ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL FROM DAIRY MANURE TO MEET NITROGEN:PHOSPHORUS CROP NUTRIENT REQUIREMENTS

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THESIS SUBMITTED TO THE FACULTY OF THE

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

BIOLOGICAL SYSTEMS ENGINEERING

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NOVEMBER 21, 2002

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KEYWORDS: NUTRIENT MANAGEMENT, DAIRY MANURE WASTEWATER, FERMENTATION POTENTIAL, ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL, MODELING, ECONOMIC FEASIBILITY

Enhanced Biological Phosphorus Removal from Dairy Manure to Meet Nitrogen:Phosphorus Crop Nutrient Requirements

by

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(**Abstract)**

Over the last two decades, livestock operations have become highly concentrated due to growing trends towards larger, more confined facilities and a decrease in cropland on smaller farms. This has led to greater amounts of excess manure nutrients on farms, increasing the potential for nutrient pollution of water bodies from runoff. The purpose of this study was to determine if enhanced biological phosphorus removal (EBPR) is a viable alternative for managing excess manure nutrients on dairy farms. Assessment of EBPR involved the investigation of various aspects of wastewater treatment modeling and design and farm nutrient management. The fermentation potential (volatile fatty acid (VFA) production) of dairy manure was determined through laboratory analysis to be 15.3% of the total COD. Total VFA production was composed of 57, 23, and 20% acetic, propionic, and butyric acids, respectively. The EBPR component of the BioWin wastewater treatment model was evaluated through a sensitivity analysis. The parameters to which effluent phosphate (PO_4) concentration was most sensitive were maximum specific growth rate, growth yield, aerobic PO_4 uptake rate per unit poly-β-hydroxybutyrate (PHB) utilized, PHB yield from VFA, PO_4 release per unit VFA uptake, and fraction of releasable PO_4. An EBPR sequencing batch reactor (SBR) was designed for a dairy farm with 700 lactating cows and 325 ha of corn silage. An economic analysis of EBPR for dairy farms employing P-based manure applications was completed. The cost of hauling excess manure to nutrient deficient farms was the most significant expense in comparing costs of manure management with and without EBPR. For a herd of 700 lactating cows, utilizing EBPR was more economical for farms with 270 ha or less cropland, while EBPR did not offer an economic advantage for farms over 270 ha.

Acknowledgments

I would like to thank my major advisor, Dr. Mary Leigh Wolfe, for her support and guidance in my work. Her extensive feedback and revisions helped to further the development of my research skills. I would also like to thank my advisor Dr. Nancy Love for her input and guidance in conducting laboratory research and sparking my interest in, and further study of, wastewater treatment. I would also like to thank Dr. Katherine Knowlton and Darrell Bosch for their guidance and service as committee members. Their input on dairy operations and agricultural economics were valuable in assessing the practical application of my research.

I would like to extend appreciation to Julie Petruska, Jody Smiley, and David Whichard, who provided me with laboratory training and assistance in conducting my experimental analysis. I would also like to thank Julie McKinney for her assistance in collecting samples at the Virginia Tech Dairy and for sample analysis. I would also like to acknowledge the Virginia Tech Biological Systems Engineering Department for granting me a research assistantship throughout my graduate studies.

Lastly, I would like to thank my mother. I am grateful for her encouragement and support throughout my studies at Virginia Tech.

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Nomenclature

Acronym	*Description*
AnS	Anaerobic Stabilization
ASM No. 1	Activated Sludge Model Number 1
ASM No. 2	Activated Sludge Model Number 2
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
DO	Dissolved Oxygen
EBPR	Enhanced biological phosphorus removal
ED	Entner-Doudoroff
EMP	Embden-Meyerhof Parnas
HRT	Hydraulic retention time
N	Nitrogen
N_2	Nitrogen gas
NADH	Nicotinamide adenine dinucleotide-hydrogen
NH_3	Ammonia
NO_3^-	Nitrate
NPS	Nonpoint source
P	Phosphorus
PAO	Phosphate accumulating organism
PHA	polyhydroxy-alkanoic acid
PHB	Poly-3-hydroxy-butyrate
PHV	Poly-3-hdroxy-valerate
PMF	Proton motive force
PO_4	Phosphate
SBR	Sequencing batch reactor
SRT	Sludge retention time
TCA	Citric acid cycle
TSS	Total suspended solids
VFA	Volatile fatty acid
VSS	Volatile suspended solids

Chapter 1: Introduction

1.1 Problem Statement

Manure is an excellent source of nutrients, however, its nitrogen (N) to phosphorus (P) ratio does not correspond to that required by most crops. When a farmer applies livestock manure on an N-basis, the P requirement is often exceeded. Nitrogen-based applications often eliminate the need for commercial N and P fertilizers but increase the potential for P nutrient pollution from surface water runoff. If manure is applied to satisfy (and not exceed) the P requirement, additional N fertilizer must be used. Although a P-based application is better from an environmental standpoint, the resulting N fertilization requirement is an added expense for the farmer. Removing some P from manure would increase the N:P ratio enabling farmers to apply more manure to their crops and decrease the costs of fertilizer and off-farm manure transport.

Biological removal of P from wastewater can be achieved by intermittent aeration, which promotes the growth of P accumulating organisms (PAOs). These bacteria store P, removing it from the liquid fraction of the waste stream. Biomass is then separated from the wastewater resulting in a liquid with a lower P concentration and a solid fraction (sludge) with a higher P concentration. The P sequestering activity of PAOs is referred to as enhanced biological phosphorus removal (EBPR). This technology is commonly used for municipal wastewater treatment and has also been applied to swine manure treatment.

Dairy manure was chosen as the focus of this study due to the lack of information on dairy manure treatment and excess P applications (due to N-based manure application) common on dairies in Virginia. Dairy manure wastewater has higher concentrations of organic matter (measured as chemical oxygen demand (COD)), nutrients, and solids than municipal wastewaters. Aeration of such high strength wastes is not practical due to large energy requirements of aeration needed for the reduction of the organic matter and mechanical difficulties in aerating wastewater with a high solid content. Such wastes are typically treated anaerobically in lagoons, where reduction of organic matter occurs through methanogenic reactions. The application of EBPR to dairy manure may require pretreatment in which both the solid content and COD are reduced, resulting in wastewater characteristics more comparable to municipal wastewater and more conducive to growth of PAO heterotrophs. Solid separation

pretreatment has been adopted on some farms that apply manure to their crops, particularly those that use liquid application requiring spraying or irrigation systems.

Economic feasibility must also be evaluated to determine if EBPR can be practically applied to dairy manure wastewater. This will depend on the existing facility characteristics such as land base, soil P levels, herd size, storage facilities, equipment availability, and space available for additional treatment basins. Incorporation of this technology into an existing manure management plan would allow farmers to apply more liquid manure to their fields without over-applying nutrients.

Although the treated liquid fraction would increase fertilization efficiency, the resulting solid fraction may present an obstacle. The EBPR process will result in a significant volume of P-enriched sludge, presenting additional waste management challenges. Existing solids management practices and/or regionally dependent disposal alternatives will dictate whether or not EBPR sludge volume and characteristics can be accommodated economically.

The treatment system would include a solid separation unit and an EBPR unit (Figure 1.1). The system may also have a prefermentation unit for production of volatile fatty acids (VFAs) (required to support PAO growth) depending on the P concentration relative to the COD of the wastewater. Enhanced biological P removal can be achieved using a sequencing batch reactor (SBR), which would require only a single basin. Sequencing batch reactors have been used for livestock waste treatment due to space limitations on farms and smaller, intermittent waste flows, characteristic of farms compared to municipal wastewater treatment facilities.

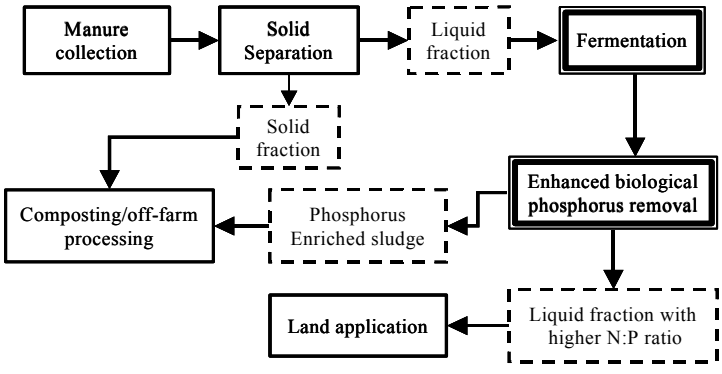

Figure 1.1: Process components involved in EBPR from dairy manure. Solid lines represent steps in manure handling or processing, dotted lines represent manure products, and bold lines highlight the processes that are the focus of this study.

1.2 Objectives

The goal of this research was to determine if EBPR is a viable alternative for decreasing excess manure nutrients on dairy farms. Assessment of EBPR involved the investigation of various aspects of wastewater treatment design and farm manure management. The specific objectives of this project were:

1) To determine the fermentation potential (VFA production) of dairy manure;

2) To determine if the EBPR component of the BioWin wastewater treatment model could be used in the design of an EBPR system for dairy manure;

3) To design an EBPR treatment system for dairy manure to meet N:P crop requirements without over applying either nutrient; and

4) To evaluate the economic feasibility of EBPR for dairy manure management.

Chapter 2: Literature Review

2.1 Introduction

This chapter includes an overview of nutrient pollution from agriculture, followed by a comparison of manure nutrients with nutrients requirements of crops to which manure is commonly applied. Biological wastewater treatment is then discussed with an in-depth review of enhanced biological phosphorus removal (EBPR). Applications of biological wastewater treatment to livestock manure are presented. Background information on both wastewater treatment microbes and process design is presented since both theoretical modeling and design were involved in meeting the research objectives. Biochemical models of EBPR are presented with a specific focus on the model used in BioWin, the software used in this research.

2.2 Nutrient Loading in the Environment

In the past two decades, livestock concentrations on farms have increased due to the movement towards fewer, larger livestock facilities (Kellogg et al., 2000). This trend is seen throughout the United States for all livestock types. Nutrient inputs often exceed nutrient exports resulting in nutrient accumulation on farms. Between 1982 and 1997, excess nitrogen (N) and phosphorus (P) on farms increased by over 60%; in 1997, approximately 60% of N and 65% of P on farms were excess nutrients (Kellogg et al., 2000). Excess farm nutrients may be transported from the farm through surface water runoff, leaching, and volatilization. A study on a New York dairy farm indicated that 72% of imported N and 57% of imported P were not accounted for in crops, animals, or milk produced (Hutson et al., 1998). Brown et al. (1989) determined that nonpoint source (NPS) runoff from dairy barnyards accounted for more than 80% of total and dissolved P in the Cannonville Reservoir in the Delaware River Watershed of New York.

Excess farm nutrients increase the potential for nutrient pollution in the environment. Manure application capacity of land is limited by crop nutrient requirements. Over-application of N and P does not result in excess plant uptake and higher yields (Sutton et al., 1986). Excess nutrients can be transported to surface water where they contribute to eutrophication. Excess P

in the environment is of particular concern with respect to eutrophication in inland surface waters where algal growth is usually P limited (Sharpley et al., 1994; Thomann and Mueller, 1987).

2.3 Dairy Manure Characteristics

Nutrient content in dairy manure varies both seasonally and between farms due to animal diet, lactation, and waste handling (Rieck-Hinz et al., 1996). Average nutrient values for both swine and dairy cattle are shown in Table 2.1. Although this research focuses on dairy waste, swine waste characteristics are also shown for comparison as much current waste treatment research focuses on swine manure.

Table 2.1: Manure nutrient, COD, and dry matter production characteristics of dairy and swine

Manure[*]	*Total P*[†]	*Ortho P*[†]	*NH_3*[†]	*TKN*[†]	*COD*[†]	*Dry Matter*[‡]
	(kg per 1000 kg live animal mass per day)					*(%)*
Dairy cattle	0.094	0.061	0.079	0.45	11.0	12.7
Swine	0.180	0.120	0.290	0.52	8.4	9.2

[*]Fresh manure as excreted, wet basis.
[†]ASAE (1997).
[‡]MWPS (1998).

Nutrient losses from manure may occur during both storage and handling. Because of variability in farming operations, waste treatment and nutrient management planning must be based on site-specific data. Handling has a significant effect on manure characteristics. Manure can be collected either by scraping or by flushing alleys. Manure is diluted when flushed from barns with water. Manure may also be settled or screened prior to land application using irrigation equipment or spray systems. Manure solids can also be land applied. Manure with a solid content of 5% or less is considered liquid manure and can be easily pumped or sprayed (USDA, 1992).

The solid fraction of the manure contains a significant amount of nutrients (some bound to the particles) and accounts for a large fraction of the total chemical oxygen demand (COD) (Rieck-Hinz et al., 1996). The solid fraction of the COD also affects the concentration of readily biodegradable COD and fermentable COD. Manure collection, transport, and storage alter manure characteristics and must be taken into account prior to land application.

Differences in wastewater characteristics must be addressed in applying municipal wastewater treatment technologies to livestock manure. The strength (COD concentration) of livestock manure is much higher than that of municipal wastewater, which is significant from a treatability standpoint (Table 2.2). Other significant differences are the variable and relatively small flows of farm wastes in comparison to municipal treatment plants, and the more limited capital on farms available for design, construction, and maintenance of advanced treatment systems.

Table 2.2: Comparison of municipal and dairy manure wastewater

Wastewater Type	*TKN*	*P*	*COD*	*COD/TKN*	*COD/P*
		(mg/L)		*(mg COD/ mg TKN,P)*	
Domestic wastewater					
Range[*]	20-85	4-8	200-780	---	---
Typical (1)[*]	40	6	400	360	67
Typical (2)[†]	40	8	500	12.5	63
Dairy manure					
Whichard (2001)[‡]	498	88	5370	10.8	61

[*]Typical values for raw domestic wastewater (Qasim, 1999).

[†]Typical values for liquid fraction of domestic wastewater (Llabres et al., 1999).

[‡]Dairy manure characteristics after dilution from flushing and solid separation. Because of wide variation of collection and storage, typical values are hard to define.

2.4 Crop Nutrient Uptake

Nutrient requirements depend on crop type, soil type, and soil nutrient levels. Different crops have different nutrient needs, which vary depending on the yield of the crop (DCR, 1995). Since potential crop yields are associated with various soil types, nutrient removal/requirements for individual crops are specified for a particular yield (Table 2.3). Soil testing prior to fertilization is important in determining application requirements.

Nitrogen-based manure applications often result in P build-up in soils. Based on average crop yields, if both N and P are completely depleted from the soil, a P-based manure application would result in N deficits of 114 and 47 kg ha^{-1} yr^{-1} for corn and ryelage, respectively (Table 2.4). An N-based application would result in over-application of P by 71 and 29 kg ha^{-1} yr^{-1} for corn and ryelage, respectively.

Table 2.3: Nutrient recommendations for corn silage and ryelage (DCR, 1995)

Crop	*N‡ (kg ha^{-1} yr^{-1})*	*P‡ (kg ha^{-1} yr^{-1})*	*N:P*
Corn Silage*	145.7	19.6	7.4
Ryelage†	78.4	19.6	4.0

*Nutrient recommendation based on corn silage yield of 1542 kg/ha.
†Assuming a single, late winter application.
‡Elemental N and P recommendations.

Table 2.4: Nutrient deficits for corn silage and ryelage resulting from N and P-based applications of solid separated dairy manure

Crop	*Crop N:P requirement**	*Nutrient deficits for given application method (kg ha^{-1}yr^{-1})*			
		N-based		*P-based*	
		N	*P*	*N*	*P*
Corn Silage	7.4	0	-71	114	0
Ryelage	4.0	0	-29	47	0

*Based on crop nutrient requirements in Table 2.3.
*Based on solid separated dairy manure with an N:P ratio of 1.6 (Table 2.2) assuming 58% organic N and 42% NH_4-N and crop availability coefficients of 0.35 and 0.20, respectively (DCR, 1995).

2.5 Nutrient Removal from Wastewater

Nutrients can be removed through physical, biological, and chemical processes. Most wastewater treatment systems employ a combination of these three treatment methods. Physical treatment includes screening and settling, which removes solids, are referred to as grit removal or solid separation. Solid separation is used in most wastewater treatment systems as an initial or pretreatment step (Grady et al., 1999). Many nutrients are removed with the solid fraction of the waste stream (Randall et al., 1992; Converse et al. 2000; Jones and Brown, 2000). The liquid waste can then be biologically and/or chemically treated to remove dissolved components. Biological nutrient removal processes are based on the ability of microorganisms to utilize nutrients to harness energy needed for metabolism. All cells need nutrients such as N and P to form cell components. Assimilation into cell components, however, accounts for a very small fraction of nutrients removed in biological N and P removal processes (Grady et al., 2000). Biological N removal employs the biochemical processes of nitrification and denitrification and is widely used in municipal wastewater treatment. The use of biological P removal has also

become widely used in domestic wastewater treatment in recent years. Chemical precipitation is a popular method of P removal but results in a large volume of sludge (Grady et al., 1999; Paul et al., 2001).

2.6 Biological Nitrogen Removal

Biological N removal is achieved through nitrification where ammonia (NH_3) is transformed to nitrate (NO_3^-) ($O_2 + NH_3^- \rightarrow H_2O + NO_2^-, NO_3^-$) and denitrification where NO_3^- is transformed to nitrogen gas (N_2) (organic carbon (C) + $NO_3^- \rightarrow CO_2 + N_2$) (Figure 2.1). Nitrification is an aerobic process in which autotrophs use dissolved oxygen (DO) as a terminal electron acceptor for energy production (there are heterotrophs that nitrify, however, autotrophs are the dominant nitrifiers). Denitrification occurs in anoxic zones (lacking oxygen) where heterotrophic bacteria use NO_3^- as their terminal electron acceptor in the absence of DO. Dissolved oxygen is used preferentially above other electron acceptors. Therefore, significant denitrification does not occur until nitrification is inhibited by lowered DO concentrations. Since two different electron acceptors are required to transform NH_3 to N_2, two different growth environments must be provided to promote this microbial activity. Although simultaneous nitrification and denitrification has been observed in systems with low DO concentrations (Whichard, 2001), methods to maintain this activity and control the responsible mechanisms are not yet well developed. Alternating aerobic and anoxic zones are typically used to promote nitrification and denitrification to convert NH_3 to N_2.

2.7 Enhanced Biological Phosphorus Removal

Enhanced biological phosphorus removal refers to bacterial uptake of P exceeding the amount needed for cell components. Although P requirements vary among different bacteria, the growth requirement is commonly approximated as one fifth of the N requirement (0.087 mg N/mg COD formed), or 0.017 mg P/mg COD formed (Grady et al., 1999). These nutrient requirements are based on an empirical formula commonly used for biomass: $C_5H_7O_2N$. This formula is assumed to apply to both autotrophic and heterotrophic biomass. Enhanced biological P removal occurs in alternating aerobic and anaerobic conditions, which encourages the growth of P accumulating organisms (PAOs). Phosphorus accumulating organisms are heterotrophs which uptake and store P in greater quantities than needed for cell components. In EBPR, the

anaerobic environment is required for fermentation of COD to volatile fatty acids (VFAs) and the storage and concomitant release of phosphate (PO_4). Phosphorus accumulating organisms transport VFA (mainly acetate) into their cells and store it as polyhydroxyalkanoic acid (PHA) under anaerobic conditions. Poly-3-Hydroxybutyrate (PHB) is the most abundant form of PHA accumulated when acetate is the dominant organic substrate (Comeau et al., 1987; Wang et al., 2002).

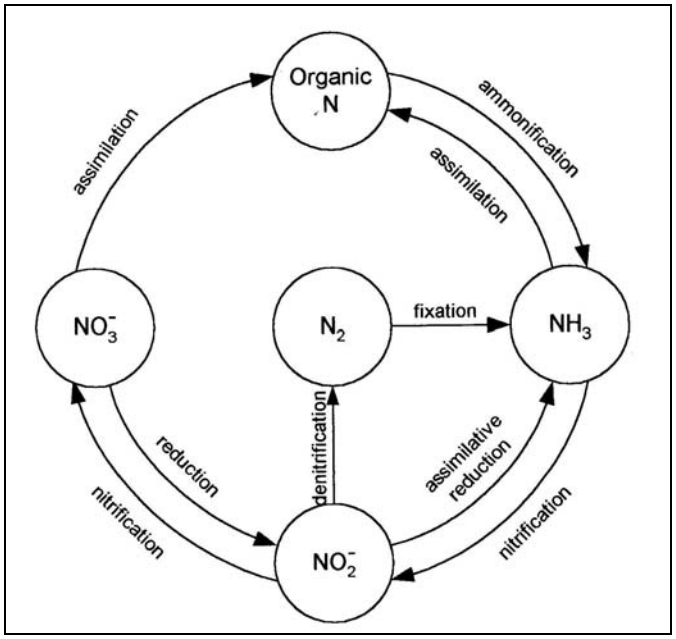

Figure 2.1: The nitrogen cycle (Grady et al., 1999).

Phosphorus accumulating organisms store PHA using energy from the hydrolysis of intracellular polyphosphate, releasing inorganic PO_4 from the cell (Figure 2.2). When DO becomes available (in the aerobic zone), PAOs grow using the previously stored PHA for energy. During metabolism, PO_4 is taken up in the aerobic environment by PAOs (Wentzel et al., 1990). Due to microbial growth, more PO_4-P is taken up in the aerobic environment than is released in the anaerobic environment, thus concentrating the PO_4-P in the biomass. Although P is removed from the liquid fraction of the wastewater, it remains in the biomass solids, which are separated from the liquid. Although the resulting high-P sludge must be disposed of, it is a much smaller volume than high-P sludge resulting from chemical precipitation of P by addition of salts such as lime ($CA(OH)_2$) or alum ($Al_2(SO_4)_3$. Paul et al. (2001) found that excess sludge production associated with P removal from EBPR was 30 to 60% of the volume of sludge obtained in

chemical removal of P by precipitation with iron (Fe). Sludge production volume, which is highly dependent on BOD/P (or COD/P) ratio and sludge characteristics, were 20 to 30 mg BOD/mg P, or approximately 22.8 to 34.2 mg COD/mg P based on conversions given in Grady et al. (2000).

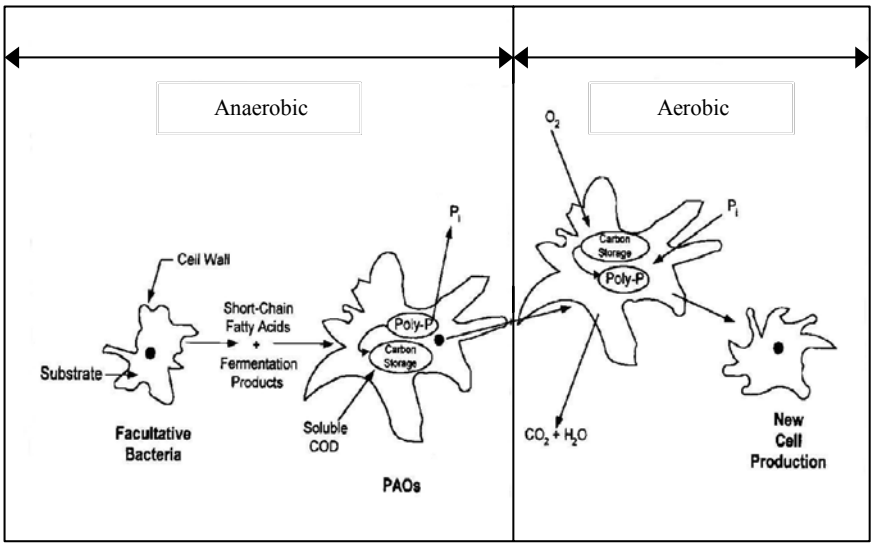

Figure 2.2: Relationship between phosphorus and organic matter metabolism in the anaerobic and aerobic zones of an EBPR system (Grady et al., 1999).

2.7.1 Anaerobic Process Control for EBPR

Anaerobic activity involves a complex series of biochemical reactions (Figure 2.3). In EBPR, the desired fermentation products are VFAs. Preventing subsequent methanogenesis provides PAOs with more VFAs to convert to stored energy. Some significant factors affecting microbial activity in the anaerobic zone are sludge retention time (SRT), hydraulic retention time (HRT), temperature, and pH (Elefsiniotis and Oldham, 1991; Munch and Koch, 1999; and Skalskey and Daigger, 1995). Controlling these factors can help optimize microbial activity. Methanogenesis can be limited by controlling the SRT in the anaerobic zone. Fermentation of amino acids and simple sugars typically occurs within one day; whereas anaerobic oxidation of VFAs and aceticlastic methanogenesis does not begin until four and three days, respectively (Figure 2.4). Aceticlastic methanogens (which are responsible for most of the resulting methane (CH_4) production in methanogenesis) do not grow as quickly as fermenting bacteria. Therefore,

in operating an anaerobic fermenter for VFA production, the SRT should be long enough to permit the growth of the hydrolytic and fermentative bacteria but prevent significant methanogens (Grady et al., 1999).

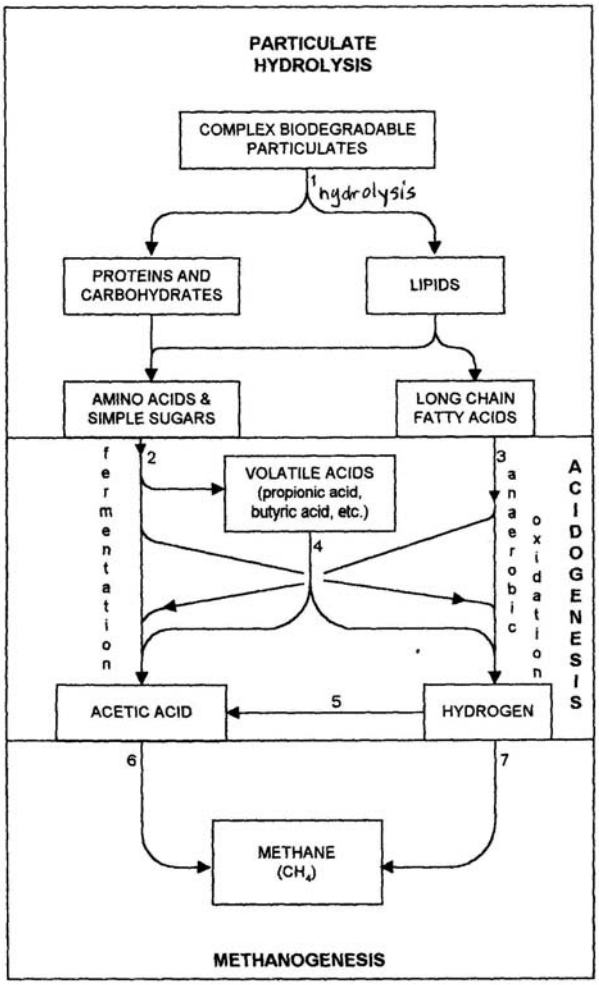

Figure 2.3: Multistep nature of anaerobic operations (Grady et al., 1999).

Although minimum SRTs given in Figure 2.4 are specifically for 35°C, the respective order of occurrence of hydrolysis, acidogenesis, and methanogenesis remains the same at lower temperatures (Grady et al., 1999). Although microbial activity is typically faster at increased temperatures, fermentation bioreactors are usually operated at ambient temperatures. The increased growth rates (at 35°C versus 25°C, for example) are typically not justified by the extra expense of heating (Grady et al., 1999). The growth of aceticlastic methanogens is slower at lower temperatures, increasing VFA availability to PAOs. To optimize acidogenesis,

fermentation bioreactors are usually operated at pH less than six, which is much lower than in methanogenic processes. Elefsiniotis and Oldham (1991) reported inhibition of VFA production at pH above 7.0. Low pH also helps to limit the growth of aceticlastic methanogens (Vavilin et al., 1998; Grady et al., 1999).

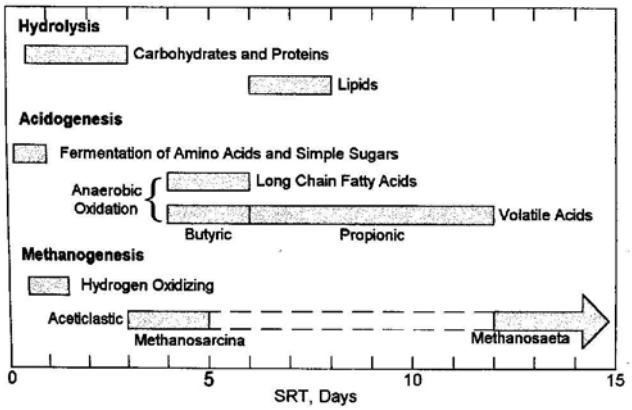

Figure 2.4: Typical SRT ranges for various biochemical conversions in anaerobic bioreactor systems at 35°C (Grady et al., 1999).

2.7.2 Aerobic Process Control for EBPR

Enhanced biological P removal occurs when conditions favoring PAOs exist. Two of the major operational controls used to encourage PAO growth are SRT and aeration. The minimum SRT required for PAOs is less than that of nitrifiers at temperatures below 25 °C. As temperature increases, the difference between the minimum required SRTs decreases, making it more difficult to ensure PAO growth without nitrification. At 25 °C, the minimum SRT for both nitrifiers and PAOs is approximately 1.5 days (Figure 2.5). When nitrification occurs, NO_3^- becomes available as an electron acceptor. Denitrification proceeds faster than fermentation reactions. Nitrate availability therefore decreases the fermentation rate of facultative heterotrophs, reducing VFA production (Ekama and Wentzel, 1999).

2.7.3 Conventional Process Configurations for EBPR

Intermittent aeration is necessary for proliferation of PAOs. If non-VFA readily biodegradable COD is available in large quantities in the aerobic zone, non-PAO heterotrophs

may interfere with PAO growth. Therefore, selecting the correct aeration cycle time is critical in maximizing PO_4 removal. Controlling the redox environment is also critical in the promotion of EBPR. The presence of NO_3^- reduces P release in the anaerobic zone (Osada et al., 1991; Choi et al., 1996). Therefore, nitrification can interfere with EBPR by preventing fermentation and PHA storage by PAOs in the anaerobic zone. Nitrate is used preferentially as the electron acceptor (in the absence of oxygen) because microbes grow faster and derive more energy from NO_3^- than from degradation of C compounds. Nitrification decreases activity of fermenters and storage of fermentation products by PAOs. If nitrification occurs in the aerobic zone, this could be problematic if a recycle stream is returned to the anaerobic zone.

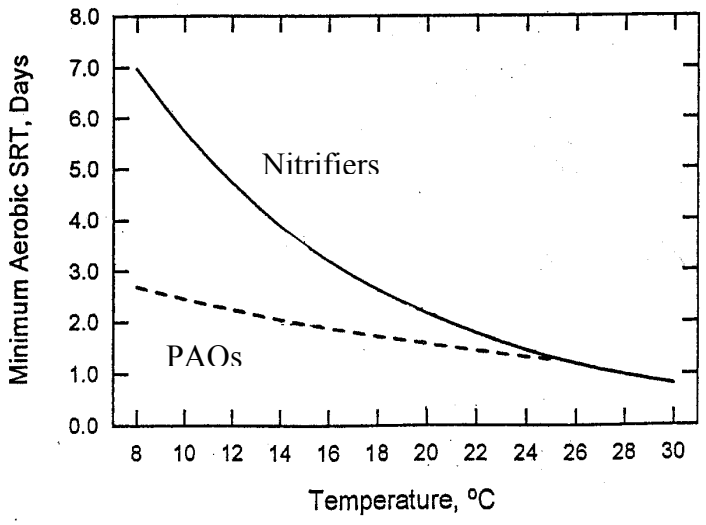

Figure 2.5: Effect of temperature on minimum aerobic SRT required to grow nitrifiers and PAOs adapted from Grady et al. (1999).

Phosphate removal is generally lower in systems supporting both P and N removal, than in systems that isolate P removal. This is due to limitations on COD availability as well as the difficulty in maintaining optimal growth environments for both nitrifiers and PAOs. If wastewater is exposed to anoxic conditions after P uptake in an aerobic zone, PAOs may re-release PO_4. The two different release mechanisms are distinguished as primary and secondary PO_4 release. Primary PO_4 release is that associated with VFA intake and secondary PO_4 release is that occurring during anoxic conditions (Sedlak, 1991; Grady et al., 1999).

Two common configurations used for EBPR are the Phoredox process (Sedlak, 1991; Grady et al., 1999) and Phostrip® process (Randall et al., 1992; Grady et al., 1999). Both configurations support high P removal and limited N removal. The Phoredox (also referred to as the A/O™ process) requires the least reactor volume space, is simple to operate, and tends to have good settleability (Grady et al., 1999). Although the Phostrip® process has superior PO_4 removal capabilities, its operation is more complicated.

Primary release is used in the Phoredox process (Figure 2.6) whereas both mechanisms are utilized in the Phostrip® process (Figure 2.7). In the Phoredox process, primary release occurs in the anaerobic zone (ANA), is taken up in the aerobic zone (AER), and is removed with the biomass in the waste stream (WAS). In the anaerobic settling basin (ANA) of the Phostrip® process, P is also released and is precipitated (stripped) from the overflow by treatment with lime. Unless chemical precipitation is to be used in P removal, secondary P release should be avoided (Danesh and Oleszkiewicz, 1997).

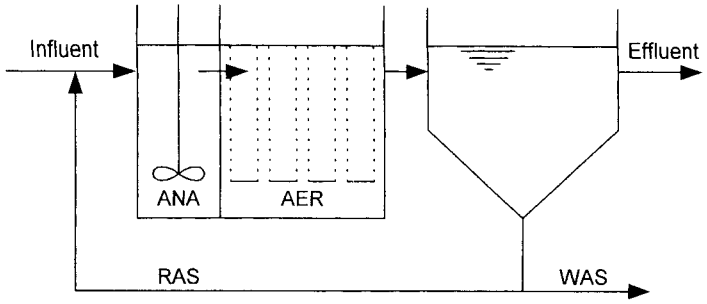

Figure 2.6: Phoredox process includes anaerobic (ANA) and aerobic (AER) zones followed by clarifier from which waste activated sludge (WAS) and return activated sludge (RAS) are removed (Grady et al., 1999).

Efficiencies of nutrient removal systems are often compared based on required COD:TKN and COD:P (mg COD required for removal of 1 mg N or P) ratios of a wastewater, a lower ratio being more efficient as less COD is required for the removal of the nutrient. Grady et al. (1999) give typical COD ratios for both N and P removal. The Phoredox process is considered highly efficient for P removal with COD:P typically ranging from 26 to 34 mg COD/ mg P. Less efficient processes require over 40 mg COD for removal of one mg of P. The COD required for biological removal of N is less than that required for EBPR, i.e. N removal is more efficient. Grady et al. (1999) state that N removal can occur in some systems at a COD:TKN

ratio of five but is optimal in most systems at ratios above nine. The COD of NO_3^- as an electron acceptor is 2.86 g COD per g NO_3^-. More COD than this is required for complete denitrification due to incorporation of COD into biomass, N incorporation into biomass, and slow biodegradation of a fraction of the COD.

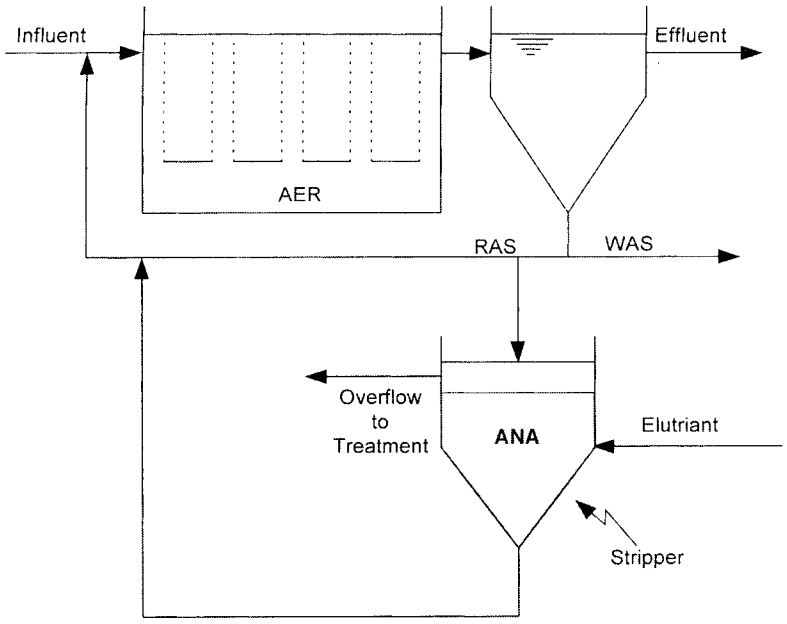

Figure 2.7: Phostrip® process includes an aerobic (AER) zone and an anaerobic (ANA) stripper. Waste activated sludge (WAS) and return activated sludge (RAS) are removed from the clarifyer follwing the AER zone (Grady et al., 1999).

The ratio of COD to nutrients in a wastewater determines its treatability and the most appropriate process configuration required to meet treatment objectives. In systems that combine treatment objectives, COD requirements are additive. Carbon-limited wastewaters do not contain enough COD to meet nutrient removal goals. It can be assumed that N removal will occur first, preferentially to P removal, in combined removal systems if NO_3^- is present (Grady et al., 1999). The degradability of the COD also affects nutrient removal and fermentation; some of the influent COD is slowly biodegradable.

