary and secondary data collected before and after PMR addition.

Day	Feed (mg.L^{-1})				Digester 1 effluent (mg.L^{-1})						Digester 2 effluent (mg.L^{-1})					
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})	1	2	3	Mean ± SD	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})
0	315	320	321	319 ± 3	97	102	105	101 ± 4	68	3	102	109	107	106 ± 4	67	-8
9	325	332	324	327 ± 4	101	102	101	101 ± 1	71	-118	105	109	104	106 ± 3	72	14
14	301	298	297	299 ± 2	96	92	93	94 ± 2	65	60	90	92	92	91 ± 1	66	-12
21	347	352	355	351 ± 4	102	105	104	104 ± 2	62	-22	101	102	99	101 ± 2	74	-25
28	206	202	202	203 ± 2	135	138	131	135 ± 4	63	11	86	97	91	91 ± 6	66	-8
35	264	262	261	262 ± 2	73	74	78	75 ± 3	67	2	73	66	70	70 ± 4	67	14
42	289	287	285	287 ± 2	85	86	85	85 ± 1	64	51	87	88	85	87 ± 2	66	64
49	325	322	326	324 ± 2	101	104	102	102 ± 2	79	-28	97	99	96	97 ± 2	80	-40
56	255	257	258	257 ± 2	68	65	67	67 ± 2	69	-2	66	67	66	66 ± 1	71	-5
63	234	237	224	232 ± 7	80	78	79	79 ± 1	70	3	77	74	76	76 ± 2	65	7
78	290	275	287	284 ± 8	71	70	69	70 ± 1	74	-3	83	82	79	81 ± 2	75	-14
85	239	245	247	244 ± 4	73	75	72	73 ± 2	69	1	69	73	73	72 ± 2	66	-4
92	248	249	252	250 ± 2	75	78	74	76 ± 2	72	3	82	84	85	84 ± 2	70	17
99	278	281	282	280 ± 2	69	71	72	71 ± 2	75	-3	75	72	77	75 ± 3	73	8
106	250	255	254	253 ± 3	71	72	68	70 ± 2	70	-1	79	75	74	76 ± 3	68	-6
113	241	249	252	247 ± 6	76	75	74	75 ± 1	67	1	81	82	79	81 ± 2	73	-1
141	264	269	260	264 ± 5	82	81	82	82 ± 1	70	-2	64	68	69	67 ± 3	72	-5
148	251	259	255	255 ± 4	78	79	81	79 ± 2	65	2	72	74	77	74 ± 3	71	-20
155	248	254	260	254 ± 6	92	91	88	90 ± 2	72	-1	76	74	72	74 ± 2	67	7
162	251	259	255	255 ± 4	71	69	72	71 ± 2	70	-2	83	81	84	83 ± 2	70	-20
169	231	235	238	235 ± 4	78	77	76	77 ± 1	67	5	74	78	79	77 ± 3	70	26
176	279	266	273	273 ± 7	75	77	78	77 ± 2	72	4	68	72	69	70 ± 2	73	-5
183	299	302	295	299 ± 4	78	79	75	77 ± 2	78	-1	72	75	71	73 ± 2	79	10
191	281	288	291	287 ± 5	64	67	68	66 ± 2	76	-3	65	63	61	63 ± 2	72	2
198	280	290	298	289 ± 9	65	69	70	68 ± 3	67	-4	81	79	80	80 ± 1	75	149
205	231	235	238	235 ± 4	95	92	96	94 ± 2	67	0	74	71	75	73 ± 2	68	-10
212	224	226	232	227 ± 4	75	79	77	77 ± 2	68	5	76	74	73	74 ± 2	64	-17
219	252	258	249	253 ± 5	76	71	74	74 ± 3	70	0	82	79	83	81 ± 2	66	-5
226	252	258	245	252 ± 7	73	75	76	75 ± 2	72	-2	87	84	85	85 ± 2	69	0
233	239	231	229	233 ± 5	67	71	74	71 ± 4	64	3	76	79	81	79 ± 3	74	-9
240	278	282	275	278 ± 4	81	85	86	84 ± 3	66	-1	62	63	60	62 ± 2	72	21
247	248	252	257	252 ± 5	92	93	95	93 ± 2	69	0	75	78	79	77 ± 2	70	0
263	266	260	264	263 ± 3	75	78	79	77 ± 2	69	0	79	71	75	75 ± 4	68	-1
270	278	280	284	281 ± 3	81	85	82	83 ± 2	65	0	83	86	85	85 ± 2	65	-1
277	289	284	278	284 ± 6	98	94	99	97 ± 3	63	-3	99	101	95	98 ± 3	66	-11
284	254	241	256	250 ± 8	104	101	107	104 ± 3	55	4	99	95	94	96 ± 3	56	7
291	278	282	284	281 ± 3	112	115	111	113 ± 2	61	1	106	110	112	109 ± 3	61	-4
298	299	301	304	301 ± 3	111	109	113	111 ± 2	61	-2	108	113	106	109 ± 4	62	-24
305	265	261	271	266 ± 5	115	119	120	118 ± 3	56	0	115	111	117	114 ± 3	51	-1
312	254	256	259	256 ± 3	115	114	119	116 ± 3	56	-1	128	131	132	130 ± 2	53	5
319	245	248	242	245 ± 3	117	111	114	114 ± 3	50	4	118	120	120	119 ± 1	48	12
326	278	282	285	282 ± 4	126	121	120	122 ± 3	59	-4	122	131	127	127 ± 5	56	26
333	238	227	224	230 ± 7	119	117	112	116 ± 4			121	125	126	124 ± 3		
Before PMR addition	**Min**			203				67	62	-118				66	65	-40
	Mean ± SD			263 ± 22				91 ± 19	65 ± 7	-2 ± 35				90 ± 21	65 ± 8	-1 ± 22
	Max			324				135	75	60				106	80	64
After PMR addition	**Min**			235.00				66	50	-4				62	51	-24
	Mean ± SD			273 ± 37				86 ± 17	69 ± 4	0 ± 3				83 ± 13	70 ± 4	7 ± 33
	Max			301				122	72	5				127	79	149

Table A7 Chloride primary and secondary data collected before and after PMR addition.

Day	Feed (mg.L^{-1})				Digester 1 effluent (mg.L^{-1})				Digester 2 effluent (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	1	2	3	Mean ± SD
0	83	84	90	86 ± 4	69	70	72	70 ± 2	73	70	75	73 ± 3
9	95	98	95	96 ± 2	72	74	71	72 ± 2	76	75	71	74 ± 3
14	74	73	72	73 ± 1	85	83	88	85 ± 3	94	91	92	92 ± 2
21	87	86	85	86 ± 1	67	68	65	67 ± 2	75	78	77	77 ± 2
28	58	56	55	56 ± 2	81	80	78	80 ± 2	86	82	84	84 ± 2
35	83	81	84	83 ± 2	75	78	72	75 ± 3	61	65	62	63 ± 2
42	102	105	109	105 ± 4	72	74	76	74 ± 2	74	78	77	76 ± 2
49	45	46	46	46 ± 1	71	75	70	72 ± 3	75	71	74	73 ± 2
56	56	55	57	56 ± 1	63	66	64	64 ± 2	68	71	70	70 ± 2
63	135	133	135	134 ± 1	84	82	88	85 ± 3	65	68	67	67 ± 2
78	42	41	40	41 ± 1	72	74	75	74 ± 2	92	87	87	89 ± 3
85	52	54	52	53 ± 1	92	90	93	92 ± 2	94	96	91	94 ± 2
92	47	47	48	47 ± 1	84	81	85	83 ± 2	81	84	85	83 ± 2
99	58	59	57	58 ± 1	63	67	65	65 ± 2	69	73	70	71 ± 2
106	61	62	63	62 ± 1	65	67	63	65 ± 2	59	62	64	62 ± 2
113	74	75	75	75 ± 1	71	70	68	70 ± 2	75	79	78	77 ± 2
141	21	16	18	18 ± 3	76	79	80	78 ± 2	79	83	84	82 ± 3
148	75	78	77	77 ± 2	63	65	66	65 ± 2	65	68	67	67 ± 2
155	156	155	152	154 ± 2	72	75	71	73 ± 2	76	78	75	76 ± 2
162	58	59	58	58 ± 1	75	74	74	74 ± 1	69	68	71	69 ± 2
169	201	205	202	203 ± 2	110	114	118	114 ± 4	140	148	145	114 ± 4
176	372	374	378	375 ± 3	190	194	187	190 ± 4	230	235	236	234 ± 3
183	488	486	482	485 ± 3	245	241	239	242 ± 3	270	274	275	273 ± 3
191	1050	1040	1030	1040 ± 10	270	280	260	270 ± 10	290	280	290	287 ± 6
198	960	980	950	963 ± 15	360	350	350	353 ± 6	380	370	380	377 ± 6
205	1020	1010	1010	1013 ± 6	450	460	460	457 ± 6	490	510	500	500 ± 10
212	940	930	940	937 ± 6	480	460	490	477 ± 15	510	500	520	510 ± 10
219	1000	990	980	990 ± 10	540	550	530	540 ± 10	570	560	550	560 ± 10
226	1100	1000	1050	1050 ± 50	670	670	650	663 ± 12	720	730	740	730 ± 10
233	980	970	990	980 ± 10	740	760	750	750 ± 10	770	760	780	770 ± 10
240	960	990	970	973 ± 15	780	790	770	780 ± 10	820	810	800	810 ± 10
247	1000	1050	1050	1033 ± 29	890	880	880	883 ± 6	910	920	920	917 ± 6
263	980	990	1000	990 ± 10	950	960	970	960 ± 10	970	980	990	980 ± 10
270	1050	1000	990	1013 ± 32	1000	990	1000	997 ± 6	990	980	1000	990 ± 10
277	1000	980	990	990 ± 10	990	1000	990	993 ± 6	990	1000	990	993 ± 6
284	970	990	990	983 ± 12	990	1000	1100	1030 ± 61	980	990	990	987 ± 6
291	990	980	1000	990 ± 10	970	970	980	973 ± 6	1000	980	1000	993 ± 12
298	1100	1050	1000	1050 ± 50	990	980	1000	990 ± 10	990	1000	1050	1013 ± 32
305	1050	1000	1100	1050 ± 50	1000	1100	1000	1033 ± 58	1100	1050	1000	1050 ± 50
312	980	970	990	980 ± 10	1050	1100	1000	1050 ± 50	1050	1000	1000	1017 ± 29
319	1000	1000	1100	1033 ± 58	1100	1050	1050	1067 ± 29	1000	1100	1050	1050 ± 50
326	990	1000	1050	1013 ± 32	990	1000	990	993 ± 6	1050	1100	1100	1083 ± 29
333	1050	1100	1050	1067 ± 29	980	1000	990	990 ± 10	980	990	1000	990 ± 10
Before PMR addition	**Min**			18				64				62
	Mean ± SD			74 ± 33				74 ± 8				76 ± 9
	Max			134				92				94
After PMR addition	**Min**			58				73				69
	Mean ± SD			886 ± 33				703 ± 345				722 ± 338
	Max			1067				1067				1083

Table A8 Phosphate primary and secondary data collected before and after PMR addition.

Day	**Feed (mg.L^{-1})**				**Digester 1 effluent (mg.L^{-1})**				**Digester 2 effluent (mg.L^{-1})**			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
0	4.5	4.7	4.5	4.6 ± 0.1	5.8	5.4	5.2	5.5 ± 0.3	5.8	5.5	5.2	5.5 ± 0.3
9	3.8	3.8	4.0	3.9 ± 0.1	5.7	5.8	5.5	5.7 ± 0.2	6.3	6.6	6.6	6.5 ± 0.2
14	5.8	5.4	5.5	5.6 ± 0.2	9.3	9.2	9.3	9.3 ± 0.1	9.0	9.5	10.1	9.5 ± 0.6
21	4.1	4.3	4.1	4.2 ± 0.1	10.2	10.5	10.4	10.4 ± 0.2	10.8	10.7	10.8	10.8 ± 0.1
28	3.2	3.5	3.6	3.4 ± 0.2	11.6	11.5	11.4	11.5 ± 0.1	11.7	11.5	11.7	11.6 ± 0.1
35	5.8	5.9	5.7	5.8 ± 0.1	13.4	13.2	13.0	13.2 ± 0.2	12.4	12.5	12.6	12.5 ± 0.1
42	6.4	6.2	6.5	6.4 ± 0.2	12.2	12.3	12.5	12.3 ± 0.2	12.8	12.9	12.6	12.8 ± 0.2
49	4.3	4.4	4.1	4.3 ± 0.2	12.8	12.2	12.5	12.5 ± 0.3	13.0	13.0	13.2	13.0 ± 0.1
56	3.2	3.3	3.3	3.3 ± 0.1	14.3	14.7	14.9	14.6 ± 0.3	14.5	14.7	14.9	14.7 ± 0.2
63	5.2	5.4	5.5	5.4 ± 0.2	15.9	15.7	16.1	15.9 ± 0.2	16.7	16.6	16.7	16.7 ± 0.1
78	1.6	1.8	1.9	1.8 ± 0.2	14.6	14.6	14.5	14.6 ± 0.1	16.2	15.9	16.4	16.2 ± 0.3
85	3.6	3.7	3.8	3.7 ± 0.1	15.6	16.0	15.9	15.8 ± 0.2	15.5	15.5	15.7	15.6 ± 0.1
92	7.4	7.1	7.3	7.3 ± 0.2	13.9	13.4	12.9	13.4 ± 0.5	14.3	14.1	14.9	14.4 ± 0.4
99	5.3	5.5	5.5	5.4 ± 0.1	14.5	14.8	14.1	14.5 ± 0.4	13.4	13.1	13.2	13.2 ± 0.2
106	4.9	5.1	4.8	4.4 ± 0.2	12.2	12.1	12.3	12.2 ± 0.1	11.8	12.4	11.4	11.9± 0.5
113	5.2	5.3	5.1	5.2 ± 0.1	10.8	9.3	9.8	10.0 ± 0.8	10.5	10.2	10.6	10.4 ± 0.2
141	3.3	2.9	3.2	3.1 ± 0.2	11.7	11.8	11.2	11.6 ± 0.3	11.2	11.5	11.7	11.5 ± 0.3
148	5.7	5.8	6.1	5.9 ± 0.2	12.5	12.1	12.7	12.4 ± 0.3	10.4	10.2	9.9	10.2 ± 0.3
155	3.0	3.2	3.2	3.1 ± 0.1	9.9	9.8	9.6	9.8 ± 0.1	9.9	10.3	10.6	10.3 ± 0.4
162	0.8	0.7	1.1	0.9 ± 0.2	10.6	10.7	10.8	10.7 ± 0.1	10.9	11.2	11.7	11.3 ± 0.4
169	0.6	0.6	0.7	0.6 ± 0.1	11.4	11.6	11.1	11.4 ± 0.3	11.5	11.7	11.2	11.5 ± 0.3
176	0.0	0.0	0.0	0.0 ± 0.0	10.7	10.9	10.1	10.6 ± 0.4	11.7	11.4	11.9	11.7 ± 0.3
183	0.0	0.0	0.0	0.0 ± 0.0	7.6	7.8	7.5	7.6 ± 0.2	8.4	8.0	8.0	8.1 ± 0.2
191	0.0	0.0	0.0	0.0 ± 0.0	7.0	6.9	7.2	7.0 ± 0.2	8.2	7.7	7.6	7.8 ± 0.3
198	0.0	0.0	0.0	0.0 ± 0.0	8.1	7.8	8.2	8.0 ± 0.2	9.2	9.5	9.1	9.3 ± 0.2
205	0.0	0.0	0.0	0.0 ± 0.0	7.9	8.2	8.5	8.2 ± 0.3	8.4	8.6	8.9	8.6 ± 0.3
212	0.0	0.0	0.0	0.0 ± 0.0	7.4	7.0	6.9	7.1 ± 0.3	8.0	8.1	7.6	7.9 ± 0.3
219	0.0	0.0	0.0	0.0 ± 0.0	7.3	7.1	7.3	7.2 ± 0.1	7.5	7.8	7.3	7.5 ± 0.3
226	0.0	0.0	0.0	0.0 ± 0.0	7.1	7.4	7.5	7.3 ± 0.2	7.8	8.2	7.4	7.8 ± 0.4
233	0.0	0.0	0.0	0.0 ± 0.0	6.9	7.3	7.1	7.1 ± 0.2	6.4	6.8	6.2	6.5 ± 0.3
240	0.0	0.0	0.0	0.0 ± 0.0	5.4	5.8	5.6	5.6 ± 0.2	5.5	5.2	5.1	5.3 ± 0.2
247	0.0	0.0	0.0	0.0 ± 0.0	4.8	4.6	4.8	4.7 ± 0.1	4.7	4.8	4.2	4.6 ± 0.3
263	0.0	0.0	0.0	0.0 ± 0.0	3.2	3.5	3.3	3.3 ± 0.2	3.1	3.7	3.4	3.4 ± 0.3
270	0.0	0.0	0.0	0.0 ± 0.0	1.5	1.8	1.7	1.7 ± 0.2	2.1	2.2	1.7	2.0 ± 0.3
277	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
284	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
291	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
298	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
305	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
312	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
319	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
326	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
333	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0	0.0	0.0	0.0	0.0 ± 0.0
Before PMR addition	**Min**			1.8				5.5				5.5
	Mean ± SD			4.6 ± 1.4				11.8 ± 2.9				12.0 ± 3.0
	Max			5.9				15.9				16.7
After PMR addition	**Min**			0.0				0.0				0.0
	Mean ± SD			0.1 ± 0.2				4.5 ± 4.1				4.7 ± 4.4
	Max			3.1				11.4				11.7

Table A9 Primary data collected for pH before and after PMR addition.

Day	Feed			Digester 1 effluent			Digester 2 effluent		
	1	2	3	1	2	3	1	2	3
0	7.52	7.54	7.61	7.24	7.26	7.31	7.44	7.41	7.39
9	6.83	6.88	6.83	7.45	7.41	7.51	7.61	7.68	7.59
14	7.74	7.75	7.79	7.14	7.19	7.21	7.39	7.42	7.48
21	8.58	8.49	8.54	7.56	7.54	7.49	7.31	7.35	7.29
28	7.09	7.13	7.14	7.74	7.79	7.81	7.54	7.56	7.61
35	7.08	7.12	7.05	7.58	7.63	7.67	7.79	7.82	7.74
42	7.37	7.38	7.31	7.51	7.47	7.49	7.68	7.72	7.69
49	7.12	7.01	7.22	7.14	7.14	7.24	7.45	7.49	7.52
56	7.74	7.69	7.74	7.23	7.28	7.21	7.67	7.62	7.69
63	8.41	8.37	8.47	6.99	7.02	6.97	7.31	7.35	7.29
78	7.85	7.79	7.75	7.45	7.49	7.41	7.01	7.03	6.99
85	7.01	7.2	7.14	7.69	7.59	7.64	7.46	7.44	7.4
92	7.88	7.92	7.91	7.21	7.21	7.21	7.25	7.22	7.29
99	7.23	7.29	7.34	7.64	7.69	7.63	7.44	7.49	7.51
106	6.87	6.92	6.95	7.48	7.41	7.51	7.69	7.73	7.77
113	8.22	8.25	8.37	7.44	7.39	7.44	7.52	7.51	7.48
141	7.63	7.69	7.71	7.26	7.26	7.28	7.14	7.16	7.21
148	7.11	7.18	7.21	7.01	7.05	7.09	7.47	7.41	7.39
155	6.83	6.94	6.85	7.47	7.41	7.49	7.69	7.62	7.65
162	5.97	6.01	5.94	7.21	7.14	7.26	7.47	7.49	7.51
169	5.63	5.69	5.71	7.45	7.46	7.39	7.89	7.93	7.93
176	5.45	5.54	5.59	7.34	7.36	7.39	7.75	7.79	7.82
183	5.62	5.52	5.51	7.58	7.49	7.56	7.31	7.38	7.35
191	5.44	5.54	5.48	7.41	7.46	7.51	7.62	7.59	7.61
198	5.69	5.61	5.71	7.31	7.28	7.35	7.47	7.49	7.52
205	5.67	5.64	5.64	7.34	7.36	7.41	7.69	7.72	7.64
212	5.55	5.62	5.54	7.48	7.51	7.52	7.14	7.19	7.11
219	5.64	5.68	5.62	7.41	7.42	7.37	7.54	7.53	7.59
226	5.47	5.52	5.42	7.39	7.42	7.45	7.41	7.42	7.39
233	5.47	5.48	5.52	7.33	7.31	7.29	7.26	7.33	7.3
240	5.69	5.73	5.64	7.09	7.11	7.04	7.01	7.05	7.02
247	5.51	5.55	5.58	6.8	6.88	6.79	6.95	7.01	7.06
263	5.44	5.41	5.39	6.66	6.68	6.58	6.67	6.71	6.69
270	5.22	5.28	5.31	6.1	6.15	6.18	5.64	5.66	5.67
277	5.79	5.82	5.74	5.89	5.92	5.91	5.74	5.79	5.72
284	5.67	5.69	5.7	5.99	6.01	6.05	5.87	5.83	5.85
291	5.44	5.41	5.42	5.56	5.59	5.51	5.92	5.85	5.87
298	5.64	5.62	5.69	6.09	6.04	6.12	5.99	5.9	5.92
305	5.22	5.26	5.31	5.9	5.99	5.87	5.99	6.03	6.01
312	5.19	5.22	5.17	5.94	5.96	5.94	5.87	5.81	5.82
319	5.91	5.84	5.92	5.56	5.51	5.59	5.97	5.99	6.01
326	5.46	5.47	5.34	5.99	6.03	5.94	6.01	6.02	6.05
333	5.63	5.69	5.74	6.29	6.31	6.31	6.17	6.11	6.19
Before PMR	6.84 - 8.54			6.99 - 7.78			7.01 - 7.78		
After PMR	5.19 - 6.87			5.55 - 7.54			5.83 - 7.92		

APPENDIX B

PRIMARY DATA FOR THE AEROBIC BENCH SCALE INVESTIGATION

Table B1 Aeration tank MLSS concentration before and after PMR wastewater additions.