2.7.4 EBPR in Sequencing Batch Reactors

The reactor configurations mentioned above are only two of many configurations used for nutrient removal from municipal and industrial wastewater. Enhanced biological P removal

has been widely used for municipal and industrial wastewater treatment (Arvin, 1983). Advanced wastewater treatment systems and techniques are just starting to be applied to agricultural wastes. The treatment configuration most commonly used for agricultural wastes is a sequencing batch reactor (SBR) (Bicudo et al., 1995; Tilche et al., 1999). An SBR is a single, completely mixed basin within which reactor conditions are sequenced to accomplish multiple treatment objectives. Typical cycles include periods of feeding, mixing, aeration, settling, drawing (of treated supernatant), and wasting (sludge removal) (Figure 2.8). Intermittent aeration can be used to control electron acceptor availability to meet treatment objectives. Wastewater is treated and removed in a batch, in contrast to a continuous flow reactor to which waste is fed continuously. Sequencing batch reactors are well suited for agricultural waste treatment due to intermittent and relatively low flows of waste on farms. Sequencing batch reactors are also more likely to meet economic and space constraints on farms.

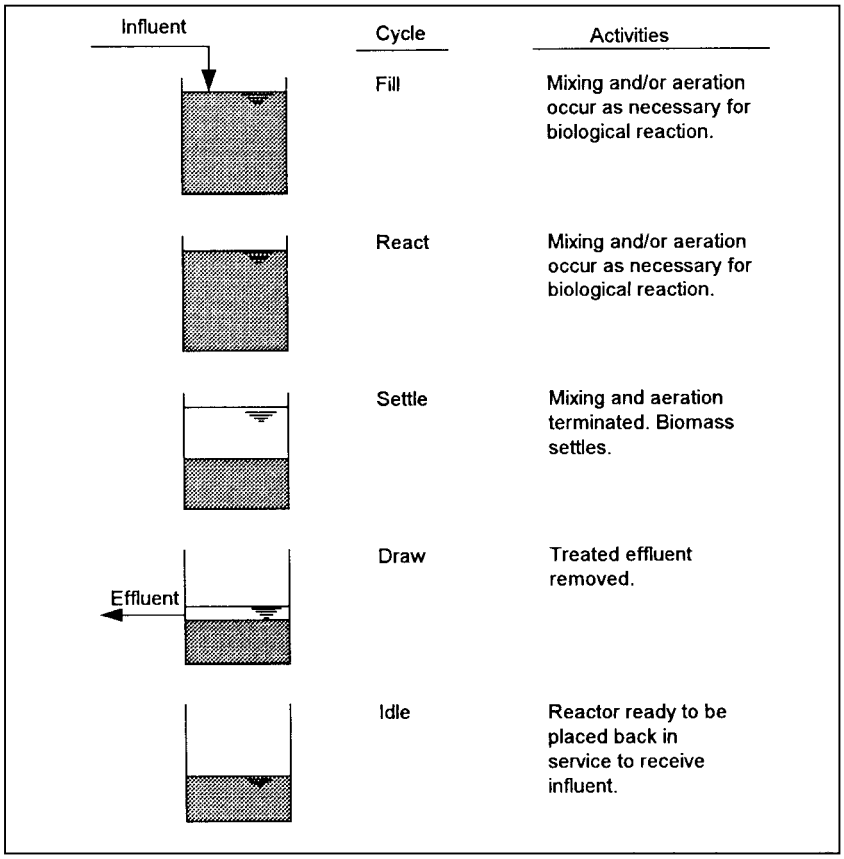

Figure 2.8: Operation of sequencing batch reactor (Grady et al., 1999).

2.7.5 COD Requirements for EBPR

As discussed earlier, nutrient removal processes can be limited by COD availability depending on wastewater characteristics (nutrient and COD concentrations). In EBPR, P uptake in the aerobic zone is directly related to the amount of PO_4 released in the anaerobic zone (Comeau et al., 1987). The release of PO_4 allows cells to harness energy, which is used to store C as PHA. The presence of VFA (the C source) spurs PHA formation. Increased VFA availability increases PHA formation, PO_4 release, and, ultimately, PO_4 uptake. Similarly, decreases in PHA formation cause PAO activity to slow, increasing effluent PO_4 concentrations (Temmink et al., 1996). Therefore, removal efficiency in EBPR is ultimately dependent on COD availability. Tam et al. (1992) reported 84% removal of P in simultaneous removal of N and P with the addition of external C sources. Danesh and Oleszkiewicz (1997) reported that the amount of P release associated with VFA uptake was 0.6 mg of P per mg of VFA.

Preferred VFAs of PAOs are acetic and propionic acids (GonCalves, 1994; Skalsky and Daigger, 1995; Wentzel et al., 1989a). These are the shortest chain VFAs and have been found to be the most abundant of the four main fermentation products (acetic, propionic, butyric, and valeric acids). Wentzel et al. (1989a) found 1:1 ratio of acetic to propionic acid in municipal wastewater. GonCalves (1994) found that production of acetic acid accounted for approximately 90% of the total VFAs with propionic acid accounting for the remaining portion in municipal wastewater. Skalsky and Daigger (1995) found 38 to 41% acetic acid, 36 to 44% propionic acid, 9 to 16% butyric acid, and 5 to 10% valeric acid in the fermenter products of two separate full-scale fermenting systems. Elefsionitis and Oldham (1991) found that acetic and propionic acids together made up 75 to 80% of total fermentation products in fermentation of primary solids. Of the four common VFAs, acetic acid has been found to be the most preferred by PAOs. Acetic acid is the shortest chain VFA and has the lowest COD (Table 2.5).

Table 2.5: COD equivalents for volatile fatty acids

Volatile fatty acid (VFA)	mg VFA/ mg COD
Acetic acid	1.067
Propionic acid	1.514
Butyric acid	1.818
Valeric acid	2.039

Abu-ghararah and Randall (1991) determined that at least 20 mg VFA-COD (acetic acid) was needed for removal of 1 mg P. Lie et al. (1997) found that 20 mg VFA-COD removed 1 mg P. Barnard (1994) determined a requirement of 6 to 9 mg of VFA-COD for the removal of 1 mg of P. Although nearly complete removal of both N and P is theoretically possible in a single SBR, reactions are usually C-limited. The COD to nutrient ratio needed for high P removal is COD:P of 26 to 34 without nitrification (Grady et al., 1999). Depending on desired nutrient removal, COD may need to be added to meet effluent goals.

2.7.6 Prefermentation for Improved EBPR

The anaerobic zone serves two purposes in EBPR: production of VFA and storage of VFA by PAOs. The former is the rate-limiting step of PAO energy storage (Wentzel, 1987; Barnard, 1994; Danesh and Oleszkiwicz, 1997) and is highly variable, depending on the nature of the incoming wastewater, i.e., the solid concentration and fermentable fraction of influent COD. Depending on wastewater characteristics, it may be difficult to yield sufficient amounts of VFAs (for desired P removal) in the anaerobic zone. Addition of VFA-COD (or separation of fermentation and EBPR processes) improves EBPR (Lotter et al., 1992; Tam et al., 1992; Comeau et al., 1996; Danesh and Oleszkiewicz, 1997; Christensson et al., 1998).

Available VFA-COD includes VFAs in the influent and the fermentable COD, also called the VFA potential. Influent VFA concentrations are often low and depend on the oxygen environment in the wastewater storage and conveyance systems. The fermentable fraction (VFA potential) of a wastewater can be determined to assess EBPR performance. Volatile fatty acid potential is usually measured as percent VFA-COD yield from the total COD entering a fermenter.

Most VFA yields reported are of fermentation processes treating the solid fraction of wastewater rather than the entire waste stream. At typical SRTs (4-10 days) and ambient temperatures, only a portion of the biodegradable organic matter of the solid fraction is converted to VFAs. Typical yields range from 0.05 to 0.3 g VFA produced/ g volatile solids (VS) fed to the fermenter (Grady et al., 2000). Wentzel et al. (1989b) reported maximum yields of 0.125 g VFA/g VSS. Munch and Koch (1999) compared the VFA production of nine full-scale operational prefermenters. The conversion of total COD to VFA-COD ranged from 2 to 14%. Elefsiniotis and Oldham (1991) reported VFA production rates of 0.06 to 0.12 mg

VFA/mg VS/d. These rates were based on the reactor VS concentration rather than the concentration of VS in the feed. Lilley et al. (1988) reported a maximum conversion of sludge COD to VFA (as COD) of 17%. GonCalves et al. (1994) also reported a maximum of 17% conversion of primary sludge COD to VFA-COD in an upflow sludge blanket. Lie and Welander (1997) found the average VFA potential of municipal wastewater to be 24% of the total COD.

Lee et al. (1997) fermented swine waste solids and added them to a SBR during the anoxic phase of the cycle. The operating cycle for this SBR was 13-hr aeration, 7-hr non-aerated, 3-hr aeration, 40-min settling, and 10-min draw. Supplemental VFAs from the fermented manure increased total P removal from 15 to 89%.

Observations of fermentation systems, particularly those used in conjunction with EBPR systems, have demonstrated that COD losses are not fully accounted for in biomass and fermentation products (Wable and Randall, 1992; Barker and Dold, 1995). Barker and Dold (1995) suggested that COD losses could possibly be due to the production of hydrogen gas (H_2) by facultative organisms during acidogenesis, methane production by methanogens (a few of which have been reported to exist at low oxygen concentrations), or the production of other volatile compounds. Wable and Randall (1992) investigated potential COD loss processes, terming the difference between actual and theoretical COD use "Anaerobic Stabilization" (AnS). They determined that H_2, CH_4, and carbon monoxide gas evolution accounted for an insignificant fraction of AnS and hypothesized that aeration-induced stripping of reduced volatile species may be responsible for AnS. Some COD is lost in the form of CH_4 due to the growth of H_2-utilizing methanogens which grow faster than aceticlastic methanogens and are able to survive at SRTs employed.

2.7.7 Temperature Effects

Most organisms considered in wastewater treatment are mesophilic, growing well at temperatures between 10 and 35° C. Within this range, growth rates are typically greater at higher temperatures. While EBPR has been reported at temperatures ranging from 3 to 40° C (Helmer and Kunst, 1997; Jones and Stephenson, 1996; and Converti et al., 1995; Baetens et al., 1999), efficiency of EBPR systems tends to slow above temperatures of 25° C and is often maximized at temperatures as low as 10° C. Helmer and Kunst (1997) found that aerobic PO_4

uptake increased with temperature between 10 and 20° C but remained constant between 5 and 10° C.

Temperature effects are most commonly modeled using the Arrhenius relationship (Grady et al., 1999):

$$K(@T°C) = K(@20°C) \times \theta^{(T-20)} \quad \textbf{[2.1]}$$

where K(@20° C) = Value of a given kinetic parameter at 20° C,
θ = Temperature coefficient,
T = Temperature (° C), and
K(@T° C) = Adjusted value of the given kinetic parameter.

This relationship is only valid for the temperature range within which growth increases at increasing temperatures. Temperature coefficients (θ) with values other than one indicate temperature dependency. Temperature coefficients are typically designated for individual kinetic parameters.

Temperature coefficients have been determined experimentally for EBPR processes (Brdjanovic et al., 1998b; Mamais and Jenkins, 1992; Helmer an Kunst, 1997; Baetens et al, 1999). Temperature effects are more difficult to quantify for PAO heterotrophs than for non-PAO heterotrophs due to the multiple processes involved in EBPR, each of which responds differently to temperature changes. Temperature has a greater effect on anaerobic processes than on aerobic processes (Baetens et al., 1999; Brdjanovic et al., 1998b). In addition, the effects of temperature are different for different aerobic sub-processes such as PHA consumption and PO_4 uptake (Brdjanovic et al., 1998b). Therefore, a single Arrhenius relationship cannot be used to describe such temperature effects. Contrary to these findings, Mamais and Jenkins (1992) were able to describe experimental changes in temperature with a single Arrhenius equation applicable to temperatures ranging from 5 to 36° C.

2.7.8 Effect of Solid Content

Typical feed to fermenters is primary solids. Solids content has a significant influence on both the kinetics and yields of fermentation. GonCalves et al. (1994) reported that 60% of VFA came from the soluble fraction of the wastewater when fermenting untreated wastewater (not just the sludge). GonCalves et al. (1994) found that VFA production was greatest when

solubilization was maximized. The maximum solubilization achieved was 0.13 mg filtered COD/mg influent particulate COD. Skalsky and Daigger (1995) found that VFA production was more efficient (mg VFA produced/mg VS feed) in wastewater with lower solids concentrations. The wastewater had higher VFA yields than sludge and better settleability than wastewater not treated with fermentation. They speculated that this may have been due to better mixing, increasing hydrolysis reactions and substrate uptake, or that a more dilute reactor decreased the inhibitory effects of fermentation products.

2.8 Modeling EBPR in Wastewater Treatment Systems

Accurate modeling of biological wastewater treatment is difficult due to the complex nature of microbial populations. Biological activity is dependent on reactor configuration, wastewater characteristics, and environmental conditions such as electron acceptor availability and temperature. Interaction of these factors determines the physiological state of the organisms, their resulting activity, and extent of wastewater treatment. Shock loads and seasonal fluctuations result in a constantly changing environment, which also hinders predicting treatment extent. In addition, no two wastewaters are the same, making it more difficult to evaluate and apply models to full-scale treatment systems.

For biomass growing in a particular wastewater, growth parameters are determined by measuring oxygen uptake, changes in biomass concentration, changes in substrate concentration, concentrations of nutrients, and concentrations of other various constituents affected by microbial growth. Experimental analysis is required to better understand the mechanisms responsible for microbial activity. Increased knowledge of microbial energetics will continue to aid in the development of more mechanistic (rather than empirical) models. Further development of more mechanistic model components of EBPR may improve the reliability of a single model over a broad range of applications.

General wastewater modeling equations are presented in the following sections, followed by brief descriptions of EBPR models. A complete model description of the EBPR component used in BioWin is then given. Two of the first conceptual models that were developed are referred to as the "Comeau-Wentzel" and "Mino" models. These models have served as the basis of other models that have evolved as knowledge of EBPR has increased. The International

Association on Water Quality (IAWQ) task group (Henze et al., 1995) developed Activated Sludge Model Number 1 (ASM No. 1) to simulate C oxidation, nitrification and denitrification in wastewater treatment. This was expanded to include EBPR in Activated Sludge Model Number 2 (ASM No. 2). BioWin, the simulation tool used in this research, is based on ASM No. 2 and a model by Barker and Dold (1997), who further expanded the EBPR model components.

2.8.1 Monod Kinetics

Growth kinetics are commonly modeled according to relationships first demonstrated by Monod (1949). The equations presented in this section are from Grady et al. (1999). Bacterial growth has been shown to be a first order process:

$$r_{ZB} = \mu X_B \qquad \textbf{[2.2]}$$

where r_{ZB} = Microbial growth rate (mg/d),
μ = Specific growth rate (d^{-1}), and
X_B = Microbial mass (mg).

The specific growth rate (μ) depends on the type of organism present and its physiological state, which changes with temperature, reactor configuration, reactor operation, wastewater composition, and redox environment. The specific growth rate is ultimately dependent on the concentration of the limiting substrate or nutrient needed for growth. At lower substrate concentrations, the specific growth rate has a first order relationship with substrate concentration. At higher substrate concentrations, the specific growth rate approaches the maximum specific growth rate (μ_{MAX}) and becomes independent of substrate concentrations. The maximum specific growth rate is the highest rate at which an organism will grow in a specific physiological state. This relationship was described by Monod (1949) and has been widely applied in describing microbial growth behavior in wastewater treatment systems:

$$\mu = \frac{\mu_{MAX} S_S}{K_S + S_S} \qquad \textbf{[2.3]}$$

where μ_{MAX} = Maximum specific growth rate (d-1),
S_S = Substrate concentration (mg/L), and
K_S = Half saturation coefficient (mg/L).

The half saturation coefficient is the concentration of substrate at which μ is half of μ_{MAX}. The half saturation coefficient is lower for faster growing organisms and higher for those that tend to grow slower. If the substrate concentration is high, then microbial biomass grows fast, but there is a lot of substrate left. In the case where the substrate is a pollutant, μ should be kept low so that substrate is kept low. The specific growth rate can be controlled by changing the pumping rate in a reactor, i.e. by controlling the SRT. In actuality, μ is dependent on more than just a single substrate upon which microbes grow. In addition to energy (electron donor), microbial growth also requires an electron acceptor (such as oxygen or nitrate) and nutrients. These factors are included in the basic Monod equation by the addition of switching functions:

$$\mu = \mu_{MAX}\left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_O}{K_O + S_O}\right) \qquad \textbf{[2.4]}$$

where K_O = Half saturation coefficient for oxygen (mg/L), and
S_O = Dissolved oxygen concentration (mg/L).

Maximum specific growth rate of a system is dependent on the organisms present, the substrate, and the environmental conditions of that particular system. Systems with more readily biodegradable substrates tend to have higher μ_{MAX} values than those with more slowly degradable substrate. Maximum specific growth rate is the rate at which biomass could grow if substrate concentrations are high. In systems where substrate is in solution, μ is dependent on the SRT. The SRT can be adjusted to control the substrate concentration. This concept cannot be applied to EBPR since the substrate is stored within the biomass. Changing the aerobic SRT will not directly affect the growth rate of biomass if not enough substrate is stored in the anaerobic phase.

2.8.2 Comeau-Wentzel Model

The Comeau-Wentzel Model and the Mino Model have been used as the basis for describing biochemical processes associated with EBPR. Acetate is the most abundant and most common VFA used by PAOs. It is also the simplest and shortest chain VFA and is therefore used to explain the biochemical pathways involved in metabolism of PAOs. This section briefly describes the Comeau-Wentzel model (Figure 2.9).

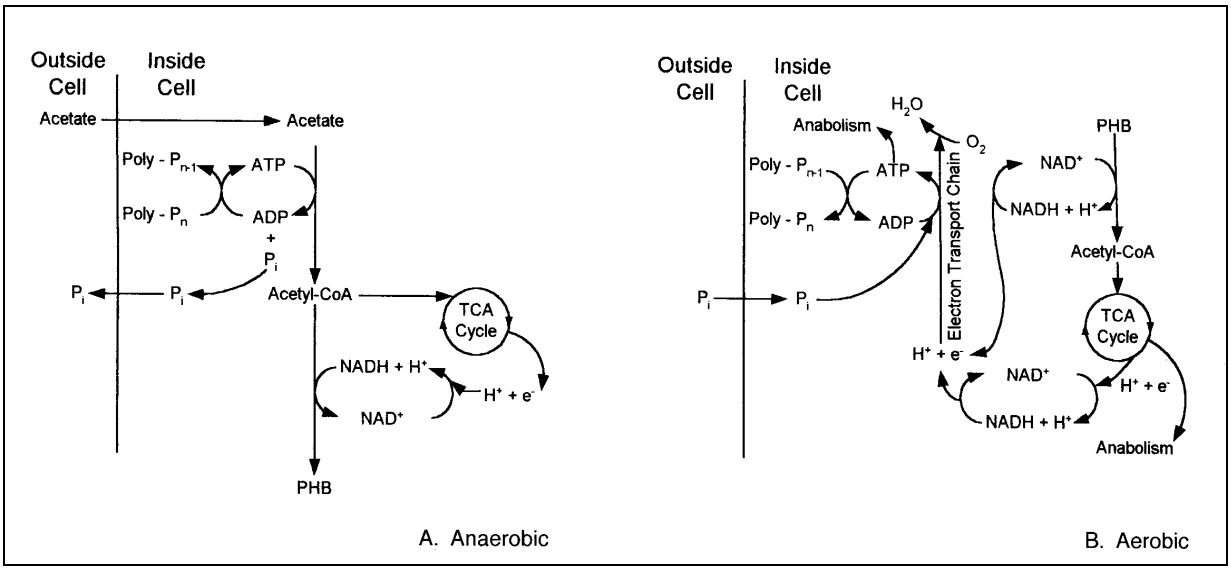

Figure 2.9: Comeau-Wentzel model for the uptake and release of inorganic phosphate by PAOs (Grady et al., 1999).

In the anaerobic zone, acetate is diffused passively (due to concentration gradient) through the cell membrane. Acetate is then activated to acetyl-CoA by coupled adenosine triphosphate (ATP) hydrolysis yielding adenosine diphosphate (ADP). Undissociated acetic acid causes protons to be transported from the membrane, which results in a loss of the proton motive force (PMF) at the cell membrane. Some ATP therefore must be used to maintain the PMF. The use of ATP results in a decrease in the ATP/ADP ratio, stimulating ATP synthesis from stored polyphosphate. The stored polyphosphate provides energy for ATP synthesis without which acetate would build up in the cell causing passive transport to cease. Hydrolysis of polyphosphate increases the intracellular concentration of inorganic PO_4 that is subsequently released into the bulk solution. Some of the acetyl-CoA is metabolized through the citric acid (TCA) cycle to provide nicotinamide adenine dinucleotide-hydrogen (NADH+ H^+) required for PHB synthesis. (PHB and PHV are the two types of PHA. Some models use the PHA encompassing both, however, it has been shown that PHA is mostly PHB.) The rest of the acetyl CoA is converted directly to PHB. Approximately 90% of the acetate C is conserved in this storage polymer which later serves as the energy source for the PAOs.

Dissolved oxygen is required for PAO metabolism. The PHB that was produced and stored in the anaerobic zone is used as the C and energy source for PAO growth. Adenosine

triphosphate is generated through electron transport phosphorylation. As the ATP/ADP ratio increases, polyphosphate synthesis is stimulated, removing PO_4 from the bulk solution. Because of the greater ATP yields in aerobic metabolism, PAOs take up all of the P originally released into solution in addition to the P which was originally present in solution.

2.8.3 Mino Model

The defining difference between the Comeau-Wentzel and Mino models is that the latter includes glycogen formation (Figure 2.10). In the anaerobic zone, energy required for PHB synthesis from acetyl-CoA comes from the metabolism of glucose released from glycogen. Glucose is oxidized to pyruvate through Entner-Doudoroff (ED) or Embden-Meyerhof-Parnas (EMP) pathway depending on the type of PAO. This provides some ATP, which is needed to convert acetate to acetyl-CoA and some of the energy needed for PHB synthesis. All of the acetate taken up by cells, as well as some C from the glycogen, is stored as PHB. The processes in the aerobic zone are the same as in the Comeau-Wentzel model except that PHB is also used to replenish stored glycogen.

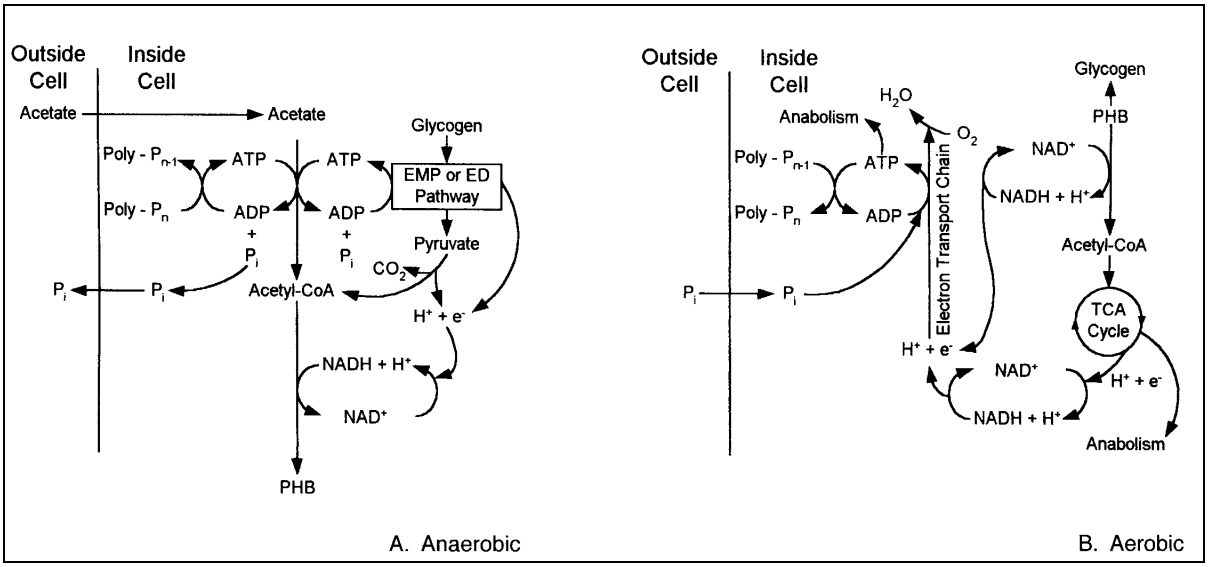

Figure 2.10: Mino Model for uptake and release of inorganic phosphate by PAOs (Grady et al., 1999).

2.8.4 ASM No. 2 Model

The International Association on Water Quality (IAWQ) has developed computer models based on those described above to predict effluent quality from biological waste treatment. Model evaluations indicated that ASM No. 2 (Henze et al., 1995) can be used to simulate EBPR with reasonable accuracy when properly calibrated (Barbeau et al., 1995; Daigger and Nolasco, 1995). Seco et al. (2001) found that the model was reasonably accurate at lower P concentrations but inaccurate at P concentrations above 15 mg/L.

Phosphorus accumulating organisms have not yet been well characterized which poses significant limitations to the model. Many assumptions have been made in ASM No. 2, particularly for P removal mechanisms (Henze et al., 1995). Although some PAOs have been shown to denitrify (Vlekke, 1988; Kuba et al., 1996) this is not taken into account in the model. The model does not account for glycogen uptake by PAOs although there is evidence that glycogen plays an important role in PAO metabolism (Smolders et al., 1994; Lie et al., 1997; Wang et al., 2001). Activated Sludge Model No. 2 assumes PAOs can only grow on internally stored C.

2.8.5 BioWin Model

Some of the limitations in ASM No. 2 have been addressed in a model developed by Barker and Dold (1997). Anoxic growth of PAOs has been included as well as ammonification. The ASM No. 2 model divides all of the variables into particulate and soluble whereas Barker and Dold (1997) added a colloidal fraction. This revised model is implemented in the BioWin (Envirosim Associates Ltd, 2001) software.

Variables used in the EBPR model component of BioWin are given in Table 2.6. There are 15 EBPR model processes in BioWin (Table 2.7). There are four different growth rate equations for PAO heterotrophs depending on whether or not extracellular PO_4 is limiting or not and the N source for cell synthesis (NH_3 or NO_3^-). The growth rate is based on the Monod relationship and the amount of substrate stored in the PAO biomass (rather than the substrate concentration in solution). Anoxic growth of PAO heterotrophs is modeled as a fraction of growth when DO is available as an electron acceptor. Concomitant PO_4 uptake is also a fraction of that which occurs with DO as the electron acceptor. Decay of PAO heterotrophic biomass is

modeled with the lysis-regrowth formulation (reference above equation) as is non-PAO heterotrophic growth.

Table 2.6: EBPR variables in BioWin

Variable	*Description*
Z_{BP}	PAO heterotroph biomass
Z_E	Endogenous residue from organism decay
S_{PHB}	Stored VFA
PP_{LO}	Releasable stored VFA
PP_{HI}	Fixed stored VFA
S_{BSA}	Acetic acid COD
N_{OS}	Soluble biodegradable organic nitrogen
S_{US}	Soluble unbiodegradable COD
ALK	Alkalinity

Table 2.7: EBPR processes in BioWin

Process #	*Description*
1	Aerobic growth of PAO heterotrophs on S_{PHB} with NH_3
2	Aerobic growth of PAO heterotrophs on S_{PHB} with NO_3^-
3	Aerobic growth of PAO heterotrophs on S_{PHB} with NH_3 if PO_4-P limited
4	Aerobic growth of PAO heterotrophs on S_{PHB} with NO_3^- if PO_4-P limited
5	Aerobic decay of PAO heterotrophs
6	PP_{LO} lysis on aerobic death of PAO heterotrophs
7	S_{PHB} lysis on aerobic death of PAO heterotrophs
8	Anaerobic decay of PAO heterotrophs
9	PP_{LO} lysis on anaerobic death of PAO heterotrophs
10	S_{PHB} lysis on anaerobic death of PAO heterotrophs
11	Cleavage of polyphosphate for anaerobic maintenance
12	Sequestration of acetate by PAO heterotrophs
13	Anoxic growth of PAO heterotrophs on S_{PHB} with NH_3
14	PP_{HI} lysis on aerobic death of PAO heterotrophs
15	PP_{HI} lysis on anaerobic death of PAO heterotrophs

A major difference between ASM No. 2 and Barker and Dold (1997) is that the latter model decay with multiple equations to account for the effects of different electron acceptors and

stored N, P, and PHB. Cleavage of polyphosphate is modeled as first order to the mass of PAO heterotrophs. The release of cleaved cellular PO_4 is directly proportional to the uptake of acetate, which is zero order with respect to extracellular acetate concentration and first order with respect to PAO biomass concentration. Storage of PHB is a fraction of the acetate uptake as COD. As with previously mentioned models, VFA uptake is assumed to be uptake of acetate or similar compounds and storage products are assumed to be in the form of PHB.

There are 55 microbial growth parameters, including nine kinetic growth parameters for PAOs (Table 2.8) and 14 stoichiometric growth parameters for PAOs (Table 2.9). Default values in Tables 2.8 and 2.9 are those suggested by Barker and Dold (1997) and are used in the model unless otherwise specified by the user.

Table 2.8: BioWin kinetic parameters for PAO heterotrophs

Parameter	*Description*	*Units*	*Default*
μ_{ZBP}	Maximum specific growth rate	d^{-1}	0.95
μ_{PLIM}	Maximum specific growth rate (P-limited)	d^{-1}	0.42
$K_{S,ZBP}$	Half-saturation coefficient	mg/L as COD	0.1
$K_{S,PLIM}$	Half-saturation coefficient (P-limited)	mg/L as COD	0.05
b_{ZBP}	Endogenous respiration rate	d^{-1}	0.04
$b_{ZBP,AN}$	Anaerobic decay rate	d^{-1}	0.03
K_{SCFA}	Anaerobic uptake of short chain fatty acids	d^{-1}	6
$\eta_{AX,ZBP}$	Anoxic growth factor	---	0.4

Stoichiometric relationships between processes and variables are shown in matrix form (Table 2.10). For each process (Table 2.7), the stoichiometric change is given for every related EBPR variable. A reference variable is given the value of one (or -1). Changes in other variables relative to this reference variable are given by an equation. For example, in Process 1 (Aerobic growth of PAO heterotrophs on S_{PHB} with NH_3), variables are expressed in terms of Z_{BP}. The concentration of stored PHB (S_{PHB}) changes by ($-1/Y_{ZBP}$) mg COD for every mg COD growth of PAO heterotrophs (Z_{BP}). If the biomass yield on PHB (Y_{ZBP}) is 10, then S_{PHB} decreases by 1/10 mg COD for a 1 mg (as COD) increase in Z_{BP}.

Table 2.9: BioWin stoichiometric parameters for PAO heterotrophs

Parameter	*Description*	*Units*	*Default*
Y_{ZBP}	Organism yield for growth	g COD/ g COD	0.639
$f_{P/PHB,AER}$	Aerobic phosphate uptake per unit PHB utilized for growth	g PO_4-P/ g PHB*	0.95
$f_{P/PHB,ANOX}$	Anoxic phosphate uptake per unit PHB utilized for growth	g PO_4-P/ g PHB*	0.35
Y_{PHB}	PHB yield per unit VFA	g PHB*-COD/ g VFA*	0.889
$f_{N,ZBP}$	N content of active biomass	g N/ g COD	0.07
$f_{N,ZE,ZBP}$	N content of endogenous residue	g N/ g COD	0.07
$f_{N,SE,ZBP}$	N content of unbiodegradable soluble material from endogenous decay	g N/ g COD	0.07
$f_{P,ZBP}$	P content of active biomass	g P/ g COD	0.021
$f_{P,ZE,ZBP}$	P content of endogenous residue	g P/ g COD	0.021
$f_{ZE,ZBP}$	Fraction of decaying biomass adding to endogenous residue	---	0.25
$f_{SE,ZBP}$	Fraction of decaying biomass adding to soluble unbiodegradable COD	---	0.2
$f_{P/AC}$	PO_4 release per unit VFA uptake	g PO_4-P/ g VFA*	0.49
$f_{CV,ZBP}$	Conversion factor for biomass and endogenous residue	---	1.42
Y_{PP-LO}	Fraction of P taken up which can be released	---	0.94

*PHB and VFA are measured as COD.

Model rate equations (equations 2.5 through 2.19) corresponding to each of the 15 EBPR processes (Table 2.7) are given below. Switching functions alter process rates in the presence or absence of metabolic requirements. The following switching functions are used in BioWin process rate equations:

DOYesHet	=	Dissolved oxygen concentration,
NH3Yes	=	Ammonia concentration,
PO4Upt Yes	=	Phosphate concentration,
AlkYes	=	Alkalinity concentration, and
NO3Yes	=	Nitrate concentration.

Process variables used in equations (2.5) through (2.19) are defined in Table 2.6. Model parameters are defined in Table 2.8. The following equations are presented by Envirosim Associates Ltd. (2001).

Table 2.10: Stoichiometric changes for BioWin model components of EBPR

	Variables[†]							
Process[*]	*1* Z_{BP}	*2* Z_E	*3* S_{PHB}	*4* S_{BSA}	*5* S_{US}	*6* DO	*7* PP_{LO}	*8* PP_{HI}
1	1		$-\frac{1}{Y_{ZBP}}$			$-\frac{1-Y_{ZBP}}{Y_{ZBP}}$	$\frac{Y_{PP-LO}\cdot f_{P/PHB,AER}}{Y_{ZBP}}$	$\frac{(1-Y_{PP-LO})\cdot f_{P/PHB,AER}}{Y_{ZBP}}$
2	1		$-\frac{1}{Y_{ZBP}}$			$-\frac{1-Y_{ZBP}}{Y_{ZBP}}$	$\frac{Y_{PP-LO}\cdot f_{P/PHB,AER}}{Y_{ZBP}}$	$\frac{(1-Y_{PP-LO})\cdot f_{P/PHB,AER}}{Y_{ZBP}}$
3	1		$-\frac{1}{Y_{ZBP}}$			$-\frac{1-Y_{ZBP}}{Y_{ZBP}}$	$-f_{P,ZBP}$	
4	1		$-\frac{1}{Y_{ZBP}}$			$-\frac{1-Y_{ZBP}}{Y_{ZBP}}$	$-f_{P,ZBP}$	
5	-1	$f_{ZE,ZBP}$				$-(1-f_{ZE,ZBP}-f_{SE,ZBP})$		
6							-1	
7				1				
8	-1	$f_{ZE,ZBP}$			$1-f_{ZE,ZBP}$			
9							-1	
10			-1	1				
11							-1	
12			Y_{PHB}	-1			$-f_{P/AC}$	
13	1		$-\frac{1}{Y_{ZBP}}$				$\frac{Y_{PP-LO}\cdot f_{P/PHB,ANOX}}{Y_{ZBP}}$	$\frac{(1-Y_{PP-LO})\cdot f_{P/PHB,ANOX}}{Y_{ZBP}}$
14								-1
15								

[*]Numbers correspond to processes listed in Table 2.7.
[†]Units of variables 1 through 6 are mg COD/L; Units of variables 7 through 8 are mg P/L.

Table 2.10: Continued

Process*	Variable†				
	9 PO_4	10 NH_3	11 NO_3	12 N_{OS}	13 Alk
1	$-\frac{f_{P/PHB,AER}}{Y_{ZBP}} - f_{P,ZBP}$	$-f_{N,ZBP}$			$\frac{-f_{N,ZBP}}{14}$
2	$-\frac{f_{P/PHB,AER}}{Y_{ZBP}} - f_{P,ZBP}$		$-f_{N,ZBP}$		$\frac{f_{N,ZBP}}{14}$
3					$\frac{-f_{N,ZBP}}{14}$
4			$-f_{N,ZBP}$		$\frac{f_{N,ZBP}}{14}$
5	$f_{P,ZBP} - f_{ZE,ZBP} \cdot f_{P,ZE,ZBP}$	$f_{N,ZBP} - f_{ZE,ZBP} \cdot f_{N,ZE,ZBP} - f_{SE,ZBP} \cdot f_{N,SE,ZBP}$		$f_{SE,ZBP} \cdot f_{N,SE,ZBP}$	$\frac{f_{N,ZBP} - f_{ZE,ZBP} \cdot f_{N,ZE,ZBP} - f_{SE,ZBP} \cdot f_{N,SE,ZBP}}{14}$
6	1				
7					$-1/64$
8	$f_{P,ZBP} - f_{ZE,ZBP} \cdot f_{P,ZE,ZBP}$	$f_{N,ZBP} - f_{ZE,ZBP} \cdot f_{N,ZE,ZBP} - f_{SE,ZBP} \cdot f_{N,SE,ZBP}$		$f_{SE,ZBP} \cdot f_{N,SE,ZBP}$	$\frac{f_{N,ZBP} - f_{ZE,ZBP} \cdot f_{N,ZE,ZBP} - f_{SE,ZBP} \cdot f_{N,SE,ZBP}}{14}$
9	1				
10					$-1/64$
11	1				
12	$f_{P/AC}$				$1/64$
13	$-\frac{f_{P/PHB,ANOX}}{Y_{ZBP}} - f_{P,ZBP}$	$-f_{N,ZBP}$	$\frac{1 - Y_{ZBP}}{2.86 \cdot Y_{ZBP}}$		$\frac{1 - Y_{ZBP}}{2.86 \cdot 14 \cdot Y_{ZBP}} - \frac{f_{N,ZBP}}{14}$
14	1				
15	1				

*Numbers correspond to processes listed in Table 2.7.
†Units of variable 9 are mg P/L; 10 through 12 are mg N/L; Units of variable 13 are mmol/L.