Day	Aeration tank 1 (mg.L^{-1})				Aeration tank 2 (mg.L^{-1})			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
8	200	200	200	200 ± 0	200	300	300	267 ± 58
11	200	100	100	133 ± 58	300	300	400	333 ± 58
15	400	500	500	467 ± 58	400	500	400	433 ± 58
18	300	300	400	333 ± 58	200	200	200	200 ± 0
22	100	200	100	133 ± 58	100	100	200	133 ± 58
25	900	1000	1000	967 ± 58	1400	1400	1300	1367 ± 58
29	700	600	700	667 ± 58	1000	1100	1100	1067 ± 58
32	500	600	600	567 ± 58	700	800	800	767 ± 58
36	1100	1100	1200	1133 ± 58	1400	1300	1300	1333 ± 58
43	600	500	500	533 ± 58	800	700	700	733 ± 58
46	400	400	500	433 ± 58	500	400	500	467 ± 58
50	700	800	700	733 ± 58	600	700	600	633 ± 58
53	800	900	800	833 ± 58	700	800	700	733 ± 58
57	600	500	500	533 ± 58	500	400	400	433 ± 58
60	300	400	400	367 ± 58	200	200	100	167 ± 58
64	300	300	400	333 ± 58	300	200	300	267 ± 58
67	200	300	300	267 ± 58	200	200	300	233 ± 58
70	400	400	400	400 ± 0	300	400	300	333 ± 58
74	400	500	500	467 ± 58	300	300	300	300 ± 0
77	500	600	500	533 ± 58	200	100	100	133 ± 58
81	400	400	500	433 ± 58	100	100	0	133 ± 58
84	400	500	500	467 ± 58	100	200	100	133 ± 58
88	400	300	400	367 ± 58	200	200	300	233 ± 58
91	600	500	600	567 ± 58	300	300	200	267 ± 58
95	500	500	500	500 ± 0	200	100	200	167 ± 58
98	400	500	400	433 ± 58	300	300	400	333 ± 58
102	400	300	400	367 ± 58	300	200	200	233 ± 58
105	300	300	400	333 ± 58	400	400	300	367 ± 58
108	700	600	600	633 ± 58	200	500	600	433 ± 208
110	700	600	600	633 ± 58	600	700	700	667 ± 58
113	600	600	700	633 ± 58	600	700	700	667 ± 58
115	500	600	600	656 ± 58	700	600	600	633 ± 58
117	600	500	400	500 ± 100	600	700	700	667 ± 58
120	600	600	700	633 ± 58	800	700	800	767 ± 58
123	500	600	600	567 ± 58	600	700	700	667 ± 58
125	700	800	800	767 ± 58	700	700	700	700 ± 0

Day	**Aeration tank 1 (mg.L^{-1})**				**Aeration tank 2 (mg.L^{-1})**			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
129	800	700	700	733 ± 58	900	900	1000	933 ± 58
130	700	700	600	667 ± 58	800	800	900	833 ± 58
132	700	800	700	73 ± 58	1000	1000	900	966 ± 58
135	700	700	600	667 ± 58	1100	1100	1000	1067 ± 58
137	500	400	400	433 ± 58	600	600	500	567 ± 58
139	400	500	500	467 ± 58	500	500	600	533 ± 58
142	700	700	600	667 ± 58	800	800	900	833 ± 58
144	800	700	800	7667 ± 58	800	800	700	767 ± 58
146	700	600	700	667 ± 58	700	700	700	700 ± 0
149	700	700	800	733 ± 58	700	700	800	733 ± 58
156	800	900	900	867 ± 578	600	600	700	633 ± 58
158	700	600	600	633 ± 58	600	600	600	600 ± 0
160	900	800	800	833 ± 58	600	700	700	667 ± 58
162	1000	1000	1100	1033 ± 58	800	900	900	867 ± 58
166	1500	1500	1600	1533 ± 58	1300	1300	1400	1333 ± 58
169	1000	1100	1100	1067 ± 58	1300	1200	1200	1233 ± 58
171	900	900	1000	933 ± 58	1100	1100	1200	1133 ± 58
177	1000	1000	900	967 ± 58	1200	1200	1400	1267 ± 115
180	1000	900	900	933 ± 58	900	1000	800	900 ± 100
183	1000	1000	1000	1000 ± 0	1000	1100	900	1000 ± 100
185	900	900	900	900 ± 0	900	900	900	900 ± 0
192	2500	2400	2400	2067 ± 58	1100	1200	1100	1133 ± 58
197	2100	2100	2000	2000 ± 58	1600	1500	1600	1567 ± 58
201	2000	2000	2000	1200 ± 68	1400	1400	1400	1400 ± 0
204	2000	2200	2000	2067 ± 115	1900	1900	1700	1833 ± 115
211	1100	1200	1300	1200 ± 100	1100	1100	1100	1100 ± 0
218	1100	1000	1000	1033 ± 58	1300	1200	1200	1233 ± 58
225	900	1000	900	933 ± 58	1100	1000	1100	1066 ± 58
227	1000	1100	1100	1067 ± 58	1000	800	900	900 ± 100
229	900	900	800	867 ± 58	600	600	500	567 ± 58
232	900	1000	800	900 ± 100	600	600	600	600 ± 0
234	900	900	900	900 ± 0	600	600	500	567 ± 58
240	1000	1100	1000	1033 ± 58	600	600	700	633 ± 58
243	900	900	1000	933 ± 58	700	800	700	733 ± 58
245	1100	1100	1200	1133 ± 58	1100	1000	900	1000 ± 100
Before PMR addition	**Min**			200				133
	Mean ± SD			543 ± 201				550 ± 319
	Max			1133				1367
After PMR addition	**Min**			633				567
	Mean ± SD			1189 ± 466				2013 ± 68
	Max			2067				1333

Table B2 Aeration tank effluent SS concentration before and after PMR wastewater additions.

Day	Aeration tank 1 effluent (mg.L^{-1})				Aeration tank 2 effluent (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
8	52	55	48	52 ± 4	42	46	48	45 ± 3
11	48	50	42	47 ± 4	45	40	51	45 ± 6
15	49	51	55	52 ± 3	53	49	54	52 ± 3
18	57	54	50	54 ± 4	59	55	50	55 ± 5
22	54	55	50	53 ± 3	46	52	53	50 ± 4
25	57	62	63	61 ± 3	52	48	54	51 ± 3
29	48	43	50	47 ± 4	47	53	49	50 ± 3
32	44	48	52	48 ± 40	56	50	55	54 ± 3
36	45	50	56	50 ± 6	53	48	50	50 ± 3
43	52	47	45	48 ± 4	49	43	50	47 ± 4
46	55	53	50	53 ± 3	50	55	56	54 ± 3
50	45	49	51	48 ± 3	47	49	53	50 ± 3
53	49	44	45	46 ± 3	48	53	44	48 ± 5
57	51	58	54	54 ± 4	52	59	51	54 ± 4
60	63	60	57	60 ± 3	59	54	56	56 ± 3
64	49	53	44	49 ± 5	56	50	58	55 ± 4
67	55	49	50	51 ± 3	46	49	52	49 ± 3
70	54	55	56	55 ± 1	49	53	50	51 ± 2
74	59	63	61	61 ± 2	51	47	49	49 ± 2
77	49	53	47	50 ± 3	62	54	52	56 ± 5
81	46	50	44	46 ± 3	57	53	49	53 ± 4
84	44	48	51	48 ± 4	49	56	50	52 ± 4
88	47	41	40	43 ± 4	48	51	49	49 ± 2
91	45	49	46	47 ± 2	56	50	55	54 ± 3
95	52	56	50	53 ± 3	53	49	53	52 ± 2
98	56	51	58	55 ± 4	47	50	53	50 ± 3
102	61	57	53	57 ± 4	46	50	56	51 ± 5
105	54	50	47	50 ± 4	58	54	50	54 ± 4
108	55	50	46	50 ± 5	56	53	52	54 ± 2
110	62	56	51	56 ± 6	53	47	49	50 ± 3
113	47	50	44	47 ± 3	56	50	55	54 ± 3
115	54	56	58	56 ± 2	49	53	54	52 ± 3
117	56	47	41	48 ± 8	46	49	53	49 ± 4
120	52	45	41	46 ± 6	56	54	50	53 ± 3
123	58	50	55	54 ± 4	58	53	57	56 ± 3
125	47	56	42	48 ± 7	47	59	54	53 ± 6
129	45	50	53	49 ± 4	51	55	49	52 ± 3
130	53	47	43	48 ± 5	53	56	49	53 ± 4
132	49	53	46	49 ± 4	56	51	59	55 ± 4

Day	Aeration tank 1 effluent (mg.L^{-1})				Aeration tank 2 effluent (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
135	55	50	47	51 ± 4	46	53	49	49 ± 4
137	59	55	62	59 ± 4	49	53	53	52 ± 2
139	41	45	49	45 ± 4	57	55	50	54 ± 4
142	46	41	50	46 ± 5	59	49	55	54 ± 5
144	47	45	41	44 ± 3	54	50	49	51 ± 3
146	53	46	40	46 ± 7	43	49	51	48 ± 4
149	56	50	59	55 ± 5	62	55	58	58 ± 4
156	59	50	49	53 ± 6	58	55	53	55 ± 3
158	61	52	63	59 ± 6	59	54	50	54 ± 5
160	65	61	68	65 ± 4	56	50	56	54 ± 3
162	57	63	59	60 ± 3	62	68	56	62 ± 6
166	62	54	68	61 ± 7	67	64	50	60 ± 9
169	55	49	58	54 ± 5	64	60	58	61 ± 3
171	67	60	69	65 ± 5	58	63	59	60 ± 3
177	64	67	60	64 ± 4	59	57	63	60 ± 3
180	58	63	67	63 ± 5	63	67	61	64 ± 3
183	60	68	65	64 ± 4	65	66	59	63 ± 4
185	62	57	54	58 ± 4	58	54	55	56 ± 2
192	59	66	69	65 ± 5	67	61	69	66 ± 4
197	66	60	59	62 ± 4	62	57	56	58 ± 3
201	67	64	60	64 ± 4	69	66	60	65 ± 5
204	55	59	64	59 ± 5	59	63	67	63 ± 4
211	58	55	60	58 ± 3	57	59	54	57 ± 3
218	64	61	57	61 ± 4	56	60	63	60 ± 4
225	63	66	60	63 ± 3	63	60	57	60 ± 3
227	58	52	50	53 ± 4	64	58	67	63 ± 5
229	55	63	67	62 ± 6	54	51	63	56± 6
232	63	68	60	64 ± 4	58	54	63	58 ± 5
234	61	69	64	65 ± 4	69	57	65	64 ± 6
240	67	66	63	65 ± 2	64	63	61	63 ± 2
243	64	60	67	64 ± 4	51	58	61	57 ± 5
245	58	63	55	59 ± 4	57	63	67	62 ± 5
Before PMR addition	**Min**			43				45
	Mean ± SD			51 ± 6				52 ± 4
	Max			59				58
After PMR addition	**Min**			53				54
	Mean ± SD			61 ± 5				60 ± 5
	Max			65				66

Table B3 Settleable solids and sludge volume index (SVI) data collected before and after PMR wastewater additions.

Day		Aeration tank 1		Aeration tank 2	
		Settleable solids ($ml.L^{-1}$)	SVI ($ml.g^{-1}$)	Settleable solids ($ml.L^{-1}$)	SVI ($ml.g^{-1}$)
105		84	26	24	68
108		39	24	23	58
110		35	23	38	33
113		63	38	29	60
115		51	29	25	46
117		50	25	31	38
120		49	31	21	40
123		39	21	40	33
125		56	40	54	61
129		60	50	40	47
130		56	40	39	55
132		68	39	31	46
135		56	42	44	35
137		115	39	33	88
139		30	14	25	67
142		42	21	26	31
144		29	20	12	29
146		53	35	30	20
149		63	43	35	40
156		28	26	39	54
158		82	46	46	60
160		76	56	58	79
162		62	58	57	75
166		52	92	64	45
169		75	70	60	65
171		92	80	64	58
177		79	68	58	55
180		75	64	54	67
183		60	52	56	60
185		67	51	65	69
192		38	68	72	69
197		58	104	83	54
201		41	72	88	71
204		38	70	40	55
211		60	60	59	42
218		74	64	33	55
225		77	60	34	39
227		60	57	27	41
229		67	48	25	49
232		62	46	32	45
234		50	41	28	64
240		39	38	46	51
243		59	48	49	71
245		54	52	53	55
Before PMR addition	**Min**	29	14	12	20
	Mean ± SD	55 ± 20	32 ± 10	32 ± 10	47 ± 17
	Max	115	50	54	68
After PMR addition	**Min**	28	26	28	39
	Mean ± SD	61 ± 16	32 ± 10	52 ± 17	58 ± 17
	Max	92	104	88	79

Table B4 Ammonia concentration primary and secondary data collected before and after PMR wastewater additions.

Day	Feed (mg.L^{-1})				Aeration tank 1 effluent (mg.L^{-1})						Aeration tank 2 effluent (mg.L^{-1})					
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})	1	2	3	Mean ± SD	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})
8	17.0	18.0	18.0	17.7 ± 0.6	22.0	22.0	23.0	22.3 ± 0.6	-26.4	1.0	22.0	24.0	23.0	23.0 ± 1.0	-30.2	1.8
11	19.5	18.7	19.2	19.1 ± 0.4	21.2	20.9	20.7	20.9 ± 0.3	-9.4	0.9	19.5	18.9	19.2	19.2 ± 0.3	-0.3	0.6
15	20.2	18.7	21.1	20.0 ± 1.2	19.5	18.5	16.9	18.3 ± 1.3	8.5	2.1	16.9	17.4	18.4	17.6 ± 0.8	12.2	1.0
18	21.7	21.5	21.9	21.7 ± 0.2	13.6	13.9	14.0	13.8 ± 0.2	36.3	2.9	15.9	16.2	16.3	16.1 ± 0.2	25.7	3.3
22	20.4	20.3	19.9	20.2 ± 0.3	0.7	0.4	0.8	0.6 ± 0.2	96.9	0.1	1.5	1.3	1.5	1.4 ± 0.1	92.9	0.4
25	21.1	20.4	19.2	20.2 ± 1.0	0.4	0.4	0.3	0.3 ± 0.0	98.3	1.0	0.2	0.2	0.2	0.2 ± 0.0	99.2	1.0
29	24.3	23.7	24.0	24.0 ± 0.3	0.2	0.2	0.2	0.2 ± 0.0	99.3	-1.7	0.1	0.1	0.1	0.1 ± 0.0	99.8	-1.7
32	19.0	18.2	19.2	18.8 ± 0.5	0.1	0.2	0.1	0.1 ± 0.0	99.3	-0.1	0.1	0.1	0.1	0.1 ± 0.0	99.7	-0.1
36	19.1	18.5	18.6	18.7 ± 0.3	0.5	0.4	0.5	0.5 ± 0.1	97.5	0.2	0.4	0.4	0.4	0.4 ± 0.0	98.0	0.2
43	19.6	20.4	19.8	19.9 ± 0.4	0.1	0.1	0.1	0.1 ± 0.0	99.3	0.5	0.1	0.1	0.1	0.1 ± 0.0	99.7	0.4
46	21.5	21.1	21.3	21.3 ± 0.2	0.1	0.2	0.1	0.1 ± 0.0	99.4	-0.5	0.1	0.1	0.1	0.1 ± 0.0	99.7	-0.4
50	20.4	19.0	19.5	19.6 ± 0.7	0.6	0.6	0.6	0.6 ± 0.0	96.9	-0.2	0.1	0.1	0.1	0.1 ± 0.0	99.7	-0.1
53	20.1	19.5	19.1	19.6 ± 0.5	1.3	1.3	1.3	1.3 ± 0.0	93.4	-0.2	0.3	0.3	0.3	0.3 ± 0.0	98.6	-0.2
57	19.0	18.7	18.5	18.7 ± 0.3	1.1	1.1	1.1	1.1 ± 0.0	94.1	0.2	0.2	0.2	0.2	0.2 ± 0.0	99.0	0.1
108	27.4	27.3	27.6	27.4 ± 0.2	1.2	1.2	1.2	1.2 ± 0.0	95.6	-1.8	2.2	2.1	2.2	2.2 ± 0.0	92.2	-1.3
110	24.1	24.5	24.3	24.3 ± 0.2	1.7	1.6	1.6	1.6 ± 0.0	93.3	-1.2	1.7	1.7	1.7	1.7 ± 0.0	93.1	-1.1
113	19.0	19.8	19.5	19.4 ± 0.4	0.5	0.5	0.4	0.5 ± 0.0	97.6	0.1	0.1	0.1	0.1	0.1 ± 0.0	99.5	0.5
115	20.5	20.1	20.4	20.3 ± 0.2	1.7	1.7	0.2	1.2 ± 0.9	94.2	1.1	0.1	0.1	0.1	0.1 ± 0.0	99.8	0.9
117	22.4	22.1	22.1	22.2 ± 0.2	0.8	0.8	0.8	0.8 ± 0.0	96.4	-0.3	0.2	0.2	0.2	0.2 ± 0.0	99.3	-0.8
120	21.3	21.5	21.0	21.3 ± 0.3	0.9	0.8	0.9	0.9 ± 0.0	96.0	-0.2	1.7	1.7	1.7	1.7 ± 0.0	92.0	-0.1
123	20.9	20.7	20.7	20.8 ± 0.1	0.9	0.9	0.9	0.9 ± 0.0	95.8	-0.4	1.5	1.6	1.6	1.6 ± 0.0	92.6	-2.2
125	20.1	19.9	20.0	20.0 ± 0.1	0.9	0.9	0.9	0.9 ± 0.0	95.3	1.0	5.2	5.1	5.0	5.1 ± 0.1	74.5	1.7
129	23.1	24.0	23.6	23.6 ± 0.5	0.6	0.6	0.6	0.6 ± 0.0	97.4	-2.2	1.9	1.9	1.8	1.9 ± 0.0	92.1	-2.3
130	21.5	21.2	21.5	21.4 ± 0.2	0.7	0.6	0.6	0.6 ± 0.0	97.1	-1.4	2.0	2.0	2.1	2.0 ± 0.0	90.6	-0.9
132	18.7	18.1	18.1	18.3 ± 0.4	0.4	0.4	0.4	0.4 ± 0.0	98.0	1.5	0.8	0.8	0.8	0.8 ± 0.0	95.7	1.6
135	22.5	23.6	22.8	23.0 ± 0.6	0.6	0.6	0.6	0.6 ± 0.0	97.4	0.8	0.7	0.8	0.8	0.7 ± 0.0	96.8	0.8
137	24.2	25.7	24.8	24.9 ± 0.8	0.8	0.9	0.9	0.9 ± 0.0	96.6	0.2	1.1	1.2	1.2	1.2 ± 0.0	95.3	0.3
139	25.4	25.1	24.9	25.1 ± 0.3	0.8	0.8	0.7	0.8 ± 0.0	97.0	0.6	0.8	0.8	0.8	0.8 ± 0.0	96.9	0.5
142	26.9	27.1	26.7	26.9 ± 0.2	0.6	0.7	0.7	0.7 ± 0.0	97.6	-3.0	0.9	0.9	1.0	0.9 ± 0.0	96.5	-2.9
144	21.3	21.5	21.3	21.4 ± 0.1	1.2	1.2	1.2	1.2 ± 0.0	94.4	0.0	1.2	1.2	1.2	1.2 ± 0.0	94.3	0.4
146	21.3	21.3	21.6	21.4 ± 0.2	1.2	1.2	1.3	1.2 ± 0.0	94.3	0.2	0.6	0.6	0.5	0.6 ± 0.0	97.4	0.0
149	21.1	21.2	21.1	21.1 ± 0.1	0.3	0.3	0.3	0.3 ± 0.0	98.6	0.9	0.3	0.3	0.3	0.3 ± 0.0	98.4	1.8
156	36.0	38.0	34.0	36.0 ± 2.0	8.5	8.8	8.5	8.6 ± 0.2	76.1	-6.5	2.8	2.8	2.6	2.8 ± 0.1	92.4	-8.8
158	33.1	32.4	32.9	32.8 ± 0.4	18.1	18.2	18.6	18.3 ± 0.3	44.2	1.2	17.2	16.9	17.2	17.1 ± 0.2	47.9	0.6
160	34.5	33.4	34.6	34.2 ± 0.7	17.3	17.3	17.4	17.3 ± 0.1	49.3	4.6	16.9	17.6	17.5	17.3 ± 0.4	49.3	4.8
162	41.6	41.9	41.8	41.8 ± 0.2	15.4	15.8	16.0	15.7 ± 0.3	62.3	-6.1	15.5	15.3	15.4	15.4 ± 0.1	63.1	-5.6
166	49.2	47.1	45.6	47.3 ± 1.8	45.3	45.5	45.6	45.5 ± 0.2	3.9	-0.8	43.3	43.6	43.2	43.4 ± 0.2	8.3	-1.3
169	46.2	47.0	46.9	46.7 ± 0.4	47.2	47.2	47.1	47.2 ± 0.1	-1.0	10.4	46.0	46.7	46.9	46.5 ± 0.5	0.4	10.9
171	62.1	62.3	62.2	62.2 ± 0.1	42.2	41.7	41.9	41.9 ± 0.3	32.6	-3.4	40.4	40.2	39.9	40.2 ± 0.3	35.4	-3.8
177	53.0	50.3	51.2	51.5 ± 1.4	52.0	50.5	51.7	51.4 ± 0.8	0.2	-0.4	51.9	52.2	52.4	52.2 ± 0.3	-1.3	-0.9
180	52.3	48.4	47.5	49.4 ± 2.6	51.2	49.1	51.3	50.5 ± 1.2	-2.3	0.3	53.3	52.5	52.7	52.8 ± 0.4	-7.0	0.4
183	51.7	49.8	51.3	50.9 ± 1.0	52.2	52.1	49.1	51.1 ± 1.8	-0.4	0.9	53.0	53.2	53.0	53.1 ± 0.1	-4.2	1.2
185	59.2	57.2	58.5	58.3 ± 1.0	57.4	56.3	56.5	56.7 ± 0.6	2.7	-0.6	57.7	58.3	57.9	58.0 ± 0.3	0.6	-0.4
192	61.2	57.2	57.1	58.5 ± 2.3	60.7	60.6	61.3	60.9 ± 0.4	-4.0	-0.1	60.8	61.0	61.1	61.0 ± 0.2	-4.2	-0.6
197	62.2	67.2	61.2	63.5 ± 3.2	67.8	67.3	64.3	66.5 ± 1.9	-4.6	7.3	69.4	68.6	68.5	68.8 ± 0.5	-8.3	8.4
201	95.0	96.0	97.0	96.0 ± 1.0	69.6	69.9	69.7	69.7 ± 0.2	27.4	6.5	67.4	68.4	67.9	67.9 ± 0.5	29.3	3.6
204	141.0	138.0	135.0	138.0 ± 3.0	92.0	93.0	92.0	92.3 ± 0.6	33.1	-8.6	97.0	101.0	99.0	99.0 ± 2.0	28.3	-8.2
211	108.0	103.0	100.0	103.7 ± 4.0	122.0	118.0	114.0	118.0 ± 4.0	-13.8	1.5	123.0	123.0	121.0	122.3 ± 1.2	-18.0	2.2
218	79.0	84.0	88.0	83.7 ± 4.5	91.0	80.0	92.0	87.7 ± 6.7	-4.8	-0.2	83.0	88.0	89.0	86.7 ± 3.2	-3.6	-0.4
225	110.0	104.0	104.0	106.0 ± 3.5	110.0	113.0	111.0	111.3 ± 1.5	-5.0	2.7	113.0	111.0	111.0	11.7 ± 1.2	-5.3	5.0
227	110.0	107.0	110.0	109.0 ± 1.7	108.0	106.0	113.0	109.0 ± 3.6	0.0	0.8	102.0	106.0	106.0	104.7 ± 2.3	4.0	-2.5
229	102.0	105.0	100.0	102.3 ± 2.5	98.0	103.0	101.0	100.7 ± 2.5	1.6	0.7	97.0	105.0	107.0	103.0 ± 5.3	-0.7	1.4
232	119.0	111.0	118.0	116.0 ± 4.4	109.0	114.0	114.0	112.3 ± 2.9	3.2	-1.0	109.0	116.0	112.0	112.3 ± 3.5	3.2	1.0
234	112.0	109.0	109.0	110.0 ± 1.7	107.0	110.0	108.0	108.3 ± 1.5	1.5	-0.1	100.0	105.0	108.0	104.3 ± 4.0	5.2	0.4
240	116.0	117.0	118.0	117.0 ± 1.0	117.0	117.0	113.0	115.7 ± 2.3	1.1	1.1	107.0	108.0	111.0	108.7 ± 2.1	7.1	-2.2
243	114.0	113.0	112.0	113.0 ± 1.0	109.0	108.0	108.0	108.3 ± 0.6	4.1	-1.5	111.0	110.0	113.0	111.3 ± 1.5	1.5	2.7
245	112.0	114.0	115.0	113.7 ± 1.5	111.0	113.0	112.0	112.0 ± 1.0	1.5	-2.5	108.0	107.0	105.0	106.7 ± 1.5	6.2	-2.0
247	105.0	107.0	103.0	105.0 ± 2.0	115.0	107.0	103.0	108.3 ± 6.1			101.0	105.0	100.0	102.0 ± 2.7		
Before PMR addition	**Min**			17.7				0.1	-26.4	-1.8				0.1	-30.2	-2.2
	Mean ± SD			21.3 ± 2.5				3.0 ± 6.2	84.9 ± 32.9	0.1 ± 0.3				3.2 ± 6.2	84.1 ± 32.8	0.1 ± 1.3
	Max			27.4				22.30	99.4	2.9				23.0	99.8	3.3
After PMR addition	**Min**			32.8				8.6	-5.0	-8.6				2.8	-18.0	-8.8
	Mean ± SD			78.7 ± 32.6				72.5 ± 36.1	12.4 ± 23.7	1.2 ± 4.1				71.9 ± 36.2	13.17 ± 26.25	0.24 ± 4.45
	Max			138.0				118	76.1	10.4				122.3	92.4	10.9

Table B5 Nitrite concentration primary and secondary data collected before and after PMR wastewater additions.