Process 1. Aerobic growth of PAO heterotrophs on S_{PHB} with NH_3:

$$r_{ZBP} = \mu_{MAX,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} Z_{BP} \cdot DOYesHet \cdot NH_3Yes \cdot PO_4UptYes \cdot AlkYes \quad \textbf{[2.5]}$$

where r_{ZBP} = Growth rate of PAO heterotrophs (mg COD L^{-1} d^{-1}),

Process 2. Aerobic growth of PAO heterotrophs on S_{PHB} with NO_3:

$$r_{ZBP} = \mu_{MAX,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} Z_{BP} \cdot DOYesHet \cdot NH_3No \cdot PO_4UptYes \cdot NO_3No \quad \textbf{[2.6]}$$

Process 3. Aerobic growth PAO heterotrophs on S_{PHB} with NH_3 if PO_4-P limited:

$$r_{ZBP} = \mu_{MAX,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} Z_{BP} \cdot DOYesHet \cdot NH_3No \cdot PO_4UptNo \cdot AlkYes \quad \textbf{[2.7]}$$

Process 4. Aerobic growth of PAO heterotrophs on S_{PHB} with NO_3 if PO_4-P limited:

$$r_{ZBP} = \mu_{MAX,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} Z_{BP} \cdot DOYesHet \cdot NH_3No \cdot PO_4UptNo \cdot NO_3Yes \quad \textbf{[2.8]}$$

Process 5. Aerobic decay of PAO heterotrophs:

$$-r_{ZBP} = b_{ZBP} \cdot Z_{BP} \cdot DOYesHet \quad \textbf{[2.9]}$$

Process 6. PP_{LO} lysis on aerobic death of PAO heterotrophs:

$$r_{PO4} = b_{ZBP} \cdot Z_{BP} \cdot DOYesHet \cdot \left(\frac{PP_{LO}}{Z_{BP}} \right) \quad \textbf{[2.10]}$$

Process 7. S_{PHB} lysis on aerobic death of PAO heterotrophs:

$$r_{SPHB} = b_{ZBP} \cdot Z_{BP} \cdot DOYesHet \cdot \left(\frac{S_{PHB}}{Z_{BP}} \right) \quad \textbf{[2.11]}$$

Process 8. Anaerobic decay of PAO heterotrophs:

$$-r_{ZBP} = b_{ZBP,AN} \cdot Z_{BP} \cdot DONoHet \quad \textbf{[2.12]}$$

Process 9. PP_{LO} lysis on anaerobic death of PAO heterotrophs:

$$r_{PO4} = b_{ZBP,AN} \cdot Z_{BP} \cdot DONoHet \cdot \left(\frac{PP_{LO}}{Z_{BP}} \right) \quad \textbf{[2.13]}$$

Process 10. S_{PHB} lysis on anaerobic death of PAO heterotrophs:

$$r_{SPHB} = b_{ZBP,AN} \cdot Z_{BP} \cdot DONoHet \cdot \left(\frac{S_{PHB}}{Z_{BP}} \right) \quad \textbf{[2.14]}$$

Process 11. Cleavage of polyphosphate for anaerobic maintenance:

$$r_{PO4} = b_{ZBP,AN} \cdot Z_{BP} \cdot PolyPYes \cdot DONoHet \quad \textbf{[2.15]}$$

Process 12. Sequestration of acetate by PAO heterotrophs:

$$-r_{SBSA} = K_{SCFA} \cdot Z_{BP} \cdot PolyPYes \cdot S_{BSA}Yes \quad \textbf{[2.16]}$$

Process 13. Anoxic growth of PAO heterotrophs on S_{PHB} with NH_3:

$$r_{ZBP} = \mu_{MAX,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} Z_{BP} \cdot \eta_{AX,ZBP} \cdot DONoHet \cdot NH_3Yes \cdot PO_4UptYes \cdot NO_3Yes \cdot AlkYes \quad \textbf{[2.17]}$$

Process 14. PP_{HI} lysis on aerobic death of PAO heterotrophs:

$$r_{PO4} = b_{ZBP} \cdot Z_{BP} \cdot DOYesHet \cdot \left(\frac{PP_{HI}}{Z_{BP}} \right) \quad \textbf{[2.18]}$$

Process 15. PP_{HI} lysis on anaerobic death of PAO heterotrophs:

$$r_{PO4} = b_{ZBP,AN} \cdot Z_{BP} \cdot DONoHet \cdot \left(\frac{PP_{HI}}{Z_{BP}} \right) \quad \textbf{[2.19]}$$

Growth parameters for non-PAO heterotrophs and autotrophs are given in Table 2.11 through Table 2.14. Since microbial activity of non-PAO heterotrophs and autotrophs is not the focus of this research, process matrices and equations are not given. Details are included in Barker and Dold (1997) or the user manual for BioWin (EnviroSim Associates Ltd., 2001).

Settling is modeled using nine layers in the sequencing batch reactor. Between the top and bottom layer is a feed layer (designated by the user). All other layers are designated as layers "above" or layers "below" the feed layer and are modeled accordingly. The maximum flux of solids from one layer is the sum of the gravity settling and bulk movement flux. The flux of solids through one layer is restricted by the flux of solids out of the layer below. Sludge settling velocity is modeled according to the Vesilind equation for hindered settling:

$$V_S = V_O e^{-KX} \quad \textbf{[2.20]}$$

where V_S = Sludge settling velocity,
V_O = Maximum settling velocity (m/d),
K = Settling parameter (m^3/kg TSS), and
X = Total settleable solids (TSS) concentration (kg TSS/m^3).

Settling parameters are given in Table 2.15.

BioWin models oxygen transfer and calculates DO concentrations at different depths based on aeration and wastewater specifications. A constant DO can also be specified by the user. Oxygen transfer parameters that may be specified by the user are given in Table 2.16 and Table 2.17. Details of the oxygen transfer model are included in the user manual for BioWin (EnviroSim Associates Ltd., 2001).

Table 2.11: BioWin stoichiometric parameters for non-PAO heterotrophs

Parameter	*Description*	*Units*	*Default*
$Y_{ZBH,AER}^{D}$	Organism yield for aerobic growth	g COD/ g COD	0.666
$Y_{ZBH,AN}$	Organism yield for anaerobic growth	g COD/ g COD	0.1
$Y_{AC,ZBH}$	Organism yield for anaerobic fermentation	g COD/ g COD	0.4
$f_{N,ZBH}$	N content of active biomass	g N/ g COD	0.068
$f_{N,ZE,ZBH}$	N content of endogenous residue	g N/ g COD	0.068
$f_{P,ZBH}$	P content of active biomass	g P/ g COD	0.021
$f_{P,ZE,ZBH}$	P content of endogenous residue	g P/ g COD	0.021
$f_{ZE,ZBH}$	Fraction of decaying biomass adding to endogenous residue	---	0.08
$f_{CV,ZBH}$	Conversion factor for biomass and endogenous residue	---	1.48
$Y_{ZBH,ANOX}$	Organism yield for anoxic growth	g COD/ g COD	0.403
ADS_{MAX}	Factor for calculating adsorption rate of slowly biodegradable colloidal COD	---	1

Table 2.12: BioWin kinetic parameters for non-PAO heterotrophs

Parameter	*Description*	*Units*	*Default*
$\mu_{MAX,ZBH}^{D}$	Maximum specific growth rate for aerobic/anoxic growth	d^{-1}	3.2
$K_{S,ZBH}^{D}$	Half-saturation coefficient for aerobic/anoxic growth	mg/L as COD	5
b_{ZBH}^{D}	Decay rate	d^{-1}	0.62
$\eta_{HYD,AX}$	Anoxic hydrolysis factor	---	1
$\eta_{HYD,AN}$	Anaerobic hydrolysis factor	---	0.5
$\eta_{AX,ZBH}$	Anoxic growth factor	---	0.37
K_H	Hydrolysis rate for stored biodegradable COD	d^{-1}	2.81
$K_{S,HYD}$	Half-saturation coefficient for hydrolysis	mg/L as COD	0.15
K_{ADS}	Rate constant for adsorption of colloidal COD	d^{-1}	0.8
$\mu_{ZBH,AN}^{D}$	Maximum specific growth rate in anaerobic fermentation	d^{-1}	4
$K_{S,ZBH,AN}$	Half-saturation coefficient for fermentation	mg/L as COD	5
$K_{R,AMMON}$	Conversion rate of soluble organic N to ammonia	L COD (mg d)$^{-1}$	0.08

Table 2.13: BioWin stoichiometric parameters for autotrophs

Parameter	*Description*	*Units*	*Default*
Y_{ZBA}	Organism yield for aerobic growth	g COD/ g COD	0.15
$f_{N,ZBA}$	N content of active biomass	g N/ g COD	0.068
$f_{N,ZE,ZBA}$	N content of endogenous residue	g N/ g COD	0.068
$f_{P,ZBA}$	P content of active biomass	g P/ g COD	0.021
$f_{P,ZE,ZBA}$	P content of endogenous residue	g P/ g COD	0.021
$f_{ZE,ZBA}$	Fraction of decaying biomass adding to endogenous residue	---	0.08
$f_{CV,ZBA}$	Conversion factor for biomass and endogenous residue	---	1.42

Table 2.14: BioWin kinetic parameters for autotrophs

Parameter	*Description*	*Units*	*Default*
$\mu_{MAX,ZBA}^{D}$	Maximum specific growth rate	g COD/ g COD	0.5
$K_{S,ZBA}$	Half saturation coefficient	mg NH_4/L	1
b_{ZBA}^{D}	Decay rate	d^{-1}	0.04

Table 2.15: BioWin settling parameters

Parameter	*Units*	*Default*
Maximum Vesilind settling velocity (V_o)	m/d	170
Vesilind model parameter (K)	m^3/ kg TSS	0.00037
Clarification switching function	mg/L	20
Maximum compactability constant	mg/L	15000

Table 2.16: BioWin aeration parameters

Parameter	*Default*
Alpha F	0.5
Beta	0.95
Surface pressure	101.325
Fractional effective saturation depth	0.325
Saturation concentration	9.07
Oxygen mass fraction	0.232
Set point controller gain	1

Table 2.17: BioWin diffuser parameters

Parameter	*Default*
k1 in C = k1(PC)^0.25 + k2	2.5656
k2 in C = k1(PC)^0.25 + k3	0.0432
Y in Kla = C Usg^Y	0.82
Area of one diffuser m^2	0.041
% of tank area covered by diffusers	15
Min coverage %	1
Max coverage %	50
Min air flow rate per diffuser m^3/hr	0.5
Max air flow rate per diffuser m^3/hr	10

Chapter 3: Fermentation Potential

3.1 Introduction

Availability of fermentation products is one of many important factors in supporting enhanced biological phosphorus removal (EBPR). Liquid dairy manure tends to have a high concentration of phosphate (PO_4) relative to soluble chemical oxygen demand (COD) (Whichard, 2001), increasing the likelihood that addition of volatile fatty acids (VFAs) would be required for EBPR. Utilizing other sources of VFA-COD add to the total treatment volume, increasing the size of the system. While manure solids or other carbon (C) sources could be fermented and added to the liquid waste to provide some of the required VFA, fermentation of the liquid waste stream has advantages. The liquid fraction of wastewater contains more readily fermentable COD than the solid fraction. If enough VFA could be yielded from fermentation of the liquid fraction, wastewater could be fermented after solid separation, reducing the total volume needed for the fermenter. In addition, prefermentation would reduce non VFA-COD and, therefore, the subsequent nutrient removal process would more readily select for PAO heterotrophs (rather than non-PAO heterotrophs) if the substrate types were more limited.

The fermentation potential of dairy manure is unknown. The objective of the experiment described in this chapter was to determine the potential for VFA production from fermentation of the liquid manure fraction.

3.2 Methodology

Dairy manure was fermented to determine the extent of VFA production. Manure was collected from four dairy cows. Two of the cows were fed a high phosphorus (P) diet and two of the cows were fed a low P diet. Laboratory analysis of manure samples was conducted to measure VFA potential.

3.2.1 Manure Collection

Manure was collected from four cows at the Virginia Tech dairy. Feces were scraped from stalls where cows were enclosed separately for 24 hours. Urine was collected through catheters for this 24-hour period. Manure from each cow was kept separate throughout

collection and analysis. At the end of the 24-hour collection period, the feces and urine were combined and mixed thoroughly with a high-powered drill resulting in a separate manure sample for each cow. The manure mixture was diluted 1:1 to better resemble manure collected by flushing and to facilitate solid separation. After dilution, the manure was settled 24 hours prior to solid separation. Each of the four manure mixtures was passed separately through a mechanical solid separator with a 2-mm screen. As solids were separated from the manure, the liquid fraction was collected beneath the screen on a plastic tray.

3.2.2 Experimental Design

Volatile fatty acid potential was measured using a procedure presented by Lie and Welander (1997). Immediately following solid separation, manure samples were diluted 1:20 to enable syringe sampling and filtration required for VFA analysis. Initial VFA concentrations were determined for diluted manure from each cow. Manure was then added to 50-ml serum bottles, filling each to the brim. After adding manure, each bottle was purged with nitrogen gas for 30 minutes to remove oxygen. Bottles were then sealed with butyl rubber stoppers and aluminum crimping caps. Three bottles were prepared for each of the four cows, resulting in 12 bottles. Two control serum bottles with 100 mg/L VFA were purged and sealed identically to the manure samples to assess the potential leakage throughout the sampling period. Bottles were stored in the dark at 23 ± 2° C.

Concentrations of acetic, propionic, butyric, and valeric acids were measured daily for each bottle. Samples were removed using a syringe and then filtered through a 0.45-µg filter and frozen until analysis. Bottles were sampled over a period of 13 days at which point the VFA concentration was no longer increasing in any of the 12 bottles. The peak concentrations of VFA that occurred during this time were used to determine the total VFA potential.

To determine off-gas formation, a second set of bottles was filled, purged, and sealed in triplicate as done for those used for VFA analysis. For these bottles, only 35 ml was added to the 50-ml bottles to enable sampling of the headspace. These bottles were also stored in the dark at 23 ± 2° C for the entire sampling period. On the last day of VFA sampling, the headspace of these bottles was analyzed for methane (CH_4) and carbon dioxide (CO_2).

3.2.3 Sample Analysis

Samples were analyzed for acetic, propionic, butyric, and valeric acid with a Hewlett Packard 5890 gas chromatograph equipped with a Carbopack (60/80) column (length 1.8 m, diameter 3.2 mm) and a flame ionization detector (FID). The temperatures of the column, injector, and detector were 145° C, 225° C, and 250° C, respectively. Nitrogen gas saturated with phosphoric acid was used as a carrier gas (40 ml/min). Each sample was analyzed in duplicate. Samples not analyzed immediately were frozen until analysis. The headspace gas was analyzed for CO_2 and CH_4 using a Shimatsu gas chromatograph equipped with thermal conductivity detector (TCD). Chemical oxygen demand (COD), volatile suspended solids (VSS), and total suspended solids (TSS) concentrations were measured for all manure samples. This analysis was done as described in Standard Methods (APHA et al., 1998) by the Virginia Tech Dairy Nutrition Laboratory.

3.3 Results and Discussion

Due to equipment failure, VFA analysis could not be completed for all samples. Only data from cows 1 and 2 are discussed here. Data from cow 3 were not included because samples for days three and four (time of peak VFA production) could not be analyzed. Data from cow 4 were not included because only two samples were analyzed. Complete results for samples from each of the four cows are presented in Appendix A.

Cow 1 was on a low P diet and cow 2 was on a high P diet. Peak VFA concentrations of acetic, butyric, and propionic acids were identified for each of the manure samples. Although valeric acid peaks were detected using gas chromatography, they were below the reliable detection level of 10 mg/L of the gas chromatograph. Total VFA production hereafter refers to the combined concentrations of only acetic, butyric, and propionic acids.

Acid concentrations were plotted as they were analyzed to identify the peak concentration. Because of the equipment problems, sample analysis lagged behind sample acquisition. In Cow 1 fermenters (1A, 1B, and 1C), peak acid concentrations occurred between days three and four (Figures 3.1 through 3.3), which was consistent with findings by Lie and Welander (1997) for municipal wastewater.

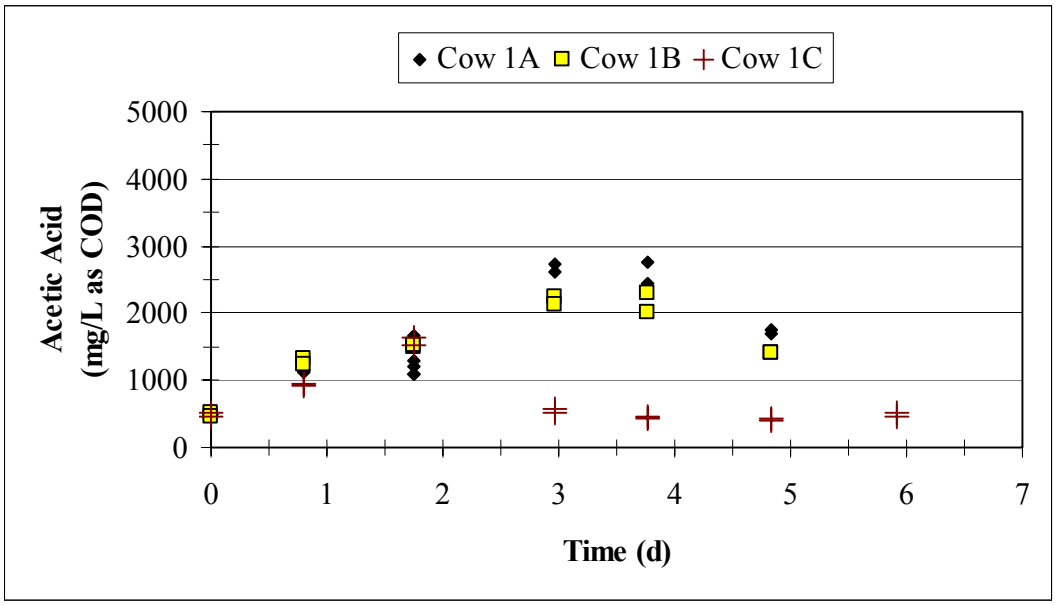

Figure 3.1: Acetic acid concentrations in three laboratory-scale fermenters each containing manure from cow 1 measured over a seven day period.

On day seven, headspace was analyzed for fermenters 1A, 1B, and 1C. No CH_4 was detected in the off-gas indicating that methanogenesis was not yet taking place on day 7 of fermentation of manure from cow 1. No further gas analysis was completed due to equipment problems.

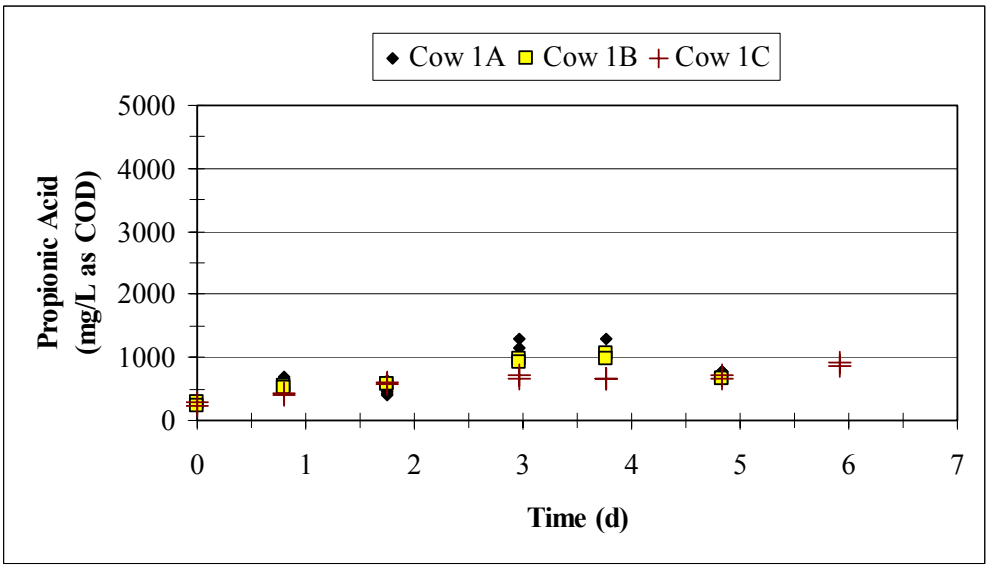

Figure 3.2: Propionic acid concentrations in three laboratory-scale fermenters containing manure from cow 1 measured over a seven day period.

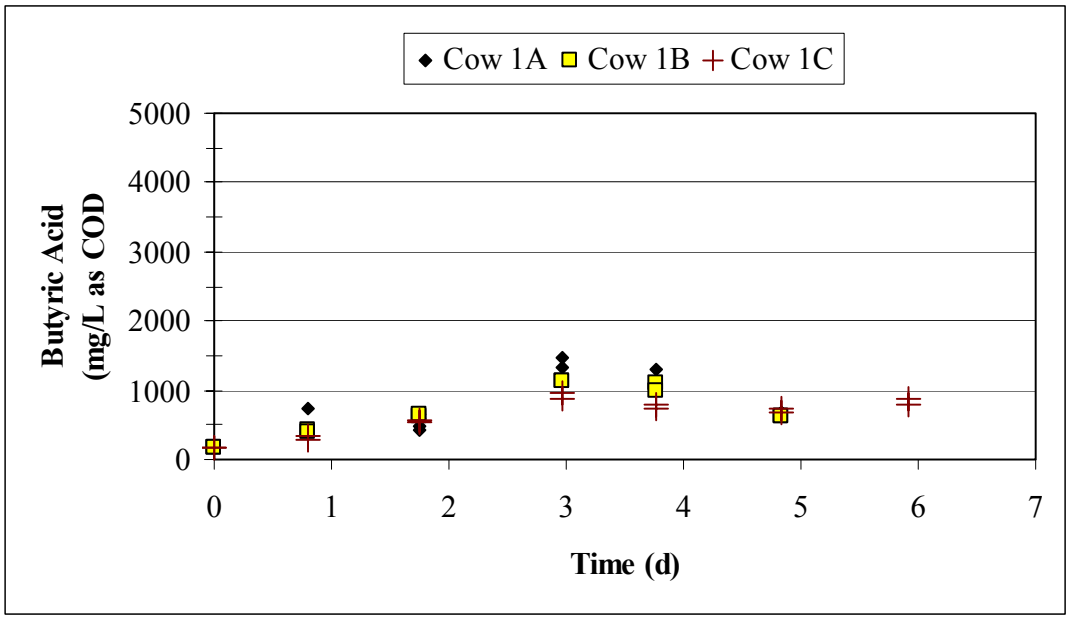

Figure 3.3: Butyric acid concentrations in three laboratory-scale fermenters containing manure from cow 1 measured over a seven day period.

Volatile fatty acid production for fermenters 2A, 2B and 2C, containing manure from cow 2, peaked later than those from cow 1 (Figures 3.4 through 3.6). Peak concentrations were also not as clearly defined for cow 2 manure. Peak concentrations of acetic acid were higher for cow 2 (high-P diet) than for cow 1 (low P diet) (Table 3.1). However, without analyzing fermented manure from the other two cows (cows 3 and 4), differences in cow diet could not be implicated as a cause of variation in VFA production. The highest VFA concentration for fermented manure from cow 2 was on day 11, which was the last day of sampling. This was not consistent with results from cow 1 and posed a question about the adequacy of sample preservation. Samples were analyzed multiple times due to equipment problems and may have been subject to volatilization from repeated thawing and air exposure.

The total average peak VFA concentration was 4479 mg COD/L (Table 3.1). This peak VFA concentration corresponded to 15.3% of the total COD prior to fermentation (Table 3.2). Acetic acid was produced in greatest abundance (Table 3.1), accounting for 57% of the total VFA produced as COD. Propionic and butyric acid accounted for 23 and 20% of the total VFA COD produced, respectively. Acetic acid was most plentiful in agreement with literature (GonCalves, 1994; Skalsky and Daigger, 1995). Butyric acid made up a more significant fraction of the VFA production than compared to other experimentally determined values

(Elefsionitis and Oldham, 1991; GonCalves, 1994; Skalsky and Daigger, 1995; Wentzel et al., 1989b).

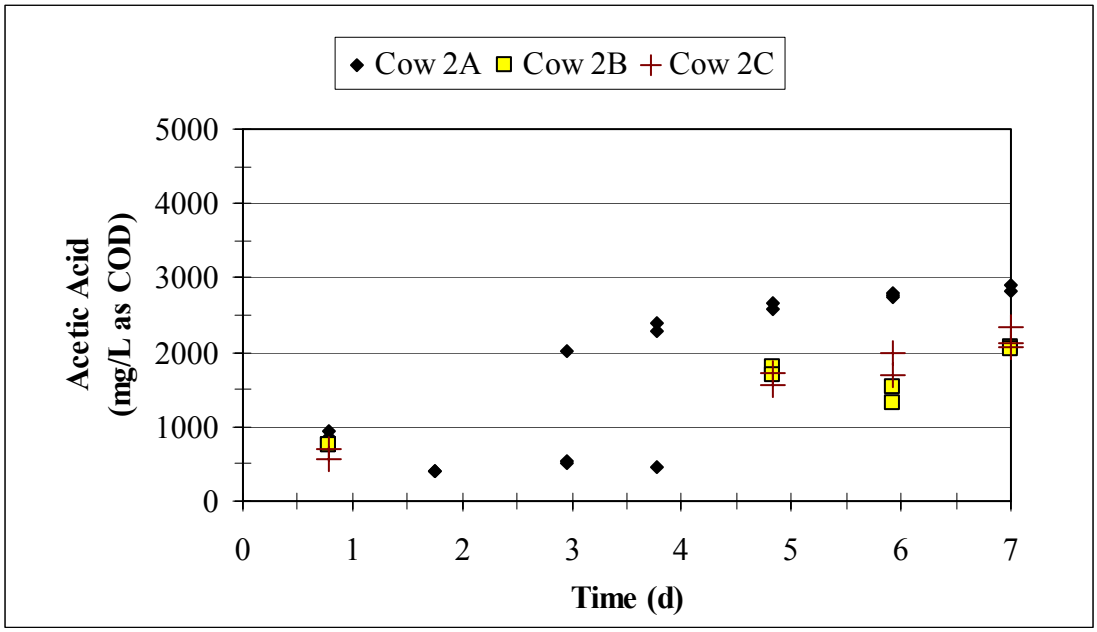

Figure 3.4: Acetic acid concentrations in three laboratory-scale fermenters each containing manure from cow 2 measured over an 11-day period.

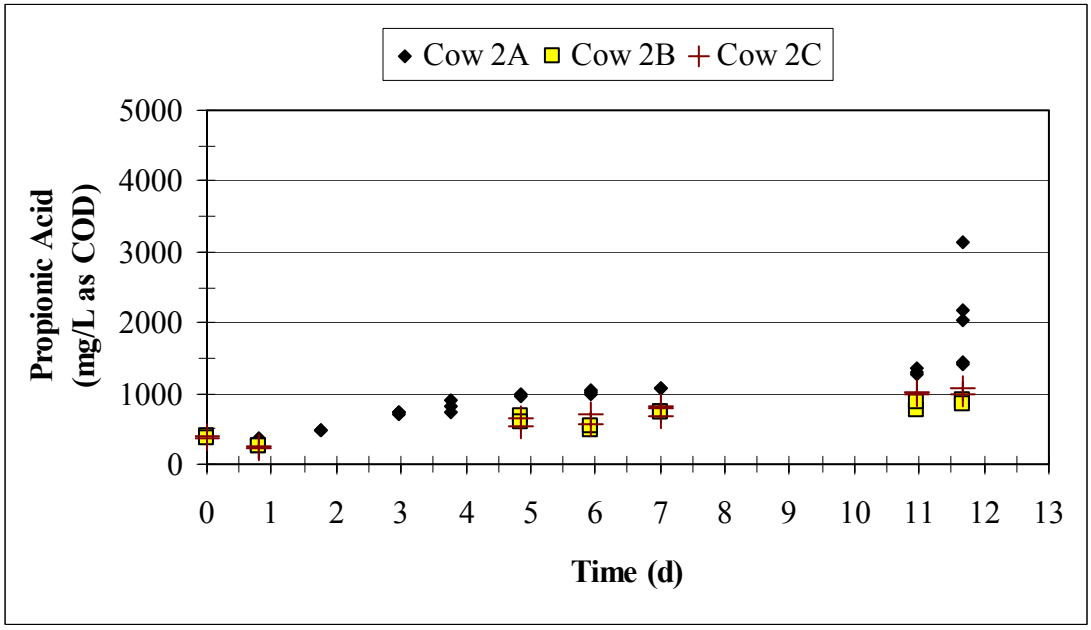

Figure 3.5: Propionic acid concentrations in three laboratory-scale fermenters containing manure from cow 2 measured over a seven day period.

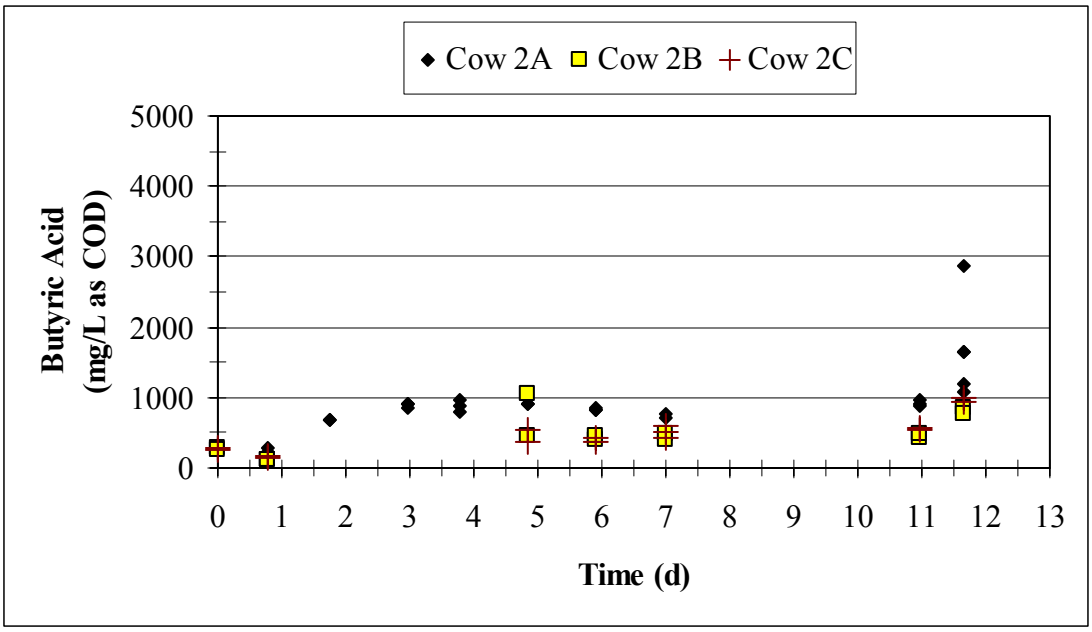

Figure 3.6: Butyric acid concentrations in three laboratory-scale fermenters containing manure from cow 2 measured over an 11-day period.

Table 3.1: Peak acid concentrations of fermented cow manure

Sample[*]	*Diet*	*Peak acid concentration (mg VFA-COD*[†]*/L)*			
		Acetic	*Propionic*	*Butyric*	*Total*
1A	Low P	2670	1217	1405	5292
1B	Low P	2195	1021	1130	4346
1C	Low P	1592	888	917	3397
Cow 1 Average		*2152*	*1042*	*1151*	*4345*
2A	High P	3548	1306	918	5772
2B	High P	2487	827	446	3760
2C	High P	2762	1001	546	4309
Cow 2 Average		*2932*	*1045*	*637*	*4614*
Overall Average		*2542*	*1043*	*894*	*4479*

[*]Sample number designation refers to cow; letter designation refers to fermented triplicate.
[†]Acid concentrations given as COD.

Given pretreated wastewater characteristics of dairy manure (Whichard, 2001), and assuming conversion of 15.3% of influent COD to VFA, the VFA concentration resulting from fermentation would be between 594 and 822 mg VFA-COD, depending on the extent of hydrolysis of particulate COD (Table 3.3).

Table 3.2: Volatile fatty acid produced as percent of soluble COD available prior to fermentation

Cow	*Diet*	*COD*[*]	*VFA-COD*[†]	*VFA Yield*[‡]
		(mg COD/L)		*(%)*
1	Low P	25400	4345	17.1
2	High P	33200	4614	13.9
Average	---	29300	4480	15.3

[*]Soluble COD, filtered through 0.45 μg prior to analysis.
[†]As given in Table 3.1.
[‡]As percent conversion of total available COD prior to fermentation.

Table 3.3: Chemical oxygen demand and VFA production in dairy manure

COD Fraction	*Concentration of COD (mg/L)*				
	Before Fermentation[*]	*After fermentation*[†]		*After Fermentation*[‡]	
		Non-VFA	*VFA*	*Non-VFA*	*VFA*
Soluble readily biodegradable	1848	1565	283	1565	283
Slowly biodegradable particulate	1492	1492	0	1264	228
Colloidal biodegradable	2030	1719	311	1719	311
Inert particulate	983	983	0	983	0
VFA-COD	0		594		822

[*]Whichard (2001).
[†]Assuming fermentation of soluble and colloidal COD.
[‡]Assuming fermentation of soluble, colloidal, and particulate COD.

Phosphate removal is also dependent on the type of VFAs. Phosphate removal by the addition of individual VFAs of acetic, propionic, and butyric acids were 18.8, 31.5, and 39 mg PO_4-P/mg COD, respectively (Abu-ghararah and Randall, 1991). Given the average production of acetic, propionic, and butyric acids as 57, 23, and 20% of the total VFA-COD (Table 3.1), 36 mg PO_4-P could be removed according to the PO_4-P removal efficiencies determined by Abu-ghararah and Randall (1991) (Table 3.4).

Most EBPR activity is characterized with respect to acetic acid as it is typically produced in greatest abundance. Volatile fatty acid requirements for removal of 1 mg PO_4-P/L range from 6 to 20 mg acetic acid (as COD)/mg PO_4-P removed (Abu-ghararah and Randall, 1991; Barnard et al., 1994; Lie et al., 1997). Based on manure characteristics (Table 3.3), and removal of 1 mg PO_4-P per 20 mg VFA-COD, total PO_4-P removal would be between 30 and 41 mg PO_4-P/L (Figure 3.4).

Table 3.4: Phosphate removal ability based on VFA production from fermentation of dairy manure

Volatile fatty acid	*VFA Produced*[*] *(mg/L COD)*		*PO_4-P removed*[§] *(mg PO_4-P/L)*	
	No part.[†]	*w/ part.*[‡]	*No part.*[†]	*w/ part.*[‡]
Acetic	339	475	18	25
Propionic	137	192	4	6
Butyric	119	167	3	4
Total	594	833	25	36

[*]Assuming 15.3 percent COD conversion by fermentation of manure characterized by Whichard (2001).
[†]Assuming fermentation of soluble and colloidal COD.
[‡]Assuming fermentation of soluble, colloidal, and particulate COD.
[§]Assuming 18.8, 31.5, and 39 mg VFA-COD/mg PO_4-P removed for acetic, propionic, and butyric acids (Abu-ghararah and Randall (1991).

No COD analysis was conducted on manure samples after fermentation. Analysis of COD concentrations would have been beneficial in balancing COD. Knowledge of COD recovery would also give more confidence in results, which was limited by equipment malfunction. Further analysis of COD on manure samples after fermentation would also provide information on COD losses experienced through fermentation. Chemical oxygen demand losses between 15 and 20% of the initial COD due to anaerobic stabilization (Chapter 2) have been identified in EBPR systems (Wable and Randall, 1992). Such COD losses were not taken into account when estimating the effects of fermentation on influent wastewater composition (Chapter 4).

Given that peak concentrations identified may not be representative of the actual peak concentrations due to the inability to complete sample analysis, it is expected that VFA potential is at least as high as indicated by the results. In addition to volatilization from samples, these values do not take into account possible volatilization due to leaks in the fermenters, which may have occurred through small holes formed in the butyl rubber stoppers from piercing them with a syringe for sample extraction. Analysis of control samples indicated that leakage may have contributed to reduced VFA concentrations. For acetic acid, control analysis indicated 25 and 31% leakage at days one and seven respectively. Due to the sensitivity of the gas chromatograph (±10 mg/L) and the lack of samples analyzed, VFA losses during the experiment could not be confirmed and, therefore were not accounted for in VFA potential (Table 3.2).

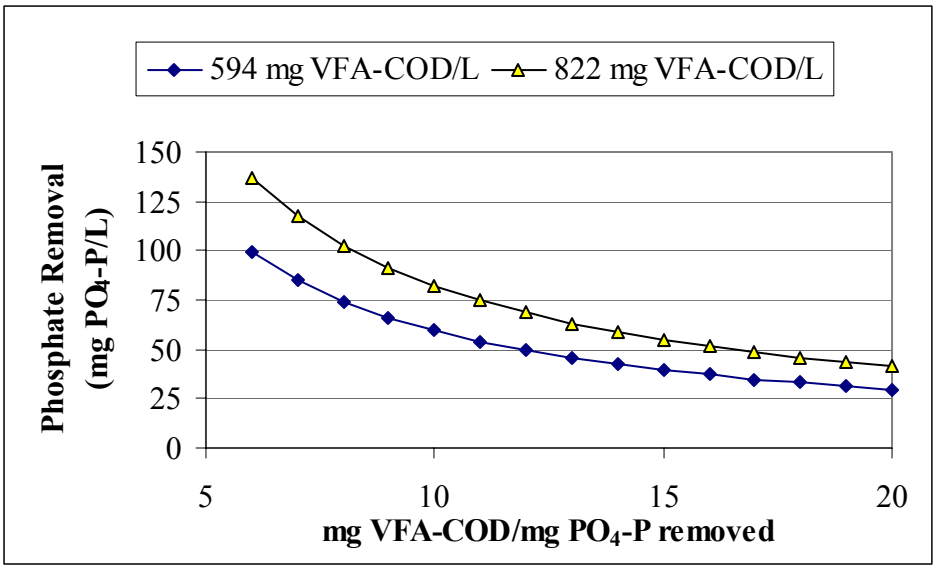

Figure 3.7: Phosphate removal for given removal ratios for different amounts of VFA-COD derived from fermentation. The lower line indicates fermentation of soluble COD fractions and the higher line indications fermentaion of colliodal and soluble COD fractions.

Results for total VFA production are in agreement with COD transformations reported in literature (Table 3.5). Factors that affect VFA production are solids content, temperature, and reactor configuration. All of the data given in Table 3.5 were reported for ambient temperatures (approximately 20° C). As solids fermentation is a common practice, most experimental data for VFA production is for fermentation of the solid fraction of wastewater (primary solids). GonCalves et al. (1994) reported a VFA-COD yield of 17% of total influent COD, which was the highest value reported for total wastewater.

Table 3.5: Experimentally determined VFA production from fermentation of municipal wastewater as percent of total influent COD

Source	*Wastewater Fraction*	*VFA-COD/Total COD (%)*
GonCalves et al. (1994)*	Total	2-17
Lilley et al. (1988)*†	Solid	17
Ranges as reported by Grady et al. (2000)	Solid	4-21
Elefsiniotis and Oldham (1991)	Solid	4-8
Skalsky and Daigger (1995)	Solid	4-18
Moser-Engeler et al. (1999)	Solid	4-7
Munch and Koch (1999)	Total	2-14

*Converted from units given in mg VFA/mg VSS assuming 1.42 mg COD/mg VSS

†As reported in Skalsky and Daigger (1995).

3.4 Summary

Fermentation potential was determined experimentally for the liquid fraction of solid separated dairy manure. Fermented manure was analyzed for concentrations of acetic, propionic, butyric, and valeric acids. Acetic, propionic, and butyric acids made up 57, 23, and 20%, respectively, of the total VFA production. Significant amounts of valeric acids were not detected. The average peak VFA production was 15.3% of the fermented COD. It is suspected that VFA losses due to volatilization were a factor in sample analysis. Therefore, the reported VFA yields may be underestimated. Although maximum values reported in literature are similar, many of the yields in literature represent that of primary solids from wastewater rather than the total wastewater. Phosphate removal is dependent on the available VFA-COD with respect to PO_4-P and the removal efficiency. With fermentation of soluble and colloidal COD in dairy manure, it was estimated that potential PO_4-P removal would be between 30 and 99 mg PO_4-P/L. With fermentation of soluble, colloidal, and particulate COD, the PO_4-P removal was estimated between 25 and 36 mg PO_4-P/L.

Chapter 4: Sensitivity Analysis

4.1 Introduction

Wastewater treatment models have been developed to predict nitrification, denitrification, carbon (C) oxidation, and enhanced biological phosphorus removal (EBPR). The lack of information on mechanisms responsible for EBPR has hindered the development of EBPR models. Application of EBPR models is largely limited by experimental measurements of model parameters. Most experimentally determined parameters are intrinsic, reflecting growth on unlimited substrate under optimal conditions. Such parameter measurements are not applicable for systems at other physiological states. Therefore, applying models accurately can be difficult without experimentally determining microbial growth parameters for the specific system configuration and wastewater at hand.

Since BioWin was developed for municipal wastewater, it could not be used confidently in modeling dairy manure wastewater without further investigation of the model. Experimental determination of microbial growth parameters for pretreated dairy manure was beyond the resources of this project. Since no parameters could be measured, each had to be estimated in order to utilize the model. By determining the sensitivity of model outputs to different input parameter values, the effects of parameter estimation could be quantified.

The objectives of the sensitivity analysis were to identify the most critical EBPR parameters and to determine if BioWin were accurate enough to be used for process design. Identifying the most critical parameters would aid in calibration of the model so that it could be used more accurately for design.

4.2 Procedure

To conduct a sensitivity analysis of BioWin, a baseline scenario was selected based on the treatment needs of this research. Simulations were run to determine the sensitivity of model outputs to microbial growth parameters. Model evaluation was based on the range of parameter values enabling EBPR in BioWin simulations.

A reactor configuration was selected to establish a baseline from which to analyze the EBPR model component of BioWin. The baseline scenario consisted of a sequencing batch

reactor (SBR) configured to promote EBPR. The BioWin model was not used to simulate prefermentation because experimental data were collected that accounted for changes in manure wastewater characteristics due to fermentation. Model parameters and wastewater characteristics were estimated based on information found in the literature and results from Chapter 3. Simulations were run to determine model sensitivity to microbial growth parameters of each of the three microorganism classifications used in BioWin: phosphorus accumulating organism (PAO) heterotrophs, non-PAO heterotrophs, and autotrophs. Model output was used to identify critical parameters, i.e. parameters to which phosphate (PO_4) is most sensitive. Parameters to which PO_4 concentrations were most sensitive were further analyzed by completing the following tasks:

1. Identify the range of values within which each critical parameter supports EBPR;
2. Compare the EBPR ranges determined in BioWin simulations to those found in literature;
3. Evaluate model relationships based on information found in literature; and
4. Choose parameter values for BioWin simulations to design an EBPR system for dairy manure.

4.2.1 Baseline Scenario in BioWin

The baseline scenario was defined by SBR configuration settings, model parameters, influent wastewater composition, and other BioWin model settings. BioWin model parameters included selected microbial growth parameters, settling parameters, and aeration parameters. The influent wastewater composition was based on solid separated manure (Whichard, 2001) adjusted for changes in the COD concentrations based on results from the fermentation analysis (Chapter 3).

Two different baselines were established using an SBR configured to promote EBPR. The first baseline (BL_1) was configured to enable complete removal of PO_4. Analysis of results indicated that model response from an incomplete PO_4 removal system would be beneficial. Therefore, a second baseline (BL_2), configured to promote incomplete PO_4 removal, was established. BioWin settings described in the following sections were used for both BL_1 and BL_2

with the exception of the aeration settings. Unless otherwise indicated, BioWin default values and settings were used in simulations.

4.2.1.a Sequencing Batch Reactor Configuration

Complete PO_4 removal was chosen as the first baseline (BL_1) to represent the greatest possible desired PO_4 removal. Dissolved oxygen concentration, cycle times, and retention times were selected to enable complete PO_4 removal from the system. The SBR was 0.3 m deep, 0.058 m wide, and 0.2 m long (Figure 4.1). The liquid volume of the SBR was 3.5 L when full (at the end of the last feed cycle).

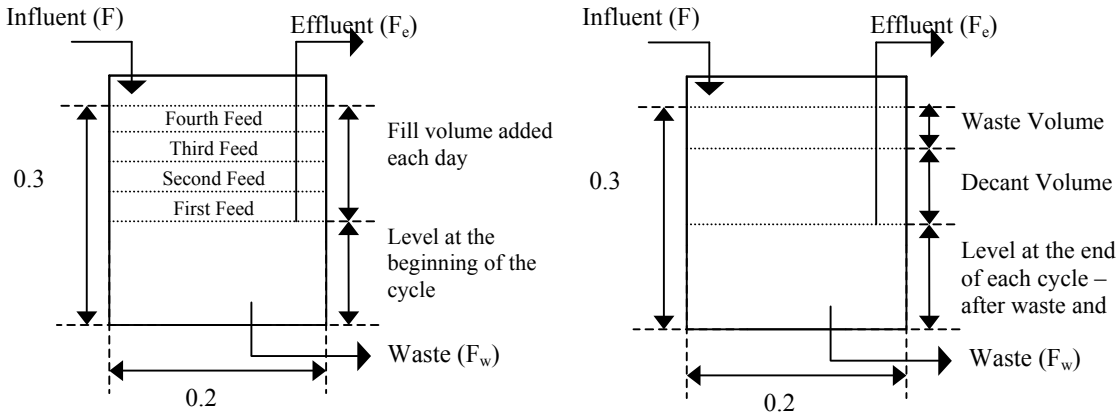

Figure 4.1: Sequencing batch reactor dimensions and flow streams. First figure demonstrates feed volumes throughout the one-day cycle and the second figure demonstrates relative volumes of waste and decant removed at the end of the one-day cycle.

The reactor was continuously mixed except for a one-hour settling period. The total cycle time was one day. An effective sludge retention time (SRT) of three days and an effective hydraulic retention time (HRT) of two days were chosen for SBR operation. Influent, decant (effluent), and wastage (underflow) flow rates were calculated based on effective HRT and effective SRT, which account for time in the SBR not devoted to biological reactions, i.e., time needed for settling and decant. The effective reaction time was 22.5 hours. Influent (F) and wastage flowrates (F_w) were calculated (Appendix B.1) based on relationships given by Grady et al., (1999):

$$F = \frac{\zeta \cdot V}{\tau_e} \quad \textbf{[4.1]}$$

where F = influent flowrate to SBR (L/d),
τ_e = effective HRT (d),
ζ = fraction of the total cycle devoted to fill plus react, and
V = volume of SBR (L).

$$F_w = \frac{\zeta \cdot V}{\Theta_{ce}} \quad \textbf{[4.2]}$$

where F_w = the wastage flow rate (L/d), and
Θ_{ce} = effective SRT (d).

The SBR was fed and intermittently aerated four times per day (Figure 4.2). Sludge was wasted once per day at the end of the last mixing/aerobic react period. Biomass wastage was specified as a scheduled flow rate. A Garrett configuration (Grady et al., 1999) was assumed for biomass wastage. In a Garrett configuration, biomass is removed from the reactor by removing mixed liquor (during mixing) rather than removing settled solids (biomass) as is done in a conventional configuration. Treated effluent was decanted from the system once per day beginning 1 hour after the start of the settling period. BioWin input tables detailing the scheduled flow rates are presented in Appendix B.2 (Tables B.1 through B.3).

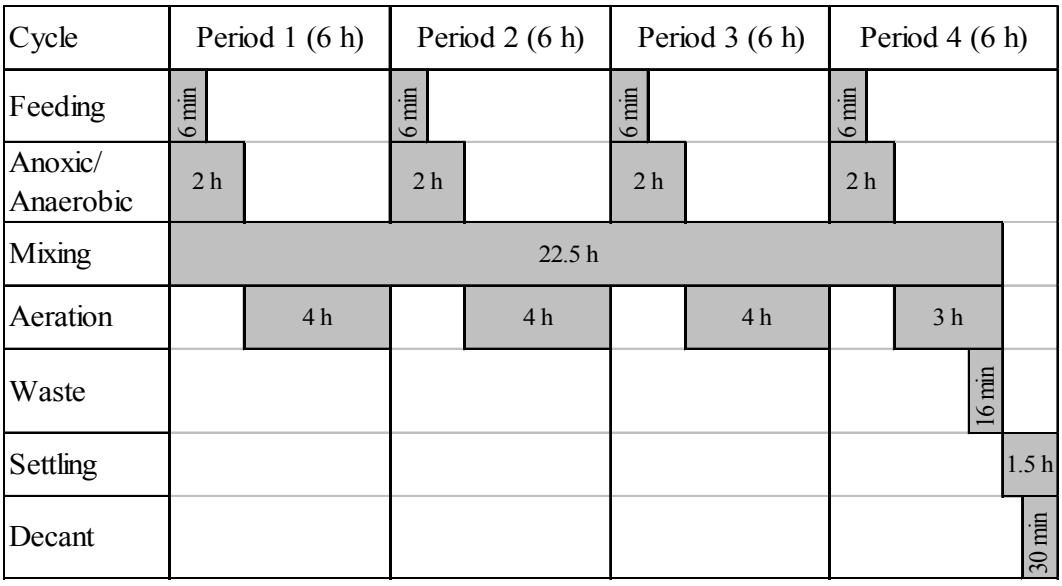

Figure 4.2: Sequencing batch reactor schedule for a one-day cycle used in BioWin simulations (time increments are not drawn to scale).

Effluent was removed from the SBR using the *minimum decant level* option in BioWin, which allows the user to specify the exact volume of effluent to be removed. The minimum decant level was 53.12% of the total volume, which was calculated based on the reactor volume and the desired HRT. Calculations for determining these model settings are included in Appendix B.1.

The dissolved oxygen (DO) concentration was set at 2 mg/L during each of the four aeration cycles (Table B.4). At the beginning of the aeration period, the DO concentration was equal to 2 mg/L and remained at that concentration until the end of the aeration period (beginning of anaerobic period) at which point it became zero. Although, in reality, the DO concentration would not remain constant throughout the cycle (nor could it change instantaneously from zero to 2 mg/L), a set DO concentration was chosen to isolate the effects of changes in microbial growth parameters. Based on the portion of the cycle dedicated to aeration (Figure 4.2), the aerobic SRT (SRT_{AER}) was two days, which is a typical value shown to enable growth of phosphorus accumulating organisms (PAOs) while excluding nitrifiers (Grady et al., 1999). Nitrifiers require longer SRTs to become established in activated sludge systems. BioWin default aeration and diffusion parameters were used.

4.2.1.b Model Parameters

BioWin default values for microbial parameters were used for the baseline, with the exception of those values determined experimentally by Whichard (2001) (Table 4.1), the fermentation rate (Table 4.1), and settling parameters (Table 4.2). The fermentation rate was set to zero to eliminate fermentation reactions and the use of that model component. It was assumed that fermentation would not occur within the SBR because the anaerobic periods of the cycle were short and the most readily fermentable COD would already be transformed in the prefermentation process. In actuality, some fermentation would occur within the SBR. However, it was assumed that VFA production within the SBR would be minimal compared to VFA produced during prefermentation and the amount of VFA required for the target P removal. Settling parameters were adjusted from the default values to achieve ideal settling, i.e., eliminating total suspended solids (TSS) from the decanted effluent.

Table 4.1: Baseline parameter values differing from BioWin default values

Parameter	*Units*	*Default*	*Baseline Value*
Non-PAO heterotrophic stoichiometric parameters			
Yield (aerobic growth)*	g COD/ g COD	0.666	0.42
Non-PAO kinetic stoichiometric parameters			
Mu Max (aerobic/anoxic growth)*	d^{-1}	3.2	6
K_S COD*	mg/L as COD	5	207
Decay rate*	d^{-1}	0.62	0.2448
Fermentation rate†	d^{-1}	4	0
Autotroph kinetic parameters			
Mu Max*	g COD/ g COD	0.5	0.768
K_s NH_4*	mg NH_4/L	1	1
Decay rate*	d^{-1}	0.04	0.072

* Values determined experimentally by Whichard (2001).

† Set to zero to turn off fermentation component of model.

Table 4.2: BioWin settling parameters

Parameter	*Units*	*Default*	*Baseline Value*
Maximum Vesilind settling velocity (V_o)	m/d	170	288
Vesilind model parameter (k)	m^3/ kg TSS	0.00037	0.00015
Clarification switching function	mg/L	20	0
Maximum compactability constant	mg/L	15000	30000

4.2.1.c Influent Wastewater Composition

Dairy manure wastewater characteristics determined by Whichard (2001) were used for model input except for colloidal biodegradable COD (X_{sc}) and soluble readily biodegradable non-VFA COD (S_{bsc}), which were adjusted for prefermentation. The manure analyzed by Whichard (2001) was collected at a Pennsylvania dairy by scraping and pretreated with solid separation. Prior to analysis, Whichard diluted the manure 1:2.844 to better resemble manure collected by flushing.

Concentrations of colloidal and readily biodegradable COD were adjusted to account for prefermentation based on experimentally determined fermentation potential of manure collected at the Virginia Tech dairy (Chapter 3). It was estimated that 15.3% of the combined soluble and colloidal COD would be recovered from prefermentation of dairy manure. It was assumed that the retention time in the fermenter would not be sufficient for significant hydrolysis of slowly biodegradable particulate COD (X_{sp}). Influent wastewater characteristics (Table 4.3) were entered as scheduled flow rates (Appendix B.2, Table B.5), which is required for variable flow systems in BioWin.

Table 4.3: Influent wastewater characteristics

State Variable	*Units*	*Description*	*Before fermenter*[*]	*After fermenter*[†]
Z_{bh}	mg/L	Non PAO active heterotrophic biomass	0	0
Z_{ba}	mg/L	Active autotrophic biomass	0	0
Z_{bp}	mg/L	Active PAO biomass	0	0
Z_e	mg/L	Debris	0	0
X_{sp}	mg/L	Slowly biodegradable particulate COD	1492	1492
X_{sc}	mg/L	Colloidal biodegradable COD	2030	1719
X_i	mg/L	Inert particulate COD	983	983
X_{on}	mg N/L	Organic particulate nitrogen	46.9	46.9
S_{phb}	mg/L	Stored PHB	0	0
PP-lo	mg P/L	Releasable poly phosphate	0	0
PP-hi	mg P/L	Non- releasable poly phosphate	0	0
S_{bsc}	mg/L	Soluble readily biodegradable non-VFA COD	1848	1565
S_{bsa}	mg/L	Soluble VFA COD	0	593
NH_3-N	mg N/L	Ammonia	498	498
N_{os}	mg N/L	Organic soluble nitrogen	56	56
NO_3^--N	mg N/L	Nitrate	0	0
PO_4-P	mg P/L	Phosphate	88	88
S_{us}	mg/L	Soluble unbiodegradable COD	748	748
N_{us}	mg N/L	Soluble unbiodegradable nitrogen	0	0
ISS	mg/L	Inert suspended solids	800	800
Alk.	mmol/L	Alkalinity	57	57
DO	mg/L	Dissolved oxygen	0	0

*Values from Whichard (2001).
[†]Adjusted concentrations based on experimentally determined fermentation activity.

4.2.1.d Other BioWin Model Settings

Other model options included accuracy and seed sludge settings. Dynamic simulation accuracy settings were changed from default values to increase the accuracy of integration calculations. The variable "accuracy" that controls integration step size was set to one, the highest possible accuracy in BioWin. The "theta" variable controls the growth rate of integration step sizes. Higher theta values allow steps to grow more rapidly. Theta was set to 50%, the lowest possible value. The seed sludge age was set at three days, which was the SRT of the SBR.

Initial concentrations of the state variables can be specified by the user or can be computed in BioWin based on the seed sludge age, reactor dimension, and influent wastewater characteristics. Calculation by BioWin was selected. These concentrations (Table 4.4) were placed in the reactor at time zero of each simulation. Although the initial concentrations should not theoretically affect the steady state results, they do affect the exact numerical outputs due to integration calculations.

4.2.1.e Model Settings for Baseline 2

Since the original baseline configuration was for complete PO_4 removal (effluent concentration = 0.03 mg P/L), it was not possible to evaluate effects of parameter changes that resulted in a decrease in PO_4 concentration. Therefore, a second baseline (BL_2) with incomplete PO_4 removal was established and simulations were run again for the six most critical parameters identified using BL_1. A target N:P ratio of 7 was calculated based on manure characteristics, nutrient requirements of corn silage, and estimated nutrient losses during storage and land application (Appendix B.3).

Given the manure characteristics used in previous simulations (Table 4.3), the PO_4 reduction required to achieve the target ratio was calculated and a new target effluent concentration of 14 mg P/L was determined. All model inputs remained the same except for the aeration settings, which were altered to meet the new PO_4 effluent criteria. The DO concentration was decreased from 2 to 1 mg/L and the last aeration period was decreased by 30 minutes to prevent complete PO_4 removal. The DO schedule, as inputted into BioWin, is presented in Appendix B.2 (Table B.8).

Table 4.4: Initial state variable concentrations in SBR at time zero

State Variable	*Description*	*Value*	*Units*
Z_{bh}	Non-PAO heterotrophic organism mass	2505.56	mg COD/L
Z_{ba}	Autotrophic organism mass	188.776	mg COD/L
Z_{bp}	PAO heterotrophic organism mass	2010.12	mg COD/L
Z_e	Endogenous residue from organism decay	351.646	mg COD/L
X_{sp}	Slowly biodegradable particulate COD	250.556	mg COD/L
X_{sc}	Slowly biodegradable colloidal COD	11.7461	mg COD/L
X_i	Particulate unbiodegradable COD	2871.28	mg COD/L
X_{on}	Particulate biodegradable organic nitrogen	21.3311	mg N/L
S_{phb}	Stored VFA	460.324	mg COD/L
PP-lo	Releasable stored polyphosphate	201.012	mg P/L
PP-hi	Fixed stored polyphosphate	100.506	mg P/L
S_{bsc}	Soluble readily biodegradable complex COD (non-VFA)	1	mg COD/L
S_{bsa}	Acetic acid COD	0.01	mg COD/L
NH_3-N	Ammonia nitrogen	0.21941	mg N/L
N_{os}	Soluble biodegradable organic nitrogen	1	mg N/L
NO_3^--N	Nitrate nitrogen	214.176	mg N/L
PO_4-P	Soluble orthophosphate	1	mg P/L
S_{us}	Soluble unbiodegradable COD	748	mg COD/L
N_{us}	Soluble unbiodegradable organic nitrogen	0	mg N/L
ISS	Inert suspended solids	2335.01	mg/L
Alk.	Alkalinity	3	mmol/L
DO	Dissolved oxygen	1.24864	mg O/L
Vol.	Volume of liquid in SBR	1.6408	L
Temp.	Temperature in SBR	20	° C

4.2.2 BioWin Simulations

The sensitivity of model output to each BioWin microbial parameter was evaluated by running simulations for a range of values for each parameter. For each parameter, ranges of variability were identified from the literature (Table 4.5 through Table 4.10). Since little information on microbial growth in dairy manure wastewater was available, growth parameters

for municipal and other agricultural wastewaters were considered in defining parameter ranges. Although growth parameters are highly dependent on physiological state and wastewater characteristics, this literature assessment gave a general idea of parameter variability. In addition, Whichard (2001) showed that some parameters are similar for dairy manure and municipal wastes.

Table 4.5: BioWin stoichiometric parameters for non-PAO heterotrophs

Parameter[*]	*Units*	*Default*	*Literature*	*Range*
$Y_{ZBH,AER}$[D]	g COD/g COD	0.666	0.54[†f], 0.48-0.72[‡], 0.63[§], 0.42[#]	0.42 - 0.72
$Y_{ZBH,AN}$	g COD/g COD	0.1	None	None
$Y_{AC,ZBH}$	g COD/g COD	0.4	None	None
$f_{N,ZBH}$	g N/g COD	0.068	0.07[†], 0.086[‡]	0.068 – 0.086
$f_{N,ZE,ZBH}$	g N/g COD	0.068	0.03[†], 0.06[‡]	0.03 - 0.068
$f_{P,ZBH}$	g P/g COD	0.021	0.02[†]	0.02 - 0.021
$f_{P,ZE,ZBH}$	g P/g COD	0.021	0.01[†]	0.01 - 0.021
$f_{ZE,ZBH}$	g COD/g COD	0.08	0.10[†]	0.08 - 0.10
$f_{CV,ZBH}$	g COD/g VSS	1.48	None	None
$Y_{ZBH,ANOX}$	g COD/g COD	0.403	0.666[¥]	0.403 - 0.666
ADS_{MAX}	--	1	None	None

[*]Corresponding parameter descriptions in Table 2.11; [†]Arsov et al. (1995); [‡]Grady et al. (1999); [§]Henze et al. (1995); [#]Whichard et al. (2001); [¥]Barker and Dold (1997); [e]Experimentally determined; [f]Fitted; [D]Baseline value is different from default (Table 4.1).

Simulations were run varying one microbial growth parameter at a time to evaluate model sensitivity to each parameter. Each parameter was varied above and below the baseline value in 10, 30, and 50% increments. In cases where these percentages did not cover the entire range of values found in the literature, additional simulations were run. Four to eight simulations were run for each parameter depending on the range of reported values.

Since the environment in an SBR is constantly changing, the microbial populations never reach a numerical steady state. In an SBR, a "steady" response is defined by consistently repeated responses to the changing redox environment. This response is more accurately referred to as "quasi-steady state." At quasi-steady state, a reactor constituent has the same concentration at time t in every cycle (which in this case was one day). For the purpose of the

sensitivity analysis, data were compared at the same cycle time for consecutive days to identify the steady state response. Each simulation began with the same initial reactor concentrations (Table 4.4). Simulations were run for four months with the expectation that all variables would reach steady state within that time. The steady state concentrations were taken to be those in the system on the last simulation day.

Table 4.6: BioWin stoichiometric parameters for PAO heterotrophs

Parameter[*]	*Units*	*Default*	*Literature*	*Range*
Y_{ZBP}	g COD/g COD	0.639	0.50[†f], 0.41[‡f], 0.732[§e], 0.63[#f], 0.607-0.636[¥e]	0.41 – 0.732
$f_{P/PHB,AER}$	g P/g COD	0.95	0.9-1.1[¥e]	0.9 – 1.1
$f_{P/PHB,ANOX}$	g P/g COD	0.35	0.55[¤f], 0.56[**e]	0.35 – 0.55
Y_{PHB}	g COD/g COD	0.889	0.34-0.78[††e], 0.69[††e], 0.89[¤f], 1.5[§§e], 1.4-1.83[**e], 0.52[§e]	0.34 – 0.89
$f_{N,ZBP}$	g N/g COD	0.07	0.068[¥e], 0.087[##f], 0.07[#f], 0.098[‡e]	0.068 - 0.086
$f_{N,ZE,ZBP}$	g N/g COD	0.07	0.068[¥e], 0.06[¥¥f], 0.03[#f]	0.03 – 0.07
$f_{N,SE,ZBP}$	g N/g COD	0.07		
$f_{P,ZBP}$	g P/g COD	0.021	0.02[¥e], 0.017[##f]	0.017 - 0.021
$f_{P,ZE,ZBP}$	g P/g COD	0.021	0.02[¥e], 0.01[#f]	0.01 – 0.021
$f_{ZE,ZBP}$	g COD/g COD	0.25		
$f_{SE,ZBP}$	g COD/g COD	0.2		
$f_{P/AC}$	g P/g SCFA COD	0.49	0.48-0.55[¥e], 0.8-1.0[¥e], 0.33-0.76[¤¤e], 0.52[¤f]; 0.24-0.72[§§e], 0.35[***e], 0.019-0.103[§e], 0.68-0.77[**e], 0.48[‡e]	0.019 - 1.0
$f_{CV,ZBP}$	g COD/g VSS	1.42	1.48[¥e]	
Y_{PP-LO}	---	0.94		

[*]Corresponding parameter descriptions in Table 2.8; [†]Arsov et al., (1995); [‡]Smolders et al., (1994b); [§]Stante et al. (1997); [#]Henze et al., (1995); [¥]Wentzel et al. (1987); [¤]Barker and Dold (1997); [**]Comeau et al. (1987); [††e]Arun et al. (1988); [§§]Smolders et al. (1994a); [##]Grady et al., (1999); [¥¥]Henze et al., (1987); [¤¤e]Arvin and Kristensen (1985); [***]Smolders et al. (1995a); [e]Experimentally determined; [f]Fitted.

Using the four-month stopping criteria, 325 simulations were run. The amount of time it took each simulation to reach steady state varied depending on the parameter change. In most simulations, steady state was reached within four months. In simulations for 11 parameters, steady state was not reached within four months. This presented problems in comparing sensitivity for parameters that reached steady state at different times. Steady state was typically

reached within three to four SRTs. Simulations described above are referred to as "preliminary simulations" throughout the rest of the thesis. Additional simulations were run to better quantify the sensitivity of the model utilizing different stopping criteria (explained below) for steady state determination. To distinguish between simulation results, the stopping criterion described above is referred to as stopping criterion 1 (SC_1) and the stopping criterion described in the next paragraph is referred to as stopping criterion 2 (SC_2).

Table 4.7: BioWin stoichiometric parameters for autotrophs

Parameter[*]	*Units*	*Default*	*Literature*	*Range*
Y_{ZBA}	g COD/g COD	0.15	0.15[†f], 0.26[#f], 0.024-0.35[‡], 0.024[§]	0.024 - 0.35
$f_{N,ZBA}$	g N/g COD	0.068	0.086[‡], 0.07[§]	0.068 - 0.086
$f_{N,ZE,ZBA}$	g N/g COD	0.068	0.06[‡], 0.03[§]	0.03 - 0.068
$f_{P,ZBA}$	g P/g COD	0.021	0.02[§]	0.02 - 0.021
$f_{P,ZE,ZBA}$	g P/g COD	0.021	0.01[§]	0.01 - 0.021
$f_{ZE,ZBA}$	g COD/g COD	0.08	0.1[§]	0.08 - 0.10
$f_{CV,ZBA}$	g COD/g VSS	1.48		

[*]Corresponding parameter descriptions in Table 2.13; [†]Wentzel et al. (1987); [‡]Grady et al., (1999); [§]Henze et al. (1995); [#]Arsov et al. (1995); [e]Experimentally determined; [f]Fitted.

A revised stopping criterion (SC_2) was established and simulations were run again for the six parameters to which PO_4 was most sensitive in the preliminary simulations. Steady state determination in SC_2 was based on the mixed liquor concentration of PAO heterotrophs (Z_{bp}) at 23:00, the end of the last mixing period in the 24-hr cycle. The system was considered to be at steady state when value of Z_{bp} was identical three days in a row at time 23:00 to 10^{-1} mg COD/L. Although the effluent PO_4 concentration was the most critical output variable, Z_{BP} concentration was a better indicator of steady state. If a parameter was changed to a value that would not support a PAO population, i.e., PAOs could not grow faster than they were wasted from the system, washout will occur. Under such a condition, PO_4 removal would still occur until PAO heterotrophs no longer existed in the system. Complete PO_4 removal could still be occurring as PAO heterotrophs are diminishing. Since PAO washout begins before EBPR decreases, biomass concentration was used as the steady state indicator.

To characterize both the microbial activity and resulting effluent, model output concentrations were analyzed at different cycle times. Mixed liquor biomass concentrations of

Z_{bp}, Z_{bh}, total P, and VSS were observed at 23:00, the end of the last mixing period in the one-day cycle. Effluent concentrations, S_{bsc}, S_{bsa}, NH_3, and PO_4 were observed at 23:45, which was halfway through the decant time period and considered to be the average effluent concentrations.

Table 4.8: BioWin kinetic parameters for non-PAO heterotrophs

Parameter[*]	*Units*	*Default*	*Literature*	*Range*
$\mu_{MAX,ZBH}^{D}$	d^{-1}	3.2	0.98[†f], 2.88-13.26[‡], 6.00[§f].	0.98-13.26
$K_{S,ZBH}^{D}$	mg/L	5	229[†f], 234[#], 10-180[‡], 4.00[§].	4 – 234
b_{ZBH}^{D}	d^{-1}	0.62	0.07[†f], 0.238-0.25[#], 0.4[§], 0.048-0.408[‡]	0.048 - 0.62
$\eta_{HYD,AX}$	---	1	0.6[†], 0.4[‡]	0.4 – 1
$\eta_{HYD,AN}$	---	0.5	0.1[†]	0.1 - 0.5
$\eta_{AX,ZBH}$	---	0.37	0.8[†‡]	0.37 - 0.8
K_H	d^{-1}	2.81	2.208[‡], 3.00[†]	2.208 – 3.00
$K_{S,HYD}$	g COD/ g COD	0.15	0.10[†], 0.15[‡]	0.10 - 0.15
K_{ADS}		0.8		
$\mu_{ZBH,AN}^{D}$	d^{-1}	4	0.06-6[‡], 0.01[¥]	0.01 – 6
$K_{S,ZBH,AN}$	mg COD/ L	5	0.03-0.21,20-25[‡]; 500[¥], 2.0[¤]	0.03 – 500
$K_{R,AMMON}$	L/mg COD/d	0.08	0.16[‡]	0.08 - 0.16

[*]Corresponding parameter descriptions in Table 2.12; [†]Arsov et al. (1995); [‡]Grady et al. (1999); [§]Henze et al. (1995); [#]Whichard et al. (2001); [¥]Bryers et al. (1984); [¤]Barker and Dold (1997); [e]Experimentally determined; [f]Fitted; [D]Baseline value is different from default (Table 4.1).

Table 4.9: BioWin kinetic parameters for PAO heterotrophs

Parameter[*]	*Units*	*Default*	*Literature*	*Range*
$\mu_{MAX,ZBP}$	d^{-1}	0.95	0.75-0.95[†e], 0.84[‡e], 1.00[§f], 2.4[#e], 3.34[¥f]	0.75 - 3.34
μ_{PLIM}	d^{-1}	0.42	0.35[†e]	0.35-0.42
$K_{S,ZBP}$	g COD/g COD/d	0.1	0.15[†e]	0.1-0.15
$K_{S,PLIM}$	g COD/g COD/d	0.05	0.15[†e]	0.05-0.15
b_{ZBP}	d^{-1}	0.04	0.04[¤f], 0.03-0.04[†e], 0.06[**e]	0.03-0.06
$b_{ZBP,AN}$	d^{-1}	0.03	0.06[†f]	0.03-0.06
K_{SCFA}	g COD/g COD/d	6	2-2.5[†e], 5-6[†e], 2.00[††f]	2.00 – 6
$\eta_{AX,ZBP}$	---	0.4	0.8[¥‡‡f], 0.5[§§e]	0.4 - 0.8

[*]Corresponding parameter descriptions in Table 2.8; [†]Wentzel et al. (1987); [‡]Tandoi et al. (1987); [§]Henze et al. (1995); [#]Smolders et al. (1995b); [¥]Filipe and Daigger (1998); [¤]Arsov et al., (1995); [**]Smolders et al., 1994b); [††]Barker and Dold (1997); [‡‡]Grady et al. (1999); [§§]Kuba et al. (1996); [e]Experimentally determined; [f]Fitted.

Table 4.10: BioWin kinetic parameters for autotrophs

Parameter[*]	*Units*	*Default*	*Literature*	*Range*
$\mu_{MAX,ZBA}^{D}$	d^{-1}	0.5	0.46[†f], 0.2-1.0[‡], 0.144-2.21[§],1.00[#], 0.72-0.75[¥]	0.144 - 2.21
$K_{S,ZBA}$	mg N /L	1	6.95[†f], 0.06-8.4[§], 0.01[¤], 1.0[#]	0.06 - 8.4
b_{ZBA}^{D}	d^{-1}	0.04	0.03[†f], 0.0048-0.168[§]; 0.15[#]	0.0048 - 0.168

[*]Corresponding parameter descriptions in Table 2.14; [†]Arsov et al. (1995); [‡]Barker and Dold (1997); [§]Grady et al. (1999); [#]Henze et al. (1995); [¥]Whichard et al. (2001); [¤]Guyer et al., (1995); [e]Experimentally determined; [f]Fitted; [D]Baseline value is different from default (Table 4.1).

Three sets of simulations were completed (Table 4.11). In the first set, all of the microbial parameters were evaluated. In the second set, the stopping criterion was changed to the second method described above (SC_2). For the second set, only the parameters to which effluent PO_4 concentrations were highly sensitive were evaluated. These same parameters were evaluated in the third set of simulations using BL_2 (incomplete PO_4 removal).

Table 4.11: Summary of three sets of simulations

Simulations Data Sets	*Baseline*[*]	*Parameters*	*Stopping Criteria*[‡]
Preliminary	1	All	-1
Baseline 1 (BL_1)	1	Most critical[†]	2
Baseline 2 (BL_2)	2	Most critical[†]	2

[*] BL_1 was complete PO_4 removal, BL_2 was incomplete PO_4 removal.
[†]Most significant parameters included $\mu_{MAX,ZBP}$, $f_{P/AC}$, Y_{PHB}, $Y_{PP\text{-}LO}$, $f_{P/PHB,AER}$, Y_{ZBP} as presented in section 4.3.
[‡]Using SC_1, steady state was assumed after 4 months. Using SC_2, steady state was based on replication of Z_{BP}.

4.2.3 Analysis of Model Response

Relative sensitivity (Saltelli et al., 2000) was calculated for the mixed liquor and effluent concentrations as well as for the P/VSS ratio, a common measure of EBPR activity, for each simulation:

$$S_R = \frac{(O - O_b)}{(P - P_b)} \frac{P_b}{O_b} \qquad \textbf{[4.3]}$$

where: S_R = relative sensitivity,
O = model output variable of interest,
P = parameter value, and
b = subscript indicating baseline scenario.

Since the results of the sensitivity analysis were to aid in designing a PO_4 removal treatment system, relative sensitivity of model output of PO_4 was considered to be of greatest importance and was used to identify key growth parameters.

A scale was designated to classify the varying degrees of relative sensitivity as "slight", "moderate", "high", or "extreme" (Table 4.12). Since simulations were run for multiple values of each parameter, multiple values of relative sensitivity were calculated for each parameter. This scale was used to group simulation results by level of sensitivity.

Table 4.12: Relative sensitivity scale

Relative Sensitivity (RS)*	*Level of sensitivity*
0 – 0.1	Not
0.1< RS ≤ 1	Slight
1< RS ≤ 10	Moderate
10< RS ≤ 100	High
>100	Extreme

*Absolute value of relative sensitivity defined by Equation 4.3.

4.3 Results and Discussion

In the following sections, results from the preliminary simulations are discussed first and the most critical parameters are identified. Parameters to which PO_4-P was highly or extremely sensitive (RS > 10), or which could not maintain EBPR with the tested range of values, were considered critical. Six parameters were critical according to results from preliminary simulations. The six critical parameters were further evaluated using SC_2 for both BL_1 and BL_2. Results from the second and third sets of simulations are then discussed. Each of the six critical parameters is then discussed in individual sections. For each critical parameter, the corresponding sensitivity is presented and BioWin model behavior is described. The range within which EBPR occurred in BioWin simulations was identified and compared to that indicated by literature. The BioWin model response is then compared to experimental observations in literature. Model results for parameters to which PO_4 had no response (RS = zero) are presented in Appendix C.1.

4.3.1 Preliminary Simulations

In preliminary simulations, 123, 132, and 70 simulations were run for non-PAO heterotrophs, PAO heterotrophs, and autotrophic growth parameters, respectively. As expected, PO_4 removal was not affected by changes in autotrophic growth parameters. Inadequate growth conditions existed in the reactor for propagation of these organisms. Relative sensitivity to all autotrophic growth parameters was zero.