Day	Feed (mg.L^{-1})				Aeration tank 1 effluent (mg.L^{-1})				Aeration tank 2 effluent (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	1	2	3	Mean ± SD
8	0.01	0.01	0.01	0.01 ± 0.00	0.02	0.01	0.01	0.01 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00
11	0.01	0.01	0.01	0.01 ± 0.00	0.02	0.01	0.01	0.01 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00
15	0.01	0.01	0.01	0.01 ± 0.00	0.01	0.01	0.01	0.01 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00
18	0.01	0.02	0.03	0.02 ± 0.01	1.50	1.30	1.40	1.40 ± 0.14	1.90	1.50	1.70	1.70 ± 0.20
22	0.28	0.29	0.28	0.28 ± 0.01	16.00	16.00	14.00	15.33 ± 1.15	16.00	17.00	17.00	16.67 ± 0.58
25	0.00	0.00	0.00	0.00 ± 0.00	0.12	0.13	0.13	0.13 ± 0.01	0.38	0.40	0.36	0.38 ± 0.02
29	0.00	0.00	0.01	0.00 ± 0.00	0.12	0.13	0.13	0.13 ± 0.01	0.08	0.08	0.08	0.08 ± 0.00
32	0.10	0.10	0.10	0.10 ± 0.00	0.08	0.07	0.07	0.07 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00
36	0.09	0.11	0.10	0.10 ± 0.01	0.38	0.38	0.39	0.38 ± 0.01	0.16	0.15	0.15	0.15 ± 0.01
43	0.02	0.02	0.02	0.02 ± 0.00	0.13	0.13	0.13	0.13 ± 0.00	0.07	0.07	0.07	0.07 ± 0.00
46	0.02	0.02	0.02	0.02 ± 0.00	0.11	0.11	0.11	0.11 ± 0.00	0.06	0.07	0.07	0.07 ± 0.01
50	0.02	0.02	0.02	0.02 ± 0.00	0.50	0.49	0.49	0.49 ± 0.01	0.10	0.10	0.10	0.10 ± 0.00
53	0.11	0.10	0.11	0.11 ± 0.01	0.82	0.83	0.83	0.83 ± 0.01	0.44	0.44	0.43	0.44 ± 0.01
57	0.15	0.15	0.15	0.15 ± 0.00	1.54	1.54	1.54	1.54 ± 0.00	0.83	0.84	0.83	0.83 ± 0.01
108	0.02	0.02	0.02	0.02 ± 0.00	5.80	5.70	5.50	5.67 ± 0.15	9.10	8.90	9.00	9.00 ± 0.10
110	0.02	0.02	0.02	0.02 ± 0.00	6.30	6.50	6.40	6.40 ± 0.10	9.70	9.80	9.60	9.70 ± 0.10
113	0.50	0.50	0.50	0.50 ± 0.00	0.59	0.63	0.63	0.62 ± 0.02	0.75	0.73	0.73	0.74 ± 0.01
115	0.04	0.04	0.04	0.04 ± 0.00	4.10	4.20	4.90	4.40 ± 0.44	4.00	3.90	3.80	3.90 ± 0.10
117	0.02	0.02	0.02	0.02 ± 0.00	3.40	3.40	3.40	3.40 ± 0.00	3.30	3.20	3.20	3.23 ± 0.06
120	0.02	0.02	0.02	0.02 ± 0.00	2.90	2.90	3.10	2.97 ± 0.12	3.10	3.00	2.90	3.00 ± 0.10
123	0.02	0.02	0.02	0.02 ± 0.00	2.50	2.60	2.30	2.47 ± 0.15	2.60	2.80	2.50	2.63 ± 0.15
125	0.05	0.05	0.05	0.05 ± 0.00	1.50	1.50	1.50	1.50 ± 0.00	2.40	2.30	2.30	2.33 ± 0.06
129	0.02	0.02	0.02	0.02 ± 0.00	2.00	2.00	2.00	2.00 ± 0.00	3.90	3.90	4.10	3.97 ± 0.12
130	0.03	0.03	0.03	0.03 ± 0.00	1.70	1.80	1.70	1.73 ± 0.06	3.90	3.80	3.80	3.83 ± 0.06
132	0.02	0.02	0.02	0.02 ± 0.00	0.50	0.50	0.50	0.50 ± 0.00	0.90	0.90	0.90	0.90 ± 0.00
135	0.02	0.02	0.02	0.02 ± 0.00	1.40	1.50	1.50	1.47 ± 0.06	3.80	3.70	3.50	3.67 ± 0.15
137	0.23	0.23	0.24	0.23 ± 0.01	0.05	0.05	0.05	0.05 ± 0.00	0.05	0.05	0.05	0.05 ± 0.00
139	0.02	0.02	0.02	0.02 ± 0.00	0.05	0.05	0.05	0.05 ± 0.00	0.06	0.06	0.06	0.06 ± 0.00
142	0.04	0.04	0.04	0.04 ± 0.00	0.05	0.05	0.05	0.05 ± 0.00	0.11	0.12	0.11	0.11 ± 0.01
144	0.02	0.02	0.02	0.02 ± 0.00	0.05	0.05	0.05	0.05 ± 0.00	1.20	1.30	1.20	1.23 ± 0.06
146	0.02	0.02	0.02	0.02 ± 0.00	4.90	4.80	4.80	4.83 ± 0.06	4.90	4.90	5.00	4.93 ± 0.06
149	0.04	0.04	0.03	0.04 ± 0.01	17.00	16.00	17.00	16.67 ± 0.58	16.00	17.00	15.00	16.00 ± 1.00
156	0.03	0.03	0.03	0.03 ± 0.00	5.60	5.50	5.40	5.50 ± 0.10	5.40	5.60	5.10	5.37 ± 0.25
158	0.06	0.05	0.04	0.05 ± 0.01	8.70	8.50	8.50	8.57 ± 0.12	8.50	8.40	8.40	8.43 ± 0.06
160	0.86	0.87	0.88	0.87 ± 0.01	7.30	7.50	7.50	7.43 ± 0.12	7.10	7.20	7.10	7.13 ± 0.06
162	0.33	0.33	0.31	0.32 ± 0.01	4.00	4.10	3.90	4.00 ± 0.10	3.20	3.40	3.40	3.33 ± 0.12
166	0.02	0.02	0.02	0.02 ± 0.00	0.21	0.19	0.21	0.20 ± 0.01	0.20	0.20	0.21	0.20 ± 0.01
169	0.37	0.37	0.36	0.37 ± 0.01	0.09	0.08	0.08	0.08 ± 0.01	0.06	0.06	0.07	0.06 ± 0.01
171	0.02	0.02	0.02	0.02 ± 0.00	0.41	0.42	0.41	0.41 ± 0.01	0.38	0.39	0.38	0.38 ± 0.01
177	0.02	0.02	0.02	0.02 ± 0.00	0.07	0.07	0.07	0.07 ± 0.00	0.07	0.07	0.07	0.07 ± 0.00
180	0.27	0.27	0.26	0.27 ± 0.01	0.08	0.06	0.06	0.07 ± 0.01	0.05	0.05	0.06	0.05 ± 0.01
183	0.17	0.17	0.17	0.17 ± 0.00	0.07	0.07	0.07	0.07 ± 0.00	0.05	0.05	0.05	0.05 ± 0.00
185	0.13	0.13	0.13	0.13 ± 0.00	0.04	0.04	0.05	0.04 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00
192	0.25	0.26	0.25	0.25 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00
197	0.18	0.18	0.17	0.18 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00
201	0.16	0.16	0.15	0.16 ± 0.01	0.02	0.02	0.02	0.02 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00
204	0.12	0.12	0.12	0.12 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00
211	0.27	0.26	0.26	0.26 ± 0.01	0.05	0.05	0.05	0.05 ± 0.00	0.06	0.04	0.04	0.05 ± 0.01
218	0.13	0.16	0.15	0.15 ± 0.02	0.02	0.02	0.02	0.02 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00
225	0.12	0.12	0.12	0.12 ± 0.00	0.09	0.08	0.11	0.09 ± 0.02	0.08	0.12	0.09	0.10 ± 0.02
227	0.15	0.15	0.15	0.15 ± 0.00	0.08	0.09	0.09	0.09 ± 0.01	0.08	0.10	0.07	0.08 ± 0.02
229	0.15	0.15	0.15	0.15 ± 0.00	0.06	0.08	0.07	0.07 ± 0.01	0.05	0.06	0.06	0.06 ± 0.01
232	0.11	0.11	0.11	0.11 ± 0.00	0.11	0.11	0.10	0.11 ± 0.01	0.06	0.06	0.06	0.06 ± 0.00
234	0.03	0.03	0.03	0.03 ± 0.00	0.06	0.07	0.07	0.07 ± 0.01	0.05	0.06	0.06	0.06 ± 0.01
240	0.02	0.02	0.02	0.02 ± 0.00	0.02	0.02	0.02	0.02 ± 0.00	0.04	0.04	0.04	0.04 ± 0.00
243	0.09	0.10	0.09	0.09 ± 0.01	0.04	0.05	0.04	0.04 ± 0.01	0.06	0.05	0.05	0.05 ± 0.01
245	0.11	0.11	0.12	0.11 ± 0.01	0.06	0.07	0.07	0.07 ± 0.01	0.08	0.07	0.09	0.08 ± 0.01
247	0.16	0.15	0.15	0.15 ± 0.01	0.08	0.08	0.09	0.08 ± 0.01	0.08	0.07	0.11	0.09 ± 0.02
Before PMR addition	**Min**			0.00				0.01				0.02
	Mean ± SD			0.06 ± 0.10				2.36 ± 4.00				2.81 ± 4.32
	Max			0.50				16.67				16.67
After PMR addition	**Min**			0.02				0.02				0.02
	Mean ± SD			0.17 ± 0.17				1.05 ± 2.42				1.00 ± 2.34
	Max			0.87				8.57				8.43

Table B6 Nitrate primary and secondary data collected before and after PMR additions.

Day	Feed (mg.L^{-1})				Aeration tank 1 effluent (mg.L^{-1})				Aeration tank 2 effluent (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	1	2	3	Mean ± SD
8	0.1	0.1	0.1	0.10 ± 0.00	0.1	0.1	0.1	0.10 ± 0.00	0.1	0.1	0.1	0.10 ± 0.00
11	0.1	0.1	0.1	0.10 ± 0.00	0.1	0.1	0.1	0.10 ± 0.00	0.1	0.1	0.1	0.10 ± 0.00
15	0.1	0.1	0.1	0.10 ± 0.00	0.1	0.1	0.1	0.10 ± 0.00	0.1	0.1	0.1	0.10 ± 0.00
18	0.5	0.4	0.1	0.33 ± 0.21	0.3	0.5	0.4	0.40 ± 0.10	0.7	0.8	1.0	0.83 ± 0.15
22	0.1	0.1	0.4	0.20 ± 0.17	4.4	4.6	4.4	4.47 ± 0.12	3.7	4.0	3.7	3.79 ± 0.19
25	0.1	0.1	0.1	0.10 ± 0.00	14.8	14.9	14.8	14.83 ± 0.06	11.2	11.2	11.5	11.30 ± 0.17
29	0.5	0.4	0.5	0.47 ± 0.06	14.6	15.4	14.8	14.93 ± 0.42	12.5	12.6	12.6	12.57 ± 0.06
32	0.5	0.4	0.5	0.47 ± 0.06	19.6	19.6	19.3	19.50 ± 0.17	20.4	20.3	19.8	20.17 ± 0.32
36	0.5	0.4	0.4	0.43 ± 0.06	20.6	19.0	19.4	19.67 ± 0.83	20.5	20.1	19.9	20.17 ± 0.31
43	0.0	0.0	0.0	0.00 ± 0.00	13.1	13.0	13.0	13.03 ± 0.06	14.5	14.4	14.1	14.33 ± 0.21
46	0.5	0.5	0.5	0.50 ± 0.00	20.4	20.2	20.1	20.23 ± 0.15	20.5	20.5	20.8	20.60 ± 0.17
50	0.5	0.5	0.5	0.50 ± 0.00	20.5	20.4	20.0	20.30 ± 0.26	21.6	21.4	21.2	21.40 ± 0.20
53	0.9	0.9	0.8	0.87 ± 0.06	18.3	18.3	18.2	18.27 ± 0.06	17.6	17.5	17.6	17.57 ± 0.06
57	0.5	0.5	0.5	0.50 ± 0.00	19.6	19.1	19.2	19.30 ± 0.26	20.2	19.9	20.2	20.10 ± 0.17
108	0.5	0.5	0.5	0.50 ± 0.00	14.9	14.7	15.3	14.97 ± 0.31	11.0	11.0	11.1	11.03 ± 0.06
110	0.5	0.5	0.5	0.50 ± 0.00	14.7	14.6	14.8	14.70 ± 0.10	11.7	12.5	12.3	12.17 ± 0.42
113	0.5	0.5	0.5	0.50 ± 0.00	15.3	15.2	15.7	15.40 ± 0.26	18.1	18.0	18.3	18.13 ± 0.15
115	0.5	0.5	0.5	0.50 ± 0.00	13.3	13.5	13.7	13.50 ± 0.20	16.5	15.9	16.0	16.13 ± 0.32
117	0.5	0.5	0.5	0.50 ± 0.0	15.4	15.7	15.8	15.63 ± 0.21	16.8	16.7	16.3	16.60 ± 0.26
120	0.5	0.5	0.5	0.50 ± 0.00	16.2	16.5	16.4	16.37 ± 0.15	14.5	14.6	14.5	14.53 ± 0.06
123	0.5	0.5	0.5	0.50 ± 0.00	15.4	15.8	15.7	15.63 ± 0.21	13.9	13.8	14.0	13.90 ± 0.10
125	0.5	0.5	0.5	0.50 ± 0.00	18.1	18.2	18.3	18.20 ± 0.10	12.9	12.8	12.5	12.73 ± 0.21
129	0.5	0.5	0.5	0.50 ± 0.00	20.6	20.3	21.3	20.73 ± 0.51	18.3	18.4	18.1	18.27 ± 0.15
130	0.5	0.5	0.5	0.50 ± 0.00	20.6	21.1	21.2	20.97 ± 0.32	19.3	19.5	19.4	19.40 ± 0.10
132	2.0	2.3	2.1	2.13 ± 0.15	23.0	23.0	22.8	22.93 ± 0.12	20.1	20.2	20.4	20.23 ± 0.15
135	0.5	0.5	0.5	0.50 ± 0.00	20.8	20.7	20.8	20.77 ± 0.06	22.0	22.1	21.8	21.97 ± 0.15
137	0.5	0.5	0.5	0.50 ± 0.00	3.4	3.5	3.4	3.43 ± 0.06	3.8	3.7	3.6	3.70 ± 0.10
139	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
142	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
144	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
146	0.5	0.5	0.5	0.50 ± 0.00	0.7	1.0	0.8	0.83 ± 0.15	1.0	1.1	1.0	1.03 ± 0.06
149	0.5	0.5	0.5	0.50 ± 0.00	3.7	3.3	3.4	3.47 ± 0.21	4.2	4.0	4.0	4.07 ± 0.12
156	0.5	0.5	0.5	0.50 ± 0.00	6.0	6.2	6.5	6.23 ± 0.25	7.3	7.3	7.7	7.43 ± 0.23
158	0.5	0.5	0.5	0.50 ± 0.00	9.7	9.5	9.8	9.67 ± 0.15	10.9	11.1	11.6	11.20 ± 0.36
160	0.5	0.5	0.5	0.50 ± 0.00	9.9	9.9	9.9	9.90 ± 0.00	11.8	11.8	11.9	11.83 ± 0.06
162	0.5	0.5	0.5	0.50 ± 0.00	14.8	14.9	14.7	14.80 ± 0.10	13.1	13.1	13.5	13.12 ± 0.23
166	0.5	0.5	0.5	0.50 ± 0.00	6.4	6.1	6.3	6.27 ± 0.15	7.2	7.5	7.6	7.43 ± 0.21
169	0.5	0.5	0.5	0.50 ± 0.00	6.9	6.6	7.0	6.83 ± 0.21	7.4	6.9	7.0	7.10 ± 0.26
171	0.5	0.5	0.5	0.50 ± 0.00	6.2	6.1	6.2	6.17 ± 0.06	5.8	5.4	5.8	5.67 ± 0.23
177	0.5	0.5	0.5	0.50 ± 0.00	2.3	2.3	2.7	2.43 ± 0.23	2.9	2.8	2.4	2.70 ± 0.26
180	0.5	0.5	0.5	0.50 ± 0.00	3.2	3.5	3.2	3.30 ± 0.17	3.1	3.1	3.2	3.13 ± 0.06
183	0.5	0.5	0.5	0.50 ± 0.00	2.2	2.3	2.1	2.20 ± 0.10	1.9	2.1	2.0	2.00 ± 0.10
185	0.5	0.5	0.5	0.50 ± 0.00	1.6	1.2	1.4	1.40 ± 0.20	1.7	1.5	1.6	1.60 ± 0.10
192	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
197	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
201	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
204	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
211	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
218	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
225	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
227	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
229	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00	0.5	0.5	0.5	0.50 ± 0.00
232	2.2	2.9	2.4	2.50 ± 0.36	2.6	2.8	2.1	2.50 ± 0.36	3.1	2.6	3.2	2.97 ± 0.32
234	4.1	4.0	4.5	4.20 ± 0.26	2.6	2.7	2.4	2.57 ± 0.15	2.4	2.6	2.7	2.57 ± 0.15
240	1.9	1.5	1.7	1.70 ± 0.20	1.6	1.8	1.7	1.70 ± 0.10	1.6	1.5	1.8	1.63 ± 0.15
243	2.5	2.6	2.3	2.47 ± 0.15	2.2	2.3	2.2	2.23 ± 0.06	2.5	2.4	2.5	2.47 ± 0.06
245	2.3	2.0	2.1	2.13 ± 0.15	2.5	2.5	2.6	2.13 ± 0.06	2.8	2.8	2.7	2.77 ± 0.06
247	2.9	2.8	2.9	2.87 ± 0.06	3.4	2.7	3.2	3.10 ± 0.36	3.1	3.2	2.7	3.00 ± 0.26
Before PMR addition	Min			0.00				0.10				0.10
	Mean ± SD			0.48 ± 0.35				12.01 ± 8.26				11.52 ± 8.04
	Max			2.13				22.93				21.97
After PMR addition	Min			0.50				0.05				0.05
	Mean ± SD			0.99 ± 1.00				3.40 ± 3.67				3.59 ± 3.83
	Max			4.20				14.80				13.12

Table B7 COD primary and secondary data collected before and after PMR addition.

Day	Feed (mg.L^{-1})				Aeration tank 1 effluent (mg.L^{-1})						Aeration tank 2 effluent (mg.L^{-1})					
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**Removal efficiency (%)**	**Removal rate (mg.m^{-3}.day^{-1})**	**1**	**2**	**3**	**Mean ± SD**	**Removal efficiency (%)**	**Removal rate (mg.m^{-3}.day^{-1})**
8	108	110	114	110 ± 3	113	112	112	112 ± 1	-2	3	112	111	112	112 ± 1	-1	4
11	116	116	115	116 ± 1	107	108	114	110 ± 3	5	-2	105	105	104	105 ± 0	10	-3
15	115	115	115	115 ± 0	117	116	117	117 ± 0	-1	0	116	113	114	115 ± 1	0	0
18	117	117	117	110 ± 0	116	120	120	118 ± 2	-1	5	117	116	117	117 ± 0	0	4
22	117	116	116	116 ± 0	99	97	97	98 ± 1	16	7	102	101	100	101 ± 1	13	12
25	141	137	139	139 ± 2	102	93	99	98 ± 4	29	1	81	91	89	87 ± 5	37	3
29	112	119	109	113 ± 5	66	67	72	68 ± 3	40	12	47	46	51	48 ± 3	58	2
32	124	111	130	122 ± 10	48	40	37	42 ± 6	66	0	48	49	51	49 ± 2	59	4
36	147	144	149	147 ± 3	69	64	67	67 ± 3	55	-3	60	56	58	58 ± 2	60	-5
43	123	118	121	121 ± 3	62	61	60	61 ± 1	49	-12	64	67	65	65 ± 2	46	-6
46	96	98	95	96 ± 2	70	74	73	72 ± 2	25	2	58	63	60	60 ± 3	37	-1
50	115	110	114	113 ± 3	83	84	82	83 ± 1	27	54	83	79	78	80 ± 3	29	50
53	254	249	242	248 ± 6	54	57	55	55 ± 2	78	27	64	67	62	64 ± 3	74	24
57	335	336	334	335 ± 1	33	33	34	33 ± 1	90	0	56	54	57	56 ± 2	83	0
108	334	334	330	333± 2	57	56	56	56 ± 1	83	-35	58	60	57	58 ± 2	82	-33
110	251	254	255	253 ± 2	48	47	48	48 ± 1	81	-17	45	46	46	46 ± 1	82	-17
113	199	197	195	197 ± 2	40	41	45	42 ± 3	79	41	43	38	41	41 ± 3	79	48
115	274	276	280	277 ± 3	42	40	39	40 ± 2	85	-7	23	24	24	24 ± 1	91	-16
117	265	267	264	265 ± 2	45	44	42	44 ± 2	84	-4	43	42	45	43 ± 2	84	-6
120	255	252	250	252 ± 3	43	44	40	42 ± 2	83	-10	48	49	47	48 ± 1	81	-10
123	234	230	228	231 ± 3	49	50	51	50 ± 1	78	3	59	56	57	57 ± 2	75	11
125	246	247	244	246 ± 2	63	58	59	60 ± 3	76	3	51	51	51	51 ± 0	79	1
129	258	257	252	256 ± 3	59	57	60	59 ± 2	77	3	59	57	60	59 ± 2	77	1
130	256	257	254	256 ± 2	55	57	55	56 ± 1	78	-5	57	59	56	57 ± 2	78	-2
132	246	252	241	246 ± 6	58	54	56	56 ± 2	77	2	51	51	52	51 ± 1	79	0
135	254	256	258	256 ± 2	60	61	59	60 ± 1	77	5	59	62	64	62 ± 3	76	8
137	268	270	272	270 ± 2	62	67	65	65 ± 3	76	0	61	60	57	59 ± 2	78	-3
139	271	269	272	271 ± 2	66	66	67	66 ± 1	75	-12	67	68	65	67 ± 2	75	-14
142	225	230	228	228 ± 3	57	60	61	59 ± 2	74	-6	64	68	65	66 ± 2	71	2
144	219	221	217	219 ± 2	62	63	61	62 ± 1	72	-1	55	56	51	54 ± 3	75	-5
146	223	213	225	220 ± 6	65	66	64	65 ± 1	70	68	62	70	61	64 ± 5	71	74
149	442	432	440	438 ± 5	77	83	78	79 ± 3	82	-6	60	57	59	59 ± 2	87	-7
156	385	389	392	389 ± 4	75	73	72	73 ± 2	81	-7	56	59	58	58 ± 2	85	-12
158	361	361	368	363 ± 4	61	61	63	62 ± 1	83	-30	52	56	60	56 ± 4	85	-34
160	287	297	295	293 ± 5	52	51	51	51 ± 1	82	-18	50	54	55	53 ± 3	82	-21
162	265	258	262	262 ± 4	57	56	57	57 ± 1	78	-28	66	62	65	64 ± 2	75	-22
166	159	161	163	161 ± 2	67	69	67	68 ± 1	58	29	58	49	50	52 ± 5	67	22
169	228	237	238	234 ± 6	55	52	54	54 ± 2	77	55	54	60	62	59 ± 4	75	62
171	344	335	348	342 ± 7	55	50	51	52 ± 3	85	-12	43	45	43	44 ± 1	87	-13
177	258	272	281	270 ± 12	56	51	56	54 ± 3	80	2	50	51	56	52 ± 3	81	2
180	267	274	268	270 ± 4	51	48	44	48 ± 4	82	-35	42	48	46	45 ± 3	83	-37
183	156	160	169	162 ± 7	49	42	45	45 ± 4	72	-23	45	47	52	48 ± 4	70	-25
185	125	118	127	123 ± 5	49	55	53	52 ± 3	58	3	53	64	61	59 ± 6	52	5
192	155	161	152	156 ± 5	65	64	59	63 ± 3	60	21	53	51	57	54 ± 3	66	19
197	265	222	243	243 ± 22	39	47	43	43 ± 4	82	-9	45	47	52	48 ± 4	80	-4
201	229	220	238	229 ± 9	65	66	61	64 ± 3	72	30	53	53	48	51 ± 3	78	24
204	298	288	307	298 ± 10	39	41	49	43 ± 5	86	1	50	48	45	48 ± 3	84	1
211	300	323	329	317 ± 15	50	56	53	53 ± 3	83	-5	61	65	60	62 ± 3	80	-4
218	280	286	292	286 ± 6	55	57	53	55 ± 2	81	-8	59	58	55	57 ± 2	80	-8
225	220	239	241	233 ± 12	66	60	54	60 ± 6	74	15	54	66	62	61 ± 6	74	17
227	249	246	258	251 ± 6	47	52	45	48 ± 4	81	-20	45	44	47	45 ± 2	82	-23
229	220	218	193	210 ± 15	44	48	50	47 ± 3	77	-13	50	52	48	50 ± 2	76	-15
232	169	174	175	173± 3	32	54	56	47 ± 13	73	95	56	60	59	58 ± 2	66	100
234	353	361	365	360 ± 6	47	41	44	44 ± 3	88	13	44	46	44	45 ± 1	88	15
240	455	447	458	453 ± 6	69	66	51	62 ± 10	86	-28	51	48	48	49 ± 2	89	-30
245	415	409	422	415 ± 7	48	52	47	49 ± 3	88	7	45	47	48	47 ± 2	89	8
247	423	441	423	429 ± 10	46	53	46	48 ± 4			44	45	47	45 ± 2		
Before PMR addition	**Min**			96				33	-2	-12				24	-1	-33
	Mean ± SD			210 ± 83				67 ± 23	59 ± 30	4 ± 20				65 ± 23	60 ± 29	4 ± 21
	Max			438				118	90	68				117	91	74
After PMR addition	**Min**			123				43	58	-30				44	52	-34
	Mean ± SD			280 ± 90				54 ± 8	79 ± 9	6 ± 33				52 ± 6	78 ± 9	2 ± 31
	Min			429				73	83	95				62	89	100

Table B8 Chloride primary and secondary data collected before and after PMR addition.