Phosphate concentration was sensitive (RS > 0.1) to six non-PAO heterotrophic growth parameters within the ranges used in these simulations (Table 4.5 Table 4.8). Phosphate concentration was moderately sensitive to non-PAO heterotrophic growth yield ($Y_{ZBH,AER}$) and slightly sensitive to P content of active biomass ($f_{P,ZBH}$), maximum specific growth rate ($\mu_{MAX,ZBH}$), half saturation coefficient for aerobic growth ($K_{S,ZBH}$), decay rate (b_{ZBH}), and half saturation coefficient for hydrolysis (K_H) (Table 4.13 through Table 4.18).

Table 4.13: Relative sensitivity of PO_4 to aerobic growth yield for non-PAO heterotrophs ($Y_{ZBH,AER}$)

	$Y_{ZBH,AER}$ (mg COD/mg COD)	PO_4 (mg P/L)	Relative Sensitivity
	0.720	0.48	9.8
Baseline	0.666	0.06	n/a
	0.630	0.08	0.7
	0.546	0.08	1.1
	0.462	0.06	0.0
	0.378	0.05	1.7
	0.294	0.05	0.6
	0.210	0.04	0.7

Table 4.14: Relative sensitivity of PO_4 to P content of active heterotrophic biomass ($f_{P,ZBH}$)

	$f_{P,ZBH}$ (mg P/mg COD)	PO_4 (mg P/L)	Relative Sensitivity
	0.0315	0.06	0.0
	0.0273	0.06	0.0
	0.0231	0.06	0.0
Baseline	0.0210	0.06	n/a
	0.0189	0.06	0.0
	0.0147	0.05	0.6
	0.0105	0.05	0.3

Table 4.15: Relative sensitivity of PO_4 to maximum specific growth rate for non-PAO heterotrophs ($\mu_{MAX,ZBH}$)

	$\mu_{MAX,ZBH}$ (d^{-1})	PO_4 (mg P/L)	Relative Sensitivity
	10.00	0.05	-0.25
	9.00	0.06	0
	7.80	0.06	0
	6.60	0.06	0
Baseline	6.0	0.06	n/a
	5.40	0.06	0
	4.20	0.06	0
	3.00	0.06	0
	0.98	0.10	-0.80

Table 4.16: Relative sensitivity of PO_4 to half saturation coefficient for aerobic/anoxic growth of non-PAO heterotrophs ($K_{S,ZBH}$)

	$K_{S,ZBH}$ (mg COD/L)	PO_4 (mg P/L)	Relative Sensitivity
	300	0.06	0
	260	0.06	0
	220	0.06	0
Baseline	200	0.06	n/a
	180	0.06	0
	140	0.06	0
	100	0.06	0
	4	0.05	0.17

Table 4.17: Relative sensitivity of PO_4 to decay rate of non-PAO heterotrophs (b_{ZBH})

	b_{ZBH} (d^{-1})	PO_4 (mg P/L)	Relative Sensitivity
	0.62	0.07	0.11
	0.3672	0.07	0.33
	0.3182	0.06	0.00
	0.2693	0.06	0.00
Baseline	0.2448	0.06	n/a
	0.2203	0.06	0.00
	0.1714	0.06	0.00
	0.1224	0.05	0.33

Table 4.18: Relative sensitivity of PO_4 to half saturation coefficient for hydrolysis (K_H)

	K_H (d^{-1})	PO_4 (mg P/L)	Relative Sensitivity
	4.22	0.06	0.00
	3.65	0.06	0.00
	3.09	0.06	0.00
Baseline	2.81	0.06	n/a
	2.53	0.06	0.00
	1.97	0.06	0.00
	1.41	0.07	-0.33

Non-PAO heterotrophs did not interfere with PO_4 removal due to the availability of sufficient energy sources (both VFA-COD and non-VFA COD) in the influent wastewater (Table 4.3). Changes in heterotrophic biomass concentrations did not significantly affect PO_4 removal capacity of PAO heterotrophs. In simulations where changes in growth parameters eliminated non-PAO heterotrophs from the system ($Z_{bh} = 0$), PAO-heterotrophs continued to grow. Fermentation by non-PAO heterotrophs was not necessary in the SBR since sufficient VFA-COD was available for PAO heterotrophic growth in the pre-fermented influent.

Phosphate concentration was sensitive to ten PAO heterotrophic parameters. Phosphate concentration was moderately sensitive to half saturation coefficient for biomass growth ($K_{S,ZBP}$), biomass decay rate (b_{ZBP}), and anaerobic uptake of volatile fatty acids (VFAs) (K_{SCFA}) (Table 4.19 through 4.21), and slightly sensitive to anaerobic decay rate ($b_{ZBP,AN}$) (Table 4.22).

Table 4.19: Relative sensitivity of PO_4 to half saturation coefficient for aerobic/anoxic growth of PAO heterotrophs ($K_{S,ZBP}$)

	$K_{S,ZBP}$ (mg COD/L)	PO_4 (mg P/L)	Relative Sensitivity
	0.15	0.11	1.25
	0.13	0.06	0.00
	0.11	0.06	0.00
Baseline	0.10	0.06	n/a
	0.09	0.06	0.00
	0.07	0.06	0.00
	0.05	0.06	0.00

Table 4.20: Relative sensitivity of PO_4 to decay rate for PAO heterotrophs (b_{ZBP})

	b_{ZBP} (d^{-1})	PO_4 (mg P/L)	Relative Sensitivity
	0.06	0.07	0.33
	0.052	0.06	0.00
	0.044	0.05	-1.67
Baseline	0.040	0.06	n/a
	0.036	0.05	1.67
	0.028	0.05	0.56
	0.020	0.05	0.33

Table 4.21: Relative sensitivity of PO_4 to anaerobic uptake of volatile fatty acids (K_{SCFA})

	K_{SCFA} (mg COD mg COD^{-1} d^{-1})	PO_4 (mg P/L)	Relative Sensitivity
	9.0	0.06	0
	7.8	0.06	0
	6.6	0.06	0
Baseline	6.0	0.06	n/a
	5.4	0.06	0
	4.2	0.06	0
	3.0	0.12	-2.0

Table 4.22: Relative sensitivity of PO_4 to anaerobic decay of PAO heterotrophs ($b_{ZBP,AN}$)

	$b_{ZBP,AN}$ (d^{-1})	PO_4 (mg P/L)	Relative Sensitivity
	0.045	0.07	0.33
	0.039	0.07	0.56
	0.033	0.06	0.00
Baseline	0.030	0.06	n/a
	0.027	0.06	0
	0.021	0.05	0.56
	0.015	0.05	0.33

Phosphate concentration was highly or extremely sensitive to six PAO heterotrophic parameters including one kinetic growth parameter – maximum specific growth rate ($\mu_{MAX,ZBP}$) (Table 4.23) and five stoichiometric growth parameters (Table 4.24 through Table 4.28):

1. Growth yield (Y_{ZBP}),
2. Aerobic PO_4 uptake rate per unit PHB utilized for growth ($f_{P/PHB,AER}$),
3. PHB yield per unit VFA uptake (Y_{PHB}),
4. Phosphate release per unit VFA uptake ($f_{P/AC}$), and
5. Fraction of phosphate taken up which can be released (Y_{PP-LO}).

Model sensitivity to Y_{ZBP}, $f_{P/PHB,AER}$, Y_{PHB}, $f_{P/AC}$, and Y_{PP-LO} was greatest due to the direct relationships of these parameters to PO_4 uptake and release mechanisms. A change in one of these parameters affected the PO_4 removal through the chain of COD transformations (Figure 4.3). For simulations in which PAOs could not grow fast enough to remain in the system, EBPR was not achieved. These results helped identify appropriate parameter values for maintaining EBPR, but relative sensitivity was not a meaningful value for PO_4 concentrations after PAO washout.

Table 4.23: Relative sensitivity of PO_4 to maximum specific growth rate of PAO heterotrophs ($\mu_{MAX,ZBP}$)

	μ_{ZBP} (d^{-1})	*PO_4 (mg P/L)*	*Relative Sensitivity*
	3.34	0.06	0
	1.425	0.06	0
	1.235	0.06	0
	1.045	0.05	-1.67
Baseline	0.950	0.06	n/a
	0.855	2.57	-418.3
	0.665	52.09	n/a
	0.475	52.09	n/a

Table 4.24: Relative sensitivity of PO_4 to growth yield of PAO heterotrophs (Y_{ZBP})

	Y_{ZBP} (mg COD/mg COD)	*PO_4 (mg P/L)*	*Relative Sensitivity*
	0.959	1.45	46.26
	0.831	0.07	0.55
	0.703	0.06	0.00
Baseline	0.639	0.06	n/a
	0.575	0.05	1.66
	0.447	0.05	0.55
	0.320	0.04	0.67

Table 4.25: Relative sensitivity of PO_4 to aerobic PO_4 uptake per unit PHB utilized for PAO heterotrophic growth ($f_{P/PHB,AER}$)

	$f_{P/PHB,AER}$ (mg P/mg COD)	PO_4 (mg P/L)	Relative Sensitivity
	1.425	0.06	0
	1.235	0.06	0
	1.045	0.05	-1.67
Baseline	0.950	0.06	n/a
	0.855	0.06	0
	0.665	52.09	n/a
	0.475	52.09	n/a

Table 4.26: Relative sensitivity of PO_4 to PHB yield per unit VFA utilized (Y_{PHB})

	Y_{PHB} (mg COD/mg COD)	PO_4 (mg P/L)	Relative Sensitivity
	1.0000	0.06	0
	0.9779	0.06	0
Baseline	0.8890	0.06	n/a
	0.8001	0.09	-5
	0.6223	51.74	-2871
	0.4445	52.09	n/a

Table 4.27: Relative sensitivity of PO_4 to PO_4 release per unit VFA uptake ($f_{P/AC}$)

	$f_{P/AC}$ (mg P/mg VFA-COD)	PO_4 (mg P/L)	Relative Sensitivity
	0.735	52.09	n/a
	0.637	52.09	n/a
	0.539	0.22	26.67
Baseline	0.49	0.06	n/a
	0.441	0.06	0
	0.343	0.06	0
	0.245	0.05	0.33

Table 4.28: Relative sensitivity of PO_4 to fraction of releasable PO_4 (Y_{PP-LO})

	Y_{PP-LO}	PO_4 (mg P/L)	Relative Sensitivity
	1	0.06	0
Baseline	0.94	0.06	n/a
	0.846	0.06	0
	0.658	1.51	-80.56
	0.470	52.09	n/a

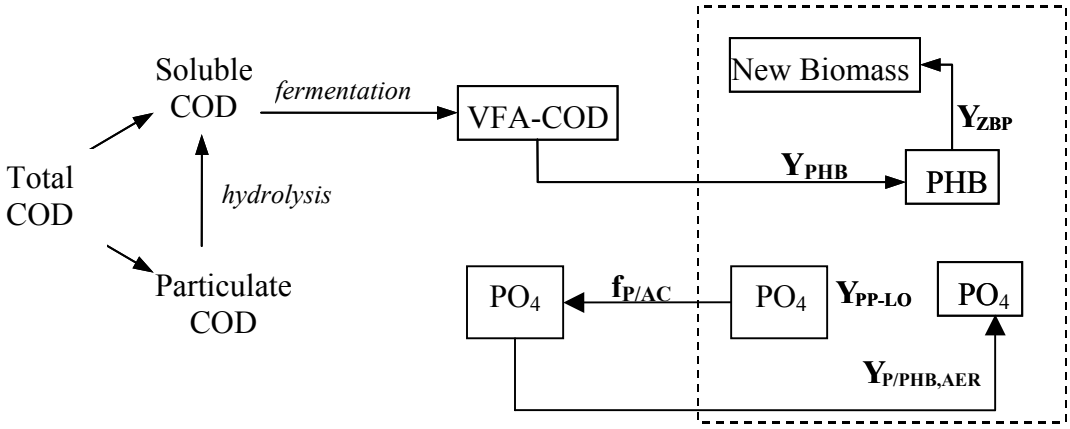

Figure 4.3: COD transformations in EBPR. Area inside dotted lines represents intracellular activity.

4.3.2 Critical Parameters

The six parameters to which the model was most sensitive (as determined by preliminary simulations) were further evaluated using SC_2 and two different baselines (BL_1 and BL_2). For BL_1, PO_4 concentration was highly sensitive to Y_{ZBP} and extremely sensitive to $\mu_{MAX,ZBP}$, $f_{P/AC}$, Y_{PHB}, Y_{PP-LO}, and $f_{P/PHB,AER}$. For BL_2, PO_4 concentration was only slightly sensitive to Y_{ZBP}, and was moderately sensitive to $\mu_{MAX,ZBP}$, $f_{P/AC}$, Y_{PHB}, Y_{PP-LO}, and $f_{P/PHB,AER}$. At parameter values past the point of washout, relative sensitivity of PO_4-P continued to change but no longer increased because the PO_4 concentration no longer changed, as it had reached the maximum limit of 52.9 mg P/L. Although parameter values past the point of washout were identified, the exact

parameter values at which washout occurred were not determined. Specific results for each of the six most sensitive parameters are presented in the following sections.

For each of the six parameters to which PO_4 was most sensitive, there was a range of values within which the growth and activity of PAOs could be supported in BioWin. The ranges of parameter values within which EBPR took place in BioWin simulations were similar for both baselines (Table 4.29). The only parameter range that differed was that of $\mu_{MAX,ZBP}$ (discussed in following section). Once the parameter dropped below (or exceeded) that range, EBPR was no longer supported. When PAO heterotrophs stopped growing faster than they were wasted from the system, they gradually decreased in concentration and eventually washed from the system. Therefore, the limits of BioWin parameter values required to maintain EBPR were identified by noting when PAO biomass was eliminated from the system (Figure 4.4).

Table 4.29: Parameter ranges enabling EBPR in BioWin for BL_1 and BL_2.

Parameter	*Units*	*Range Tested*	*EBPR Range*	
			BL_1	*BL_2*
$\mu_{MAX,ZBP}$	d^{-1}	0.475-3.34	0.855-3.340	0.95-3.340
$f_{P/AC}$	---	0.245-0.735	0.245-0.539	0.245-0.539
Y_{PHB}	g COD/g COD	0.4445-1	0.8001-1.0	0.8001-1.0
Y_{PP-LO}	---	0.470-1	0.846-1.0	0.846-1.0
$f_{P/PHB,AER}$	g P/g COD	0.475-1.425	0.855-1.425	0.855-1.425
Y_{ZBP}	G COD/g COD	0.320-0.959	0.320-0.959	0.320-0.959

Ranges summarized in Table 4.29 include only the values at which EBPR was achieved. The exact parameter values at which PAO biomass growth could be sustained were not determined. For example, in preliminary simulations, the smallest $\mu_{MAX,ZBP}$ at which EBPR was observed using BL_2 was 0.855 d^{-1}. At 0.665 d^{-1}, no EBPR took place. The lowest $\mu_{MAX,ZBP}$ value at which EBPR could be supported is between 0.665 and 0.855 d^{-1}. The reduction in PO_4 after washout of PAOs is due to nutrient requirements for cell growth and precipitation. The PO_4 concentrations at the point of washout were 52.4 and 52.9 mg PO_4-P/L for BL_1 and BL_2, respectively (Table 4.30).

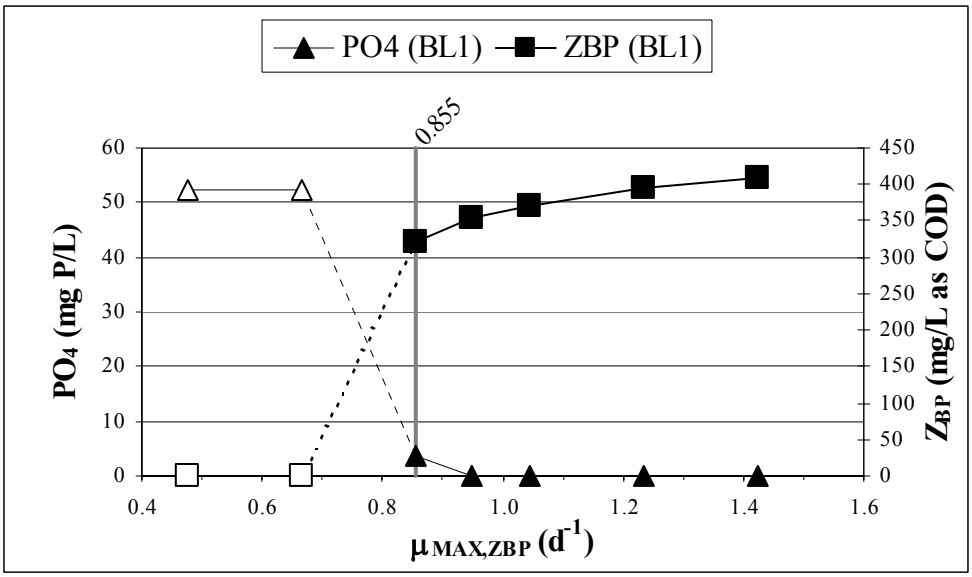

Figure 4.4: Effluent PO_4 concentrations and corresponding mixed liquor Z_{BP} concentrations for model outputs at distinct values of $\mu_{MAX,ZBP}$ for BL_1. Dotted lines indicate unknown model behavior between $\mu_{MAX,ZBP}$ values of 0.665 and 0.855 d^{-1}. Solid symbols indicate $\mu_{MAX,ZBP}$ values enabling EBPR and open symbols indicate washout of PAO heterotrophs (Z_{BP}).

Table 4.30: Steady state PO_4 and non-PAO heterotrophic biomass concentrations after washout of PAO heterotrophs

Baseline	PO_4-P (mg/L)	Z_{BH} (mg COD/L)
BL_1 (Complete PO_4 removal)	52.4	2424
BL_2 (Incomplete PO_4 removal)	52.9	2397

In the following sections, ranges of critical parameters permitting EBPR for BL_1 and BL_2 are compared to those in literature. Ranges determined in this sensitivity analysis are based strictly on the specific configuration modeled, the baseline parameter inputs, and models used in BioWin. Variations in the modeling procedure would result in different model outputs.

4.3.3 Maximum Specific Growth Rate of PAO Heterotrophs ($\mu_{MAX,ZBP}$)

BioWin Model response

The range of $\mu_{MAX,ZBP}$ values which supported EBPR was 0.855 through 3.340 d^{-1} for BL_1 and 0.950 through 3.340 d^{-1} for BL_2 (Table 4.31). For complete PO_4 removal (BL_1), higher

DO concentrations and longer aeration periods allowed PAO heterotrophs to maintain higher specific growth rates (μ_{ZBP}) relative to $\mu_{MAX,ZBP}$. Consequently, PAO growth could be sustained at lower $\mu_{MAX,ZBP}$ values due to higher DO concentrations. Effluent PO_4 concentration reached a limit at $\mu_{MAX,ZBP}$ values of 0.665 and 0.855 d^{-1} for BL_1 and BL_2, respectively (Figure 4.7), at which point PAO heterotrophs washed from the system.

Table 4.31: Relative sensitivity of PO_4 to maximum specific growth rate of PAO heterotrophs ($\mu_{MAX,ZBP}$)

	$\mu_{MAX,ZBP}$ (d^{-1})	*PO_4 (mg P/L)*		*Relative Sensitivity*	
		BL_1	*BL_2*	*BL_1*	*BL_2*
	3.340	0.03	0.8	-0.073	-0.4
	1.425	0.03	0.8	-0.159	-1.9
	1.235	0.03	0.8	-0.460	-3.1
	1.045	0.03	8.1	-0.277	-4.3
Baseline	0.950	0.03	14.0	n/a	n/a
	0.855	3.68	52.9	-1175	n/a
	0.665	52.4	52.9	n/a	n/a
	0.475	52.4	52.9	n/a	n/a

At values higher than the baseline (0.95 d^{-1}), PAO biomass concentrations increased (Figures 4.5 and 4.6). Nearly complete PO_4 removal occurred for BL_1. Using BL_2, PO_4 removal reached 99%, resulting in effluent PO_4 concentrations of 0.8 mg P/L at $\mu_{MAX,ZBP}$ values of 1.235 d^{-1} and higher. Although higher Z_{BP} concentrations were reached at higher values of $\mu_{MAX,ZBP}$, PO_4 concentrations did not decrease with corresponding increases of PAO heterotrophic biomass at $\mu_{MAX,ZBP}$ values greater than 1.235 d^{-1}.

Experimentally determined values

Maximum specific growth rate is determined by measuring oxygen uptake in a batch reactor. The rates of oxygen uptake, substrate utilization, and biomass production are used with empirically derived Monod kinetics to determine $\mu_{MAX,ZBP}$. Although they use different metabolic pathways, non-PAO heterotrophs and PAO heterotrophs grow in the same redox environment and utilize the same substrate for growth. Some PAO heterotrophs metabolize VFA by direct aerobic utilization even when PHB storage is high (Wentzel et al., 1988). This makes it

difficult to differentiate between the two types of bacteria in measuring $\mu_{MAX,ZBP}$ in a mixed culture. Experimentally determined values of $\mu_{MAX,ZBP}$ for municipal wastewaters range from 0.75 to 2.4 d^{-1} (Smolders et al., 1995b; Tandoi et al., 1987; Wentzel et al., 1987).

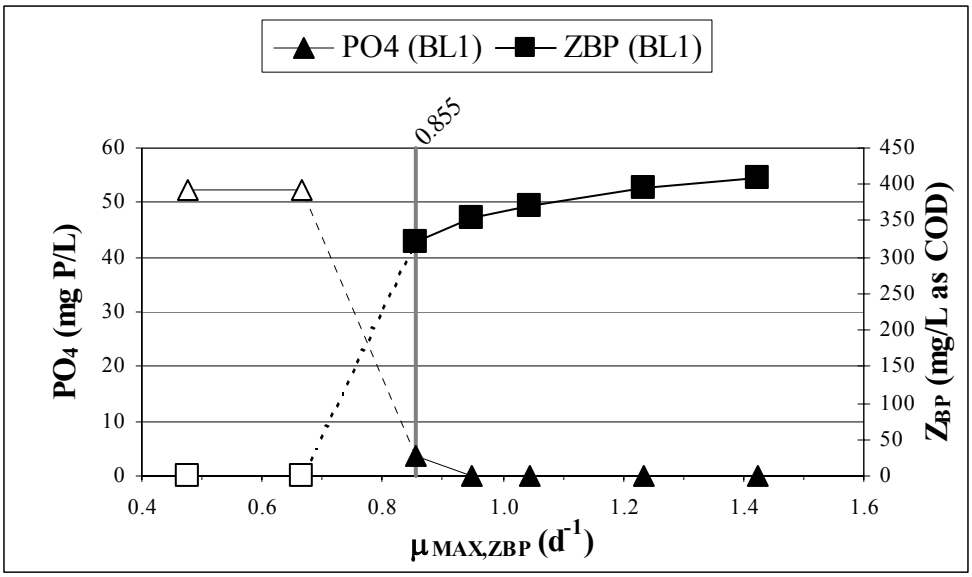

Figure 4.5: Effluent PO_4 concentrations and corresponding mixed liquor Z_{BP} concentrations for model outputs at distinct values of $\mu_{MAX,ZBP}$ for BL_1. Dotted lines indicate unknown model behavior between $\mu_{MAX,ZBP}$ values of 0.665 and 0.855 d^{-1}. Solid symbols indicate $\mu_{MAX,ZBP}$ values enabling EBPR and open symbols indicate washout of PAO heterotrophs (Z_{BP}).

Parameter estimations for modeling

Kinetics varies widely depending on the physiological state of the biomass. Therefore, an accurate estimate for $\mu_{MAX,ZBP}$ could not be made without experimental measures. Values used in models are fitted through calibration. Filipe (1995) and Henze (1995) estimated $\mu_{MAX,ZBP}$ to be 3.34 d^{-1} and 1.00 d^{-1}, respectively. The Dold (1995) model used in BioWin suggests a value of 0.95 d^{-1} for $\mu_{MAX,ZBP}$, which was used as the baseline parameter for this sensitivity analysis. Based on experimental data, Whichard (2001) estimated the maximum specific growth rate for non-PAO heterotrophs ($\mu_{MAX,ZBH}$) to be 1.84 d^{-1}. This value was obtained for dairy manure in bench scale nitrifying SBRs running at an eight-day SRT.

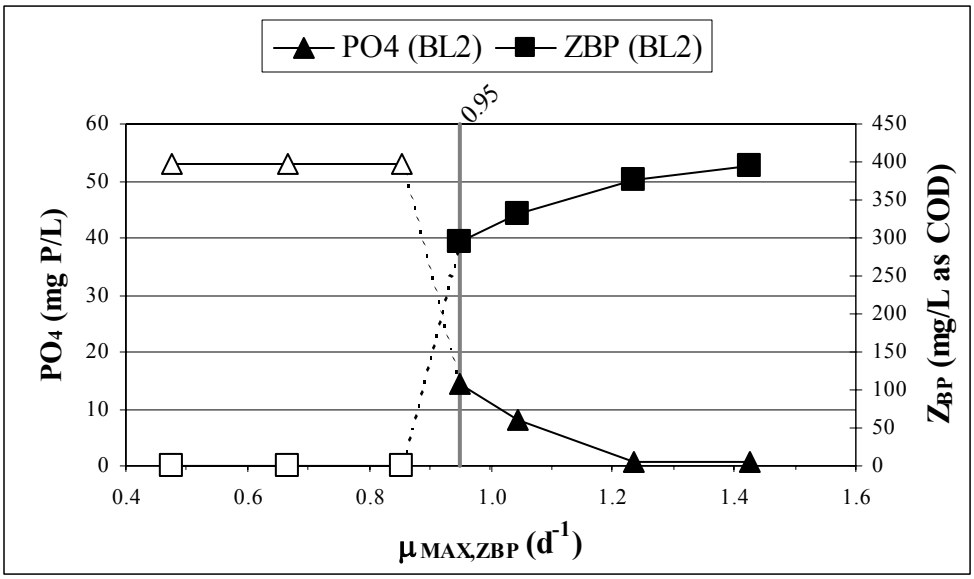

Figure 4.6: Effluent PO_4 concentrations and corresponding mixed liquor Z_{BP} concentrations for model outputs at distinct values of $\mu_{MAX,ZBP}$ using BL_2. Dotted lines indicate unknown model response between $\mu_{MAX,ZBP}$ values of 0.855 and 0.95 d^{-1}. Solid symbols indicate $\mu_{MAX,ZBP}$ values enabling EBPR and open symbols indicate washout of PAO heterotrophs (Z_{BP}).

Estimating $\mu_{MAX,ZBP}$ limits

Limits of the specific growth rate of PAO heterotrophs (μ_{ZBP}) were estimated based on empirical relationships adapted by Grady et al. (1999) and mass balances for an SBR. Biomass growth and decay rates are first order with respect to concentration of the active biomass:

$$r_{ZBP} = \mu_{ZBP} Z_{BP} - b_{ZBP} Z_{BP} \qquad \textbf{[4.4]}$$

where r_{ZBP} = growth rate (mg L^{-1} d^{-1}),
μ_{ZBP} = specific growth rate coefficient (d^{-1}),
Z_{BP} = PAO biomass (mg COD/L), and
b_{ZBP} = decay rate coefficient (d^{-1}).

Since biomass entering the system in the influent wastewater is negligible with respect to that within the reactor, the only biomass input is that which is grown in the reactor. Therefore, biomass production equals the biomass wasted from the reactor:

$$F_w Z_{BP} = (\mu Z_{BP} - b_{ZBP} Z_{BP}) V \qquad \textbf{[4.5]}$$

where F_w = Wastage flow rate (L d^{-1}) and
V = volume of reactor.

Since F_w is defined as the reactor volume (V) divided by the SRT (Θ_c), this equation can be simplified and the rate coefficients can be related as follows:

$$\mu = \frac{1}{\Theta_c} + b \qquad \textbf{[4.6]}$$

Enhanced biological phosphorus removal typically requires aerobic SRTs of 1.5 to 3.5 days (Grady et al., 2000). Decay rates of PAO heterotrophs (b_{ZBP}) ranged between 0.03 and 0.06 d^{-1} (Wentzel et al., 1987; Smolders et al., 1994). The value suggested by Barker and Dold (1997) and used as the BioWin default is 0.04 d^{-1}. Since decay rates are constant (they do not change with physiological state of biomass as do growth rates), these values were considered reliable estimates. In addition, preliminary sensitivity simulations indicated PO_4 effluent concentration was moderately sensitive to changes in b_{ZBP} (Table 4.20). Given typical values for aerobic SRTs and a decay rate of 0.04 d^{-1}, specific growth rates were estimated using equation [4.6]. For SRTs ranging from 1.5 to 3.5 d, the corresponding values of μ_{ZBP} ranged from 0.33 to 0.71 d^{-1} (Table 4.32) and demonstrated that higher growth rates are required to keep biomass from washing from the system at lower SRTs.

Table 4.32: Specific growth rates for PAO heterotrophs (μ_{ZBP}) corresponding to typical aerobic SRTs observed in EBPR systems.

SRT_{AER} (d)	μ_{ZBP} (d^{-1})
1.5	0.71
2	0.54
2.5	0.44
3	0.37
3.5	0.33

Estimated values of μ_{ZBP} were compared to experimentally determined values. Stante et al. (1997) measured an average specific growth rate of 1.08 d^{-1} for a pure culture of Lampropedia spp. growing on acetate (concentrations ranging from 100 and 500 mg/L). Smolders et al. (1995b) measured an average initial specific growth rate of 0.6 d^{-1} occurring at the start of the aerobic phase (at high substrate concentration) in a mixed culture SBR. The average specific growth rate at the end of the aerobic phase was 0.24 d^{-1}. Smolder et al.'s range (0.24 to 0.60 d^{-1}) is similar to that estimated in Table 4.32. Stante et al.'s experimentally determined rate may be

higher due to optimized growth conditions used in the experiments during which substrate concentrations were not limiting and non-PAO heterotrophs were present in the system, decreasing competition for substrate. Similar experiments by Smolders et al. (1995b) resulted in significantly higher maximum and average growth rates (1.44 and 0.72 d^{-1}, respectively) when non-PAO heterotrophic biomass was eliminated from the system.

Specific growth rates will only near the maximum specific growth rate ($\mu_{MAX,ZBP}$) at the beginning of the aeration period, when stored intracellular PHB (S_{PHB}) is highest relative to PAO biomass concentrations (Z_{BP}). Specific growth rate depends on stored substrate to biomass ratios (S_{PHB}/Z_{BP}) (Equation 2.4). Given that the biomass yield on PHB is less than one, S_{PHB} concentrations will decrease faster than biomass concentrations can increase. Intracellular PHB concentrations and Z_{BP} calculated by BioWin demonstrate the dynamic S_{PHB}/Z_{BP} ratios (Table 4.33) used by BioWin in model calculations for the specific growth rate (μ_{ZBP}). The S_{PHB}/Z_{BP} ratio calculated by BioWin at the beginning of the aerobic period (end of anaerobic period) averaged 0.8 mg COD/mg COD, which is significantly higher than those experimentally determined in literature. Stante et al. (1997) measured PHB storage in cells (pure culture) to be 31% of VSS dry weight at the end of the anaerobic period (S_{PHB}/Z_{BP} = 0.36 mg COD/mg COD). Smolders et al. (1995b) reported S_{PHB}/Z_{BP} as 0.67 mg COD/mg COD for a mixed culture SBR. In comparison to experimentally determined values, BioWin exaggerated PHB storage, which would inflate BioWin calculations of μ_{ZBP} relative to $\mu_{MAX,ZBP}$.

Table 4.33: BioWin model output of S_{PHB}/Z_{BP} at steady state of BL_2

Time (hr)[*]	*S_{PHB}/Z_{BP} ratio (mg COD/mg COD)*[†]				
	Feed Period				*Average*
	1	*2*	*3*	*4*	
2	0.81	0.81	0.81	0.78	0.80
4	0.68	0.67	0.66	0.67	0.67
6	0.55	0.55	0.54	0.62	0.57

[*]Relative to six hour cycle periods with feeding in first hour and aeration during the last four hours.

[†]For each of the four feeds in one SBR cycle from steady state output for BL_2.

As discussed in Chapter 2, switching functions are added to the simple Monod equation (Equation 2.2) to account for limiting growth factors. For PAO heterotrophs, these growth factors include DO needed for aerobic metabolism, NH_3 needed as a nutrient, and extracellular

PO_4 needed to induce aerobic metabolism. Assuming that all of these requirements are satisfied (non-limiting), S_{PHB} is the only limiting growth factor and the growth equation can be simplified to:

$$r_{ZBP} = \mu_{\max,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} Z_{BP} \qquad \textbf{[4.7]}$$

Unlike the simplified Monod equation for non-PAO heterotrophic growth on soluble substrate, the biomass term (Z_{BP}) is multiplied by the substrate term (S_{PBH}) due to the reliance of PAO heterotrophs on internally stored substrate. Writing this equation is terms of the specific growth rate gives:

$$\mu_{ZBP} = \mu_{MAX,ZBP} \frac{S_{PBH} / Z_{BP}}{K_{S,ZBP} + S_{PBH} / Z_{BP}} \qquad \textbf{[4.8]}$$

To estimate a range of possible $\mu_{MAX,ZBP}$ values, equation [4.8] was used to calculate $\mu_{MAX,ZBP}$ for estimated μ_{ZBP} values at different substrate levels. The values of μ_{ZBP} estimated for typical SRTs (Table 4.32) are considered average values that occur over the aeration cycle to maintain the given SRT. Specific growth rate changes constantly throughout the cycle in response to decreases in S_{PHB}/Z_{BP}. Since the S_{PHB}/Z_{BP} ratio decreases at a faster rate in the beginning of the aeration cycle, average ratios are more likely to be closer to the smaller end of the range of observed values. For values of S_{PHB}/Z_{BP} between 0.15 and 0.06 mg COD/mg COD, $\mu_{MAX,ZBP}$ would range from 0.55 to 1.89 d^{-1} depending on the aerobic SRT (Table 4.34). This range of $\mu_{MAX,ZBP}$ values agree with experimentally determined values in literature (Table 4.9).

Table 4.34: Estimated values of maximum specific growth rate for PAO heterotrophs ($\mu_{MAX,ZBP}$) for estimated average specific growth rate (μ_{ZBP}) values at different ratios of stored PHB to PAO biomass (S_{PHB}/Z_{BP}).

S_{PHB}/Z_{BP} (mg COD/mg COD)	Estimated $\mu_{MAX,ZBP}$ (d^{-1})		
	$\mu_{ZBP} = 0.33^*$	$\mu_{ZBP} = 0.52^*$	$\mu_{ZBP} = 0.71^*$
0.06	0.88	1.39	1.89
0.15	0.55	0.87	1.18
0.33	0.43	0.68	0.93
0.67	0.38	0.60	0.82

*Estimated specific growth rates corresponding to aerobic SRTs of 3.5, 2.5, and 1.5 d

Using equation [4.8], S_{PBH}/Z_{BP} ratios were calculated (Table 4.35) for likely values of μ_{ZBP} given in Table 4.32. Because μ_{ZBP} is constantly changing during growth in response to decreasing S_{PHB}/Z_{BP} ratios, estimated values should be considered average values occurring during growth. The aerobic SRT used in BL_2 of this sensitivity analysis, was 1.86 days. Based on the relationship in equation [4.6], the corresponding μ_{ZBP} is 0.37 d^{-1} (assuming a value of 0.04 d^{-1} for b_{ZBP}). As shown in Table 4.33, the S_{PHB}/Z_{BP} ratios (when $\mu_{MAX,ZBP} = 0.95\ d^{-1}$) exceed those expected.

Table 4.35: Estimated S_{PHB}/Z_{BP} storage ratios for various values of maximum specific growth rate of PAO heterotrophs ($\mu_{MAX,ZBP}$) at estimated specific growth rates (μ_{ZBP}).

$\mu_{MAX,ZBP}$ (d^{-1})	*Estimated S_{PHB}/Z_{BP} (mg COD/mg COD)*		
	$\mu_{ZBP} = 0.33^*$	*$\mu_{ZBP} = 0.52^*$*	*$\mu_{ZBP} = 0.71^*$*
1.045	0.05	0.10	0.21
0.95	0.05	0.12	0.30
0.855	0.06	0.16	0.49
0.665	0.10	0.36	---
0.475	0.23	---	---

*Estimated specific growth rates corresponding to aerobic SRTs of 3.5, 2.5, and 1.5 d, respectively, as estimated in Table 4.32.

As discussed in Chapter 2, $\mu_{MAX,ZBP}$ is the theoretical maximum growth rate at which a microbe can grow. This rate occurs at high substrate concentrations and no growth limiting conditions, e.g., lack of required external electron acceptor or nutrients. Specific growth rate varies in EBPR systems due to its dependence on the ratio of substrate to biomass. The relationship of the S_{PHB}/Z_{BP} and S concentrations to the K_S parameters controls how close μ is to μ_{MAX}.

Experimentally determined values of $\mu_{MAX,ZBP}$ range from 0.75 to 2.4 d^{-1} (Table 4.9). However, in BioWin simulations, EBPR did not occur for $\mu_{MAX,ZBP}$ values below 0.855 d^{-1} (for BL_1) and 0.95 d^{-1} (for BL_2). Average values of S_{PHB}/Z_{BP} calculated by BioWin at the beginning of the aerobic periods ranged from 0.57 to 0.80. This is higher than experimentally measured values of S_{PHB}/Z_{BP} ratios, which ranged from 0.36 to 0.67 (Stante et al., 1997; Smolders et al., 1995b). Overestimation of S_{PHB}/Z_{BP} ratios would result in higher values of μ_{ZBP}, thereby

underestimating the lower limits of $\mu_{MAX,ZBP}$ permitting EBPR. To the contrary, lower limits of $\mu_{MAX,ZBP}$ values permitting EBPR were higher than those reported in literature. Based on experimentally determined values of S_{PHB}/Z_{BP}, COD storage may be overestimated using the default parameter values. Due to the complex nature of EBPR relationships, accurate modeling of growth rates would require calibration with experimental data.