Day	Feed ($mg.L^{-1}$)				Aeration tank 1 effluent ($mg.L^{-1}$)				Aeration tank 2 effluent ($mg.L^{-1}$)			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
8	25	23	23	24 ± 1	21	23	21	22 ± 1	22	25	23	23 ± 2
11	27	28	28	28 ± 1	26	27	27	27 ± 0	26	27	27	27 ± 1
15	26	26	26	26 ± 0	29	29	29	29 ± 0	29	30	30	30 ± 0
18	33	32	32	32 ± 0	33	34	34	33 ± 0	33	33	33	33 ± 0
22	33	33	32	32 ± 1	31	33	32	32 ± 1	33	31	33	32 ± 1
25	29	28	30	29 ± 1	32	30	33	32 ± 2	31	30	29	30 ± 1
29	27	26	27	27 ± 1	29	30	29	29 ± 1	30	30	30	30 ± 0
32	27	27	27	27 ± 0	29	26	26	27 ± 2	28	29	24	27 ± 3
36	26	28	26	27 ± 1	31	31	31	31 ± 0	29	32	31	31 ± 2
43	28	30	27	28 ± 2	30	29	29	29 ± 1	30	33	29	31 ± 2
46	28	28	28	28 ± 0	26	27	28	27 ± 1	28	27	27	27 ± 1
50	28	26	26	27 ± 1	29	26	26	27 ± 2	27	25	27	26 ± 1
53	26	25	24	25 ± 1	27	28	27	27 ± 1	26	28	26	27 ± 1
57	29	29	31	30 ± 1	27	27	28	27 ± 1	27	29	28	28 ± 1
108	25	23	23	24 ± 1	21	23	21	22 ± 1	22	25	23	23 ± 2
110	27	28	28	28 ± 1	26	27	27	27 ± 0	26	27	27	27 ± 1
113	26	26	26	26 ± 0	29	29	29	29 ± 0	29	30	30	30 ± 0
115	33	32	32	32 ± 0	33	34	34	33 ± 0	33	33	33	33 ± 0
117	33	33	32	32 ± 1	31	33	32	32 ± 1	33	31	33	32 ± 1
120	29	28	30	29 ± 1	32	30	33	32 ± 2	31	30	29	30 ± 1
123	27	26	27	27 ± 1	29	30	29	29 ± 1	30	30	30	30 ± 0
125	27	27	27	27 ± 0	29	26	26	27 ± 2	28	29	24	27 ± 3
129	26	28	26	27 ± 1	31	31	31	31 ± 0	29	32	31	31 ± 2
130	28	30	27	28 ± 2	30	29	29	29 ± 1	30	33	29	31 ± 2
132	28	28	28	28 ± 0	26	27	28	27 ± 1	28	27	27	27 ± 1
135	29	28	26	28 ± 2	29	26	26	27 ± 2	27	25	27	26 ± 1
137	27	28	30	28 ± 2	24	26	24	25 ± 1	25	26	27	26 ± 1
139	26	28	27	27 ± 1	25	26	24	25 ± 1	27	28	29	28 ± 1
142	25	26	25	25 ± 1	26	24	25	25 ± 1	27	25	24	25 ± 2
144	24	28	26	26 ± 2	23	25	24	24 ± 1	27	25	25	26 ± 1
146	27	27	28	27 ± 1	24	24	26	25 ± 1	31	30	29	30 ± 1
149	28	29	30	29 ± 1	24	25	25	25 ± 1	28	27	26	27 ± 1
156	250	257	249	252 ± 4	27	27	27	27 ± 0	27	26	27	27 ± 1
158	251	256	258	255 ± 4	192	195	196	194 ± 2	184	186	186	185 ± 1
160	256	259	260	258 ± 2	183	184	182	183 ± 1	185	182	183	183 ± 2
162	382	383	382	382 ± 1	185	181	185	184 ± 2	181	183	182	182 ± 1
166	368	374	370	371 ± 3	396	386	392	391 ± 5	372	370	372	371 ± 1
169	374	376	376	375 ± 1	394	386	390	390 ± 4	396	386	382	388 ± 7
171	390	420	390	400 ± 17	300	280	290	290 ± 10	280	290	290	287 ± 6
177	350	350	350	350 ± 0	370	350	340	353 ± 15	360	360	350	357 ± 6
180	430	440	440	437 ± 6	370	380	380	377 ± 6	390	390	390	390 ± 0
183	440	460	470	457 ± 15	470	470	470	470 ± 0	480	480	480	480 ± 0
185	480	490	470	480 ± 10	450	440	450	447 ± 6	470	460	470	467 ± 6
192	470	470	470	470 ± 0	510	500	510	507 ± 6	510	510	500	507 ± 6
197	440	410	460	437 ± 25	560	570	550	560 ± 10	540	540	550	543 ± 6
201	850	860	860	857 ± 6	610	580	590	593 ± 15	640	610	610	620 ± 17
204	1210	1200	1200	1203 ± 6	870	860	860	863 ± 6	910	950	870	910 ± 40
211	1060	1040	1090	1063 ± 25	1110	1110	1120	1113 ± 6	1140	1050	1110	1100 ± 46
218	1110	1090	1080	1093 ± 15	830	880	820	843 ± 32	810	880	870	853 ± 38
225	1140	1080	1080	1100 ± 35	1090	1180	1080	1117 ± 55	1130	1070	1070	1090 ± 35
227	1130	1120	1040	1097 ± 49	1070	1090	1100	1087 ± 15	1070	1070	1050	1063 ± 12
229	1070	1050	1050	1057 ± 12	1120	1130	1120	1123 ± 6	1120	1120	1100	1113 ± 12
232	1120	1110	1130	1120 ± 10	1120	1120	1170	1137 ± 29	1230	1170	1140	1180 ± 46
234	1080	1060	1060	1067 ± 12	1050	1100	1110	1087 ± 32	1060	1090	1090	1080 ± 17
240	1110	1130	1110	1117 ± 12	1150	1110	1150	1137 ± 23	1160	1170	1140	1157 ± 15
243	1080	1110	1130	1107 ± 25	1160	1170	1130	1153 ± 21	1090	1120	1130	1113 ± 21
245	1110	1090	1120	1107 ± 15	1090	1120	1080	1097 ± 21	1140	1160	1110	1137 ± 25
247	1090	1190	1150	1143 ± 50	1150	1150	1140	1147 ± 6	1120	1140	1050	1103 ± 47
Before PMR addition	**Min**			24				22				23
	Mean ± SD			28 ± 2				28 ± 3				28 ± 3
	Max			32				33				33
After PMR addition	**Min**			252				27				27
	Mean ± SD			733 ± 370				687 ± 391				689 ± 340
	Max			1143				1137				1180

Table B9 Phosphate primary and secondary data collected before and after PMR addition.

Day	**Feed (mg.L^{-1})**				**Aeration tank 1 effluent (mg.L^{-1})**				**Aeration tank 2 effluent (mg.L^{-1})**			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
8	0.5	0.7	0.6	0.6 ± 0.1	0.6	0.9	0.6	0.7 ± 0.2	1.0	0.7	0.6	0.8 ± 0.2
11	1.0	1.1	1.0	1.0 ± 0.1	1.4	1.3	1.7	1.5 ± 0.2	1.4	1.4	1.6	1.5 ± 0.1
15	1.7	1.5	1.7	1.6 ± 0.1	0.7	0.8	0.7	0.7 ± 0.1	1.0	1.0	1.0	0.7 ± 0.0
18	1.7	1.9	1.8	1.8 ± 0.1	1.8	1.8	1.9	1.8 ± 0.1	1.9	1.7	1.8	1.8 ± 0.1
22	1.5	1.5	1.4	1.5 ± 0.1	2.2	2.8	2.5	2.5 ± 0.3	2.4	2.4	2.8	2.5 ± 0.2
25	2.8	2.6	2.6	2.7 ± 0.1	2.0	2.5	2.6	2.4 ± 0.3	3.6	3.7	3.7	3.7 ± 0.1
29	2.2	1.9	2.1	2.1 ± 0.2	4.5	3.9	3.5	4.0 ± 0.5	3.8	3.9	4.1	3.9 ± 0.2
32	1.7	1.4	1.3	1.5 ± 0.2	7.9	8.0	7.9	7.9 ± 0.1	10.5	9.9	9.6	10.0 ± 0.5
36	1.4	1.3	1.3	1.3 ± 0.1	6.6	6.9	6.5	6.7 ± 0.2	7.9	7.6	7.8	7.8 ± 0.2
43	1.4	1.6	1.5	1.5 ± 0.1	4.7	4.6	4.8	4.7 ± 0.1	6.4	6.1	6.4	6.3 ± 0.2
46	5.3	5.6	5.5	5.5 ± 0.2	4.8	4.9	5.0	4.9 ± 0.1	5.4	5.7	5.6	5.6 ± 0.2
50	2.8	2.9	2.9	2.9 ± 0.1	5.7	5.4	5.6	5.6 ± 0.2	5.5	5.6	5.7	5.6 ± 0.2
53	4.5	4.3	4.6	4.5 ± 0.2	6.2	6.1	6.3	6.2 ± 0.1	5.5	5.7	5.6	5.6 ± 0.1
57	6.6	6.0	6.3	6.3 ± 0.3	5.8	5.9	6.0	5.9 ± 0.1	6.0	6.0	5.8	5.9 ± 0.1
108	1.9	2.0	2.1	2.0 ± 0.1	2.3	2.0	1.8	2.0 ± 0.3	3.1	2.9	2.6	2.9 ± 0.3
110	2.9	2.8	3.0	2.9 ± 0.1	4.1	4.1	4.2	4.1 ± 0.1	4.2	4.1	4.4	4.2 ± 0.2
113	1.2	1.0	0.9	1.0 ± 0.2	2.3	2.3	2.6	2.4 ± 0.2	2.4	2.4	2.5	2.4 ± 0.1
115	2.8	2.9	2.4	2.7 ± 0.3	3.7	3.4	3.4	3.5 ± 0.2	6.6	6.7	6.5	6.6 ± 0.1
117	1.1	1.3	1.3	1.2 ± 0.1	2.3	1.8	2.0	2.0 ± 0.3	1.7	1.7	2.1	1.8 ± 0.2
120	1.8	1.7	1.8	1.8 ± 0.1	2.5	2.6	2.5	2.5 ± 0.1	2.6	2.7	2.7	2.7 ± 0.1
123	1.4	1.5	1.6	1.5 ± 0.1	2.4	2.6	2.5	2.5 ± 0.1	2.5	2.5	2.6	2.5 ± 0.1
125	2.0	2.5	2.4	2.3 ± 0.3	3.0	3.1	3.1	3.1 ± 0.1	3.3	3.0	3.0	3.1 ± 0.2
129	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± 0.0
130	1.0	1.0	1.0	1.0 ± 0.0	1.9	2.1	2.1	2.0 ± 0.1	2.0	2.2	2.0	2.1 ± 0.1
132	2.5	2.4	2.1	2.3 ± 0.2	4.0	3.9	4.1	4.0 ± 0.1	3.3	3.0	2.9	3.1 ± 0.2
135	1.7	1.7	1.6	1.7 ± 0.1	2.5	2.4	2.6	2.5 ± 0.1	2.8	2.7	2.7	2.7 ± 0.1
137	1.9	2.0	2.1	2.0 ± 0.1	3.1	2.9	3.0	3.0 ± 0.1	2.6	2.4	2.7	2.6 ± 0.2
139	2.2	2.4	2.1	2.2 ± 0.2	2.9	2.8	2.9	2.9 ± 0.1	3.4	3.3	3.5	3.4 ± 0.1
142	1.1	1.2	1.1	1.1 ± 0.1	2.7	2.7	2.7	2.7 ± 0.0	3.1	2.9	2.8	2.9 ± 0.2
144	1.7	1.5	1.6	1.6 ± 0.1	3.2	3.1	3.0	3.1 ± 0.1	2.4	2.6	2.4	2.5 ± 0.1
146	2.3	2.5	2.8	2.5 ± 0.3	2.5	2.6	2.7	2.6 ± 0.1	2.5	2.6	2.7	2.6 ± 0.1
149	2.5	2.4	2.5	2.5 ± 0.1	1.3	1.4	1.4	1.4 ± 0.1	1.5	1.5	1.4	1.5 ± 0.1
156	1.0	1.0	1.0	1.0 ± 0.0	2.6	2.5	2.5	2.5 ± 0.1	2.2	2.3	2.2	2.2 ± 0.1
158	1.7	1.7	1.7	1.7 ± 0.0	1.8	1.7	1.8	1.8 ± 0.1	1.6	1.7	1.7	1.7 ± 0.1
160	2.8	2.3	2.2	2.4 ± 0.3	1.2	1.6	1.4	1.4 ± 0.2	1.0	1.3	1.0	1.1 ± 0.2
162	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± 0.0
166	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± 0.0
169	1.0	1.0	1.0	1.0 ± 0.0	1.0	1.0	1.0	1.0 ± .00	1.6	1.7	1.7	1.7 ± 0.1
171	1.6	1.6	1.6	1.6 ± 0.0	0.4	0.4	0.5	0.4 ± 0.1	0.6	0.5	0.6	0.6 ± 0.1
177	0.4	0.5	0.4	0.4 ± 0.1	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
180	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
183	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
185	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
192	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
197	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
201	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
204	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
211	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
218	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
225	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
227	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
229	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
232	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
234	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
240	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
243	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
245	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
247	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0	0.1	0.1	0.1	0.1 ± 0.0
Before PMR addition	**Min**			0.6				0.7				0.7
	Mean ± SD			2.1 ± 1.3				3.2 ± 1.8				3.5 ± 2.1
	Max			6.3				7.9				10.0
After PMR addition	**Min**			0.1				0.1				0.1
	Mean ± SD			0.5 ± 0.6				0.4 ± 0.6				0.4 ± 0.6
	Max			2.4				2.5				2.2

Table B10 Primary data collected for pH before and after PMR addition.

Day	Feed			Aeration tank 1 effluent			Aeration tank 2 effluent		
	1	2	3	1	2	3	1	2	3
8	6.95	7.42	7.20	4.77	4.80	4.81	5.34	5.24	5.35
11	6.89	6.67	7.45	6.23	6.20	6.08	4.54	4.41	4.34
15	7.70	7.79	7.80	7.11	7.10	7.00	6.99	7.10	7.01
18	7.65	7.66	7.65	7.51	7.56	7.59	7.61	7.59	7.62
22	7.89	7.90	7.91	7.42	7.45	7.39	7.38	7.34	7.36
25	7.96	7.97	8.00	7.27	7.21	7.23	7.37	7.36	7.35
29	7.72	7.75	7.69	7.31	7.34	7.38	7.29	7.25	7.30
32	7.64	7.69	7.71	7.18	7.15	7.11	7.23	7.21	7.21
36	7.54	7.57	7.52	7.19	7.21	7.24	7.12	7.18	7.15
43	7.44	7.43	7.48	7.01	6.98	7.03	6.99	7.01	7.04
46	7.29	7.31	7.27	7.35	7.39	7.41	7.23	7.22	7.19
50	7.58	7.60	7.61	7.20	7.17	7.16	7.15	7.19	7.14
53	7.21	7.25	7.23	6.89	6.82	6.79	6.84	6.82	6.89
57	7.11	7.09	7.12	6.49	6.47	6.44	6.54	6.51	6.52
60	7.01	6.99	7.05	6.51	6.56	6.59	6.91	6.82	6.79
64	7.15	7.25	7.27	6.62	6.67	6.65	6.52	6.47	6.44
67	7.24	7.29	7.31	6.71	6.73	6.76	6.53	6.56	6.59
70	7.39	7.42	7.36	7.20	7.25	7.24	6.61	6.67	6.65
74	7.45	7.51	7.36	7.30	7.34	7.38	6.74	6.78	6.76
77	7.61	7.69	7.72	6.90	7.02	7.03	7.24	7.29	7.24
81	7.52	7.48	7.55	6.50	6.58	7.54	7.35	7.38	7.41
84	7.41	7.48	7.47	7.21	7.28	7.31	7.03	7.02	7.03
88	7.36	7.42	7.39	7.11	7.16	7.14	6.58	6.60	7.54
91	7.59	7.65	7.65	7.32	7.36	7.38	7.24	7.30	7.31
95	7.21	7.19	7.25	7.12	7.14	7.13	7.18	7.19	7.14
98	7.11	7.12	7.15	7.14	7.16	7.12	7.31	7.36	7.32
102	7.02	7.14	7.07	7.22	7.20	7.19	7.17	7.14	7.19
105	6.90	7.00	6.89	7.31	7.36	7.35	7.16	7.14	7.12
108	7.39	7.41	7.45	6.78	6.81	6.83	7.28	7.20	7.25
110	6.95	7.42	7.20	6.23	6.20	6.08	7.34	7.31	7.35
113	7.65	7.66	7.65	7.11	7.10	7.00	7.01	7.05	7.01
115	7.70	7.79	7.80	7.35	7.34	7.31	7.61	7.59	7.62
117	7.96	7.97	8.00	7.42	7.41	7.42	7.38	7.34	7.36
120	7.89	7.90	7.91	7.31	7.28	7.29	7.37	7.36	7.35
123	7.64	7.69	7.71	7.25	7.29	7.23	7.29	7.25	7.30
125	7.72	7.75	7.69	7.26	7.24	7.24	7.23	7.21	7.21
129	7.71	7.76	7.79	7.33	7.33	7.27	7.31	7.35	7.39
130	7.82	7.88	7.91	7.05	7.05	7.05	7.35	7.29	7.33
132	7.78	7.82	7.79	7.30	7.33	7.25	7.39	7.41	7.38
135	7.89	7.78	7.85	7.31	7.31	7.38	7.21	7.25	7.27
137	7.85	7.89	7.82	7.35	7.39	7.32	7.25	7.29	7.17
139	7.64	7.60	7.65	7.32	7.38	7.39	7.12	7.08	7.15
142	7.42	7.42	7.39	7.33	7.35	7.30	7.25	7.29	7.30
144	7.58	7.59	7.51	7.24	7.28	7.29	7.31	7.24	7.35
146	7.85	7.82	7.86	7.26	7.27	7.29	7.26	7.29	7.31
149	7.71	7.69	7.68	7.34	7.36	7.31	7.31	7.24	7.33
156	6.51	6.53	6.54	7.14	7.16	7.11	7.22	7.28	7.21
158	6.59	6.57	6.50	6.54	6.49	6.57	6.51	6.55	6.62
160	6.51	6.55	6.58	6.58	6.61	6.59	6.59	6.51	6.55
162	6.12	6.14	6.17	6.57	6.56	6.64	6.51	6.47	6.51
166	6.09	6.11	6.12	5.94	6.12	6.11	5.62	5.59	5.67
169	6.06	6.12	6.16	6.03	6.10	6.12	6.06	6.06	6.10
171	5.60	5.57	5.57	6.13	6.26	6.29	6.24	6.31	6.32
177	5.53	5.52	5.55	5.74	5.67	5.64	5.65	5.67	6.56
180	5.14	5.14	5.15	5.90	5.72	5.70	5.78	5.79	5.79
183	5.11	5.14	5.14	5.52	5.56	5.57	5.77	5.76	5.76
185	5.12	5.15	5.16	5.51	5.65	5.65	5.78	5.74	5.78
192	4.72	4.70	4.69	4.94	4.98	4.99	5.09	5.14	5.12
197	4.36	4.38	4.38	3.83	3.82	3.79	3.90	3.87	3.88
201	3.79	3.78	3.77	4.33	4.12	4.15	4.00	3.95	3.93
204	3.96	3.94	3.94	3.50	3.46	3.45	3.35	3.34	3.32
211	2.92	2.90	2.87	2.99	2.99	2.99	3.46	3.44	3.45
218	2.87	2.85	2.84	3.28	3.29	3.29	2.96	2.97	2.97
225	2.78	2.77	2.76	2.77	2.77	2.77	3.34	3.35	3.34
227	2.88	2.85	2.84	2.76	2.75	2.75	2.80	2.80	2.80
229	2.86	2.84	2.81	2.83	2.82	2.82	2.76	2.76	2.77
232	2.87	2.85	2.85	2.82	2.83	2.83	2.84	2.84	2.83
234	3.01	2.97	2.95	2.86	2.86	2.87	2.85	2.86	2.83
240	3.20	3.16	3.15	3.01	3.01	3.01	2.88	2.88	2.88
243	3.00	2.98	2.98	2.93	2.91	2.91	2.96	2.97	2.97
245	3.01	3.02	2.99	2.93	2.92	2.93	2.94	2.95	2.94
247	3.00	2.99	2.98	2.94	2.92	2.92	2.93	2.94	2.92
Before PMR	6.93 - 7.98			6.17 - 7.42			6.44 - 7.62		
After PMR	2.84 - 7.98			2.82 - 7.42			2.77 - 7.36		

APPENDIX C

PRIMARY DATA FOR THE PILOT SCALE INVESTIGATION

Table C1 Aeration tank MLSS concentration before and after PMR wastewater additions.

Day	Test (mg.L^{-1})				Control (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
0	3150	2970	2620	219 ± 270	2210	1700	1690	1867 ± 297
9	4220	4250	4180	4217 ± 35	1640	1680	1600	1640 ± 40
11	6280	5740	5810	5943 ± 294	2440	2130	2280	2283 ± 155
14	2030	2040	2120	2063 ± 49	3370	3470	3390	3410 ± 53
16	4350	4320	4410	4360 ± 46	3450	3330	3500	3427 ± 87
21	5410	5350	5210	5323 ± 103	3210	3330	3020	3187 ± 156
23	5050	4980	5150	5060 ± 85	3000	2980	3150	3043 ± 93
25	4990	4870	4710	4857 ± 140	2910	2780	2990	2893 ± 106
28	3390	3400	3490	3427 ± 55	2840	2660	2560	2687 ± 142
30	4870	4750	4920	4847 ± 87	2860	2890	3190	2980 ± 182
32	5100	4990	5240	5110 ± 125	3590	3330	3830	3583 ± 250
35	4390	4420	4410	4407 ± 15	3860	3840	3760	3820 ± 53
37	4020	3870	4140	4010 ± 135	3500	3460	3270	3410 ± 123
39	3870	3990	3750	3870 ± 120	3310	3130	3420	3287 ± 146
42	2990	3010	2850	2950 ± 87	2810	3010	2850	2890 ± 106
44	2750	2610	2540	2633 ± 107	2880	3030	2780	2897 ± 126
46	2640	2710	2370	2573 ± 180	2830	2220	2380	2477 ± 316
49	2550	2690	2510	2583 ± 95	2910	2580	2460	2650 ± 233
51	2540	2620	2510	2557 ± 57	2260	2130	2420	2270 ± 145
53	2850	2740	2640	2743 ± 105	2330	2300	2270	2300 ± 30
56	2010	2150	1990	2050 ± 87	2630	2820	2620	2690 ± 113
59	1630	2060	2020	1903 ± 238	2910	3210	3400	3173 ± 247
63	2090	2330	2360	2260 ± 148	2300	2480	2290	2357 ± 107
78	1260	1320	1300	1293 ± 31	2040	1920	2010	1990 ± 62
81	1690	1870	2260	1940 ± 291	2290	2410	2640	2447 ± 178
85	1720	1630	2710	2020 ± 599	2330	2490	2330	2383 ± 92
88	1680	1690	1740	1703 ± 32	2280	2360	2390	2343 ± 57
92	1840	1890	1840	1857 ± 29	2580	2640	2640	2620 ± 35
95	2740	2870	2910	2840 ± 89	2970	2840	2780	2863 ± 97
99	3650	3660	3660	3657 ± 6	3970	4040	3990	4000 ± 36
102	4370	4250	4170	4263 ± 101	3830	3850	3800	3827 ± 25
106	4600	4410	4440	4483 ± 102	4010	4030	4030	4023 ± 12
109	5130	4940	5470	5180 ± 269	4130	4140	4130	4133 ± 6
113	3370	3580	3430	3460 ± 108	2550	2650	2580	2593 ± 51
116	3900	3920	4110	3977± 116	2790	2760	2720	2757 ± 35
120	4240	4190	4290	4240 ± 50	3040	3120	3110	3090 ± 44
134	4140	4110	4240	4163 ± 68	2790	2880	2900	2857 ± 59
137	4180	4160	4140	4160 ± 20	2830	2790	2750	2790 ± 40
141	4960	4410	4600	4657 ± 279	2500	2440	2560	2500 ± 60
144	4550	5090	4710	4783 ± 277	2440	2640	2430	2503 ± 118
147	2490	2530	2970	2663 ± 266	2350	2250	2600	2400 ± 180
150	1930	1830	2010	1923 ± 90	1920	1980	1790	1897 ± 97

Day	Test (mg.L^{-1})				Control (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
154	2250	2540	2210	2333 ± 180	1980	1970	2080	2010 ± 61
157	2520	2340	2460	2440 ± 92	1820	1930	1850	1867 ± 57
163	2270	2260	2240	2257 ± 15	1780	1880	1900	1853 ± 64
167	1970	1840	1880	1897 ± 67	2210	2270	2300	2260 ± 46
170	2070	2120	2230	2140 ± 82	1920	2120	1970	2003 ± 104
174	2100	2370	2100	2190 ± 155	1940	2130	1960	2010 ± 104
177	1550	1740	1750	1680 ± 113	1850	1680	1790	1773 ± 86
181	1640	1740	1960	1780 ± 164	1260	1230	1080	1190 ± 96
185	1790	1820	1860	1823 ± 35	2300	2210	2420	2310 ± 105
188	2040	2010	1860	1970 ± 96	2080	2090	2030	2066 ± 32
191	2240	2640	2390	2423 ± 202	1800	1800	1790	1797 ± 6
195	2250	2540	2100	2297 ± 224	1740	1840	1750	1777 ± 55
198	2790	2880	2880	2850 ± 52	1670	1610	1520	1600 ± 76
202	2510	2310	2590	2470 ± 144	1630	2080	1700	1803 ± 242
205	2220	2270	2250	2247 ± 25	1850	1750	1780	1793 ± 51
212	2100	2090	2060	2083 ± 21	1850	1830	1800	1827 ± 24
216	2010	2110	2002	2040 ± 60	1740	1790	1810	17800 ± 36
219	1830	1970	1690	1830 ± 140	1720	1810	1740	1757 ± 47
223	1850	1690	1720	1753 ± 85	1720	1640	1710	1690 ± 44
226	1820	1920	1810	1850 ± 61	1680	1760	1730	1723 ± 40
230	1710	1600	1650	1653 ± 55	1690	1780	1740	1737 ± 45
234	3250	3150	3280	3227 ± 68	1710	1610	1810	2541 ± 100
238	3350	3400	3520	3423 ± 87	2490	2750	2630	2623 ± 130
241	3620	3820	3660	3700 ± 105	2680	2950	2470	2700 ± 241
246	3780	3840	3710	3777 ± 65	2320	2940	2780	2680 ± 322
248	4130	4240	4030	4133 ± 105	2970	2450	2710	2710 ± 260
253	4380	4140	4300	4273 ± 122	2610	2900	2870	2793 ± 159
255	4560	4630	4560	4583 ± 40	2390	2640	2970	2667 ± 291
259	4260	4410	4360	4343 ± 76	2300	2950	2870	2707 ± 354
262	4130	3980	4130	4080 ± 87	2130	2850	2960	2647 ± 451
266	3930	3970	3910	3937 ± 31	2890	2460	2620	2657 ± 217
Before PMR addition	**Min**			219				1640
	Mean ± SD			3398 ± 1215				2777 ± 629
	Max			5943				4133
After PMR addition	**Min**			1653				1723
	Mean ± SD			2708 ± 1018				2132 ± 463
	Max			4583				2793

Table C2 Aeration tank effluent SS concentration before and after PMR wastewater additions.

Day	Test (mg.L^{-1})				Control (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
0	51	54	53	53 ± 1	57	69	63	63 ± 6
9	44	46	52	47 ± 4	56	47	52	51 ± 5
11	69	64	71	68 ± 4	49	41	48	46 ± 4
14	82	79	70	77 ± 6	85	99	95	93 ± 7
16	82	74	74	76 ± 5	70	81	77	75 ± 6
21	84	80	80	81 ± 2	75	64	62	67 ± 7
23	59	63	57	59 ± 3	109	97	103	103 ± 6
25	42	47	50	46 ± 4	87	99	95	93 ± 6
28	85	92	86	87 ± 4	53	67	62	60 ± 7
30	86	92	89	89 ± 3	62	51	57	56 ± 6
32	79	68	76	74 ± 6	83	70	84	79 ± 8
35	75	84	82	80 ± 5	49	38	34	40 ± 8
37	80	72	73	75 ± 4	69	81	73	74 ± 6
39	64	72	70	69 ± 4	41	56	50	49 ± 8
42	79	74	78	77 ± 3	60	47	58	55 ± 7
44	88	95	84	89 ± 6	95	84	100	93 ± 8
46	40	47	44	43 ± 4	52	40	43	45 ± 6
49	62	55	60	59 ± 4	59	48	61	56 ± 7
51	38	32	43	37 ± 6	37	29	33	33 ± 4
53	79	84	84	82 ± 3	49	38	51	46 ± 7
56	50	42	49	47 ± 4	41	52	55	49 ± 7
59	128	138	145	137 ± 9	42	34	35	37 ± 4
63	97	112	102	103 ± 8	117	137	117	123 ± 12
78	84	87	71	80 ± 9	30	49	33	37 ± 10
81	111	109	121	113 ± 6	53	40	49	47 ± 7
85	63	57	60	60 ± 3	34	19	28	27 ± 8
88	87	96	94	92 ± 5	82	59	78	73 ± 12
92	96	109	102	101 ± 7	52	67	47	55 ± 10
95	79	67	78	74 ± 7	37	30	25	30 ± 6
99	66	60	65	63 ± 3	59	72	75	68 ± 9
102	70	82	77	76 ± 6	45	58	48	50 ± 7
106	68	57	55	60 ± 7	39	27	33	33 ± 6
109	52	60	54	55 ± 4	67	54	67	62 ± 8
113	49	37	43	43 ± 6	40	52	51	47 ± 7
116	76	63	69	69 ± 7	37	27	28	30 ± 6
120	40	50	60	50 ± 10	92	99	98	96 ± 4
134	80	90	90	88 ± 6	58	67	72	65 ± 7
137	2	8	5	5 ± 3	48	56	57	53 ± 5
141	100	110	100	103 ± 6	113	131	137	127 ± 12
144	95	109	97	100 ± 8	42	58	52	50 ± 8
147	150	164	168	160 ± 9	54	40	49	47 ± 7
150	80	71	68	73 ± 6	59	69	61	63 ± 5
154	82	89	85	85 ± 4	60	47	44	50 ± 9
157	84	97	92	91 ± 7	97	111	99	102 ± 8

Day	Test (mg.L^{-1})				Control (mg.L^{-1})			
	1	2	3	Mean ± SD	1	2	3	Mean ± SD
163	74	62	58	64 ± 8	104	95	92	97 ± 6
167	53	41	47	47 ± 6	52	38	43	44 ± 7
170	65	78	74	72 ± 7	48	62	59	56 ± 7
174	172	154	154	160 ± 10	120	141	139	133 ± 12
177	49	38	43	43 ± 6	30	49	33	37 ± 10
181	60	73	70	67 ± 7	85	70	76	77 ± 8
185	42	30	39	37 ± 6	42	29	30	33 ± 7
188	67	51	59	59 ± 8	52	59	41	50 ± 9
191	110	97	104	103 ± 7	73	59	69	67 ± 7
195	80	70	75	75 ± 5	52	58	47	52 ± 6
198	90	86	74	83 ± 8	43	27	29	33 ± 9
202	143	137	149	143 ± 6	57	71	74	67 ± 9
205	82	82	97	87 ± 9	95	112	100	102 ± 9
212	83	76	70	76 ± 7	102	87	99	96 ± 8
216	58	49	50	52 ± 5	53	37	57	49 ± 11
219	51	60	57	56 ± 5	65	72	54	63 ± 9
223	74	89	79	80 ± 8	56	40	51	49 ± 8
226	40	51	56	49 ± 8	54	63	62	59 ± 5
230	63	70	64	66 ± 4	95	112	104	103 ± 9
234	89	74	86	83 ± 8	83	72	74	76 ± 6
238	115	99	116	110 ± 10	42	28	41	37 ± 8
241	130	145	142	139 ± 8	100	89	97	95 ± 6
246	92	99	95	95 ± 4	62	78	63	67 ± 9
248	87	90	74	83 ± 9	53	32	40	41 ± 11
253	143	156	142	147 ± 8	114	97	99	103 ± 9
255	72	82	74	76 ± 5	56	41	52	49 ± 8
259	80	93	86	86 ± 7	47	62	51	52 ± 8
262	117	109	119	115 ± 5	99	117	102	106 ± 10
266	98	93	87	92 ± 6	85	100	112	99 ± 14
Before PMR addition	**Min**			5				27.00
	Mean ± SD			75 ± 26				62 ± 25
	Max			137				127
After PMR addition	**Min**			37				33
	Mean ± SD			85 ± 32				67 ± 27
	Max			160				133

Table C3 Settleable solids and sludge volume index (SVI) data collected before and after PMR wastewater additions.

	Day	**Control**		**Test**	
		Settleable solids (ml.L^{-1})	**SVI (ml.g^{-1})**	**Settleable solids (ml.L^{-1})**	**SVI (ml.g^{-1})**
	0	790	442	790	281
	9	590	384	580	153
	11	475	223	500	93
	14	440	176	320	218
	16	230	128	300	135
	21	590	196	420	122
	23	450	194	600	148
	25	420	156	300	93
	28	300	145	420	161
	30	510	183	430	120
	32	525	160	550	119
	35	570	170	550	150
	37	550	173	510	155
	39	480	155	475	142
	42	440	164	440	173
	44	410	155	410	182
	46	375	157	375	165
	49	290	136	280	145
	51	275	137	340	153
	53	290	141	310	131
	56	250	119	260	166
	59	260	102	210	144
	63	225	117	200	111
	78	175	95	120	116
	81	175	88	150	98
	85	160	80	125	74
	88	125	64	115	82
	92	120	55	115	75
	95	110	47	98	42
	99	98	28	85	27
	102	92	26	78	23
	106	740	211	700	178
	109	590	181	630	151
	113	310	231	375	217
	116	290	209	350	170
	120	265	159	325	130
	134	245	165	300	118
	137	210	158	275	90
	141	260	122	255	65
	144	210	100	250	63
	147	180	88	150	71
	150	200	129	170	104
	154	185	114	165	86
	157	150	107	155	74
	163	130	105	150	78
	167	115	77	120	79
	170	130	75	94	56
	174	145	90	87	48
	177	145	96	84	63
	181	104	113	97	67
	185	155	84	105	77
	188	160	85	120	76
	191	145	89	125	58
	195	110	82	125	61
	198	78	63	110	51
	202	74	55	90	45
	205	92	54	98	51
	212	89	52	95	53
	216	90	53	90	51
	219	91	56	82	54
	223	93	59	92	89
	226	87	56	75	51
	230	120	104	190	157
	234	135	59	205	74
	238	135	105	250	88
	241	145	107	275	84
	246	130	104	265	79
	248	115	98	270	76
	253	180	89	280	76
	255	150	87	295	76
	259	135	72	235	79
	262	125	73	200	80
	266	115	69	180	76
Before PMR addition	**Min**	92	26	78	23
	Mean ± SD	323 ± 179	147 ± 76	322 ± 179	123 ± 51
	Max	790	442	790	281
After PMR addition	**Min**	78	52	75	45
	Mean ± SD	121 ± 28	79 ± 19	156 ± 76	70 ± 22
	Max	185	114	295	157

Table C4 Ammonia concentration primary and secondary data collected before and after PMR wastewater additions.

Day	Control feed (mg.L^{-1})			Test feed (mg.L^{-1})			Control (mg.L^{-1})					Test (mg.L^{-1})				
	1	2	Mean	1	2	Mean	1	2	Mean	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})	1	2	Mean	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})
9	41.9	42.7	42.3	40.0	42.0	41.0	17.5	17.2	17.4	59.0	-6617.6	18.2	19.1	18.7	55.9	1285.2
11	36.6	36.0	36.3	35.0	37.0	36.0	8.2	8.5	8.4	77.0	11364.4	9.1	9.5	9.3	74.4	4282.5
14	54.5	54.9	54.7	56.0	53.0	54.5	5	4.5	4.8	91.3	-1908.3	5.2	5.7	5.5	90.0	496.1
16	48.6	46.8	47.7	47.0	48.0	47.5	1.9	2.2	2.1	95.7	-29400.0	2.1	2.5	2.3	95.2	-206.0
21	42.4	45.1	43.7	42.0	44.0	43.0	0.45	0.55	0.5	98.9	23263.9	0.7	0.7	0.7	98.5	-5476.6
23	36.5	37.5	37.0	37.0	38.0	37.5	5.2	4.8	5.0	86.5	38372.1	4.5	4.6	4.6	87.7	23164.6
25	28.4	25.7	27.0	28.0	26.0	27.0	6.2	5.8	6.0	77.8	-4370.4	6.8	6.7	6.8	75.0	-4043.7
28	22.9	24.6	23.7	25.0	22.0	23.5	0.7	0.7	0.7	97.0	3991.9	1.0	0.9	1.0	96.0	559.4
30	20.4	23.0	21.7	23.0	20.0	21.5	0.4	0.3	0.4	98.4	-15852.3	0.5	0.6	0.6	97.5	-3468.3
32	16.6	18.8	17.7	17.9	17.8	17.9	5.8	5.5	5.7	68.0	-663.0	6.3	6.5	6.4	63.8	-9936.7
35	20.1	18.3	19.2	19.1	18.9	19.0	8.2	8.5	8.4	56.4	4331.0	15.9	15.6	15.8	17.8	-5971.6
37	20.7	21.8	21.2	22.0	21.0	21.5	8.4	8.2	8.3	60.8	-13170.7	9.2	9.5	9.4	55.8	-14306.7
39	26.2	27.2	26.7	25.0	26.0	25.5	2.9	3.1	3.0	88.8	11171.2	3.4	3.6	3.5	86.9	9603.2
42	20.9	19.9	20.4	21.0	20.5	20.8	0.8	1	0.9	95.6	5966.4	1.2	1.4	1.3	93.6	2681.2
44	20.2	19.4	19.8	19.5	19.8	19.7	5.1	4.9	5.0	74.7	-2500.0	5.5	5.7	5.6	71.7	-263.2
46	16.7	17.9	17.3	17.5	16.9	17.2	2.4	2.6	2.5	85.5	1216.9	2.8	3.0	2.9	83.2	-26648.1
49	18.9	21.1	20.0	19.2	20.1	19.7	6.6	7	6.8	66.1	34855.8	0.9	0.9	0.9	95.7	391916.7
51	26.5	28.9	27.7	29.0	25.0	27.0	2.3	2.4	2.4	91.5	6197.4	0.7	0.7	0.7	97.6	136687.5
53	22.3	20.2	21.2	21.0	22.0	21.5	0.57	0.55	0.6	97.4	-108777.8	1.4	1.5	1.5	93.1	-18651.8
56	19.4	17.4	18.4	18.1	18.9	18.5	7.6	7.5	7.6	58.9	8286.3	9.1	9.1	9.1	50.5	-4697.1
59	20.1	21.2	20.6	21.0	21.0	21.0	0.06	0.05	0.1	99.7	-769.0	1.5	1.5	1.5	92.6	9863.6
63	19.7	20.8	20.2	20.1	20.1	20.1	1.23	1.12	1.2	94.2	48.3	6.9	7.0	7.0	65.6	800.6
78	19.1	19.8	19.4	19.6	19.3	19.5	1	1	1.0	94.9	-1078.8	2.0	1.8	1.9	90.2	-442.0
81	19.5	20.7	20.1	19.8	20.7	20.3	0.49	0.47	0.5	97.6	-755.5	1.3	1.3	1.3	93.6	-487.1
85	19.3	18.5	18.9	18.9	18.8	18.9	0.66	0.66	0.7	96.5	-17157.9	1.4	1.3	1.3	92.9	11229.2
88	20.7	22.4	21.5	21.2	21.3	21.3	0	0	0.0	100.0	12989.6	1.1	1.4	1.3	94.2	1802.6
92	19.0	20.0	19.5	19.5	19.6	19.6	0.05	0.04	0.0	99.8	-2516.1	1.4	1.6	1.5	92.3	1025.4
95	18.9	18.1	18.5	18.4	18.8	18.6	1.1	1.3	1.2	93.5	4503.4	0.1	0.1	0.1	99.5	744.5
99	22.1	23.1	22.6	22.5	22.7	22.6	0.8	0.9	0.9	96.2	2448.7	1.2	1.2	1.2	94.7	4463.3
102	32.8	32.0	32.4	32.1	32.3	32.2	2.2	2.4	2.3	92.9	3221.2	0.1	0.1	0.1	99.8	-1544.6
106	27.9	29.3	28.6	28.7	28.2	28.5	0.9	0.7	0.8	97.2	-14711.9	0.1	0.1	0.1	99.7	-9507.6
109	23.1	21.5	22.3	22.7	21.8	22.3	3.2	3.16	3.2	85.8	-1799.2	0.1	0.1	0.1	99.8	-712.9
113	22.5	19.1	20.8	20.4	20.8	20.6	2.4	2.41	2.4	88.4	368.7	0.5	0.5	0.5	97.7	437.7
116	18.7	19.7	19.2	19.0	19.5	19.3	2.6	2.55	2.6	86.6	13464.3	1.3	1.1	1.2	93.8	4096.8
120	25.4	27.8	26.6	26.3	26.7	26.5	1.2	1.09	1.1	95.7	-920.7	0.1	0.1	0.1	99.6	-2147.4
134	22.3	20.1	21.2	21.2	21.2	21.2	0.08	0.07	0.1	99.6	-8869.0	2.5	2.8	2.7	87.5	-32753.6
137	28.1	26.7	27.4	27.5	27.2	27.4	0	0	0.0	100.0	55237.5	1.4	1.1	1.3	95.4	1093125.0
141	14.9	16.3	15.6	15.9	15.8	15.9	2.88	2.98	2.9	81.2	-3980.8	4.0	4.1	4.0	74.1	2492.2
144	18.2	17.0	17.6	17.3	18.0	17.7	1.5	1.5	1.5	91.5	-1141633.3	2.3	2.4	2.3	86.7	-27811.4
147	4.2	5.4	4.8	5.1	4.5	4.8	0.083	0.083	0.1	98.3	-44246.2	0.1	0.1	0.1	98.3	-2079.1
150	18.9	17.9	18.4	18.3	18.5	18.4	0	0	0.0	100.0	-1701.2	0.5	0.5	0.5	97.3	-951.0
154	21.4	23.2	22.3	22.1	22.5	22.3	0.44	0.51	0.5	97.9	-12377.5	1.6	1.6	1.6	92.9	-3584.0
157	19.5	18.3	18.9	19.1	19.0	19.1	1.1	1.4	1.3	93.4	-3784.9	2.5	2.6	2.6	86.5	7031.3
163	20.7	22.5	21.6	21.4	21.6	21.5	0.67	0.72	0.7	96.8	-3718.8	0.7	0.8	0.8	96.5	-27795.5
167	22.3	21.4	21.8	42.5	42.3	42.4	0.69	0.77	0.7	96.7	-1791.0	1.1	1.3	1.2	97.2	972.2
170	20.4	18.4	19.4	41.7	41.8	41.8	0.49	0.44	0.5	97.6	1344.2	1.6	1.6	1.6	96.2	4058.2
174	17.8	18.8	18.3	58.7	56.6	57.7	0.83	0.76	0.8	95.7	256500.0	13.7	13.4	13.6	76.5	-46000.0
177	22.6	23.6	23.1	60.4	61.1	60.8	0.47	0.46	0.5	98.0	1088.0	23.8	23.3	23.6	61.2	637.3
181	23.3	21.4	22.3	79.5	81.3	80.4	0.65	0.64	0.6	97.1	623.6	44.8	44.2	44.5	44.7	-750.0
185	22.4	20.2	21.3	104.0	104.0	104.0	1.1	1.2	1.2	94.6	1302.1	68.9	67.9	68.4	34.2	-50769.2
188	24.3	25.9	25.1	102.0	104.0	103.0	0.52	0.53	0.5	97.9	7363.0	75.0	73.0	74.0	28.2	-15909.1
191	19.7	21.7	20.7	108.0	109.0	108.5	1.4	1.6	1.5	92.7	-601.9	88.0	85.0	86.5	20.3	-3584.6
195	20.9	19.7	20.3	102.0	103.0	102.5	0.9	0.1	0.5	97.5	-25000.0	88.0	86.0	87.0	15.1	30263.2
198	22.2	25.0	23.6	92.0	93.0	92.5	2.2	2.3	2.3	90.4	3820.8	85.0	92.0	88.5	4.3	-8810.2
202	21.5	19.6	20.5	75.0	75.0	75.0	2	1.8	1.9	90.7	3582.0	92.0	89.0	90.5	-20.7	-25877.2
205	21.2	22.9	22.1	97.0	93.0	95.0	1.36	1.27	1.3	94.0	63466.4	81.0	79.0	80.0	14.9	3198.3
212	18.8	20.9	19.8	90.0	93.0	91.5	4.4	3.7	4.1	79.5	79827.6	84.0	83.0	83.5	9.7	15306.1
216	26.7	28.3	27.5	89.0	85.0	87.0	2.4	2.58	2.5	90.9	78648.6	87.0	87.0	87.0	-1.2	-78125.0
219	18.9	17.4	18.1	95.0	99.0	97.0	1.9	1.74	1.8	89.9	-9062.5	89.0	88.0	88.5	9.2	-2373.4
223	19.5	17.1	18.3	95.0	91.0	93.0	0.88	0.84	0.9	95.3	-2356.3	82.0	83.0	82.5	11.8	1180.4
226	20.1	18.5	19.3	93.0	97.0	95.0	1.4	1.5	1.5	92.5	20937.5	85.0	86.0	85.5	9.0	-1549.6
230	21.9	20.2	21.0	88.0	90.0	89.0	0.79	0.82	0.8	96.2	89519.2	85.0	87.0	86.0	4.4	-18432.2
234	26.5	27.7	27.1	104.0	104.0	104.0	2.1	2.3	2.2	91.9	-1643.9	84.0	87.0	85.5	17.8	-2065.7
238	20.2	23.6	21.9	102.0	104.0	103.0	2.5	2.2	2.4	89.3	-12955.5	98.0	97.0	97.5	5.3	11016.9
241	19.4	20.6	20.0	107.0	105.0	106.0	3.7	3.6	3.7	81.8	-6763.6	95.0	93.0	94.0	11.3	3975.9
246	15.6	13.5	14.5	110.0	108.0	109.0	1.1	1.3	1.2	91.7	-95833.3	91.0	92.0	91.5	16.1	26087.0
248	19.7	21.3	20.5	108.0	109.0	108.5	0.9	0.85	0.9	95.7	-9464.3	88.0	86.0	87.0	19.8	-841.1
253	19.3	17.9	18.6	104.0	102.0	103.0	0.3	0.4	0.4	98.1	-4980.0	84.0	82.0	83.0	19.4	-7142.9
255	17.2	18.1	17.6	107.0	110.0	108.5	0.11	0.15	0.1	99.3	2745.8	89.0	92.0	90.5	16.6	3629.0
259	17.3	15.7	16.5	109.0	107.0	108.0	0.15	0.17	0.2	99.0	19928.6	85.0	86.0	85.5	20.8	5555.6
262	20.4	22.8	21.6	103.0	105.0	104.0	0.95	1.1	1.0	95.2	9065.5	84.0	87.0	85.5	17.8	3322.8
266	18.1	17.0	17.5	105.0	106.0	105.5	0.65	0.77	0.7			89.0	92.0	90.5		
Before PMR addition	**Min**		4.8			17.2			0.0	56.43	-1141.6			0.1	50.45	-32.8
	Mean ± SD		24.1 ± 9.2			24.6 ± 9.5			2.74 ± 3.39	88.7 ± 12.7	-27.3 ± 173.4			3.2 ± 4.1	86.39 ± 16.76	34.2 ± 175.3
	Max		54.7			47.5			17.4	100.00	38.4			18.7	99.80	1093.1
After PMR addition	**Min**		14.5			19.1			0.1	79.55	-95.8			0.8	-20.67	-78.1
	Mean ± SD		20 ± 3			93.8 ± 11.7			1.3 ± 1.0	94.0 ± 4.7	16.6 ± 56.9			73.7 ± 28.4	23.35 ± 26.71	-4.9 ± 21.6
	Max		23.6			109.0			4.1	97.99	89.5			97.5	97.17	30.3

Table C5 Nitrite concentration primary and secondary data collected before and after PMR wastewater additions.