4.3.4 Phosphate Release per Unit SCFA Uptake ($f_{P/AC}$)

BioWin model response

Phosphate release per unit SCFA uptake was evaluated for values ranging from 0.019 to 0.735 mg P/mg COD (Table 4.36). Model response was similar for BL_1 and BL_2. Enhanced biological P removal occurred at $f_{P/AC}$ values of 0.019 through 0.539 (Figure 4.7). At lower values of $f_{P/AC}$, PO_4 removal increased and Z_{BP} decreased.

Table 4.36: Relative sensitivity of PO_4 to PO_4 release per unit VFA uptake ($f_{P/AC}$)

	$f_{P/AC}$ (mg P/mg COD)	*PO_4 (mg P/L)*		*Relative Sensitivity*	
		BL_1	*BL_2*	*BL_1*	*BL_2*
	0.735	52.4	52.9	n/a	n/a
	0.637	52.4	52.9	n/a	n/a
	0.539	2.249	19.0	714	3.38
Baseline	0.490	0.030	14.0	n/a	n/a
	0.441	0.030	9.2	0.267	3.57
	0.343	0.029	4.2	0.217	2.35
	0.245	0.027	2.8	0.253	1.61
	0.147		2.1		1.22
	0.100		1.6		1.12
	0.019		1.0		0.97

At higher $f_{P/AC}$ values (0.735, 0.637 mg P/mg COD), not enough substrate was taken up for all of the PO_4 that is released into solution. According to the model used in BioWin, VFA (S_{BSA}) uptake depends on the availability of releasable intracellular polyphosphate (PP_{LO}) (Table 2.10). The switching function, "PolyPYes," limits S_{BSA} uptake as PP_{LO} decreases. As more PO_4 is released per unit acetate uptake, less energy is yielded in PHB. As the S_{PHB}/Z_{BP} ratio

decreases, so does μ_{ZBP}. Phosphate is taken up too slowly because of the low S_{PHB}/Z_{BP} ratio. Longer aeration periods may allow more PO_4 uptake, as S_{PHB} is not all used up at the end of the aeration period. Much more energy is available, but all soluble PO_4 is taken up before it can be used.

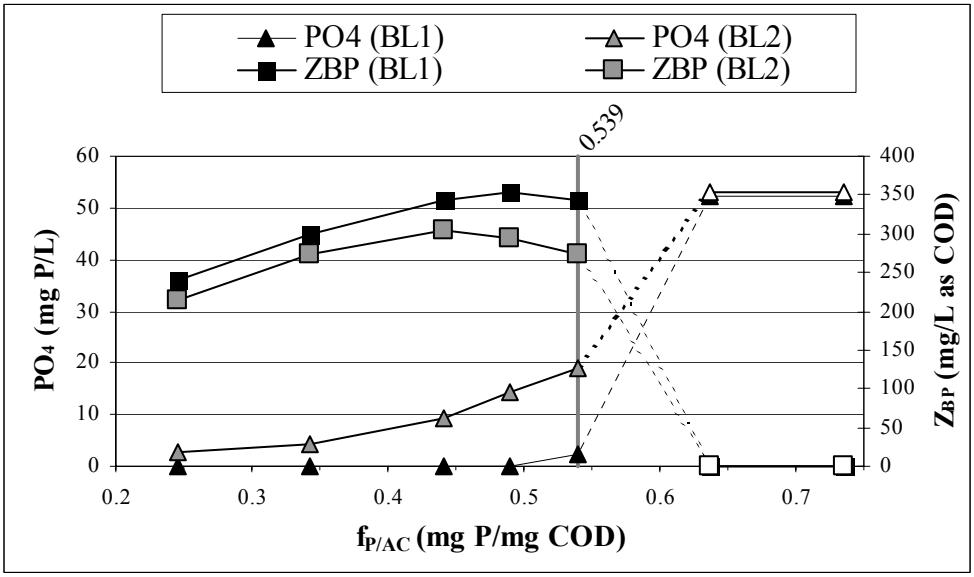

Figure 4.7: Effluent PO_4 concentration and PAO heterotroph concentration (Z_{BP}) versus $f_{P/AC}$ for BL_1 and BL_2 Dotted lines indicate unknown model response between $f_{P/AC}$ values of 0.535 and 0.637 mg P/mg COD. Solid symbols indicate $f_{P/AC}$ values enabling EBPR and open symbols indicate washout of PAO heterotrophs.

A lower $f_{P/AC}$ ratio indicates that more energy (S_{BSA}) is taken up per unit P. If $f_{P/AC}$ is lower, more energy is available in the aerobic zone relative to extracellular PO_4. Complete P removal is achieved even when biomass concentrations are much lower. At lower values of $f_{P/AC}$, less PO_4 is released and, therefore, less PO_4 is available for uptake in the aerobic zone. Much of the intracellular PHB goes unused in the aerobic zone because growth rate is dependent on the presence of extracellular PO_4 as given by the PO_4UptYes switching function (Equation 2.4).

Experimentally determined values

Ranges for $f_{P/AC}$ found in literature had a large variation, ranging from 0.019 to 1.0 mg P/mg COD. Most values were between 0.24 and 1.0 mg P/mg COD (Comeau et al., 1987, Smolders et al., 1994a; Wentzel et al., 1987). Stante et al. (1987) determined values between 0.019 and 0.103 mg P/mg COD. Arvin and Kristensen (1985) found steady state values of 0.68

and 0.41 mg P/mg COD for acetate and propionate, respectively. These values were corrected for denitrification and took into account simultaneous precipitation of PO_4. Filipe and Daigger (1998) suggested that some reported lower values of the wide range of experimentally determined values for $f_{P/AC}$ might be due to the presence of nitrate in the anaerobic zone from returned activated sludge of a nitrifying system. Acetate uptake by denitrifiers would result in less acetate available to PAOs and lower observed ratios of PO_4 release per unit acetate.

BioWin model versus other models

Other models have been proposed for anaerobic uptake of VFAs. Mino et al. (1987) concluded that anaerobic uptake of acetate was dependent on the intracellular P content on the sludge. Although it is generally accepted that the degradation of polyphosphate and acetate uptake are somehow coupled, other factors have been shown to affect this ratio. Experimentally determined values of $f_{P/AC}$ given in literature have a wide range of variation suggesting that factors other than substrate may affect $f_{P/AC}$.

Contrary to the BioWin model, Stante et al. (1997) suggested that specific rates of PO_4 release did not correlate to acetic acid and PO_4 concentrations in the media. Stante et al. (1997) also concluded that PHB was stored during aerobic cell growth and that PO_4 release without concurrent PHB synthesis had been observed. Factors that have been shown to affect fP/AC values include substrate type and pH. Arvin and Kristensen (1985) and Gerber et al. (1987) found different $f_{P/AC}$ ratios for different substrates. Smolders et al. (1994a) found a high correlation between pH and $f_{P/AC}$ due to the increase in electric potential over the cell membrane with increasing pH:

$$f_{P/AC}\left(\frac{P-mol}{C-mol}\right) = -0.85 + 0.19\,pH \qquad \textbf{[4.9]}$$

From anaerobic batch tests with acetate addition, Wentzel et al. (1988) observed an $f_{P/AC}$ of 0.52 at a pH of 7.5. Based on Smolder et al.'s relationship, a pH of 7.5 would predict an $f_{P/AC}$ of 0.575 P-mol/C-mol = 0.56 mg P/mg COD supporting Smolder et al.'s relationship. According to Equation [4.9], lower pH results in lower values of $f_{P/AC}$.

The $f_{P/AC}$ ratio has also been shown to be a function of active biomass concentration, which depends on (and can be controlled by) the SRT. Smolders et al. (1995b) found values of $f_{P/AC}$ at SRTs of 5 and 20 days to be 0.41 and 0.53 mg P/mg COD, respectively. Lower active

biomass concentrations (occurring at longer SRTs) result in a greater fraction of energy used for anaerobic maintenance. Although the relative P release per acetate uptake may be the same, the observed PO_4 release is higher due to increased maintenance needs at longer SRTs.

The source of reduction equivalents required for the production of PHB from VFA in EBPR remains unknown. The pathway by which nicotinamide-adenine dinulceotide-phosphate (NADH) is produced affects estimates of stoichiometric parameters used to describe transformations of energy. As described in Chapter 2, the Comeau-Wentzel model uses the TCA cycle and the Mino model uses the EM pathway. The latter results in ATP production, lowering the energy required for polyphosphate hydrolysis. Therefore, the resulting $f_{P/AC}$ ratio would be smaller for the EM pathway for a given system.

4.3.5 PHB Yield Per Unit VFA Uptake (Y_{PHB})

BioWin Model response

Yield of PHB on VFA was evaluated for values ranging from 0.445 to 1.0 mg COD/mg COD (Table 4.37). Enhanced biological phosphorus removal occurred at values of 0.8 mg COD/mg COD and above (Figure 4.8). The baseline value of Y_{ZBP} was 0.94 mg COD/mg COD. For BL_1, relative sensitivity of PO_4 to Y_{ZBP} was slight at values above the baseline. For BL_2, relative sensitivity of PO_4 to Y_{ZBP} was moderate at values above the baseline.

Table 4.37: Relative sensitivity of PO_4 to PHB yield per unit VFA utilized (Y_{PHB})

	Y_{PHB} (mg COD/mg COD)	PO_4 (mg P/L)		Relative Sensitivity	
		BL_1	BL_2	BL_1	BL_2
	1.0000	0.032	11.6	0.2036	-1.49
	0.9779	0.031	12.0	0.0997	-1.53
Baseline	0.8890	0.030	14.0	n/a	n/a
	0.8001	0.705	17.2	-216.9	-2.06
	0.6223	52.4	52.9	n/a	n/a
	0.4445	52.4	52.9	n/a	n/a

Higher yields of PHB on S_{BSA} resulted in higher biomass concentrations and increased PO_4 removal (Figure 4.8). At PHB yields of 0.6223 mg COD/mg COD, not enough substrate

was stored in the anaerobic zone to support growth in the aerobic zone. Changes in other BioWin parameter estimates such as $f_{P/AC}$ would change model limitations on PAO biomass yield because of their interrelationships (Figure 4.3).

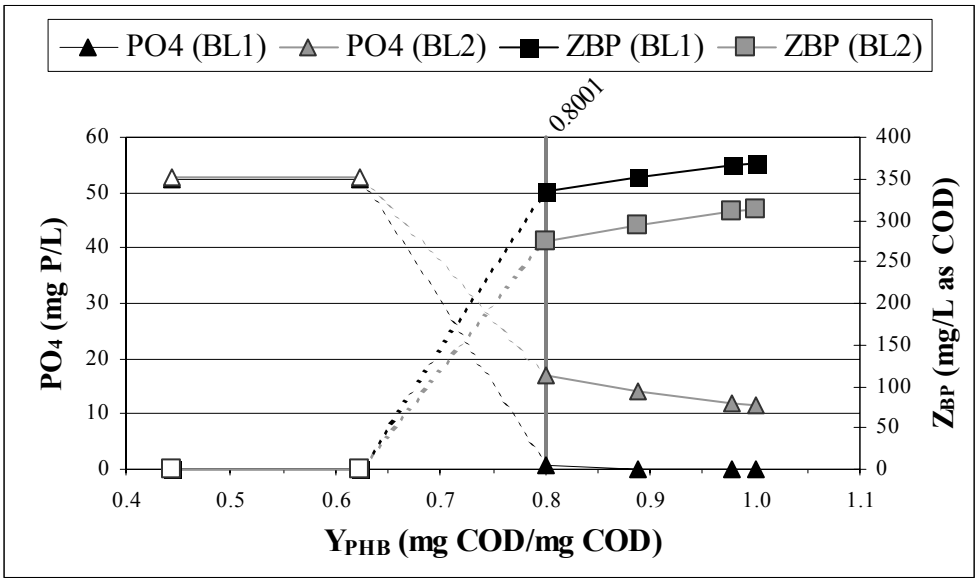

Figure 4.8: Effluent PO_4 concentration and PAO heterotroph concentration (Z_{BP}) versus Y_{PHB} for BL_1 and BL_2. Dotted lines indicate uncertainty of model response between Y_{PHB} values of 0.6223 and 0.8001 mg COD/mg COD. Solid symbols indicate Y_{PHB} values enabling EBPR and open symbols indicate washout of PAR heterotrophs.

Comparison to literature

In literature, values of Y_{PHB} range from 0.34 to 0.89 mg COD/mg COD. Stante et al. (1997) observed Y_{PHB} to be 0.52 mg COD/mg COD which would not support the growth of PAO heterotrophs in this analysis. Although PAO heterotrophs have been shown to utilize multiple substrates, most experimental data are based on acetate. Acetate is the shortest chain VFA and is easily degraded by PAO heterotrophs. It is also one of the most readily available fermentation products and is used as the basis for metabolic models. However, yields of PHB have been shown to vary for different substrates, usually with lower yields for substrates other than acetate.

The rates of aerobic metabolic processes involved in EBPR are largely dependent on the PHB content of cells (Smolders et al., 1995). Intracellular PHB content is also dependent on the amount of biomass. If the yield of PHB on acetate remains the same, larger amounts of biomass will result in less total PHB storage per cell. Therefore, biomass concentration control (by SRT

control) is a critical operational optimization factor that can be altered to achieve the biomass concentration which best meets optimal PO_4 removal needs. Based on this reasoning, Smolders et al. (1995b) proposed a model which defines the relationship between SRT and PHB content at a given acetate load.

Since μ_{ZBP} depends on S_{PHB}/Z_{BP}, increasing PHB storage would increase μ_{ZBP} according to the Dold (1995) model used in BioWin. Stante et al. (1997) found PHB storage rate to be highly correlated to acetate concentration. In addition, greater yields of PHB have been reported for shorter chain VFAs. Addition of excess fermentable substrates that yield shorter chain VFAs may increase S_{PHB} concentrations in cells.

4.3.6 Fraction of Phosphate which can be Released (Y_{PP-LO})

The fraction of PO_4 taken up which can be released was evaluated for values of 0.47 through 1.0 (Table 4.38). Enhanced biological phosphorus removal occurred at Y_{PP-LO} values of 0.846 and above (Figure 4.9). Phosphate concentrations were extremely sensitive when Y_{PP-LO} was 0.846 for BL_1 and moderately sensitive when Y_{PPLO} was 1.0 for BL_2. Lower values did not enable the release of enough PO_4 to harness energy for VFA uptake and storage as PHB. Releasable PO_4 typically ranges between 0.94 and 0.96.

Table 4.38: Relative sensitivity of PO_4 to fraction of releasable PO_4 (Y_{PP-LO})

	Y_{PP-LO}	*PO_4 (mg P/L)*		*Relative Sensitivity*	
		BL_1	*BL_2*	*BL_1*	*BL_2*
	1.000	0.031	10.0	-0.091	-4.67
Baseline	0.940	0.030	14.0	n/a	n/a
	0.846	2.985	13.6	-951	0.43
	0.658	52.4	52.9	n/a	n/a
	0.470	52.4	52.9	n/a	n/a

4.3.7 Aerobic Phosphate Uptake per unit PHB Utilized for Growth ($f_{P/PHB/AER}$)

Aerobic PO_4 uptake was evaluated for values ranging from 0.475 through 1.425 mg COD/mg COD (Table 4.39). Enhanced biological phosphorus removal occurred at values of 0.885 mg COD/mg COD and above (Figure 4.10). Relative sensitivity of PO_4 was moderate for

all values of $f_{P/PHB,AER}$ using BL_2. For BL_1 simulations, relative sensitivity of PO_4 to $f_{P/PHB,AER}$ was extreme at a value of 0.855 mg COD/mg COD and slight at 1.045 mg COD/mg COD.

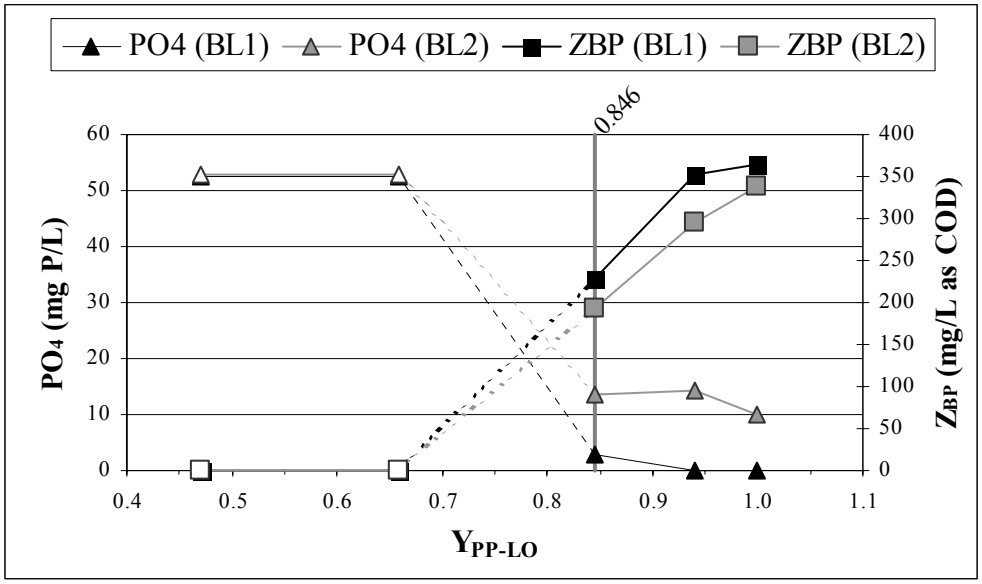

Figure 4.9: Effluent PO_4 concentration and PAO heterotroph concentration (Z_{BP}) versus Y_{PP-LO}. Dotted lines indicate unknown model response between Y_{PP-LO} values of 0.658 and 0.846 mg P/mg COD. Solid symbols indicate Y_{PP-LO} values enabling EBPR in and open symbols indicate washout of PAO hetertrophs.

Table 4.39: Relative sensitivity of PO_4 to aerobic PO_4 uptake per unit PHB utilized for PAO heterotrophic growth ($f_{P/PHB,AER}$)

$f_{P/PHB,AER}$ (mg P/mg COD)	PO_4 (mg P/L)		Relative Sensitivity	
	BL_1	BL_2	BL_1	BL_2
1.425	0.031	6.4	-0.021	-1.09
1.235	0.031	8.4	-0.038	-1.37
1.045	0.030	11.8	-0.380	-1.73
Baseline 0.950	0.030	14.0	n/a	n/a
0.855	0.871	17.4	-270.1	-2.25
0.665	52.4	52.9	n/a	n/a
0.475	52.4	52.9	n/a	n/a

At the lower values at which EBPR did not occur, not enough PO_4 was taken up in the aerobic zone for the energy utilized. In the following anaerobic periods, less intracellular PO_4

was available for release upon which S_{BSA} uptake depends. For the range within which EBPR occurred, higher values of $f_{P/PHB,AER}$, Z_{BP} decreased and PO_4 removal increased (Figure 4.10).

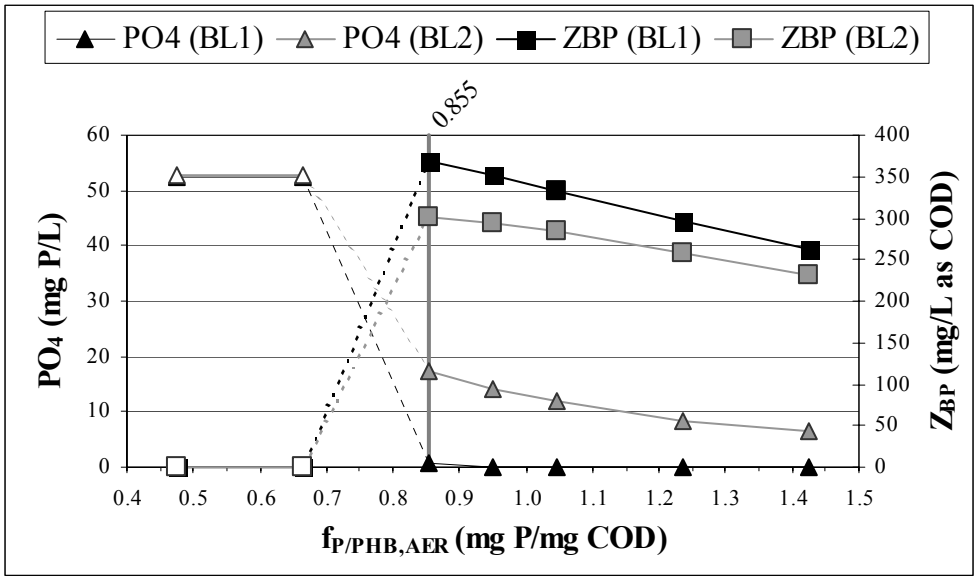

Figure 4.10: Effluent PO_4 concentration and PAO heterotroph concentration (Z_{BP}) versus $f_{P/PHB,AER}$ for BL_1 and BL_2. Dotted lines indicate uncertainty of model response between $f_{P/PHB,AER}$ values of 0.665 and 0.855 mg P/mg COD. Solid symbols indicate $f_{P/PHB,AER}$ values enabling EBPR and open symbols indicate washout of PAO heterotrophs.

Comparison to literature

The lowest experimentally determined value found in literature was 0.9 g P/g COD (Wentzel et al., 1987), which is in the range of values that supported EBPR in BioWin. The regeneration of polyphosphates occurs as P is taken up in the aerobic zone as biomass grows and is again released when exposed to anaerobic environments. Higher DO consumption has been observed during PO_4 uptake followed by a drop in DO consumption after complete PO_4 uptake (Wentzel et al., 1988; Smolders et al., 1994b). Based on this observation, Wentzel et al. (1988) suggested that growth stopped when PO_4 became limited. This is how it is modeled in BioWin. A switching function for PO_4 causes the growth rate to slow as the extracellular concentration of PO_4 decreases. Therefore, in the absence of PO_4, PAO heterotrophs do not grow. Smolders et al. (1994b), however, did not see a significant change in biomass production in the presence or absence of external PO_4, and suggested that the higher DO consumption during PO_4 uptake was due to the energy requirement of PO_4 uptake. Smolders et al. concluded that the PO_4 uptake rate is directly dependent on DO concentration rather than PHB utilized for growth indicating that

$f_{P/PHB,AER}$ is not a set ratio and depends on the availability of DO. Furthermore, PO_4 uptake is not only a function of PHB utilization if PHB is utilized in its absence.

4.3.8 Growth yield of PAO heterotrophs (Y_{ZBP})

Growth yield of PAO heterotrophs was evaluated for values ranging from 0.320 to 0.959 mg COD/mg COD. Phosphate concentration was slightly sensitive for all values of Y_{ZBP} using BL_1 except for 0.959 mg COD/mg COD to which it was highly sensitive. For BL_2, PO_4 concentration was only slightly sensitive for all values of Y_{ZBP} (Table 4.40). Enhanced biological phosphorus removal occurred for the entire range of values.

Table 4.40: Relative sensitivity of PO_4 to growth yield of PAO heterotrophs (Y_{ZBP})

Y_{ZBP} (mg COD/mg COD)		PO_4 (mg P/L)		Relative Sensitivity	
		BL_1	BL_2	BL_1	BL_2
	0.959	1.447	18.7	91.1	0.74
	0.831	0.033	17.1	0.239	0.67
	0.703	0.031	15.3	0.087	0.72
Baseline	0.639	0.030	14.0	n/a	n/a
	0.575	0.030	13.2	0.383	0.76
	0.447	0.026	11.0	0.500	0.76
	0.320	0.024	8.8	0.450	0.76

Higher yields of PAO heterotrophs resulted in higher PO_4 concentrations, i.e., less PO_4 removal (Figure 4.11). At higher values of Y_{ZBP}, a greater concentration of biomass will be maintained in the system. In the BioWin model, a set amount of polyphosphate is released for a given amount of substrate uptake. At higher yields, more biomass will be produced on a given amount of substrate. But, since the model calculates a set ratio of PO_4 released per unit substrate uptake, there will be less PO_4 released for increased growth yields: This is illustrated by the stoichiometric change given in the BioWin model matrix (Table 2.10):

$$\Delta PO_4 = -\frac{f_{P/PHB,AER}}{Y_{ZBP}} - f_{P,ZBP} \qquad [4.10]$$

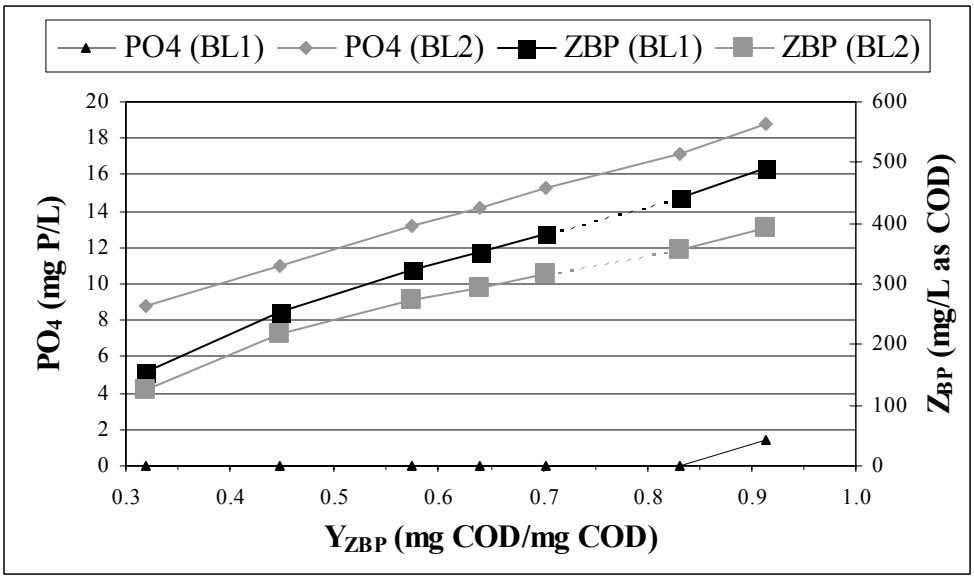

Figure 4.11: Effluent PO_4 concentration and PAO heterotroph concentration (Z_{BP}) versus $f_{P/PHB,AER}$ for BL_1 and BL_2.

Comparison to values in literature

Values for Y_{ZBP} that have been reported in literature range from 0.41 to 0.732 mg COD/mg COD (Table 4.6). Experimentally measured values include 0.41, 0.607 to 0.636, and 0.732 mg COD/mg COD as determined by Smolders et al. (1994b), Wentzel et al. (1987), and Stante et al. (1997), respectively. The former two were measured for mixed (but PAO enriched) cultures and the latter was measured for a pure culture. The default value was 0.639 mg COD/mg COD, which was deemed appropriate based on experimentally determined values. This default value was close to the range of values experimentally determined by Wentzel et al. (1987) (0.607-0.636 mg COD/mg COD). Of all the experimentally determined values, Wentzel's range was considered the most appropriate, as it was determined directly from PHB utilization. Other yields were derived from separately determined values of Y_{PHB} and biomass yields on acetate.

4.4 Summary

Since the recognition of EBPR is relatively new in comparison to other biological processes used in wastewater treatment, there is less information on experimentally determined kinetic parameters for PAO heterotrophs than for other heterotrophs and autotrophs. In addition,

biological growth parameters are more difficult to measure for PAO than for non-PAO heterotrophs due to the inability to differentiate between them in mixed EBPR cultures.

Through this analysis, it was determined that PO_4 was sensitive to six PAO heterotrophic growth parameters in BioWin. The range of values within which EBPR could be supported in BioWin was determined for each of the significant parameters. Some of these ranges were not in agreement with literature. Experimental determination of the six critical parameters identified would be beneficial in furthering modeling efforts.

As shown for $f_{P/AC}$, a discrepancy in the energy balance affects the estimation of other parameters used to describe energy conversion to PAO biomass. For example, an overestimation of $f_{P/AC}$ would result in less energy stored per unit P. This may be compensated for by also overestimating Y_{ZBP} or Y_{PHB} to account for the lost energy. Experimental determination of parameter values alone may not improve current models. Both literature and model evaluation through sensitivity analysis indicate more investigation is needed in metabolic process of EBPR.

The usefulness of measured parameters depends on the characteristics of the system to which they are applied as well as the range of variation typically exhibited by the parameter. Although generally it should not be assumed that a single set of parameter values will accurately model different systems, Barker and Dold (1997) proposed that the same set of parameter values could be applied to different municipal wastewater treatment without extensive calibration. The BioWin model was developed for municipal wastewater, which has some significantly different characteristics from dairy manure. This further supports the need for calibration to use BioWin to model dairy manure treatment.

Based on current knowledge, BioWin could not be used without calibration, which was beyond the resources of this project. It is, however, a valuable tool for furthering knowledge of microbial processes involved in wastewater treatment. It is also useful for demonstrating the effects of process design factors on microbial activity.

Chapter 5: Treatment System Design

5.1 Introduction

There is considerable variation among dairy farm manure management practices due to a range of operational differences across the United States. Although enhanced biological phosphorus removal (EBPR) may be technologically feasible, its economic feasibility is highly dependent on farm characteristics. While the application of EBPR may be an economical management alternative for a highly concentrated operation, it may not be a viable option for a smaller herd. Similarly, EBPR may be feasible in regions with regulations requiring phosphorus (P)-based manure applications but not in those allowing nitrogen (N)-based manure applications. Therefore, the selection of representative farm characteristics was an important factor in assessing the feasibility of EBPR as a nutrient management alternative.

A sequencing batch reactor (SBR) configured for EBPR was designed for a representative dairy farm. Due to operational and economic considerations, the SBR was designed to treat only a fraction of the manure, removing all of the phosphate (PO_4). The treated manure would then be blended with untreated manure to meet crop nutrient requirements. A prefermentation unit was specified to meet volatile fatty acid (VFA) required to support EBPR in the SBR. Equipment and process components including pumps, decanter, aerator, and solid separation unit were specified to meet treatment needs.

In designing the treatment system, many assumptions were made based on manure characteristics and observations from previous studies and reference manuals. Data from Whichard (2001) and Knowlton (2002) were used to characterize manure after pretreatment. Whichard (2001) characterized dairy manure from two farms using solid separation systems. Knowlton (2002) determined effects of high and low P diets on dairy manure characteristics. Manure was characterized before and after solid separation in that study. Reference manuals used in the treatment system design included the Virginia Nutrient Management Standards and Criteria (DCR, 1995) and the Livestock Waste Facilities Handbook (MWPS, 1998). Information obtained from each of these sources is summarized in Table 5.1.

Table 5.1: Summary of information used in treatment system design.

Source	*Data/Information*
Knowlton (2002)	• Source of solid separated manure for VFA analysis experiments (Chapter 3) • Dry matter content of liquid fraction of dairy manure after solid separation
Whichard (2001)	• Manure characteristics used for influent wastewater in sensitivity analysis (Chapter 4) • Dilution factor for dairy manure collection by flushing • PO_4 and N fractions of dairy manure after solid separation
MWPS (1998)	• Manure characteristics used to estimate volumetric production and nutrient content • Bedding characteristics
DCR (1995)	• Crop nutrient requirements used to calculate nutrient ratio and excess manure • Crop yields used to estimate typical land area for representative farm

The objective of the research described in this chapter was to design a treatment system to support EBPR in dairy manure. The treatment goal was to meet both N and P crop requirements with dairy manure without over applying P. The steps of the treatment system design were:

1. Select a representative dairy farm for which to design the system;
2. Determine manure treatment goals based on farm characteristics;
3. Design an SBR to meet the P removal goal through EBPR;
4. Specify pretreatment process components (outside the SBR unit) required to support EBPR treatment; and
5. Evaluate handling options for high P sludge resulting from EBPR process.

5.2 Representative Farm

The most significant factors that define manure management options on dairy farms are herd size, land availability, cropping system, and geographic location. Similarities among operations in particular geographic locations stem from regional differences in environmental regulations, climatic and topographical variations, and off-farm manure utilization options. The

cropping system is the primary factor in determining the amount of manure nutrients that can be applied to cropland without adverse environmental impacts.

Larger farms typically have more of an economic incentive to incorporate new waste management technologies into their operations than do small farms. The capital costs of implementing a new management practice or technology is spread over a larger herd. In addition, larger farms are under greater regulatory pressures than are small farms in many states. In addition, larger farms tend to have higher concentrations of livestock and are more likely to have greater amounts of excess manure.

A herd of 700 lactating cows was chosen for the representative farm, with the following assumptions. Fifteen percent of the herd was non-lactating resulting in a total milking herd of 805 dairy cows. Heifer care was contracted out, the operation was completely confined, and manure recovery was 100%. Complete confinement typically results in less variation in manure characteristics. Calving is year round with no significant seasonal variation. Therefore, seasonal variation in manure characteristics was insignificant for the purpose of system design.

Dairy farmers typically grow as much feed as possible to help meet the feed needs of their herd. A ration consisting of corn silage and soybean meal was used to estimate forage needs. The corn silage requirement for this ration was 15.36 t/cow per lactation and corresponded to a typical milk production of 9662 kg/yr. It was assumed that the cropping system consisted of 100% corn silage and that the farm had enough land to meet corn silage requirements of the herd. Soil productivity was assumed average, which corresponds to a corn silage yield of 38 t/ha (DCR, 1995). Based on corn silage requirements for the herd, crop yield, and 805 cows, the total land required to meet forage needs was 325 ha.

It was assumed that the farm has a storage pit large enough for six months of manure storage. Solids are removed from the storage pit approximately every five years and immediately spread onto the land. Therefore, there is no covered shed or storage area for manure solids. Manure is collected by flushing and cows are housed in free stalls with loose sawdust bedding. It was assumed that the farmer pays for a manure slurry spreading service and that manure slurry is pumped directly from the storage pit to the spreading truck for land application. Manure slurry is spread twice per year, once in the early spring and once in the fall. When solids are removed from the pit, they are applied using the same spreading service.

5.3 Treatment System Goals

Land required for N and P based application methods were calculated based on manure characteristics (MWPS, 1998) and crop nutrient uptake (DCR, 1995). Treatment goals were based on solid separated manure characterized by Whichard (2001) and Knowlton (2002).

5.3.1 Manure Characteristics

Based on 805 dairy cows averaging 635 kg and typical daily manure production (Table 5.2), the total volume of manure (as excreted) produced on this operation was estimated as 16,140 m^3/yr (Table 5.3). It was assumed that manure was collected by flushing with an estimated dilution factor of 1 part manure to 1.844 parts fresh water (Whichard, 2001). Based on this dilution factor, the total amount of flush water added to the manure volume was 29,762 m^3/yr (Table 5.3).

Table 5.2: As excreted manure characteristics for 635 kg dairy cows (MWPS, 1998)

Mass	*Volume*	*Density*	*Dry Matter*	*Nutrients (kg/d)*		
(kg/d)	*(L/d)*	*(kg/m³)*	*(%)*	*N*	*P_2O_5*	*K_2O*
54.43	54.93	991	12.7	0.270	0.109	0.218

Table 5.3: Manure wastewater components following collection

Wastewater Component	*Volume*		*Mass*		*Dry Matter*
	(m³/d)	*(m³/yr)*	*(kg/d)*	*(kg/yr)*	*(%)*
Manure*	44.22	16,140	43,816	15,992,895	12.7
Flush water†	81.54	29,762	81,539	29,761,805	0
Sawdust bedding‡	4.13	1507	1,585	578,541	90
Total	129.9	47,408	126,940	46,333,241	5.5

*Based on 805 dairy cows (635 kg each) and manure characteristics in Table 5.1.
†Assuming 1.844 L/d fresh water for every 1 L manure (as excreted).
‡Assuming bedding requirements of 1.97 kg/d/cow, density of sawdust is 192.2 kg/m^3 when added, and volume reduction of 50% during use (MWPS, 1998).

Bedding requirements were estimated as 1.97 kg/d per cow for loose sawdust, which has a density of 192.2 kg/m^3 (MWPS, 1998). It was assumed the bedding volume was halved during use (MWPS, 1998) and that the nutrient content of sawdust bedding was negligible. Based on estimated bedding characteristics, the total bedding volume added to the wastewater was 4.13 m^3/d or 1507 m^3/yr (Table 5.3). Based on manure production and estimated flushing, the total

volume of wastewater was estimated as 130 m^3/d, or 47,408 m^3/yr (Table 5.3). It was assumed that the farm has a storage capacity of 25,000 m^3, which is enough for 180 days of storage.

The wastewater characteristics given in Table 5.3 correspond to manure entering the storage pit. It was assumed that rainfall was equal to evaporation (Bedient and Huber, 1992). Therefore, rainfall was not accounted for in manure volume or storage calculations.

For the treatment scenario, the manure was solid separated prior to fermentation and EBPR. The effects of solid separation on the water content (WC) and dry matter (DM) of the manure were estimated based on solids removal results from Knowlton (2002) and the performance of the solid separator used in the treatment system. Nutrient content of the manure leaving the solid separator was estimated using data from Whichard (2002), since PO_4 data were not available from Knowlton (2002) (Table 5.4).

Table 5.4: Manure characteristics before and after solid separation

Wastewater Component	*Dry Matter (%)*	*Water Content (%)*	*Volume[†] (m^3/d)*
Influent[*]	5.5	94.5	129.9
Effluent Liquid	2.50	97.5	112.0
Effluent Solids	23.0	77.0	17.9

[*]Adjusted for bedding and flush water additions (Table 5.3).
[†]Detailed calculations are included in Appendix D.