Day	Control feed (mg.L^{-1})			Test feed (mg.L^{-1})			Control effluent(mg.L^{-1})			Test effluent (mg.L^{-1})		
	1	**2**	**Mean**	**1**	**2**	**Mean**	**1**	**2**	**Mean**	**1**	**2**	**Mean**
9	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03
11	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02
14	0.05	0.04	0.04	0.05	0.04	0.04	0.02	0.03	0.03	0.02	0.02	0.02
16	0.04	0.04	0.04	0.04	0.04	0.04	0.20	0.30	0.25	0.03	0.03	0.03
21	0.04	0.03	0.03	0.04	0.03	0.03	0.02	0.04	0.03	0.04	0.03	0.04
23	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.05	0.05	0.03	0.02	0.03
25	0.03	0.04	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.02	0.02	0.02
28	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.03	0.03	0.03
30	0.04	0.04	0.04	0.04	0.04	0.04	0.90	1.10	1.00	0.10	0.10	0.10
32	0.05	0.04	0.05	0.05	0.04	0.05	1.20	1.30	1.25	0.20	0.10	0.15
35	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.06	0.06	0.20	0.20	0.20
37	0.03	0.03	0.03	0.03	0.03	0.03	0.15	0.16	0.16	0.21	0.22	0.22
39	0.02	0.03	0.02	0.02	0.03	0.02	0.30	0.40	0.35	0.25	0.20	0.23
42	0.05	0.04	0.04	0.05	0.04	0.04	0.20	0.30	0.25	0.30	0.30	0.30
44	0.05	0.05	0.05	0.05	0.05	0.05	0.21	0.22	0.22	0.12	0.14	0.13
46	0.03	0.04	0.03	0.03	0.04	0.03	0.50	0.60	0.55	0.10	0.12	0.11
49	0.02	0.03	0.02	0.02	0.03	0.02	1.56	1.54	1.55	0.34	0.34	0.34
51	0.05	0.05	0.05	0.05	0.05	0.05	0.98	0.98	0.98	0.12	0.13	0.13
53	0.05	0.04	0.04	0.05	0.04	0.04	1.20	1.30	1.25	0.52	0.54	0.53
56	0.05	0.05	0.05	0.05	0.05	0.05	4.35	4.25	4.30	1.56	1.52	1.54
59	0.03	0.04	0.04	0.03	0.04	0.04	0.12	0.12	0.12	0.42	0.43	0.43
63	0.04	0.03	0.03	0.04	0.03	0.03	5.90	5.90	5.90	8.00	7.90	7.95
78	0.06	0.05	0.05	0.06	0.05	0.05	0.83	0.83	0.83	0.59	0.59	0.59
81	0.05	0.05	0.05	0.05	0.05	0.05	0.30	0.30	0.30	0.79	0.79	0.79
85	0.03	0.02	0.03	0.03	0.02	0.03	0.66	0.64	0.65	1.52	1.64	1.58
88	0.03	0.03	0.03	0.02	0.02	0.02	0.12	0.14	0.13	0.05	0.06	0.06
92	0.03	0.03	0.03	0.04	0.04	0.04	0.94	0.95	0.95	0.02	0.02	0.02
95	0.05	0.04	0.04	0.12	0.13	0.12	0.02	0.02	0.02	0.01	0.01	0.01
99	0.04	0.04	0.04	0.05	0.05	0.05	1.44	1.37	1.41	0.06	0.06	0.06
102	0.04	0.03	0.03	0.01	0.01	0.01	0.54	0.55	0.55	0.12	0.01	0.07
106	0.02	0.02	0.02	0.13	0.13	0.13	0.87	0.89	0.88	0.05	0.04	0.05
109	0.03	0.04	0.03	0.04	0.04	0.04	0.07	0.06	0.07	0.06	0.06	0.06
113	0.05	0.05	0.05	0.07	0.07	0.07	0.11	0.12	0.12	0.00	0.00	0.00
116	0.04	0.04	0.04	0.02	0.02	0.02	1.31	1.33	1.32	0.05	0.03	0.04
120	0.05	0.04	0.05	0.02	0.02	0.02	1.58	1.62	1.60	0.02	0.02	0.02
134	0.03	0.03	0.03	0.05	0.05	0.05	0.99	1.00	1.00	0.07	0.06	0.07
137	0.03	0.03	0.03	0.11	0.1	0.10	0.45	0.44	0.45	0.00	0.00	0.00
141	0.02	0.03	0.02	0.03	0.03	0.03	2.16	2.20	2.18	0.36	0.35	0.36
144	0.05	0.04	0.04	0.03	0.03	0.03	1.78	1.78	1.78	1.24	1.20	1.22
147	0.05	0.05	0.05	0.19	0.19	0.19	0.51	0.51	0.51	0.38	0.37	0.38
150	0.03	0.04	0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.27	0.27	0.27
154	0.02	0.03	0.02	0.05	0.05	0.05	0.25	0.23	0.24	0.15	0.01	0.08
157	0.05	0.05	0.05	0.03	0.03	0.03	1.65	1.72	1.69	0.14	0.01	0.08
163	0.05	0.04	0.04	0.01	0.01	0.01	0.44	0.46	0.45	0.27	0.03	0.15
167	0.05	0.05	0.05	0.02	0.02	0.02	0.62	0.63	0.63	0.00	0.00	0.00
170	0.03	0.04	0.04	0.00	0.00	0.00	0.20	0.20	0.20	0.61	0.61	0.61
174	0.04	0.03	0.03	0.00	0.00	0.00	4.10	4.05	4.08	0.39	0.39	0.39
177	0.06	0.05	0.05	0.03	0.03	0.03	0.30	0.31	0.31	0.61	0.92	0.77
181	0.05	0.05	0.05	0.00	0.00	0.00	0.28	0.28	0.28	0.04	0.05	0.05
185	0.03	0.02	0.03	0.00	0.00	0.00	0.68	0.68	0.68	0.16	0.16	0.16
188	0.04	0.04	0.04	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.00	0.00
191	0.04	0.03	0.03	0.00	0.00	0.00	0.73	0.74	0.74	0.17	0.16	0.17
195	0.02	0.02	0.02	0.00	0.00	0.00	0.05	0.05	0.05	0.22	0.02	0.12
198	0.03	0.04	0.03	0.00	0.00	0.00	0.11	0.11	0.11	0.14	0.02	0.08
202	0.05	0.05	0.05	0.00	0.00	0.00	0.07	0.07	0.07	0.02	0.02	0.02
205	0.04	0.04	0.04	0.02	0.02	0.02	0.06	0.07	0.07	0.02	0.03	0.03
212	0.05	0.04	0.05	0.03	0.02	0.03	0.07	0.07	0.07	0.00	0.00	0.00
216	0.03	0.03	0.03	0.02	0.02	0.02	1.10	1.20	1.15	0.04	0.05	0.05
219	0.03	0.03	0.03	0.01	0.01	0.01	0.98	1.00	0.99	0.14	0.01	0.08
223	0.02	0.03	0.02	0.00	0.00	0.00	0.50	0.54	0.52	0.07	0.09	0.08
226	0.05	0.04	0.04	0.00	0.00	0.00	0.03	0.03	0.03	0.05	0.06	0.06
230	0.05	0.05	0.05	0.00	0.00	0.00	0.24	0.26	0.25	0.02	0.01	0.02
234	0.03	0.04	0.03	0.01	0.02	0.01	0.26	0.26	0.26	0.00	0.00	0.00
238	0.05	0.04	0.05	0.01	0.01	0.01	0.81	0.82	0.82	0.08	0.07	0.08
241	0.03	0.03	0.03	0.00	0.00	0.00	0.05	0.05	0.05	0.11	0.10	0.11
246	0.03	0.03	0.03	0.00	0.00	0.00	0.06	0.06	0.06	0.12	0.01	0.07
248	0.02	0.03	0.02	0.02	0.01	0.02	0.21	0.22	0.22	0.45	0.05	0.25
253	0.05	0.04	0.04	0.03	0.02	0.03	0.07	0.07	0.07	1.16	1.17	1.17
255	0.05	0.05	0.05	0.01	0.01	0.01	0.75	0.74	0.75	0.13	0.12	0.13
259	0.03	0.04	0.03	0.02	0.02	0.02	0.36	0.04	0.20	0.08	0.09	0.09
262	0.02	0.03	0.02	0.00	0.00	0.00	0.45	0.05	0.25	0.06	0.05	0.06
266	0.05	0.05	0.05	0.01	0.01	0.01	0.02	0.02	0.02	0.07	0.06	0.07
Before PMR addition	**Min**		0.02			0.02			0.02			0.02
	Mean ± SD		0.04 ± 0.01			0.04 ± 0.03			0.81 ± 1.13			0.42 ± 1.22
	Max		0.05			0.19			5.19			1.58
After PMR addition	**Min**		0.02			0			0.02			0.00
	Mean ± SD		0.04 ± 0.01			0.01 ± 0.02			0.46 ± 0.78			0.17 ± 0.27
	Max		0.05			0.05			1.69			1.17

Table C6 Nitrate primary and secondary data collected before and after PMR additions.

Day	Control feed (mg.L^{-1})			Test feed (mg.L^{-1})			Control effluent(mg.L^{-1})			Test effluent (mg.L^{-1})		
	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean
9	0.3	0.4	0.4	0.4	0.3	0.4	6.5	6.8	6.7	5.5	5.7	5.6
11	0.5	0.4	0.5	0.4	0.5	0.4	5.6	5.5	5.6	7.2	6.9	7.1
14	0.5	0.4	0.5	0.4	0.5	0.4	10.1	9.8	10.0	10.5	10.9	10.7
16	0.0	0.0	0.0	0.0	0.0	0.0	10.7	10.5	10.6	12.6	12.1	12.4
21	0.0	0.0	0.0	0.0	0.0	0.0	11.8	11.2	11.5	9.8	10.2	10.0
23	0.5	0.4	0.5	0.5	0.5	0.5	9.7	9.9	9.8	11.5	11.9	11.7
25	0.3	0.3	0.3	0.4	0.3	0.3	8.1	8.5	8.3	10.2	10.8	10.5
28	0.5	0.5	0.5	0.5	0.5	0.5	18.2	18.1	18.2	18.6	18.3	18.5
30	0.0	0.0	0.0	0.0	0.0	0.0	11.9	12.5	12.2	9.5	10	9.8
32	0.4	0.4	0.4	0.4	0.4	0.4	10.1	10.5	10.3	8.8	9.5	9.2
35	0.0	0.0	0.0	0.0	0.0	0.0	13.4	13.3	13.4	7	7.1	7.1
37	0.0	0.0	0.0	0.0	0.0	0.0	9.9	10.3	10.1	11.2	11.9	11.6
39	0.0	0.0	0.0	0.0	0.0	0.0	14.1	14.9	14.5	15.4	16.1	15.8
42	0.6	0.4	0.5	0.5	0.6	0.5	17.2	17.4	17.3	18.7	18.3	18.5
44	0.0	0.0	0.0	0.0	0.0	0.0	8.9	8.7	8.8	10.5	9.8	10.2
46	0.4	0.5	0.5	0.4	0.4	0.4	10.3	10.5	10.4	15.7	15.1	15.4
49	0.0	0.0	0.0	0.7	0.5	0.6	11.4	11.2	11.3	20.7	20.7	20.7
51	0.5	0.5	0.5	0.5	0.5	0.5	15.6	15.8	15.7	15.5	15.8	15.7
53	0.0	0.0	0.0	0.0	0.0	0.0	15.3	15.2	15.3	14.8	14.4	14.6
56	0.0	0.0	0.0	0.0	0.0	0.0	14.2	14.1	14.2	13.7	13.9	13.8
59	0.0	0.0	0.0	0.0	0.0	0.0	26.8	26.2	26.5	21.2	21.8	21.5
63	0.0	0.0	0.0	0.0	0.0	0.0	15.8	16	15.9	9.4	9.2	9.3
78	0.7	0.6	0.7	0.8	0.7	0.7	13.7	13.4	13.6	14	14.2	14.1
81	0.0	0.0	0.0	0.0	0.0	0.0	13.2	13.4	13.3	9.8	8.8	9.3
85	0.0	0.0	0.0	0.0	0.0	0.0	14	14.1	14.1	13	12.4	12.7
88	0.3	0.4	0.4	0.0	0.0	0.0	16.8	17.1	17.0	15.3	15.5	15.4
92	0.5	0.4	0.5	0.0	0.0	0.0	12.4	12.6	12.5	12.4	12.6	12.5
95	0.5	0.4	0.5	0.0	0.0	0.0	16.7	16.6	16.7	14.6	14.7	14.7
99	0.0	0.0	0.0	0.5	0.6	0.5	11.5	11.4	11.5	10.9	10.3	10.6
102	0.0	0.0	0.0	0.0	0.0	0.0	14.2	14.7	14.5	16.7	16.4	16.6
106	0.5	0.4	0.5	0.0	0.0	0.0	17.4	17.3	17.4	18.2	18.5	18.4
109	0.3	0.3	0.3	0.0	0.0	0.0	15.4	16.3	15.9	22.2	21.7	22.0
113	0.0	0.0	0.0	0.0	0.0	0.0	19.6	19.5	19.6	20.4	20.3	20.4
116	0.0	0.0	0.0	0.0	0.0	0.0	19.4	19.8	19.6	21.5	21.1	21.3
120	0.4	0.4	0.4	0.8	0.9	0.8	18.2	18.3	18.3	17.6	17.9	17.8
134	0.0	0.0	0.0	0.2	0.3	0.3	16.4	16.4	16.4	15.4	15.1	15.3
137	0.0	0.0	0.0	0.0	0.0	0.0	11.9	12.2	12.1	10.2	10.6	10.4
141	0.0	0.0	0.0	0.0	0.0	0.0	8.5	8.7	8.6	8.4	8.5	8.5
144	0.6	0.4	0.5	0.0	0.0	0.0	11.1	10.6	10.9	11.3	10.6	11.0
147	0.0	0.0	0.0	0.4	0.5	0.5	13.5	13.4	13.5	14.4	13.5	14.0
150	0.5	0.6	0.6	0.0	0.0	0.0	14	14	14.0	12.6	13.3	13.0
154	0.0	0.0	0.0	0.0	0.0	0.0	18.4	18.7	18.6	17.5	17.6	17.6
157	0.0	0.0	0.0	0.3	0.2	0.3	16.4	16.4	16.4	13.4	13.6	13.5
163	0.4	0.5	0.5	0.0	0.0	0.0	14.7	14.9	14.8	12.2	12.4	12.3
167	0.5	0.6	0.6	0.0	0.0	0.0	12.1	12.2	12.2	14.5	14.6	14.6
170	0.5	0.5	0.5	0.4	0.3	0.4	13.1	13.2	13.2	16.5	16.8	16.7
174	0.0	0.0	0.0	0.0	0.0	0.0	20.6	20.2	20.4	23.2	23	23.1
177	0.7	0.6	0.7	0.0	0.0	0.0	14.6	14	14.3	15.6	15.8	15.7
181	0.0	0.0	0.0	0.0	0.0	0.0	16	16	16.0	17.9	17.6	17.8
185	0.0	0.0	0.0	0.5	0.5	0.5	15.2	15.9	15.6	10.6	11.4	11.0
188	0.0	0.0	0.0	0.4	0.5	0.4	17.2	17.4	17.3	9.2	9.3	9.3
191	0.0	0.0	0.0	0.0	0.0	0.0	15.9	16.4	16.2	8.5	8.2	8.4
195	0.0	0.0	0.0	0.0	0.0	0.0	17.4	17.1	17.3	6.2	6.3	6.3
198	0.0	0.0	0.0	0.8	0.7	0.8	19.1	19.3	19.2	4.1	4.4	4.3
202	0.8	0.7	0.8	0.0	0.0	0.0	18.6	17.5	18.1	2.9	3.1	3.0
205	0.5	0.6	0.6	0.0	0.0	0.0	20.1	20.4	20.3	3.5	3.7	3.6
212	0.0	0.0	0.0	0.0	0.0	0.0	19.4	19.8	19.6	4.1	3.9	4.0
216	0.6	0.7	0.7	0.0	0.0	0.0	18.7	18.1	18.4	3.7	3.6	3.7
219	0.0	0.0	0.0	0.1	0.2	0.1	15.4	14.9	15.2	6.7	6.6	6.7
223	0.0	0.0	0.0	0.2	0.2	0.2	16.3	17.1	16.7	8.2	8.1	8.2
226	0.6	0.5	0.6	0.4	0.4	0.4	18.7	18	18.4	8.1	8.3	8.2
230	0.6	0.6	0.6	0.8	0.7	0.8	18.4	18.9	18.7	9.5	9.7	9.6
234	0.0	0.0	0.0	0.0	0.0	0.0	19.3	18.3	18.8	11.5	11.4	11.5
238	0.0	0.0	0.0	0.0	0.0	0.0	14.8	14.9	14.9	5.7	5	5.4
241	0.0	0.0	0.0	0.0	0.0	0.0	20.6	21.2	20.9	7.4	7.5	7.5
246	0.3	0.4	0.4	0.6	0.5	0.6	21.4	20.8	21.1	9.5	9.8	9.7
248	0.4	0.5	0.5	0.4	0.4	0.4	18.7	19.2	19.0	10.2	10.3	10.3
253	0.8	0.9	0.9	0.0	0.0	0.0	20.4	21.1	20.8	14.2	14.3	14.3
255	0.0	0.0	0.0	0.0	0.0	0.0	19.9	19.3	19.6	6.8	6.8	6.8
259	0.0	0.0	0.0	0.5	0.5	0.5	18.6	18.3	18.5	9.6	9.4	9.5
262	0.0	0.0	0.0	0.2	0.2	0.2	20	21.3	20.7	5.4	5.5	5.5
266	0.6	0.5	0.6	0.4	0.4	0.4	19.4	18.4	18.9	6.3	6.4	6.4
Before PMR addition	**Min**		0.0			0.0			5.6			5.6
	Mean ± SD		0.2 ± 0.2			0.2 ± 0.2			13.7 ± 4.0			13.6 ± 4.2
	Max		0.6			0.7			26.5			22.0
After PMR addition	**Min**		0.0			0.0			12.20			3.0
	Mean ± SD		0.3 ± 0.3			0.2 ± 0.2			17.8 ± 2.4			9.3 ± 4.9
	Max		0.9			0.8			21.1			23.1

Table C7 COD primary and secondary data collected before and after PMR addition.

Day	Control feed (mg.L^{-1})			Test feed (mg.L^{-1})			Control (mg.L^{-1})					Test (mg.L^{-1})				
	1	2	Mean	1	2	Mean	1	2	Mean	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})	1	2	Mean	Removal efficiency (%)	Removal rate (mg.m^{-3}.day^{-1})
9	312	318	315	312	318	315	98	101	100	68	12132	92.0	94.0	93	70	-575
11	278	288	283	278	288	283	72	74	73	74	5959	62.0	63.0	63	78	2992
14	288	289	289	288	289	289	66	68	67	77	21967	51.0	54.0	53	82	-5219
16	325	332	329	325	332	329	57	58	58	82	-294000	53.0	51.0	52	84	-2046
21	301	298	300	301	298	300	52	54	53	82	46875	45.0	48.0	47	84	-15830
23	287	292	290	287	292	290	65	66	66	77	80233	66.0	68.0	67	77	37025
25	254	261	258	254	261	258	56	57	57	78	-225556	54.0	55.0	55	79	-165574
28	347	352	350	347	352	350	45	49	47	87	-111290	46.0	45.0	46	87	-15559
30	393	415	404	393	415	404	57	54	56	86	-90341	55.0	56.0	56	86	-18310
32	350	348	349	350	348	349	52	55	54	85	-77072	52.0	53.0	53	85	-183544
35	206	202	204	206	202	204	47	49	48	76	189085	50.0	55.0	53	74	-66114
37	315	317	316	315	317	316	69	72	71	78	12805	72.0	71.0	72	77	27101
39	287	293	290	287	293	290	54	56	55	81	82432	66.0	68.0	67	77	35714
42	264	262	263	264	262	263	58	59	59	78	-54832	54.0	56.0	55	79	-23370
44	302	299	301	302	299	301	52	53	53	83	1987500	50.0	49.0	50	84	-40263
46	327	331	329	327	331	329	55	54	55	83	65873	52.0	53.0	53	84	430556
49	289	287	288	289	287	288	99	94	97	66	738462	90.0	88.0	89	69	12425000
51	497	510	504	497	510	504	55	57	56	89	271711	55.0	57.0	56	89	3796875
53	297	300	299	297	300	299	58	57	58	81	244444	52.0	55.0	54	82	49107
56	325	322	324	325	322	324	62	59	61	81	-70940	50.0	52.0	51	84	44231
59	235	230	233	235	230	233	53	52	53	77	7759	53.0	51.0	52	78	17045
63	255	257	256	255	257	256	63	59	61	76	490	87.0	84.0	86	67	2336
78	234	237	236	234	237	236	48	45	47	80	-31364	51.0	54.0	53	78	-14310
81	271	282	277	271	282	277	53	53	53	81	10128	53.0	51.0	52	81	773
85	290	275	283	290	275	283	44	37	41	86	-189474	58.0	54.0	56	80	183333
88	325	322	324	325	322	324	45	46	46	86	575000	52.0	54.0	53	84	75000
92	235	230	233	235	230	233	48	45	47	80	21687	55.0	59.0	57	75	52174
95	255	257	256	255	257	256	51	53	52	80	-19007	58.0	55.0	57	78	-4068
99	234	237	236	234	237	236	49	51	50	79	12757	51.0	53.0	52	78	18163
102	271	282	277	271	282	277	47	48	48	83	-3606	48.0	49.0	49	82	1442
106	290	275	283	290	275	283	50	52	51	82	-45763	52.0	50.0	51	82	-37121
109	252	257	255	252	257	255	48	52	50	80	-29545	48.0	47.0	48	81	-6100
113	239	245	242	239	245	242	52	49	51	79	-7792	51.0	53.0	52	79	-8236
116	278	285	282	278	285	282	55	53	54	81	-44388	48.0	50.0	49	83	-17177
120	248	249	249	248	249	249	49	51	50	80	3214	52.0	51.0	52	79	3391
134	266	266	266	266	266	266	53	52	53	80	-10000	55.0	58.0	57	79	-63043
137	278	281	280	278	281	280	58	60	59	79	198750	56.0	55.0	56	80	4050000
141	220	225	223	220	225	223	56	54	55	75	-34483	54.0	51.0	53	76	19463
144	250	255	253	250	255	253	55	55	55	78	-9600000	54.0	53.0	54	79	-246053
147	134	140	137	134	140	137	35	36	36	74	-314516	34.0	29.0	32	77	-14465
150	241	249	245	241	249	245	45	47	46	81	-2235	47.0	48.0	48	81	-1520
154	255	252	254	255	252	254	49	51	50	80	-19118	52.0	51.0	52	80	-3252
157	249	258	254	249	258	254	55	58	57	78	-2326	55.0	56.0	56	78	-3125
163	251	259	255	251	259	255	57	55	56	78	-393750	58.0	60.0	59	77	-30682
167	264	280	272	269	272	271	51	52	52	81	-25410	52.0	52.0	52	81	33333
170	242	226	234	231	235	233	44	46	45	81	80357	49.0	52.0	51	78	-38527
174	183	164	174	224	219	222	65	69	67	61	2300000	75.0	78.0	77	65	483333
177	197	210	204	252	294	273	52	50	51	75	17430	56.0	55.0	56	80	38725
181	203	184	194	202	201	202	61	54	58	70	-37929	60.0	66.0	63	69	252500
185	284	296	290	299	302	301	64	66	65	78	-10417	62.0	60.0	61	80	-350000
188	263	238	251	257	251	254	62	60	61	76	-34247	59.0	61.0	60	76	52273
191	276	266	271	269	273	271	55	58	57	79	-12963	55.0	53.0	54	80	9651
195	277	286	282	281	288	285	52	54	53	81	0	51.0	49.0	50	82	31579
198	280	290	285	275	280	278	59	54	57	80	3538	56.0	54.0	55	80	7455
202	281	296	289	289	294	292	60	65	63	78	-31967	50.0	55.0	53	82	34649
205	276	250	263	250	258	254	55	58	57	79	138655	55.0	54.0	55	79	-9915
212	252	241	247	273	282	278	52	51	52	79	107759	61.0	65.0	63	77	-42092
216	276	254	265	291	306	299	56	58	57	78	-76577	58.0	55.0	57	81	273438
219	264	282	273	272	258	265	59	54	57	79	97656	58.0	57.0	58	78	1780
223	250	255	253	261	247	254	50	48	49	81	-17241	47.0	49.0	48	81	6374
226	249	260	255	239	251	245	47	49	48	81	191964	52.0	53.0	53	79	-4649
230	274	288	281	242	228	235	51	53	52	81	-1009615	56.0	56.0	56	76	-51483
234	244	220	232	271	278	275	55	56	56	76	12562	55.0	56.0	56	80	-4290
238	276	260	268	261	247	254	51	51	51	81	-119433	61.0	62.0	62	76	-2542
241	240	246	243	250	260	255	56	56	56	77	15273	65.0	63.0	64	75	11205
246	249	264	257	287	274	281	62	63	63	76	515152	75.0	74.0	75	73	-417391
248	207	222	215	214	226	220	55	54	55	75	557143	77.0	78.0	78	65	18785
253	289	279	284	262	252	257	47	45	46	84	-144000	81.0	81.0	81	68	28571
255	272	262	267	254	277	266	52	53	53	80	83898	82.0	82.0	82	69	-26210
259	241	220	231	240	222	231	49	50	50	79	116667	79.0	80.0	80	66	-56944
262	249	262	256	262	286	274	50	50	50		7282	82.0	81.0	82		
266	252	260	256	288	310	299	55	51	53			85.0	83.0	84		
Before PMR addition	**Min**		137			137			36	66	-9600			32	67	-246
	Mean ± SD		281 ± 56			281 ± 55			56 ± 12	80 ± 4	-161 ± 1498			56 ± 11	80 ± 4	461 ± 2024
	Max		504			504			100	89.00	1988			93	89	12425
After PMR addition	**Min**		174			202			50	61	-1010			50	51	-417
	Mean ± SD		253 ± 30			261 ± 13			55 ± 5	78 ± 4	80 ± 488			63 ± 12	74 ± 7	8 ± 155
	Max		290			301.0			67	84	2300			84	82	483

Table C8 Chloride primary and secondary data collected before and after PMR addition.

Day	Control feed (mg.L^{-1})			Test feed (mg.L^{-1})			Control effluent(mg.L^{-1})			Test effluent (mg.L^{-1})		
	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean
9	47	45	46	47	45	46	32	35	34	34	36	35
11	67	69	68	67	69	68	43	47	45	43	42	43
14	83	84	84	83	84	84	55	51	53	52	54	53
16	95	98	97	95	98	97	64	62	63	61	63	62
21	74	73	74	74	73	74	88	86	87	88	87	88
23	42	45	44	42	45	44	73	70	72	71	72	72
25	55	55	55	55	55	55	40	42	41	39	41	40
28	87	86	87	87	86	87	56	57	57	55	55	55
30	63	64	64	63	64	64	81	82	82	82	81	82
32	52	55	54	52	55	54	64	63	64	62	63	63
35	58	56	57	58	56	57	54	53	54	51	52	52
37	69	71	70	69	71	70	50	50	50	50	50	50
39	55	55	55	55	55	55	78	78	78	79	80	80
42	83	81	82	83	81	82	72	71	72	71	72	72
44	74	76	75	74	76	75	62	63	63	59	60	60
46	64	66	65	64	66	65	65	64	65	65	66	66
49	102	105	104	102	105	104	99	94	97	90	88	89
51	95	94	95	95	94	95	94	91	93	97	94	96
53	87	88	88	87	88	88	81	80	81	79	80	80
56	45	46	46	45	46	46	68	67	68	68	67	68
59	41	41	41	41	41	41	65	68	67	57	56	57
63	56	55	56	56	55	56	48	47	48	45	44	45
78	64	61	63	135	133	134	48	45	47	82	82	82
81	91	91	91	91	91	91	100	99	100	113	113	113
85	68	72	70	72	74	73	107	102	105	98	99	99
88	50	55	53	68	69	69	65	68	67	70	71	71
92	100	94	97	110	105	108	49	50	50	55	52	54
95	41	48	45	95	97	96	101	100	101	99	98	99
99	45	45	45	47	47	47	42	41	42	48	46	47
102	56	52	54	66	66	66	48	45	47	43	45	44
106	53	55	54	58	59	59	55	56	56	56	56	56
109	95	98	97	100	98	99	55	53	54	54	52	53
113	97	94	96	61	62	62	95	95	95	93	93	93
116	72	75	74	103	105	104	95	97	96	94	95	95
120	66	69	68	74	75	75	71	72	72	76	73	75
134	104	107	106	49	50	50	63	66	65	60	61	61
137	54	59	57	55	55	55	102	104	103	99	98	99
141	97	93	95	98	99	99	54	54	54	56	55	56
144	17	24	21	91	94	93	98	97	98	92	93	93
147	75	82	79	21	16	19	17	17	17	18	16	17
150	78	87	83	75	78	77	74	75	75	75	74	75
154	162	141	152	156	155	156	78	78	78	82	80	81
157	69	75	72	58	59	59	157	162	160	168	167	168
163	165	178	172	201	205	203	69	69	69	66	67	67
167	104	110	107	340	360	350	164	165	165	161	162	162
170	98	93	96	410	430	420	104	104	104	128	130	129
174	85	88	87	492	488	490	98	98	98	234	234	234
177	69	72	71	518	524	521	86	85	86	386	384	385
181	61	64	63	850	850	850	69	69	69	502	508	505
185	77	71	74	1000	970	985	61	61	61	750	730	740
188	49	55	52	940	940	940	75	77	76	860	880	870
191	54	59	57	880	860	870	49	49	49	910	950	930
195	65	66	66	850	860	855	52	54	53	890	880	885
198	46	49	48	810	830	820	64	65	65	850	860	855
202	70	76	73	750	750	750	46	46	46	790	780	785
205	58	55	57	860	880	870	72	70	71	820	840	830
212	80	83	82	890	890	890	56	58	57	850	850	850
216	62	57	60	800	820	810	84	80	82	920	900	910
219	45	49	47	820	810	815	65	62	64	790	810	800
223	93	97	95	790	810	800	43	45	44	800	810	805
226	76	77	77	910	890	900	92	93	93	810	790	800
230	80	82	81	870	870	870	74	76	75	930	920	925
234	55	59	57	960	980	970	81	80	81	860	900	880
238	63	61	62	1000	1100	1050	54	55	55	990	1000	995
241	51	55	53	960	940	950	61	63	62	1000	1100	1050
246	91	94	93	1000	1000	1000	49	51	50	970	980	975
248	54	49	52	980	1000	990	89	91	90	990	960	975
253	110	104	107	970	970	970	57	54	56	1050	1000	1025
255	88	82	85	980	980	980	109	110	110	990	980	985
259	53	56	55	1000	980	990	87	88	88	1000	1050	1025
262	55	52	54	990	1010	1000	52	53	53	980	1000	990
266	52	57	55	1100	1000	1050	54	55	55	990	970	980
Before PMR addition	**Min**		21			19			17			17
	Mean ± SD		75 ± 28			83 ± 52			70 ± 25			70 ± 25
	Max		104			134			105			113
After PMR addition	**Min**		47			59			44			67
	Mean ± SD		69 ± 41			867 ± 147			73 ± 26			796 ± 264
	Max		172			1050			110			1050

Table C9 Phosphate primary and secondary data collected before and after PMR addition.

Day	Control feed (mg.L^{-1})			Test feed (mg.L^{-1})			Control effluent(mg.L^{-1})			Test effluent (mg.L^{-1})		
	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean
9	4.5	4.7	4.6	4.5	4.7	4.6	6.2	6.4	6.3	5.2	5.1	5.2
11	3.8	3.8	3.8	3.8	3.8	3.9	5.5	5.9	5.7	7.1	6.8	7.0
14	5.8	5.4	5.6	5.8	5.4	5.6	4.5	4.8	4.7	3.5	3.8	3.7
16	4.1	4.3	4.2	4.1	4.3	4.2	5.7	5.1	5.4	4.9	5.2	5.1
21	3.2	3.5	3.4	3.2	3.5	3.4	3.8	4.2	4.0	3.2	3.4	3.3
23	5.8	5.9	5.9	5.8	5.9	5.8	3.4	3.8	3.6	2.9	3.2	3.1
25	6.4	6.2	6.3	6.4	6.2	6.4	5.6	5.7	5.7	5.2	5.4	5.3
28	4.3	4.4	4.4	4.3	4.4	4.3	6.9	7.2	7.1	6.2	6.5	6.4
30	3.2	3.3	3.3	3.2	3.3	3.3	7.1	7.2	7.2	6.4	6.7	6.6
32	5.2	5.4	5.3	5.2	5.4	5.4	5.7	5.8	5.8	5.4	5.6	5.5
35	1.6	1.8	1.7	1.6	1.8	1.8	6	6.5	6.3	6	6.2	6.1
37	3.6	3.7	3.7	3.6	3.7	3.7	7.5	7.1	7.3	7.1	7.3	7.2
39	7.4	7.1	7.3	7.4	7.1	7.3	6.8	6.4	6.6	6.4	6.6	6.5
42	5.3	5.5	5.4	5.3	5.5	5.4	5.6	5.8	5.7	5	5.2	5.1
44	4.9	5.1	5.0	4.9	5.1	4.9	5.7	5.9	5.8	5.5	5.2	5.4
46	5.2	5.3	5.3	5.2	5.3	5.2	6.9	6.4	6.7	7.2	7.1	7.2
49	3.3	2.9	3.1	3.3	2.9	3.1	5.4	5.7	5.6	6	6	6.0
51	5.7	5.8	5.8	5.7	5.8	5.9	3.8	3.9	3.9	3.6	3.6	3.6
53	4.8	4.7	4.8	4.8	4.7	4.7	5.2	5.3	5.3	4.5	4.7	4.6
56	3.1	3.3	3.2	3.1	3.3	3.2	4.9	5	5.0	5	5	5.0
59	3.8	3.7	3.8	3.8	3.7	3.7	5.8	6	5.9	5.2	5.2	5.2
63	5.1	4.7	4.9	5.1	4.7	5.0	8	7.9	8.0	8.4	8.1	8.3
78	6.5	6.5	6.5	6.5	6.5	6.5	7.2	7.1	7.2	7.8	8	7.9
81	4.6	4.3	4.5	4.6	4.3	4.4	5.1	5.3	5.2	6.4	5.9	6.2
85	7.1	6.8	7.0	7.1	6.8	6.7	6.5	6	6.3	7.2	7.3	7.3
88	4.5	4.7	4.6	5.6	5.8	5.6	7.1	7.2	7.2	6.8	6.9	6.9
92	3.8	3.8	3.8	4.2	4.5	4.3	7.8	7.9	7.9	7.5	7.3	7.4
95	5.8	5.4	5.6	4.8	4.9	4.9	3.9	3.4	3.7	4.1	4.3	4.2
99	4.1	4.3	4.2	4.1	4.3	4.3	4.2	4.3	4.3	5.5	5.1	5.3
102	3.2	3.5	3.4	7.2	7.5	7.3	4.5	4.5	4.5	3.7	3.9	3.8
106	5.8	5.9	5.9	5.2	5.6	5.3	5.6	5.5	5.6	4.3	4.3	4.3
109	6.4	6.2	6.3	5.3	4.8	4.9	7	6.9	7.0	7	7.6	7.3
113	4.3	4.4	4.4	7.4	7.4	7.5	6.8	6.4	6.6	7.4	7.1	7.3
116	3.2	3.3	3.3	5.3	5.4	5.5	6.2	6.5	6.4	7.1	7.1	7.1
120	5.2	5.4	5.3	7.1	7.5	7.4	5.3	5.5	5.4	4.5	4.6	4.6
134	1.6	1.8	1.7	7.2	7.6	7.4	7.1	7.2	7.2	6.8	6.9	6.9
137	3.6	3.7	3.7	5.7	5.8	5.8	6.2	6.4	6.3	5.2	5.3	5.3
141	7.4	7.1	7.3	4.9	4.7	4.8	4.3	4.8	4.6	4.1	4.4	4.3
144	5.3	5.5	5.4	5.2	5.4	5.2	8.1	8	8.1	5.7	6	5.9
147	4.9	5.1	5.0	1.8	1.5	1.6	3.8	3.4	3.6	3.7	3.4	3.6
150	5.2	5.3	5.3	5.5	5.6	5.6	2.1	2.4	2.3	2.4	2.1	2.3
154	3.3	2.9	3.1	6.8	6.9	6.9	3.6	3.5	3.6	3.6	3.7	3.7
157	5.7	5.8	5.8	2.7	2.4	2.4	4.3	4.1	4.2	4.2	4.1	4.2
163	4.8	4.7	4.8	6.5	6.3	6.3	6.7	6.8	6.8	6.4	6.5	6.5
167	3.1	3.3	3.2	4.8	5.2	5.0	6.7	6.8	6.8	5.1	5.2	5.2
170	3.8	3.7	3.8	5.6	5.4	5.5	2.2	2.2	2.2	3.1	3.2	3.2
174	5.1	4.7	4.9	3.7	3.8	3.8	7	7.1	7.1	3.3	3.2	3.3
177	6.5	6.5	6.5	1.9	2.1	2.3	3.4	3.1	3.3	1.8	1.8	1.8
181	4.6	4.3	4.5	1.6	1.9	2.1	4.1	4.4	4.3	0.0	0.0	0.0
185	7.1	6.8	7.0	0.0	0.0	2.3	6.8	6.2	6.5	0.0	0.0	0.0
188	5.6	5.8	5.7	0.0	0.0	0.0	7.5	7.7	7.6	0.0	0.0	0.0
191	4.2	4.5	4.4	0.0	0.0	0.0	7.3	7.2	7.3	0.0	0.0	0.0
195	4.8	4.9	4.9	0.0	0.0	0.0	6.8	6.9	6.9	0.0	0.0	0.0
198	4.1	4.3	4.2	0.0	0.0	0.0	7.2	7.1	7.2	0.0	0.0	0.0
202	7.2	7.5	7.4	0.0	0.0	1.5	7	6.5	6.8	0.0	0.0	0.0
205	5.2	5.6	5.4	0.0	0.0	0.0	6.5	6.8	6.7	0.0	0.0	0.0
212	5.3	4.8	5.1	0.0	0.0	0.0	5.5	5.2	5.4	0.0	0.0	0.0
216	7.4	7.4	7.4	0.0	0.0	0.0	7.2	7.5	7.4	0.0	0.0	0.0
219	5.3	5.4	5.4	0.0	0.0	0.0	7.4	7.9	7.7	0.0	0.0	0.0
223	7.1	7.5	7.3	0.0	0.0	0.0	4.1	4.4	4.3	0.0	0.0	0.0
226	7.2	7.6	7.4	0.0	0.0	0.0	3.9	4.3	4.1	0.0	0.0	0.0
230	5.7	5.8	5.8	0.0	0.0	0.0	6.7	6.4	6.6	0.0	0.0	0.0
234	4.9	4.7	4.8	0.0	0.0	0.0	4.4	4.3	4.4	0.0	0.0	0.0
238	5.2	5.4	5.3	0.0	0.0	0.0	5.6	5.2	5.4	0.0	0.0	0.0
241	1.8	1.5	1.7	0.0	0.0	0.0	3.2	3.8	3.5	0.0	0.0	0.0
246	5.5	5.6	5.6	0.0	0.0	0.0	7.3	7.1	7.2	0.0	0.0	0.0
248	6.8	6.9	6.9	0.0	0.0	0.0	4.4	4.6	4.5	0.0	0.0	0.0
253	2.7	2.4	2.6	0.0	0.0	0.0	3.2	3.4	3.3	0.0	0.0	0.0
255	6.5	6.3	6.4	0.0	0.0	0.0	3.3	3.5	3.4	0.0	0.0	0.0
259	4.8	5.2	5.0	0.0	0.0	0.0	5.7	5.9	5.8	0.0	0.0	0.0
262	5.6	5.4	5.5	0.0	0.0	0.0	6.8	6.4	6.6	0.0	0.0	0.0
266	4.8	5.1	5.0	0.0	0.0	0.0	4.5	4.1	4.3	0.0	0.0	0.0
Before PMR addition	**Min**		1.7			1.6			2.3			2.3
	Mean ± SD		4.7 ± 1.3			5.0 ± 1.4			5.8 ± 1.3			5.6 ± 1.5
	Max		7.3			7.4			8.1			7.3
After PMR addition	**Min**		1.7			0.0			2.2			0.0
	Mean ± SD		5.2 ± 1.4			1.2 ± 2.1			5.5 ± 1.6			0.9 ± 1.8
	Max		7.4			6.9			7.6			6.5

Table C10 Primary data collected for pH before and after PMR addition.

Day	Control feed	Test feed	Control effluent	Test effluent
0	7.68	7.68	7.53	7.48
9	7.41	7.41	7.45	7.29
11	8.21	8.21	7.99	7.84
14	7.69	7.69	7.61	7.71
16	7.46	7.46	7.55	7.52
21	7.44	7.44	7.13	7.22
23	7.92	7.92	7.62	7.74
25	7.11	7.11	7.12	6.98
28	7.63	7.63	7.25	7.14
30	7.52	7.52	7.37	7.09
32	8.21	8.21	7.63	7.45
35	7.46	7.46	7.17	7.21
37	7.68	7.68	7.51	7.46
39	7.11	7.11	6.99	6.87
42	7.25	7.25	6.87	7.02
44	7.48	7.48	7.26	7.09
46	7.79	7.79	7.66	7.54
49	8.12	8.12	7.92	7.88
51	7.14	7.14	7.21	7.31
53	7.54	7.54	7.14	7.35
56	7.63	7.63	7.55	7.41
59	7.14	7.14	7.2	7.08
63	7.26	7.26	7.14	7.12
78	7.11	7.11	7.05	6.99
81	6.78	6.78	6.71	6.82
85	7.69	7.69	7.31	7.25
88	7.12	7.12	7.52	7.45
92	8.22	8.22	7.84	7.48
95	7.45	7.45	7.22	7.33
99	7.68	7.68	7.54	7.41
102	7.14	7.14	7.25	7.01
106	7.55	7.55	7.13	7.35
109	8.21	8.21	7.82	7.78
113	7.45	7.45	7.46	7.39
116	7.66	7.66	7.44	7.51
120	7.14	7.14	7.01	7.24
134	7.35	7.35	7.35	7.26
137	7.49	7.49	7.25	7.39
141	7.84	7.84	7.63	7.58
144	7.69	7.69	7.75	7.46
147	7.46	7.46	7.31	7.21
150	8.21	8.21	7.86	7.64
154	7.45	7.45	7.35	7.15
157	7.61	7.61	7.72	7.69
163	7.74	7.35	7.48	7.58
167	7.13	7.21	7.24	7.45
170	7.74	7.06	7.51	7.31
174	7.71	6.85	7.25	7.31
177	8.54	6.39	7.32	7.00
181	8.58	5.89	7.49	6.46
185	7.58	5.62	7.25	6.21
188	7.16	5.52	7.31	5.92
191	7.98	5.69	7.11	5.64
195	7.56	5.42	7.03	5.47
198	7.19	5.5	7.28	5.23
202	7.01	5.95	7.59	5.56
205	7.09	5.37	7.67	5.17
212	7.33	5.69	7.67	5.38
216	7.68	5.54	7.54	5.67
219	7.01	5.31	7.62	5.52
223	7.44	5.49	7.41	5.75
226	7.69	5.37	7.66	5.82
230	8.21	5.24	7.46	5.54
234	7.45	5.17	7.55	5.62
238	7.66	5.29	7.42	5.47
241	7.13	5.34	7.25	5.55
246	7.58	5.25	7.49	5.63
248	7.71	5.14	7.61	5.51
253	8.32	5.19	7.54	5.71
255	7.46	5.33	7.35	5.49
259	7.15	5.27	7.22	5.54
262	7.97	5.11	7.39	5.63
266	7.55	5.45	7.21	5.74
Before PMR	7.11 - 8.22	7.11 - 8.22	6.71 - 7.92	6.98 - 7.88
After PMR	7.01 - 8.58	5.11 - 7.35	7.03 - 7.67	5.17 - 7.58

APPENDIX D

Primary Data for Wastewater Maturation and Alternative Treatment processes

Table D1 Change in pH during blended wastewater maturation.