Solid separation of diluted manure resulted in a liquid effluent with 3.85% DM and a separated solids DM of 9.89% for brush screening separation (Knowlton, 2002). The solid separator used for this design (described in following section) is also a screening system, but includes a roll press. The roll press produces solids with a DM content ranging from 20 to 25% (Rensch, 2002). Since the dilution water estimated for this study was more than twice that used in the Knowlton (2002) study, it was assumed that the DM of the liquid fraction from the solid separator would be less than 3.85%. It was assumed that the separated solids would be 23% DM and the liquid fraction was 2.5% DM.

5.3.2 Excess Manure Nutrients

Crop nutrient requirements for corn silage, assuming average soil productivity and medium to high soil test P levels, are 146 kg N/ha, 44.8 kg P_2O_5/ha, and 44.8 kg K_2O/ha (DCR, 1995). Based on these requirements, the required N:P ratio on a mass basis is 7. Typical yearly

manure nutrient production (as excreted) for N, P_2O_5, and K_2O_2 is 98.6, 39.8, and 79.6 kg/cow, respectively (Table 5.2). Taking into account manure nutrient availability (due to volatilization during storage and application) and 325 ha of corn silage, manure from 1677 cows can be utilized if manure is applied on an N-basis (Table 5.5). If manure is applied on a P-basis, 325 ha of corn silage can accommodate the manure from only 367 cows. Similarly, given 805 dairy cows, 156 ha are needed for manure application on an N-basis, and 713 ha are needed for manure application on a P-basis.

Table 5.5: Crop requirements for corn silage and capacity of cropland for manure nutrients

Nutrient	Crop Requirement (kg ha^{-1} yr^{-1})	Manure Content (kg cow^{-1} yr^{-1})	
		As Excreted	Crop Availability
N	146	98.6	28.3
P_2O_5	44.8	39.8	39.8
K_2O	44.8	79.6	79.6

*Assuming average soil productivity and medium to high soil test levels.

†Cows needed to satisfy nutrient requirement accounting for N losses during storage and application. Assuming 58% organic N and 42% NH_4-N and availability coefficients of 0.35 and 0.20, respectively.

For the representative farm, the total yearly nutrient availability from the manure of 805 dairy cows is 79,333 kg N, 32,027 kg P_2O_5, and 64,054 kg K_2O_2 (Table 5.6). It was assumed that manure was applied in the early spring by spraying without incorporation. For this manure application routine, the corresponding availability coefficients for organic N and NH_4-N are 0.35 and 0.20, respectively (DCR, 1995). Based on these factors, the total N, P, and K availability are 22,768, 32,027, and 64,054 kg/yr, respectively (Table 5.6).

Given 325 ha of corn silage, the representative farm would not have any excess nutrients if manure was applied on an N-basis. For P-based manure application, more than twice as much land would be required to utilize all of the manure nutrients. Off-site utilization would be required for more than half the manure nutrients (Table 5.7). Based on P_2O_5 nutrient requirements (44.8 kg/ha) and land availability (325 ha), the total yearly P_2O_5 requirement is 14,560 kg/year. This results in an application of only 45% of the manure and an excess of 17,467 kg P_2O_5 per year. The N crop requirement based on 325 ha is 47,450 kg N. Although the total N available in the manure is 22,768 kg N/yr, if only 45% of the manure was applied (P-based application), only 10,351 kg N would be supplied by the manure (Table 5.7). Without

solid separation, the total excess manure on a volumetric basis (65% of 47,408 m^3/yr) is 30,815 m^3/yr.

Table 5.6: Manure nutrients and crop nutrient requirements

Nutrient	*Manure Nutrient Production*[*] *(kg/yr)*	*Manure Nutrient Availability*[†] *(kg/yr)*	*Corn Silage Requirements*[‡] *(kg/yr)*
N	79,333	22,768	47,450
P_2O_5	32,027	32,027	14,560
K_2O	64,054	64,054	14,560

[*]As excreted (Table 5.2).
[†]Accounting for N losses during storage and application. Assume 58% organic N and 42% NH_4-N and availability coefficients of 0.35 and 0.20, respectively.
[‡]Based on 325 ha and corn silage nutrient requirements (Table 5.5).

Table 5.7: Nutrient management with P-based manure applications and without manure treatment on a dairy farm milking 805 cows and growing 325 ha of corn silage.

Nutrient	*Manure Nutrient Availability*[*] *(kg/yr)*	*Crop Requirements*[†] *(kg/yr)*	*Manure Nutrients Applied*[‡] *(kg/yr)*	*Commercial Fertilizer Requirements (kg/yr)*	*Excess Manure Nutrients (kg/yr)*
N	22,768	47,450	10,351	37,099	12,418
P_2O_5	32,027	14,560	14,560	0	17,467
K_2O	64,054	14,560	29,120	0	34,934

[*]Accounting for losses during storage and application (Table 5.6).
[†]Based on 325 ha corn silage.
[‡]Phosphorus-based application.

5.3.3 Treatment Requirements

Based on the DM of the liquid and solid manure fractions expected from solid separation, the volume of the resulting liquid fraction was estimated as 112 m^3/d (Table 5.4). This represents a volume reduction of 14% due to solid separation. Assuming the total volume of manure is conserved in the prefermentation process, the total liquid manure volume after pretreatment (solid separation and fermentation) is 112 m^3/d.

From an operational standpoint, it is much easier to maintain complete PO_4 removal in EBPR systems than partial PO_4 removal. The extent of microbial activity is controlled by the limiting nutrient required for growth (Grady et al., 1999). To maximize removal of a pollutant,

the pollutant must be the limiting factor in biomass activity. In EBPR, phosphorus accumulating organism (PAO) heterotrophs will continue to uptake PO_4 as long as energy required for growth (VFA) is available. It is easier to maintain complete PO_4 removal (by making VFA non-limiting) than to consistently meet a target PO_4 concentration in EBPR. Therefore, the SBR was designed for complete PO_4 removal. In addition to simplifying SBR operation, complete PO_4 removal required that only a fraction of the manure be treated and then blended with untreated manure to result in the desired crop nutrient ratio of 7. This would allow a farmer to apply all of the manure, maximizing the use of the available N (Table 5.8).

Table 5.8: Summary of nutrient management using P-based manure applications and manure treatment by EBPR on a dairy farm milking 805 cows and growing 325 ha of corn silage

Nutrient	*Manure Nutrient Availability*[*]	*Crop Requirements*[†]	*Manure Nutrients Applied*[‡]	*Commercial Fertilizer Requirements*	*Excess Manure Nutrients*
			(kg/yr)		
N	22,768	47,450	22,768	24,682	0
P_2O_5	14,560	14,560	14,560	0	0
K_2O	64,054	14,560	64,054	0	0

[*]Accounting for losses during treatment storage and application (Table 5.6).
[†]Based on 325 ha corn silage.
[‡]Phosphorus-based application.

Using manure characteristics of solid separated manure (Whichard, 2001), manure nutrients before and after EBPR treatment were estimated (Table 5.9). Based on simulation with BioWin, it was estimated that 15 mg NH_4-N/L would be utilized for biomass growth during treatment. These data (Whichard, 2001) were used because they reflect the effects of settling, solid separation, and brief exposure to anaerobic treatment.

Based on nutrient availability coefficients, crop available nutrients were estimated for treated and untreated manure fractions (Table 5.10). It was assumed that all of the soluble PO_4 was available to crops. The blending ratio required to produce an N:P ratio of 7 was determined based on nutrient availability. Complete PO_4 removal from 83% of the manure wastewater would result in an N:P ratio of 7 after blending with the remaining 17% of untreated manure.

Table 5.9: Manure wastewater nutrient content of solid separated manure before and after EBPR treatment

Nutrient	Concentration (mg/L)	
	Before Treatment*	After Treatment†
Organic N	56	0
NH_4-N	498	483
Total P	81	0

*Whichard (2001).
†Estimated 15 mg NH_4-N utilized for growth during EBPR.

Table 5.10: Manure nutrient availability before and after EBPR treatment and after blending treated and untreated manures

Nutrient	Concentration (mg/L)		
	Untreated*	Treated*	Blended†
Organic N	20	0	4
NH_4-N	100	97	97
Total P	81	0	15

*Based on values given in Table 5.9 and accounting for availability coefficients for organic N and NH_4-N of 0.35 and 0.20, respectively.
†Adding 17% of the untreated manure to 83% of the treated manure.

Given a manure wastewater volume of 112 m^3/d after pretreatment (solid separation and fermentation), EBPR treatment of 83% of the volume would result in a flow of 92.93 m^3/d to the SBR and 19.07 m^3/d to be blended. Blending occurs in the manure storage pit.

5.4 Sequencing Batch Reactor Design

The SBR was designed using information acquired from literature, generally accepted design equations, and the BioWin model. Temperature effect on EBPR was a significant design concern because this system was designed to operate at ambient temperatures. Based on literature, it was determined that the BioWin model was not reliable for temperatures outside the range of 15 to 20° C (Baetens et al, 1999; Brdjanovic et al., 1998b; Helmer et al., 1997; and Mamais and Jenkins, 1992). Therefore, BioWin could not be used to quantify temperature effects on EBPR. To address temperature effects, design factors were considered based on two (summer and winter) operation scenarios. Summer and winter SRTs were selected based on experimental observations and full-scale operation experiences identified in literature.

BioWin was used to optimize SBR aeration and feeding schedules. Since oxygen requirements are higher in the summer, the aeration system was designed based on summer requirements. The winter requirements were also considered in selecting an aerator to make sure that it had enough turn down capacity so that energy would not be wasted on excessive aeration. In addition to wasting energy, excessive aeration has been shown to inhibit EBPR (Brdjanovic et al., 1998a).

Seasonal temperature fluctuations were the basis for selecting the retention times in the SBR. Design specifications for the SBR were then calculated. After aeration specifications were calculated, BioWin was used to optimize feeding and aeration schedules using conditions represented by BL_1. The prefermentation system was sized to meet operational requirements. System components required to meet the design specifications were then selected.

5.4.1 Temperature Effects on EBPR System Design

The BioWin software uses the Arrhenius relationship (Equation 2.1) in modeling temperature effects on microbial growth. Temperatures are specified by the user and can range from 0 to 35° C. The BioWin default temperature is 20° C. Although values of temperature coefficients (θ) for the Arrhenius relationship have been measured for some EBPR process components (Baetens et al, 1999; Brdjanovic et al., 1998b; Helmer et al., 1997; and Mamais and Jenkins, 1992), little consensus exists on typical values. Therefore, BioWin default values of θ are one for all PAO heterotrophic kinetic parameters, i.e., EBPR processes are modeled with zero temperature dependency.

Effects of temperature changes on EBPR processes are commonly accommodated by seasonal changes in operation schedules. Temperature effects are of greatest concern during summer months, as the minimum SRTs for nitrifiers and PAO heterotrophs become similar at temperatures above 25° C. Phosphate removal efficiency of EBPR tends to slow above temperatures of 25° C (Baetens et al., 1999) and fail completely between 40 and 45° C (Jones and Stephenson, 1996). Nitrification is controlled by using lower aerobic SRTs during summer months.

During winter months, fermentation activity requires longer anaerobic SRTs. Reduced VFA production was experienced at lower temperatures and Skalsky and Daigger (1995) found

yields reduced 40 to 50% when the temperature was between 14 and 16° C as opposed to summer temperatures of 21 to 24° C. Phosphate uptake tends to be highest at temperatures between 10 and 15° C and can be maintained at even lower temperatures. Enhanced biological P removal was maintained at temperatures as low as 5° C in bench scale studies (Helmer and Kunst, 1997; Jones and Stephenson, 1996; and Converti et al., 1995) and as low as 3° C in a full scale SBR (Marklund and Morling, 1994).

Because of the difficulties in balancing nitrification and EBPR, accommodation of temperature changes is easier when employing EBPR without nitrification than it is to combine both EBPR and biological N removal. Fermentation is the rate limiting process in the anaerobic zone of EBPR. Prefermentation (before SBR unit) enables the use of shorter anaerobic residence time, making cycle scheduling more flexible. Prefermentation also increases readily available VFAs in the SBR, decreasing competition with nitrifiers. Using dissolved oxygen (DO) concentrations lower than 2 mg/L can also help to limit nitrification (Grady et al., 1999). Since nitrifiers have higher half saturation coefficients for oxygen than PAO heterotrophs, maintaining lower DO concentrations can decrease competition with nitrifiers. Low temperatures can be accommodated by increasing the SRT.

Mamais and Jenkins (1992) determined washout sludge retention times (SRT) at temperatures of 13.5, 17, and 20° C (Table 5.11). Typical aerobic SRTs for EBPR at 20° C are 2 to 3 d (Grady et al., 1999). Liner and Grady (1997) suggested that the anaerobic SRT can be as short as 0.5 days at 20° C if sufficient VFA is already present in the wastewater. This information was used to select retention times as discussed in the following section.

Table 5.11: Washout SRTs (d) at varying temperatures (Mamais and Jenkins (1992).

SRT (d)	*Temperature*		
	13.5° C	*17° C*	*20° C*
Aerobic	2.8	2.3	2
Anaerobic	2.1	1.75	1.5

5.4.2 Design Specifications

Both summer and winter operation were considered in determining system requirements. Sludge retention times were selected and used as the basis for biomass calculations. Oxygen

requirements were determined based on the system biomass. Power requirements were calculated to select between surface and diffused aeration systems.

SRT

Retention times were selected for operation based on winter and summer wastewater temperatures of 15 and 25° C, respectively (Table 5.12). Winter and summer aerobic SRTs were selected based on typical values used at these temperatures. Minimum winter and summer aerobic SRTs required to support EBPR were estimated as 2 and 1.3 days, respectively. A safety factor of 1.5 was applied, resulting in winter and summer aerobic SRTs of 3 and 2 days, respectively. Since all required VFA will be present in the influent (due to prefermentation), the anaerobic SRTs selected were 1.5 and 1.0 for winter and summer, respectively. The total SRTs for winter and summer operation are 4.5 and 3 d, respectively. The ratio of aerobic and anaerobic SRTs must be the same for winter and summer operation so that required SRTs can both be achieved by changing only the sludge wastage rate. A hydraulic residence time (HRT) of 1 d was selected to simplify management by coordinating daily farm operations with the SBR operation. For example, feeding the SBR could be kept in step with manure collection with a 1 day HRT.

Table 5.12: Retention times for winter and summer SBR operation

Operation	*Temp (° C)*	*HRT (d)*	*SRT (d)*			SRT_{AER}/SRT_{ANA}
			Aerobic	*Anaerobic*	*Total*	
Winter	15	1	3	1.5	4.5	2
Summer	25	1	2	1	3	2

Since the growth of PAO heterotrophs occurs only during the aerobic periods, the effective SRT (Θ_{ce}) was considered to be the aerobic SRT and was used to calculate biomass concentration (X_M), volume (V), required oxygen (RO) and solids wastage rate (W). Wastewater concentrations were based on dairy manure characterized by Whichard (2001).

Total Biomass

Biomass concentration was estimated to determine the oxygen requirements. Biomass concentration is greater in the winter due to longer SRTs resulting in less decay. Therefore, the biomass concentration and reactor volume were calculated based on the winter aerobic SRT (Grady et al., 1999):

$$X_{M,T} \cdot V = \Theta_{ce} F \left[\frac{X_{IO,T}}{i_{ZBP,T}} + \frac{\left(1 + f_D \cdot b_{ZBP} \cdot \Theta_{ce}\right) \cdot Y_{ZBP} / i_{ZBP,T} \cdot (S_{SO} + X_{SO} - S_S}{1 + b_{ZBP} \cdot \Theta_{ce}} \right] \quad \textbf{[5.2]}$$

where $X_{M,T}$ = Biomass in mixed liquor expressed as total suspended solids (TSS) concentration (mg TSS/L),
V = Reactor volume (L),
Θ_{ce} = Effective (aerobic) SRT (d),
F = Volumetric flow rate (L/d),
$X_{IO,T}$ = Influent inert suspended solids concentration (mg TSS/L),
f_D = Fraction of active biomass contributing to biomass debris,
b_{ZBP} = Decay coefficient (d^{-1}),
Y_{ZBP} = Biomass yield (mg COD/mg COD),
$i_{ZBP,T}$ = Mass of COD per mass of TSS (mg COD/mg TSS),
S_{SO} = Influent readily biodegradable substrate concentration (mg/L),
X_{SO} = Influent slowly biodegradable substrate concentration (mg/L), and
S_S = Readily biodegradable substrate concentration (mg/L).

Readily biodegradable substrate was considered to be that of the manure following pretreatment – solid separation and fermentation. The total VFA (acetic, butyric, and propionic acids) produced in fermenting dairy manure, was 4,345 mg COD/L (Chapter 3). It was assumed that acetic, butyric, and propionic acids would all be utilized by PAO heterotrophs and that nearly all of the readily biodegradable substrate would be consumed, i.e., $S_{SO} >> S_S$. BioWin default growth parameters and wastewater characteristics for solid separated manure (Whichard, 2001) were used to estimate the total suspended solids (TSS), i.e., $X_{M,T} \cdot V$ which was 1,025,279 g TSS for a 3 day aerobic SRT and 697,847 g TSS for a 2 day aerobic SRT (Table 5.13).

Table 5.13: Influent wastewater characteristics and modeling parameters used in Equation [5.2] to calculate biomass.

Component	*Units*	*Value*	*Source*
Θ_{ce}	d	3,2	SRT_{AER}
F	L/d	92,930	Section 5.3.3
X_{IO}	mg COD/L	819	Whichard (2001)*
f_D	---	0.25	BioWin default
b_{ZBP}	d^{-1}	0.04	BioWin default
Y_{ZBP}	mg COD/mg COD	0.5325	BioWin default*
$i_{ZBP,T}$	mg COD/mg TSS	1.2	Grady et al. (1999)
S_{SO}	mg COD/ L	4,345	Chapter 3
X_{SO}	mg COD/ L	1,492	Whichard (2001)
S_S	mg COD/ L	0	Assumed

*Assumed conversion of 1.2 mg COD/mg TSS (Grady et al., 1999).

Oxygen Requirement

The amount of aeration required for a desired effluent quality is fixed for a given SRT. Since the SRT will vary throughout the year to accommodate temperature changes, aeration requirements will also change. The oxygen requirement was calculated for both winter and summer SRTs (Grady et al., 1999):

$$RO = F\left(S_{SO} + X_{SO} - S_S\right)\cdot\left[1 - \frac{\left(1 + f_D \cdot b_{ZBP} \cdot \Theta_{ce}\right)Y_{ZBP}}{1 + b_{ZBP} \cdot \Theta_{ce}}\right] \qquad \textbf{[5.3]}$$

where RO = Steady state oxygen requirement (mg/d).

Decay rates are typically much higher in warmer temperatures and have a significant influence on RO. Given the same SRT, the summer RO would be greater than the winter RO because of higher decay rates in the summer. Since the SRTs are different, this may not be the case. Therefore, RO should be calculated for both winter and summer operation to determine the maximum RO. The minimum RO was also needed in specifying an aeration system to ensure that the turndown power was sufficient as to not waste energy with excess aeration.

No information was found on the effects of temperature on decay rates of PAO heterotrophs. Measured values of the decay parameter, b_{ZBP}, range from 0.03 to 0.06 d^{-1} at 20° C

(Smolders et al., 1994; Wentzel et al., 1987). Typical variation in decay rates for non-PAO heterotrophs are 0.15 and 0.22 d^{-1} at 15 and 25° C (Grady et al., 1999). Since b_{ZBP} has not been measured at higher temperatures, RO was calculated for different values of b_{ZBP} to determine the potential effects of b_{ZBP} on RO. (Table 5.14). It was assumed that the likely variation of b_{ZBP} values was 0.03 to 0.1 d^{-1}. Since decay rate is lower in winter and higher in summer, it was estimated that RO could vary between 217 and 196 kg/d.

Table 5.14: Oxygen requirements (kg/d) calculated for winter and summer aerobic SRTs and varying decay rates using Equation [5.3]. Bold values indicate estimated limit for RO.

Operation	SRT_{AER} *(d)*	b_{ZBP} *(d^{-1})*				
		0.03	*0.04*	*0.06*	*0.1*	*0.2*
Winter (15° C)	3	**217**	196	235	196	293
Summer (25° C)	2	211	196	224	**196**	270

Power

The amount of power required to supply the required oxygen was calculated for both the maximum and minimum RO (Grady et al., 1999):

$$P = \frac{RO}{\eta_P} \qquad \textbf{[5.4]}$$

where P = Power input (KW),
RO = Oxygen requirement (kg/hr), and
η_P = Energy efficiency of the mechanical aeration system (kg O_2 KW^{-1} hr^{-1}).

Typical values of η_P are 0.7 to 1.2 kg O_2 KW^{-1} hr^{-1} (Grady et al., 1999; Tchobanoglous and Burton, 1991). Since η_P is dependent on the aerator, the power requirements were determined for η_P values in this range for the upper and lower RO (Figure 5.1). Since the aerator will also be used to meet mixing requirements, the basin was also considered in selecting an aerator.

Mechanical Aeration

The power required to meet RO depends only on the system SRT and not the basin volume. Therefore, the volumetric power requirements are smaller for larger basins. There are upper and lower reactor volume limits (V_U and V_L, respectively) that correspond to the required

power input. If the reactor volume is less than V_L, then the biomass will be subjected to too much shear force, which can disrupt settling properties. If the reactor volume is greater than V_U, then the total power input needed for mixing is greater than that needed for aeration, which is not energy efficient. Therefore, the value of V_U was determined based on the minimum power required to keep solids in suspension (Grady et al., 1999):

$$V_U = \frac{P_{MIN}}{\Pi_{L,P}} \qquad \textbf{[5.5]}$$

where V_U = Reactor volume upper limit (m^3),
P_{MIN} = Power requirement to meet minimum RO (KW), and
$\Pi_{L,P}$ = Lower limit on volumetric power input (KW/1000 m^3).

The value of V_L is based on the maximum expected volumetric power input (Grady et al., 1999):

$$V_L = \frac{P_{MAX}}{\Pi_{U,P}} \qquad \textbf{[5.6]}$$

where V_L = Reactor volume (m^3),
P_{MAX} = Power requirement to meet maximum RO (KW), and
$\Pi_{U,P}$ = Upper limit on volumetric power input (KW/1000 m^3).

The lower and upper limits on volumetric power input for mechanical aeration systems are typically 14 and 60 KW/1000 m^3, respectively (Grady et al., 1999). The upper and lower reactor volume limits were calculated for varying energy efficiencies for mechanical aerators (Table 5.15).

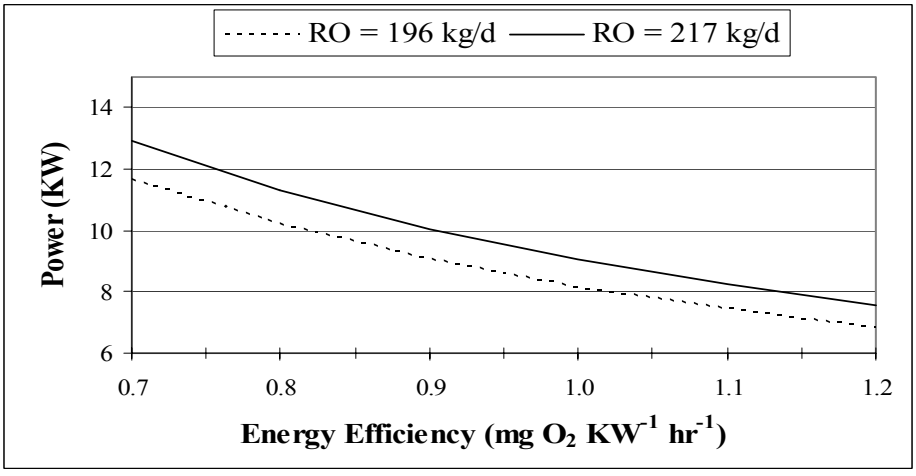

Figure 5.1: Power requirements for maximum and minimum RO and varying energy efficiencies of mechanical aerators calculated using Equation [5.4].

A higher oxygen transfer efficiency is needed to meet the required oxygen demand in a smaller volume basin without shearing the flocs (Figure 5.2). Given a 1-day HRT, a flow rate of 92.93 m^3/d, and a minimum decant level of 50%, the total treatment volume is 142.8 m^3. Given the highest aeration efficiency of the typical range for mechanical aerators, the smallest estimated reactor volume required to prevent floc shear is 126 m^3 (Table 5.15). This is assuming that the efficiency of the aerator is maintained at 1.2 kg O_2 KW^{-1} hr^{-1}. Since the system will be filled continuously for a period of 22 hours, the liquid volume will not reach 142.8 m^3 until the end of the cycle.

Table 5.15: Power requirements (KW) to meet oxygen requirements (RO) at varying energy efficiencies for mechanical aerators

Energy Efficiency*	Power Requirement†		Reactor Volume‡	
η_P	(KW)		(m^3)	
(kg O_2 KW^{-1} hr^{-1})	P_{MIN}	P_{MAX}	V_U	$V_{L,FS}$
0.7	11.7	12.9	833	216
0.8	10.2	11.3	728	189
0.9	9.1	10.1	648	168
1	8.2	9.1	583	151
1.1	7.4	8.2	530	137
1.2	6.8	7.5	486	126

*Field energy efficiency of mechanical aeration.
†P_{MIN} and P_{MAX} based on RO_{MIN} (8.2 kg/h) and RO_{MAX} (9.1 kg/h), respectively.
‡Upper and lower reactor volumes based on P_{MIN} and P_{MAX}, respectively and $\Pi_{L,P}$ and $\Pi_{U,P}$ values of 14 and 60 KW/1000m^3, respectively.

The lower volumetric limit was considered too high for aeration requirements to be met with mechanical aerators. The amount of power required to meet the oxygen requirements would require mechanical aerators, which would create too much turbulence in the SBR. Increasing the size of the system (and increasing the HRT) would enable the use of a mechanical aeration system. Increasing the basin volume would increase the costs of the SBR. While this may be offset by the lower cost of aeration equipment (mechanical aerators are typically cheaper than diffused aerators), space availability may be a limitation depending on the farm operation. Therefore, a diffused air system was selected for this process design.

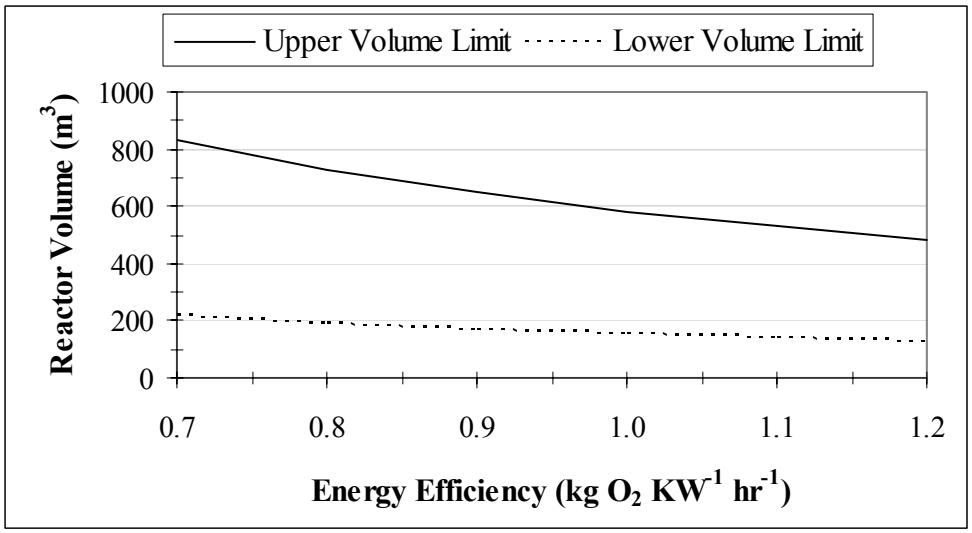

Figure 5.2: Reactor volume limits for typical energy efficiencies of mechanical aerators based on Equations [5.5] and [5.6]. The upper volume limit is based on the minimum power requirements to keep solids in suspension. The lower volume limit is based on the maximum volumetric power input that can be applied with out shearing biomass flocs.

Diffused Aeration

For diffused air systems, air requirements are determined based on the airflow rate (Q) rather than the power input (Grady et al., 1999):

$$Q = \frac{6.0RO}{\eta_Q} \qquad \textbf{[5.7]}$$

where Q = air flow rate (m^3/min),
RO = Required oxygen (kg/hr),
η_Q = field oxygen transfer efficiency expressed as the percent of the oxygen in the air transferred to the liquid.

Although η_Q is highly variable, it is typically in the range of 6 to 15% (Grady et al., 1999). Flow 7rates were calculated for this range of oxygen transfer efficiencies (Figure 5.3). Assuming a value of 10% for η_Q, the corresponding airflow rates for maximum and minimum expected RO were 4.9 and 5.4 m^3/min.

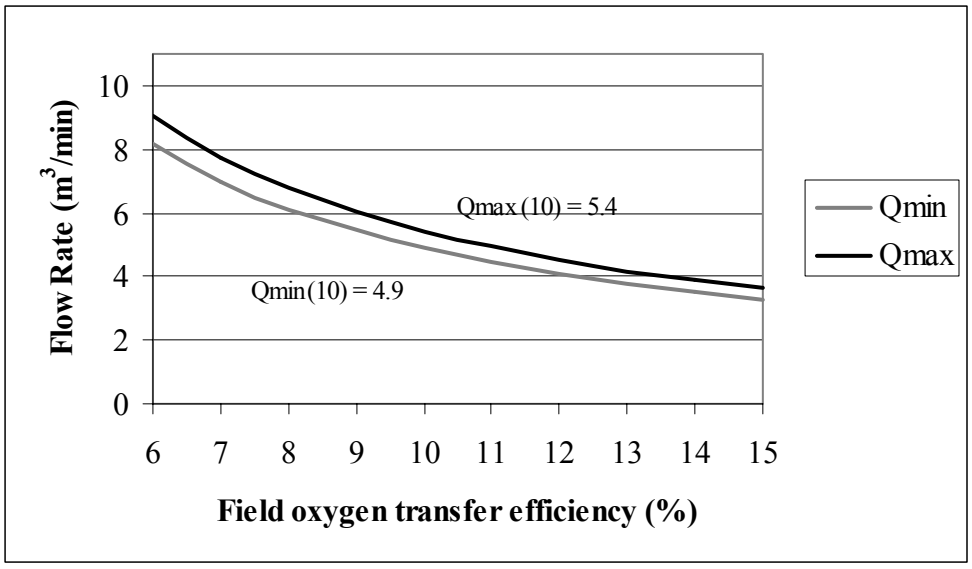

Figure 5.3: Flow rates required to meet oxygen requirements for varying oxygen transfer efficiencies (η_Q). Flow rates calculated for maximum and minimum oxygen requirements.

The minimum and maximum tank volumes were then determined based on Q. The upper volume based on the volumetric power input required to keep biomass in suspension was calculated (Grady et al., 1999):

$$V_U = \frac{Q}{\Pi_{L,Q}} \qquad \textbf{[5.8]}$$

where $\Pi_{L,Q}$ = the lower air input rate for diffused aeration required to keep biomass in suspension (m^3 (min ·1000 m^3)$^{-1}$).

The minimum air input rate ($\Pi_{L,Q}$) typically required for diffuse air systems is 20 m^3/min per 1000 m^3 of reactor volume (Grady et al., 1999). The lower volume limit required to prevent excessive shear is given by:

$$V_L = \frac{Q}{\Pi_{U,Q}} \qquad \textbf{[5.9]}$$

where $\Pi_{U,Q}$ = highest volumetric air input which can be introduced without excessive shear on biomass (m^3 (min · 1000m^3)$^{-1}$).

The typical maximum air input for diffuse aeration is 90 m^3/min per 1000 m^3 of reactor volume (Grady et al., 1999). Based on the limits for excessive shear and keeping biomass in suspension,

the upper and lower reactor volume limits were calculated for varying oxygen transfer efficiencies (Table 5.16).

Table 5.16: Flow rates required to meet oxygen requirements (RO) at varying oxygen transfer efficiencies (Equation 5.7) and corresponding upper (Equation 5.8) and lower (Equation 5.9) reactor volume limits.

Energy Efficiency, η_Q* (%)	Flow Rate, Q† (m^3/min)		Volume‡ (m^3)	
	Q_{MIN}	Q_{MAX}	Upper Limit (V_U)	Lower Limit ($V_{L,FS}$)
6	8.2	9.1	408	101
7	7.0	7.8	350	86
8	6.1	6.8	306	75
9	5.4	6.0	272	67
10	4.9	5.4	245	60
11	4.5	4.9	223	55
12	4.1	4.5	204	50
13	3.8	4.2	188	46
14	3.5	3.9	175	43
15	3.3	3.6	163	40

*Typical range of η_Q values reported for diffused aeration systems.
†Q_{MIN} and Q_{MAX} are based on RO_{MIN} and RO_{MAX}, values of 8.2 and 9.1 kg/h, respectively.
‡Upper and lower reactor volumes based on Q_{MIN} and Q_{MAX}, respectively.

Typically, volumetric oxygen transfer rates above 0.10 kg O_2 m^3 hr^{-1} cannot be sustained (Grady et al., 1999). Therefore, a lower volume limit was calculated based on this constraint:

$$V_{L,OT} = \frac{RO}{0.10} \qquad \textbf{[5.10]}$$

where RO = maximum oxygen requirement (kg O_2/hr), and
$V_{L,OT}$ = the lower volume limit based on oxygen transfer (m^3).

For the greatest expected RO (9.1 kg/hr), the lower volume limit ($V_{L,OT}$) was 91 m^3 (Figure 5.4). The greater of the two lower volume limits, $V_{L,FS}$ and $V_{L,OT}$ was taken as the lower volume limit. Except at the lowest oxygen transfer efficiencies, the lower volume limit is defined by $V_{L,OT}$ (Figure 5.4). The target volume of 142.8 m^3 used in this design is acceptable for the entire range of typical oxygen transfer efficiencies (Figure 5.4).

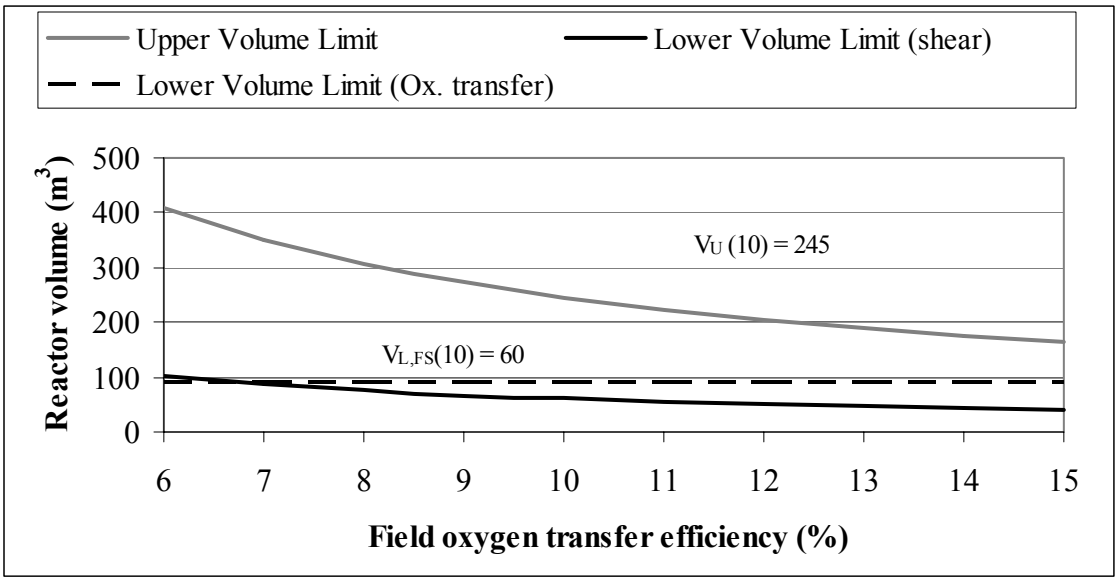

Figure 5.4: Upper and lower volume limits required to prevent shearing of flocs and to keep biomass in suspension for varying oxygen transfer efficiencies (η_Q).

Wastage

Just as with the RO, it could not be assumed that the solids wastage rate would be greater in the winter due to the different SRTs. The solids wastage rate was calculated for the summer and winter SRTs and varying decay rates (Grady et al., 1999):

$$W_{M,T} = F\left[\frac{X_{IO}}{i_{ZBP,T}} + \frac{\left(1 + f_D \cdot b_{ZBP} \cdot \Theta_{ce}\right) \cdot Y_{ZBP} / i_{ZBP,T} \cdot \left(S_{SO} + X_{SO} - S_S\right)}{1 + b_{ZBP} \cdot \Theta_{ce}}\right] \qquad \textbf{[5.11]}$$

where $W_{M,T}$ = Solids wastage rate of mixed liquor suspended solids (kg TSS/d).

It was assumed that decay rates would be 0.04 d^{-1} in the winter and as high as 0.1 d^{-1} in the summer. Based on winter and summer SRTs, the estimated wastage rate ranged from 329 to 342 kg TSS/d (Table 5.17).

Table 5.17: Wastage rates (kg TSS/d) estimated for winter and summer temperatures and decay rates

Operation	SRT_{AER} *(d)*	b_{ZBP} (d^{-1})		
		0.04	*0.1*	*0.2*
Winter (15° C)	3	**342**	315	284
Summer (25° C)	2	349	**329**	303

5.4.3 Operation Schedule

There are many considerations in selecting an operating schedule for an SBR. Reducing peak oxygen requirements can reduce efficiency requirements (oxygen transfer capabilities) of aeration systems. Decreasing aeration demands on equipment can also lower operational costs. Peak oxygen requirements can be controlled by optimally scheduling SBR feeding and aeration periods. The timing of aeration and anaerobic periods, as well as the DO concentrations maintained during aeration periods, also affect microbial activity. Scheduling of feeding and aeration are addressed in the following section. BioWin was used to examine feeding and aeration strategies and a schedule was selected for SBR operation.