Day	pH			
	1	2	3	Control
1	5.32	5.27	5.38	5.39
3	5.79	5.83	5.81	5.41
7	6.00	6.09	5.97	5.37
10	6.44	6.5	6.59	5.52
14	6.79	6.82	6.91	5.47
17	6.81	6.85	6.94	5.46
21	6.82	6.88	6.97	5.59

Table D2 COD primary and secondary data obtained during the investigation in alternative wastewater processing possibilities.

Day	Feed ($mg.L^{-1}$)				AS treatment only ($mg.L^{-1}$)					AS + algal treatment ($mg.L^{-1}$)					Algal treatment only ($mg.L^{-1}$)				
	1	2	3	Mean ± SD	1	2	3	Mean ± SD	Removal efficiency (%)	1	2	3	Mean ± SD	Removal efficiency (%)	1	2	3	Mean ± SD	Removal efficiency (%)
1	169	172	165	169 ± 4	52	54	51	52 ± 2	69	40	40	46	42 ± 3	75	120	125	118	121 ± 4	28
4	172	168	162	167 ± 5	48	51	53	51 ± 3	70	42	47	41	43 ± 3	74	134	132	137	134 ± 3	20
8	164	161	157	161 ± 4	55	52	56	54 ± 2	66	46	41	45	44 ± 3	73	117	119	121	119 ± 2	26
11	160	157	152	156 ± 4	61	63	66	63 ± 3	59	41	46	47	45 ± 3	71	125	120	117	121 ± 4	23
15	185	179	188	184 ± 5	53	51	55	53 ± 2	71	39	42	46	42 ± 4	77	128	126	124	126 ± 2	32
18	183	180	186	183 ± 3	57	55	52	55 ± 3	70	42	47	45	45 ± 3	76	135	137	136	136 ± 1	26
22	179	181	175	178 ± 3	49	52	48	50 ± 2	72	45	41	46	44 ± 3	75	154	152	150	152 ± 2	15
25	181	175	172	176 ± 5	52	56	50	53 ± 3	70	43	45	40	43 ± 3	76	162	166	161	163 ± 3	7
29	175	170	179	175 ± 5	50	53	56	53 ± 3	70	47	45	48	47 ± 2	73	158	154	158	157 ± 2	10
32	192	189	195	192 ± 3	57	51	55	54 ± 3	72	41	43	46	43 ± 3	77	153	159	156	156 ± 3	19
36	186	184	182	184 ± 2	54	54	57	55 ± 2	70	43	46	40	43 ± 3	77	149	152	157	153 ± 4	17
39	184	182	179	182 ± 3	53	55	57	55 ± 2	70	45	47	49	47 ± 2	74	145	150	154	150 ± 5	18
Min				156				50	59				84	71				119	7
Mean ± SD				176 ± 11				54 ± 4	69 ± 3				44 ± 3	75 ± 2				141 ± 16	20 ± 7
Max				192				63	72				88	77				163	32

Table D3 Ammonia primary and secondary data obtained during the investigation in alternative wastewater processing possibilities.

Day	Feed ($mg.L^{-1}$)				AS treatment only ($mg.L^{-1}$)					AS + algal treatment ($mg.L^{-1}$)					Algal treatment only ($mg.L^{-1}$)				
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**Removal efficiency (%)**	**1**	**2**	**3**	**Mean ± SD**	**Removal efficiency (%)**	**1**	**2**	**3**	**Mean ± SD**	**Removal efficiency (%)**
1	88	90	91	90 ± 2	85	87	86	86 ± 1	4	87	84	82	84 ± 3	6	85	87	88	87 ± 2	3
4	85	88	87	87 ± 2	87	88	85	87 ± 2	0	88	87	85	87 ± 2	0	84	82	85	84 ± 2	3
8	92	95	90	92 ± 2	84	86	85	85 ± 1	8	84	87	86	86 ± 2	7	87	84	86	86 ± 2	7
11	95	95	91	94 ± 2	86	87	87	87 ± 1	7	85	87	88	87 ± 2	7	86	88	85	86 ± 2	8
15	89	87	91	89 ± 2	82	81	84	82 ± 2	7	88	85	86	86 ± 2	3	83	86	87	85 ± 2	4
18	92	95	91	93 ± 2	87	85	82	85 ± 3	9	87	84	87	86 ± 2	7	88	84	82	85 ± 3	9
22	91	92	87	90 ± 3	88	84	88	87 ± 2	4	84	82	85	84 ± 2	7	90	91	87	89 ± 2	1
25	93	94	91	93 ± 2	88	87	85	87 ± 2	6	87	86	88	87 ± 1	6	89	91	90	90 ± 1	3
29	88	88	89	88 ± 1	85	84	81	83 ± 2	6	85	88	84	86 ± 2	3	92	89	88	90 ± 2	-2
32	94	93	95	94 ± 1	87	88	84	86 ± 2	8	87	84	82	84 ± 3	10	93	89	91	91 ± 2	3
36	87	89	91	89 ± 2	89	84	87	87 ± 3	3	87	87	84	86 ± 2	3	90	89	88	89 ± 1	0
39	88	85	87	87 ± 2	84	87	84	85 ± 2	2	88	84	86	86 ± 2	1	88	87	87	87 ± 1	-1
Min				87				82	0				84	0				84	-2
Mean ± SD				90 ± 3				86 ± 1	5 ± 3				86 ± 1	5 ± 3				84 ± 2	3 ± 3
Max				94				87	9				88	10				91	9

Table D4 Alkalinity of the feed and each step of the alternative wastewater processing investigation.

Day	Feed ($CaCO_3.L^{-1}$)				AS treatment only ($CaCO_3.L^{-1}$)				AS + algal treatment ($CaCO_3.L^{-1}$)				Algal treatment only ($CaCO_3.L^{-1}$)			
	1	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**	**1**	**2**	**3**	**Mean ± SD**
1	62	66	55	61 ± 6	20	15	13	16 ± 4	2	1	3	2 ± 1	5	4	3	4 ± 1
4	72	61	68	67 ± 6	18	15	12	15 ± 3	2	2	2	2 ± 0	2	2	2	2 ± 0
8	104	101	98	101 ± 3	2	1	3	2 ± 1	25	19	22	22 ± 3	11	15	13	13 ± 2
11	99	105	96	100 ± 5	2	2	2	2 ± 0	2	2	2	2 ± 0	14	12	13	13 ± 1
15	285	274	284	281 ± 6	1	2	3	2 ± 1	1	2	3	2 ± 1	7	13	13	11 ± 3
18	279	289	290	286 ± 6	2	2	2	2 ± 0	2	2	2	2 ± 0	15	10	11	11 ± 12
22	80	87	88	85 ± 4	48	46	53	49 ± 4	2	2	2	2 ± 0	127	134	129	130 ± 4
25	89	80	83	84 ± 5	44	52	51	49 ± 4	1	3	2	2 ± 1	133	126	128	129 ± 4
29	135	131	127	131 ± 4	6	9	9	8 ± 2	1	2	3	2 ± 1	99	111	108	106 ± 6
32	134	130	126	130± 4	14	10	12	12 ± 2	2	2	2	2 ± 0	114	97	107	106 ± 9
36	159	147	150	152 ± 6	3	4	5	4 ± 1	2	2	2	2 ± 0	130	138	134	134 ± 4
39					3	3	3	3 ± 0	3	4	2	3 ± 1	137	132	136	135 ± 3
Min				61				2				2				2
Mean ± SD				134 ± 76				13 ± 17				4 ± 6				66 ± 59
Max				286				49				22				135

Table D5 pH of the feed and each step of the alternative wastewater processing investigation.

Day	**Feed**			**AS treatment only**			**AS + algal treatment**			**Algal trreatment only**		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	6.63	6.68	6.62	6.73	6.78	6.75	4.65	4.59	4.57	5.99	5.91	5.97
4	6.51	6.57	6.54	6.86	6.81	6.84	4.71	4.67	4.75	4.63	4.69	4.61
8	6.87	6.83	6.84	5.07	5.13	5.10	6.97	7.05	7.01	6.15	6.07	6.10
11	6.86	6.82	6.88	5.14	5.11	5.08	5.19	5.11	5.17	6.19	6.28	6.26
15	7.36	7.31	7.35	4.87	4.93	4.92	5.11	5.07	5.12	5.79	5.77	5.55
18	7.33	7.36	7.31	4.97	4.93	4.91	5.29	5.27	5.25	5.92	5.99	5.91
22	6.09	6.12	6.10	6.79	6.73	6.74	4.83	4.79	4.88	7.19	7.09	7.11
25	6.19	6.24	6.22	6.89	6.84	6.85	4.89	4.82	4.87	7.33	7.34	7.39
29	7.04	6.99	7.01	5.81	5.79	5.83	4.79	4.83	4.81	6.87	6.93	6.94
32	6.58	6.63	6.62	7.59	7.61	7.55	4.08	3.97	4.00	6.99	6.89	6.94
36	6.68	6.62	6.82	6.04	5.97	6.09	5.49	5.54	5.46	7.21	7.17	7.25
39				5.49	5.41	5.45	5.38	5.39	5.43	7.21	7.28	7.29
Range	6.10 - 7.34			5.10-7.58			4.01-5.49			4.64-7.26		

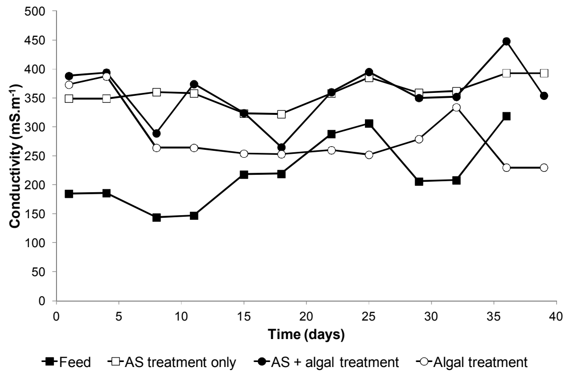


Figure D1 Conductivity

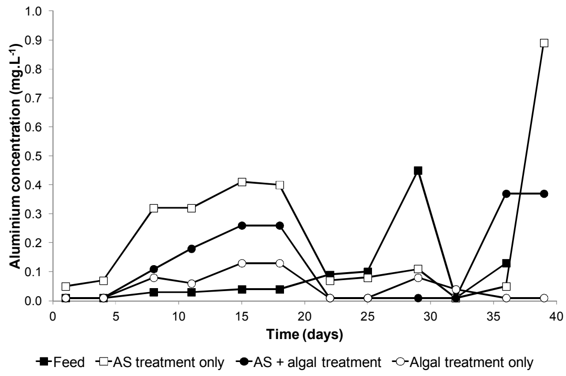


Figure D2 Aluminium

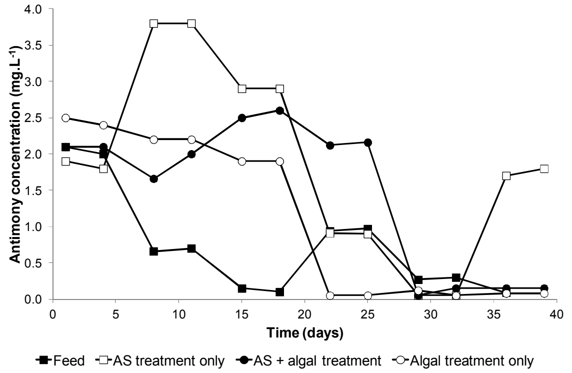


Figure D3 Antimony

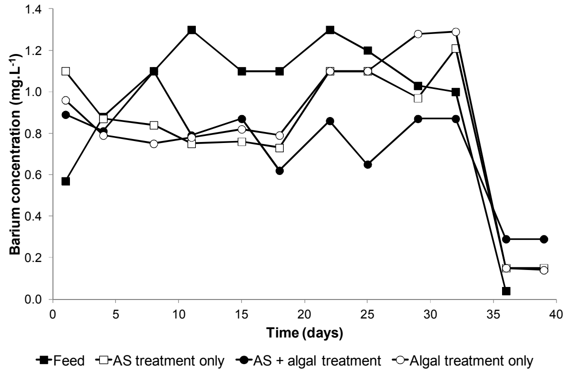


Figure D4 Barium

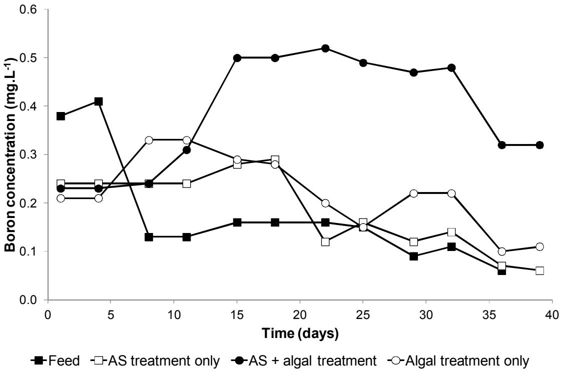


Figure D5 Boron

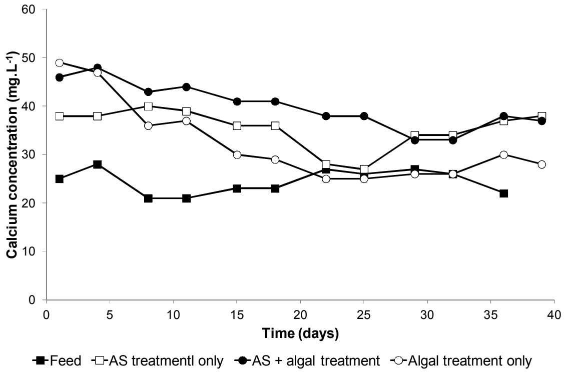


Figure D6 Calcium

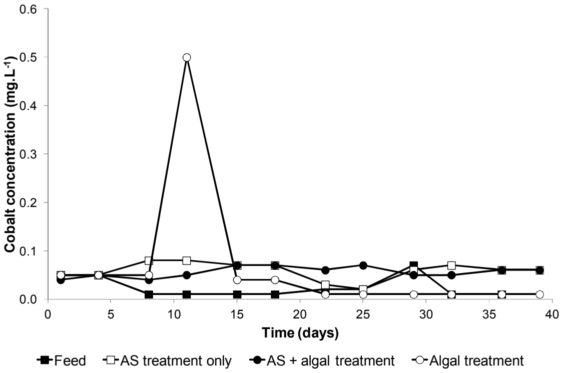


Figure D7 Cobalt

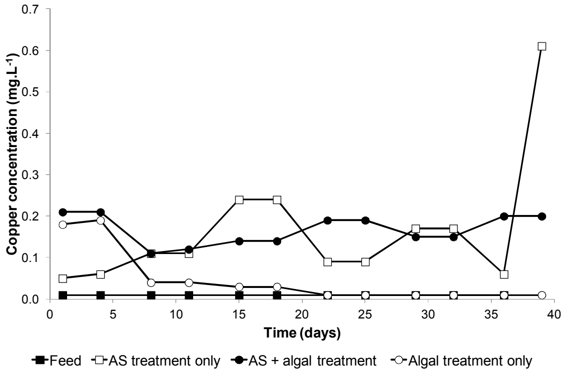


Figure D8 Copper

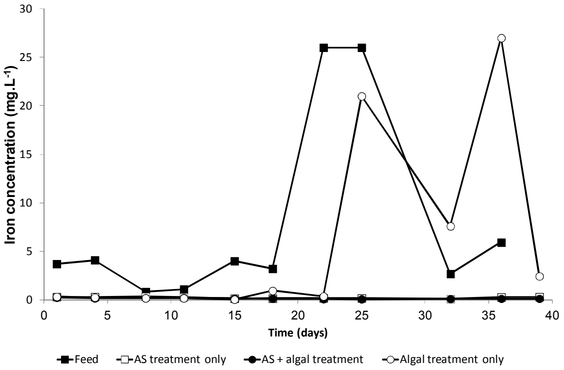


Figure D9 Iron

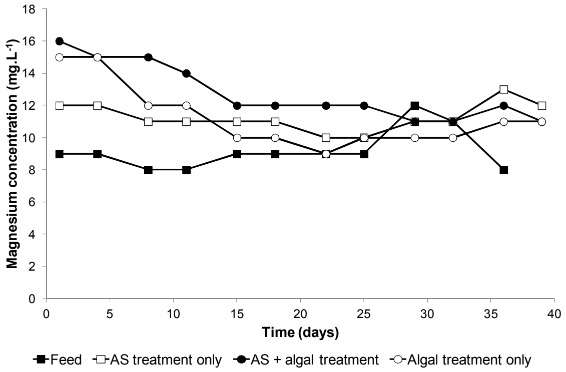


Figure D10 Magnesium

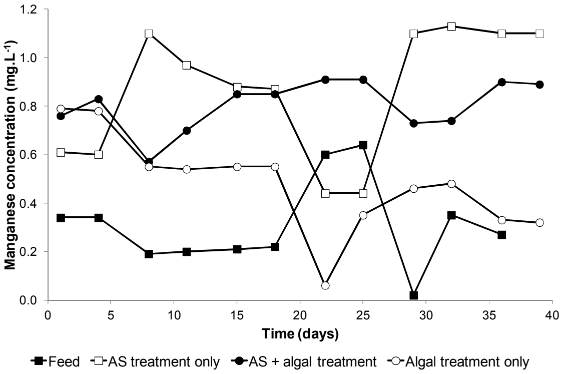


Figure D11 Manganese

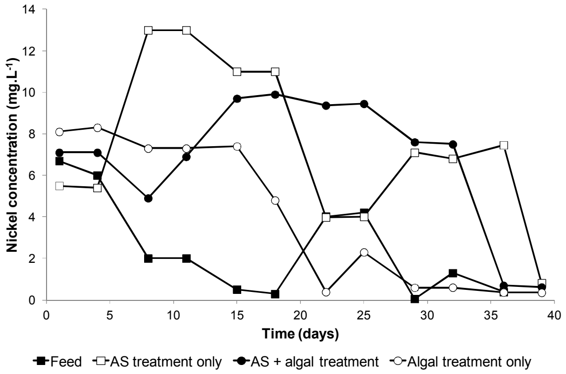


Figure D12 Nickel

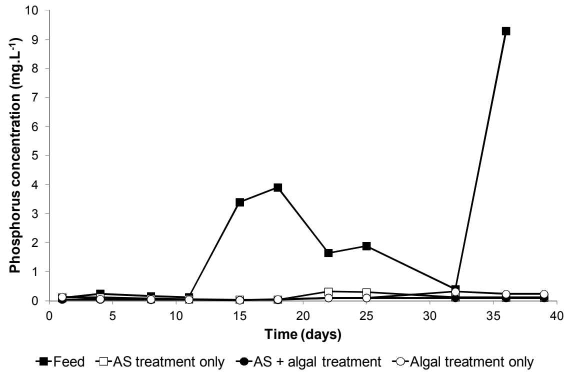


Figure D13 Phosphorus

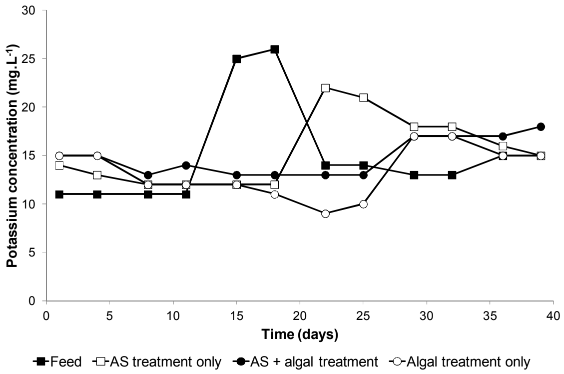


Figure D14 Potassium

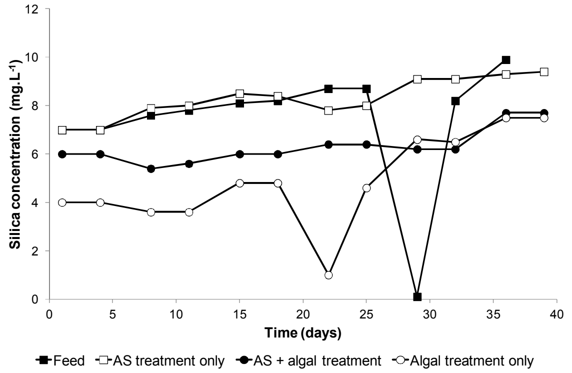


Figure D15 Silica

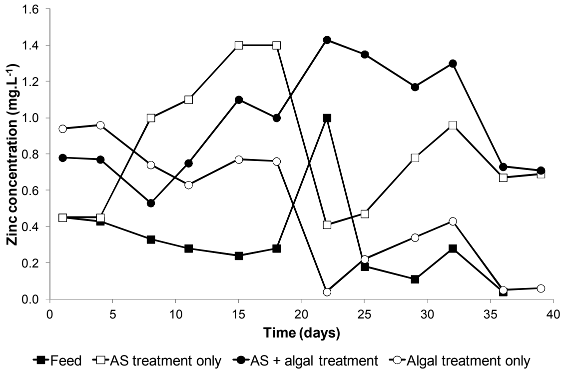


Figure D16 Zinc

APPENDIX E

PRIMARY FLOTATION GRADE RECOVERY DATA

Table E1 Grade recovery data for sulphur flotation

Recovery	Grade			
	Algal treatment only	AS + algal treatment	AS treatment only	Process Water
73.4	19.05			
83.69	13.14			
88.28	9.58			
91	7.55			
92.19	6.72			
51.39		15.88		
72.61		11.53		
84.3		8.99		
90.56		7.53		
92.23		6.74		
72.34			20.26	
83.12			13.88	
88.45			9.68	
91.06			7.86	
92.22			7.02	
41.88				16.15
65.49				11.96
77.11				9.72
85.3				8.57
87.83				7.78

Table E2 Grade recovery data for copper flotation

Recovery	Grade			
	Algal treatment only	AS + algal treatment	AS treatment only	Process Water
74.32	3.65			
85.49	2.54			
88.05	1.81			
89.25	1.4			
89.69	1.24			
73.64		4.21		
85.39		2.51		
88.05		1.74		
89.05		1.37		
89.5		1.21		
75.01			3.9	
85.4			2.65	
88.03			1.79	
89.01			1.43	
89.52			1.26	
67.7				4.75
85.56				2.84
88.38				2.03
89.27				1.63
89.71				1.44

Table E3 Grade recovery data for nickel flotation

Recovery	Grade			
	Algal treatment only	AS + algal treatment	AS treatment only	Process Water
57.88	7.57			
65.22	5.16			
69.12	3.78			
71.77	3			
72.89	2.68			
50.12		7.77		
64.16		5.11		
69.57		3.72		
71.84		3		
72.9		2.67		
57.85			8.25	
65.44			5.56	
69.8			3.89	
72.07			3.17	
73.24			2.84	
44.4				8.39
65.35				5.85
70.05				4.33
72.15				3.55
73.25				3.18

Table E4 Grade recovery data for platinum flotation

Recovery	Grade			
	Algal treatment only	AS + algal treatment	AS treatment only	Process Water
82.89	188.5			
89.6	123.25			
92.22	87.65			
93.74	68.13			
94.43	60.34			
80.7		210		
89.02		119.04		
91.95		82.55		
93.75		65.61		
94.47		58.1		
80.64			196.51	
88.78			128.98	
92.18			87.78	
93.69			70.39	
94.41			62.49	
75.83				244.28
88.25				134.62
91.62				96.49
93.54				78.49
94.29				69.75

Table E5 Grade recovery data for palladium flotation.

Recovery	Grade			
	Algal treatment only	AS + algal treatment	AS treatment only	Process Water
75.12	69.75			
83.85	47.09			
88.09	34.19			
90.62	26.89			
91.82	23.95			
66.94		71.4		
82.24		45.07		
88		32.38		
90.38		25.92		
91.56		23.08		
73.1			69.23	
82.58			46.63	
87.72			32.47	
90.18			26.34	
91.37			23.51	
62.51				81.6
83.31				51.5
88.22				37.65
90.3				30.71
91.43				27.41

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