Feeding

Peak aeration requirements are lower when feeding wastewater continuously or in steps as opposed to batch feeding. By introducing a given amount of COD into the system over a longer period, less DO is required for metabolism of microorganisms. While total oxygen requirements of step, continuous, and batch feeding may be similar, peak oxygen requirements at the beginning of a batch fed cycle may be different. As demonstrated in previous calculations, aeration system design is dependent on mixing requirements and reactor volume in addition to oxygen requirements.

Gradual addition of COD results in less variation of oxygen requirements throughout a given cycle. The greater the number of step feeds (approaching continuous feeding), the less variation in peak oxygen requirements. Because of the dependence of peak oxygen requirements on feeding, the feeding schedule was selected prior to determining aeration requirements.

Correlating step feeding to aeration cycles may better maintain PAO heterotrophs populations by giving them priority on VFAs. If step feeding occurs at the beginning of each anaerobic period, there is no DO available for non-PAO heterotrophs to metabolize VFA. Therefore, PAO heterotrophs would have less competition for substrate as they store VFA during the anaerobic period. If there is a continuous influent, then VFA inputs would be constant throughout anaerobic and aerobic periods, making VFA more available to non-PAO heterotrophs.

Bench scale studies would be required to determine the effects of reactor feeding schedules on microbial populations and optimize an SBR. To estimate potential differences in

peak oxygen requirements of step feeding and continuous feeding, feeding schedules were compared using BioWin (Figure 5.5). Complete PO_4 removal occurred sooner when feeding continuously than when step feeding (Figure 5.6). Phosphate concentrations are higher when step feeding since more influent enters the system in a given amount of time.

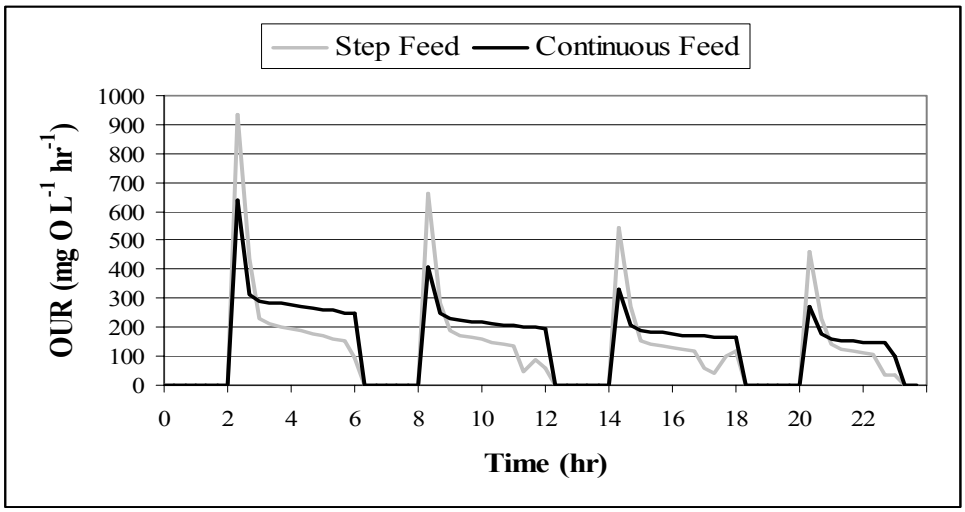

Figure 5.5: Oxygen uptake rates (OUR) estimated by BioWin for a complete SBR cycle with step and continuous feeding.

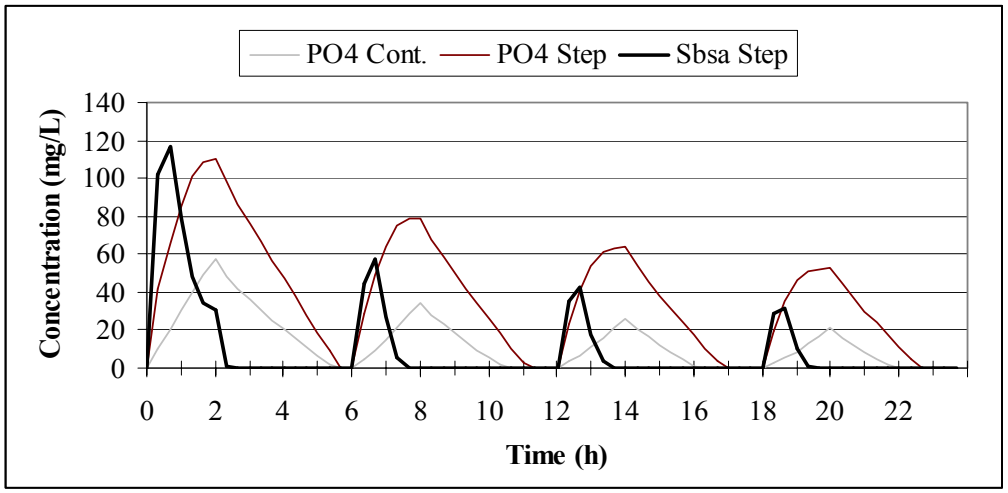

Figure 5.6: Phosphate and S_{BSA} concentrations calculated by BioWin for SBR with step and continuous feeding. In the continuously fed SBR, SBSA was taken up as fast as it was fed to the reactor and therefore does not appear on graph.

If the VFA concentration is the limiting factor in PO_4 removal, the feeding configuration may have a greater effect on the ability of PAO heterotrophs to uptake enough VFA for the

desired PO_4 removal. If VFA is in excess of PAO requirements, feeding schedules may not make as much difference. There are also differences in energy costs associated with running a high capacity pump four cycles per day and constantly running a lower capacity pump. In order to keep peak oxygen requirement lower, continuous feeding was selected for this design.

Aeration

Oxygen requirements are higher for higher temperatures for a given SRT. Temperature effects could not be demonstrated using BioWin because of the lack of information available on EBPR temperature models. An SRT of 2.5 d was chosen to represent the average oxygen requirements for the purpose of comparing effects of configuration on oxygen requirements. One deficiency in simulating effects of configuration on oxygen requirements is that SRTs in simulations are maintained by wasting mixed liquor. This results in a greater volume being removed for wastage and less decanted given the same HRT and daily flow rates into the reactor. Ideal settling was assumed to isolate the effects of changes in configuration schedule.

The aeration schedule was optimized using BioWin and BL_1 (complete PO_4 removal). Peak oxygen requirements were greater with fewer aeration periods (Figures 5.7 and 5.8). Peak oxygen requirements were also greater when the first aeration period was started later in the cycle (Figure 5.7) than when started after one hour of anaerobic reaction (Figure 5.8). Total oxygen requirements were also greater when fewer aeration periods were used (Table 5.18). The number of aeration periods used per day also affected the PO_4 concentration in the SBR. Fewer, longer aeration periods increased the PO_4 concentration throughout the cycle, but did not affect the effluent PO_4 concentration (Figure 5.9). To reduce the peak oxygen requirement, eight aeration periods were selected for SBR operation.

Table 5.18: Total daily oxygen requirements calculated by BioWin (kg) for aeration schedules differing in number of aeration periods and start times

Aeration schedule	Required oxygen (kg/d)		
	2 Aeration Periods	4 Aeration Periods	8 Aeration Periods
Different start times*	470	432	400
Aeration start at hour 1†	434	425	400

*Aeration periods scheduled to minimize duration of final anaerobic period, resulting in different start times for each initial aeration period.

†Initial aeration periods each begin at hour one.

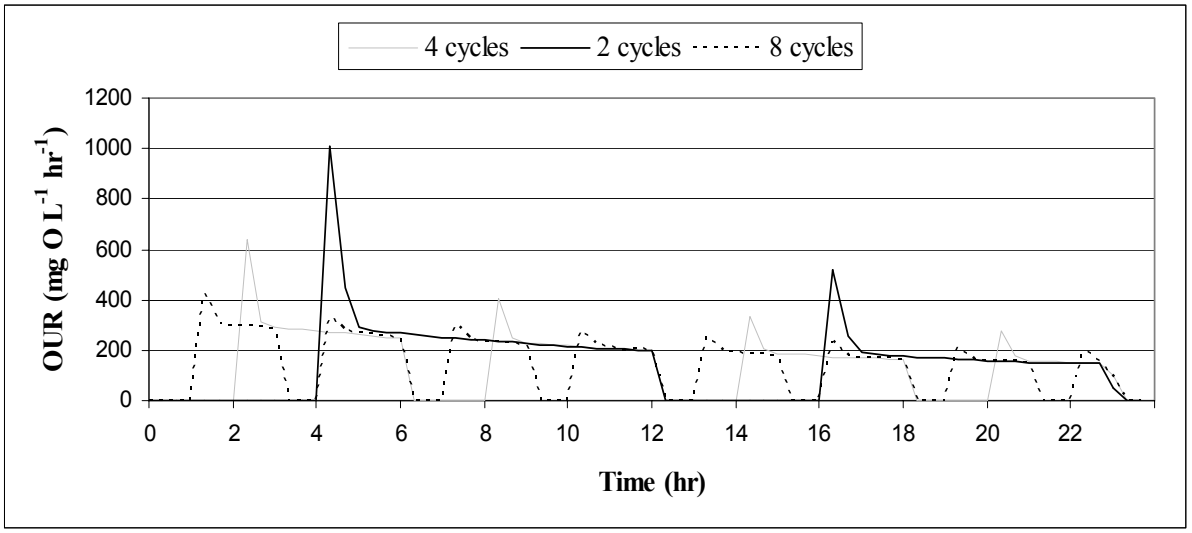

Figure 5.7: Oxygen uptake rates calculated by BioWin for continuously feed SBRs with varying number of aeration cycles per day. Each peak represents the beginning of each aeration cycle.

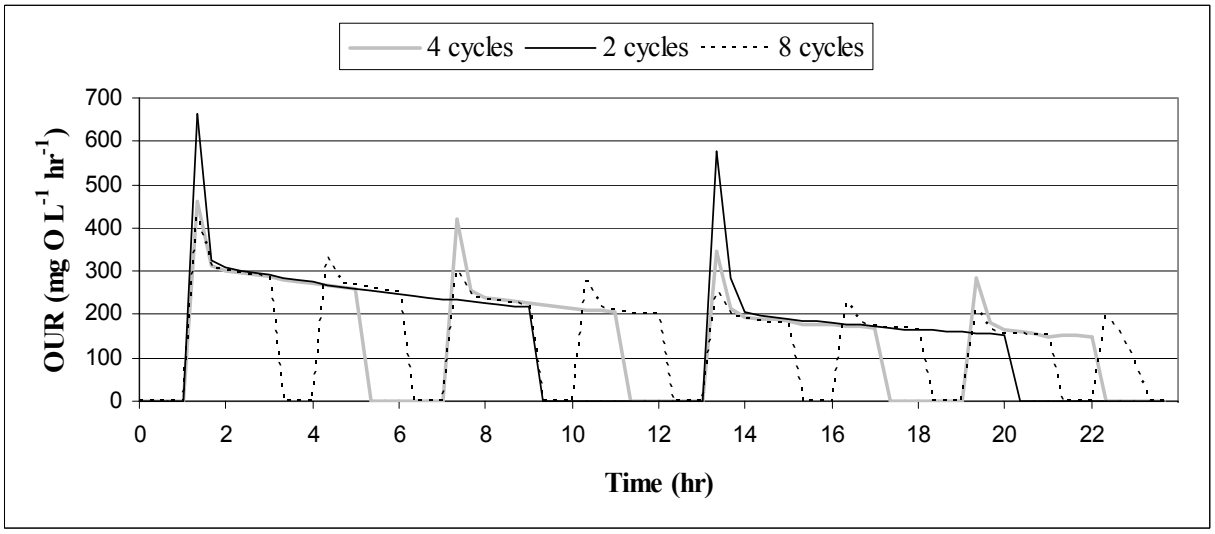

Figure 5.8: Oxygen uptake rates calculated by BioWin for continuously fed SBRs with varying number of aeration cycles per day with each first aeration period starting at hour 1. Each peak represents the beginning of each aeration cycle.

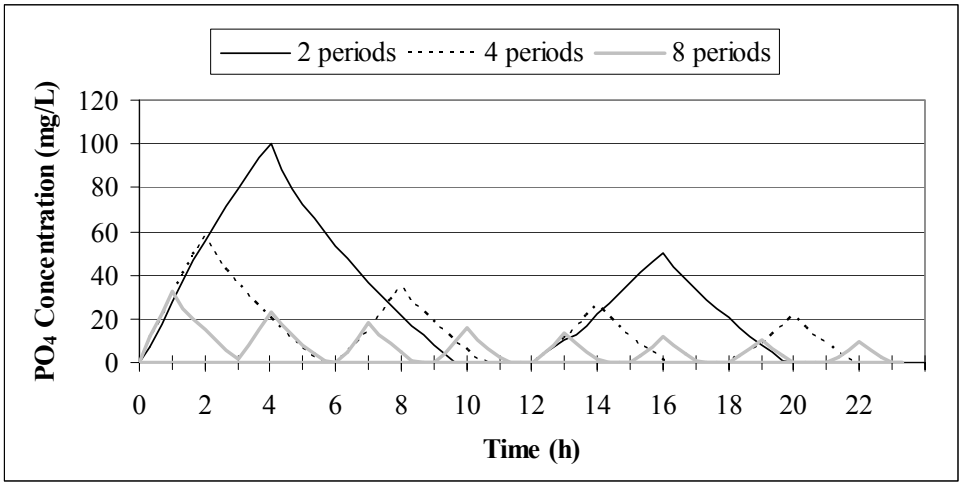

Figure 5.9: Phosphate concentrations in SBRs calculated by BioWin for varying number of aeration periods per one day cycle.

5.5 Treatment System Components

Solid Separation

An Integrity™ manure solid separator (model AQ2000D, Nutrient Control Systems, Inc.) was selected for pretreatment. The solid separator brushes manure over a screen and then presses the screened solids with a roller (Figure 5.10). Performance is best when the DM is 7% or less (Rensch, 2002). The capacity is typically between 0.76 and 1.7 m^3/min depending on the DM content of the manure and the screen size. The screens are interchangeable to provide operational flexibility. The DM content of the separated solids is 20 to 25%. The solid separator is operated by a 1.12KW electric motor.

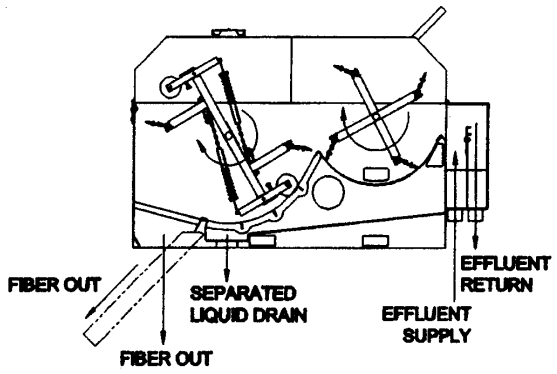

Figure 5.10: Operational cross section of Integrity™ manure solid separator (Rensch, 2002).

The solid separator is completely contained and is positioned over a reception pit in which manure is collected (Figure 5.11). Manure slurry is pumped to the solid separator from the reception pit. The separated solids are piled below the solid separator. The separated liquid exits the bottom of the machine. The solid separator is elevated such that the liquid manure flows by gravity to the fermenter and storage pit, splitting the flow 83 and 17%, respectively.

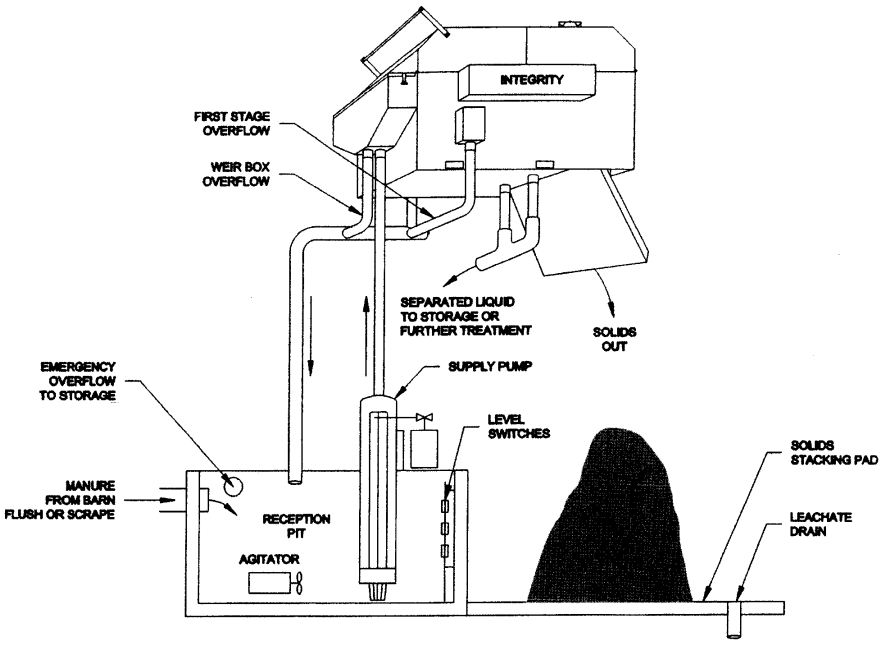

Figure 5.11: Integrity™ manure solid separator (Rensch, 2002).

Since the DM content of the manure (after mixing with bedding and flush water) was estimated to be 5.51% (Table 5.3), it is expected that the solid separator will run well under the maximum capacity of 1.7 m^3/min. Rensch (2002) recommended that a flow rate of 0.85 m^3/min be used in sizing the receptor pit from which the influent manure is pumped into the solid separator. Based on this flowrate and total daily manure volume of 130 m^3 (Table 5.4), the total run time of the solid separator is about 2.5 hr per day. This does not include time required for agitation (prior to pumping to solid separator) and purging of the separator and conveyers. It was assumed that purging takes 5 min and that the system is run six times per day based on flushing schedule and reception pit capacity. The total run time was estimated as 3 hr for calculating power costs (Chapter 6).

It was assumed that a proper reception pit already existed. Additional equipment required for solid separation includes the supply pump for manure transfer from the reception pit

to the solid separator and an agitator (4 KW) for mixing manure prior to and during solid separation. Level switches are used to activate agitation, pumping, and conveyance of manure to the solid separator.

Fermenter

Liquid effluent from the solid separator will be transferred by gravity flow to the storage pit and the fermenter. Eighty three percent of the liquid volume will be transferred to the fermenter. Peak VFA production was achieved after three days (Chapter 3). Although the volume should be minimized to reduce cost and space requirements, the fermenter was sized for an HRT of 3.5 days to ensure adequate reaction time in cooler weather. Fermented manure will be continuously fed to the SBR, and therefore, the manure level in the fermenter will decrease gradually throughout the 22-hour feeding period of the SBR. The total volume when full was 325 m^3. The dimensions of the fermenter were selected as 12 m in diameter with a depth of 2.87 m when completely full. A freeboard of approximately 0.6 m was added resulting in a total height of 3.5 m and total volume of 396 m^3. The fermenter will be concrete and covered to reduce odor.

Since the SBR is fed continuously, the fermenter requires nearly constant mixing. The required flow rate from the fermenter to the SBR is 0.07 m^3/min for 22 hours. A centrifugal pump with an open impeller (50 KW) was selected for both agitation of the fermenter and transfer of manure wastewater to the SBR.

Sequencing Batch Reactor

The SBR tank is circular and constructed of concrete. The total liquid volume when full was calculated as 139.4 m^3. When using diffused aeration, effectiveness of mixing is highly dependent on tank geometry; the tank should be between 4.6 to 7.6 m in height (Metcalf and Eddy, 1991) to maximize oxygen transfer as the diffused air travels upward. The total depth when full was selected as approximately 4.6 m to meet minimal requirements for oxygen transfer. With a freeboard of approximately 0.6 m, the total tank height was 5.2 m. The diameter was 6.2 m and the total tank volume was 157 m^3.

Biomass wasting begins 30 min after feeding has stopped. A total volume of 23 m^3 is wasted in approximately 30 min, requiring a pump capacity of 767 L/min. A centrifugal

submersible pump (7 KW) was selected for biomass wasting. The submersible pump is mounted on the floor of the SBR on the sidewall to minimize interference with the submersed aerator located at the center (discussed below).

A closed impeller centrifugal pump (37 KW) was selected for decanting from the SBR. Decanting of 69.9 m^3 begins after wastewater has settled for 45 minutes. Decanting must occur quickly to prevent the re-release of PO_4 into solution that is induced by anaerobic conditions. The total decant time is 15 min requiring a volumetric flow rate of 4.66 m^3/min. Decant continues until the SBR level reaches 50% of the total volume (a depth of 2.3 m), controlled by an inverted outlet positioned at 2.3 m. The pump must be controlled by a variable speed drive due to the change in pressure head (2.3 m depth).

Aeration/Mixing System

A submersible aerator/mixer (SAM) unit (AquaTec, Inc.) was selected to meet both oxygen and mixing requirements. The SAM is powered by a 5.6 KW motor and has a turbine impeller that distributes air in a rotary motion. The SAM is placed on the floor of the SBR. A variable speed drive and hoses are supplied with the SAM unit. The maximum airflow rate for this unit is approximately 8.5 m^3/min (rated at 0.845 m^3/min per KW). A set of two blowers, 7.5 KW each, will be used (one operating and one standby). The oxygen transfer efficiency (η_Q) of aerators is rated in clean water and by depth. Since dissolved oxygen is introduced into the system on the floor of the reactor, a greater depth allows more oxygen transfer as air bubbles float to the surface. The η_Q of this unit in clean water is 5.9 to 6.6% for every meter of depth (AquaTec, Inc.). Efficiency is greater for greater depth:width ratios and also increases at lower depths (closer to the SAM).

Since no data were available to estimate η_Q for manure wastewater, it was assumed that η_Q was 50% less than clean water test values. Given an average depth of 3.52 m, the range of η_Q was estimated as 10.4 to 11.5%. Assuming a maximum η_Q of 11%, the corresponding airflow rate (Q) required to maintain RO is 4.5 to 4.9 m^3/min (Table 5.16). Given a maximum flow rate of 8.5 m^3/min, RO could still be maintained if efficiency was as low as 6% (Table 5.16). At the beginning of the first aeration period, the reactor level is 2.44 m. The corresponding η_Q range for this depth (assuming 2.95 to 3.28% per m depth, i.e., 50% of that in clean water) is 7.2 to 8%,

which satisfies the estimated average oxygen requirements shown in Figure 5.4. (It was assumed that using average oxygen requirements was sufficient for sizing the aerator since RO peaks are minimized by the use of multiple aeration periods.)

5.6 Solids handling

Although solids handling is a significant operational concern, an in-depth analysis of solids handling options was beyond the scope of this project. Solids separated from manure slurry are often spread on fields following storage. Solids recovered from lagoon dredging are often spread on fields directly from the lagoon. The high P concentration of sludge wastage from an EBPR process presents limitations with respect to handling options. Three possibilities were considered in handling solids resulting from the EBPR process:

1. Hauling solids off the farm,
2. Composting solids on the farm, and
3. Precipitation of P from SBR solids and recycling liquid fraction back to the SBR.

The feasibility of these options is highly dependent on the specific farm operation. For this analysis, it was assumed that the sludge would be hauled off the farm. The other options of composting and struvite precipitation could minimize hauling costs and provide other operational benefits.

If an EBPR system were constructed, it is likely that the farmer would have to make operational changes to make space for the treatment components. The addition of a composting facility on top of the treatment system may not feasible due to space constraints. Composting would also be labor intensive, still requiring the movement of a large volume of waste. Composting would also require specialized equipment needed for windrow turning, which would incur additional expense if appropriate equipment were not already owned by the farmer. In addition, composting requires amendments that may or may not be easily accessible to the farmer. Crop residues are often used for compost amendments making composting advantageous for some farms. In silage production, the whole crop is harvested for feed resulting in no recoverable crop residue. Since most dairy farms use their land to produce as much feed as possible, it is unlikely that sufficient amounts of crop residue would be available for composting.

The extra effort required to make space, purchase equipment, plan and locate compost amendments, and maintain compost piles may make composting an undesirable option for a farmer who installs a wastewater treatment system. Integrating a compost facility could, however, have financial benefits. If the cost of hauling the composted product could be offset by receipts for the value-added product, this could result in the lowest cost option for solids handling. Again, the sale of such a product would also be dependent on the proximity to market.

The possibility of further solids processing is also an option. Salts of multivalent metal ions such as Ca(II), Al(III) and Fe(III) are used to precipitate P. Precipitation results in compounds such as struvite ($MgNH_4PO_4$), brushite ($CaHPO_4 \cdot 2H_2O$), and vivianite ($Fe_2(PO_4)_3 \cdot H_2O$) (Grady et al., 1999). Chemical precipitation is often used in conjunction with biological P removal such as in the Phostrip process where a sidestream reactor is used to thicken sludge and ferment solids to recycle back to the EBPR process. Chemical treatment results in increased sludge volumes and may affect the alkalinity, which in turn may affect the NH_4 concentrations. Lime is sometimes used in conjunction with biological treatment since such a high pH is required to precipitate PO_4. If chemical precipitation were incorporated into solids handling, it would be most advantageous if the liquid were recycled back to the SBR after precipitation. Therefore, lime could not be used without adjusting pH prior to recycling the liquid to the SBR. Phosphate precipitation with aluminum and iron can cause many competing reactions (Tchobanogloas and Burton, 1991). Therefore, dosages required for PO_4 precipitation must be determined experimentally.

5.7 Summary

A representative farm was chosen to estimate treatment requirements for P-based manure application. The farm characteristics are summarized in Table 5.19.

Table 5.19: Characteristics of representative farm

805 dairy cows (700 lactating)
Completely confined facility
325 ha corn silage
Manure storage capacity of 25,000 m^3

A sequencing batch reactor was designed for complete PO_4 removal from dairy manure via EBPR. Treatment system requirements for EBPR were determined based on design equations. Fermenter and SBR specifications were determined based on treatment requirements. A solid separator and other equipment required to support the manure treatment operation were selected. BioWin was used to evaluate feeding and aeration schedule options for the SBR. Solids from the solid separator and SBR wastage would be hauled from the farm. Other handling options were identified but could not be thoroughly investigated for this research.

Chapter 6: Economic Analysis

6.1 Introduction

The objective of the economic analysis was to determine if enhanced biological phosphorus removal (EBPR) was an economical nutrient management alternative for dairy farms. The costs of EBPR and off-farm transport were compared for a dairy farm employing P-based manure application. Costs were compared over a 20-year period using annualized net present values, with negative net present values representing costs to the farm. It was assumed that labor requirements of manure management with and without EBPR were similar. It was assumed that a manure pump for the storage pit and other equipment used for manure collection were already owned by the farmer and will be used similarly for both manure management scenarios. Only additional equipment required for EBPR was considered in cost estimates.

Factors affecting the economic feasibility of EBPR were addressed to identify which types of farms may benefit most from EBPR. Specific objectives of the economic analysis were to:

1. Calculate the costs of each manure management scenario using annualized net present values; and
2. Assess the effects of selected farm characteristics on the economic feasibility of EBPR.

6.2 Costs Without Manure Treatment

It was assumed that the farmer hires a service that spreads slurry at a cost of \$1.95/m^3 (Vandyke et al., 1999). The service spreads slurry with a slurry pump and tractor-drawn spreader hauling to nearby fields only. This service is used for manure applied on the farm. Excess manure would be hauled to another farm where the receiving farmer would pay for manure nutrients, which were valued at \$0.60, \$0.53, and \$0.33 per kg of nitrogen (N), P_2O_5, and K_2O, respectively (Eberly and Grover, 2001). The corresponding nutrient values on an elemental basis are \$0.60, \$1.21, and \$0.40 per kg of N, phosphorus (P), and potassium (K), respectively. These values were applied to both the purchase of commercial fertilizers and sale of manure. Although all farmers do not positively value all nutrients, it was assumed that the receiving

farmer would be willing to pay for all of the manure nutrients for this analysis. Therefore, the total cost of commercial fertilizer needed by the selling farmer, would be offset by the sale of manure nutrients (Table 6.1). The commercial fertilizer costs less receipts from manure nutrients were $6,850.

Table 6.1: Commercial fertilizer expenses and monetary receipts from sale of manure nutrients with P-based land application and without manure treatment

Nutrient	*Excess Manure Nutrients*[*]	*Commercial Fertilizer Requirements*[†]	*Nutrient Value/Cost*[‡]	*Cash Outflows*[§]	*Cash Inflows*[#]
	(kg/yr)	*(kg/yr)*	*($/kg)*	($/yr)	($/yr)
N	12,418	37,099	$0.60	-$22,259	$7,451
P_2O_5	17,467	0	0.58	0	10,131
K_2O	34,934	0	0.33	0	11,528
				-$22,259	$29,110
Total					**$6,850**

[*]Based on crop nutrients in excess manure (Table 5.7).
[†]Based on nutrient requirements of dairy farm not fulfilled following P-based application (Table 5.7).
[‡]Eberly and Grover, 2001; Used to assess both commercial fertilizer purchase and manure nutrient sales.
[§]To meet commercial fertilizer needs.
[#]For net worth of nutrients only. Does not consider hauling costs of nutrients. Assuming all manure nutrients could be sold to a neighboring farm.

The sale of manure nutrients to a receiving farmer does not include costs of hauling and spreading the manure, which would be paid by the selling farmer. Application costs for manure hauled off the farm would be the same as that for on-farm manure spreading ($1.95/$m^3$) but would also include the cost of off-farm hauling. Manure hauling was assumed to cost $5.96/$m^3$ for a haul of any distance up to 100 km. The cost for liquid manure hauling was converted from haul costs determined by Bosch et al. (1997) for turkey litter based on weight. It was assumed that farmers receiving excess manure were located within 100 km of the dairy operation. The total cost of spreading and hauling manure was $246,546 (Table 6.2).

In comparing the economics of manure management with and without manure treatment, only the management costs that would vary between the two operational scenarios were considered. It was assumed that costs of manure hauling and spreading and the sale and purchase of manure nutrients were the only costs that would be relevant in determining the

present worth of manure management without manure treatment. Based on a 20-year period, the present worth for manure management without manure treatment was -$2,817,517 (Table 6.3).

Table 6.2: Manure handling costs using P-based applications on the representative farm without manure treatment

Manure handling expense	*Volume*[*] *(m^3/yr)*	*Yearly Costs*[†]		
		Spreading	*Hauling*	*Total*
Slurry				
Applied on farm	21,553	$42,028	n/a	$42,028
Hauled off farm for application	25,856	50,418	154,099	204,518
Total	47,408	$92,446	$154,099	**$246,546**

[*]Volumes determined based on nutrient requirements (Table 5.7).
[†]Spreading manure is $1.95/$m^3$ and $5.96/$m^3$ for hauling off farm.

Table 6.3: Present worth of manure management using P-based applications on the representative farm without manure treatment over 20 years of operation

Expenses and Revenues	*Present Worth (i = 5.7%)*[†]	
	Cash Outflows	*Cash Inflows*
Hauling/Spreading: -$246,546(P/A,i,20)[*]	$2,898,036	
Commercial fertilizer: -$22,259(P/A,i,20)[*]	261,650	
Receipts for manure nutrients: +$29,110(P/A,i,20)[*]		$342,170
Total	$3,159,686	$342,170
Total Present Worth		-$2,817,517

[*](P/A,i,20) refers to present worth factor for annual payments over the next 20 years.
[†]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

6.3 Costs With Manure Treatment

Assessment of manure spreading, manure hauling, nutrient sales, and commercial fertilizer purchases were also factors in determining the economic viability of manure management with manure treatment. Additional expenses include capital and recurring costs of equipment, insurance, and personal property taxes. When P is removed from manure, more manure is applied on the farm. Therefore, the costs of spreading the manure on the farm are greater. However, since the entire liquid fraction is applied on the farm, manure hauling and commercial fertilizer costs are less. The unit costs of manure spreading, and value of manure nutrients were considered the same as those given previously.

Assuming that the nutrient concentrations of the EBPR system effluent resulted in an N:P ratio of 7 (estimated requirement of corn silage), there was no excess P in the liquid fraction of the dairy manure. Excess P would be concentrated in the manure solids. Since all of the liquid manure could be applied on a P-basis, none was hauled off the farm and sold to other farmers. Even with the application of all of the manure produced on the farm, crop requirements of N were still not met. A total of 24,682 kg N/yr in commercial fertilizer was still needed to meet the crop nutrient requirements of 325 ha of corn silage. Just as with the excess manure in the previous scenario (no treatment), it was assumed that all of the manure solids were sold for their nutrient value. Hauling manure solids off the farm was the only hauling expense with the manure treatment system scenario, resulting in a total cost of $4,678 (Table 6.4). This was much less than that estimated for manure management without manure treatment due to the sale of excess manure nutrients.

Table 6.4: Expenses and receipts for nutrients on representative farm using P-based manure applications and EBPR

Nutrient	*Excess Manure Nutrients*[*]	*Commercial Fertilizer Requirements*[†]	*Nutrient Value/Cost*[‡]	*Cash Outflows*[§]	*Cash Inflows*[#]
	(kg/yr)	*(kg/yr)*	*($/kg)*	($/yr)	($/yr)
Liquid fraction					
N	0	24,682	$0.60	-$14,809	0
P_2O_5	0	0	0.58	0	0
K_2O	0	0	0.33	0	0
Solids[¥]					
P_2O_5	17,467		0.58		$10,131
				-$14,809	$10,131
Total					**-$4,678**

[*]Assuming treated liquid manure contains exact nutrient ratio needed for corn silage and all excess P_2O_5 is conserved in manure solids.
[†]Based on P-based application (Table 5.6). Does not take into account N losses in SBR.
[‡]Eberly and Grover, 2001; Used to assess both commercial fertilizer purchase and manure nutrient sales.
[§]To meet commercial fertilizer needs.
[#]Cash inflows are for nutrient sales (receipts for selling farmer) only and does not account for the cost of transport paid for by the selling farmer.
[¥]Although some N and K_2O would remain in the solid fraction of manure, no data were available to estimate what fraction of nutrients would remain in the solids. It was assumed that K_2O requirements would still be met, as K_2O was applied in excess of crop requirements. It was assumed that conservative values used for N availability coefficients would offset potentially overestimated nutrient content of the liquid fraction of manure. Since nutrients are valued by mass, this would not affect the receipts for manure sale.

Based on a decay rate of 0.04 d^{-1}, the maximum and minimum solids wastage rates were 342 and 349 kg TSS/d (Table 5.17). The average of these values (345.5 kg TSS/d) was used in estimating costs for sludge disposal. It was assumed that the solids concentration of the gravity settled solids in the sequencing batch reactor (SBR) was 15,000 mg/L (Section 5.4.2). Based on this concentration, the required sludge volume wasted is 23 m^3/day to remove 345.5 kg. This is 16.5% of the total SBR volume (139.4 m^3) and 24.8% of the total daily SBR influent (92.93 m^3). This results in 8,395 m^3 of high P sludge produced per year. The total treated liquid effluent removed from the SBR each day is 69.9 m^3 (92.93-23). This results in a total volume of 25,518 m^3 of liquid manure applied on the land each year. Ideally, the SBR sludge would be further processed or dewatered to reduce the total volume and simplify handling. Although other solids management would be preferable, it was assumed that the sludge had to be hauled off the farm as done for the untreated slurry discussed above. (Other solids handling options are discussed below.) Since more liquid manure could be applied to the land, the hauling costs were substantially lower for manure management with manure treatment than without manure treatment. The total manure handling costs were $181,505 per year (Table 6.5).

Table 6.5: Yearly manure handling costs for EBPR

Manure Handling Expense	*Volume (m^3/yr)*	*Year Cost ($)*		
		Spreading	*Hauling*	*Total*
Liquid				
Applied on farm[†]	32,465	$63,308		$63,308
Hauled off farm for application				
Solids (all applied off-farm)				
Solid separator[‡]	6,540	$12,752	$38,976	51,728
SBR solids[§]	8,403	$16,386	$50,084	66,470
Total	47,408	$92,446	$89,059	**$181,505**

[*] Spreading manure is $1.95/$m^3$ and hauling manure off the farm is $5.96/$m^3$.
[†]Accounts for 86.2 percent recovery of volume from solid separator and 75.2 percent from SBR.
[‡]Solids accounting for 22% of original volume before solid separation.
[§]Wasted solids account for 24.8 percent of the total volume fed to the SBR.
[#]Total manure wastewater volume including flush water and bedding before treatment (Table 5.3).

Based on the EBPR treatment requirements (Chapter 5), system components were selected (Table 6.6). Energy costs (Table 6.7) were estimated for running the equipment for the EBPR treatment.

Table 6.6: Capital costs of EBPR system

Item	Cost*
Solid separation	
Solid separator†	$24,750
Agitator for reception pit‡	4,500
Supply pump‡	3,930
Fermentation	
Concrete fermentation basin (396 m^3) §	31,284
Pump, mixing/transfer‡	2,005
EBPR	
Concrete SBR basin (153 m^3) §	12,403
Submersible Aerator/Mixer#	29,000
Blowers (set of two for duplex operation)#	10,000
Independent mixer for SAM#	4,000
Decant Pump‡	5,060
SBR Waste pump‡	3,930
Total	**$130,862**

*During 20 year study period; †Nutrient Control Systems, Inc.; ‡Rensch, 2002; §Estimated construction cost (including labor and fencing) as \$79/m^3 of volume (Skyline Soil and Water Conservation District, Christiansburg,Va); #AquaTec, Inc.

Table 6.7: Energy costs of EBPR system

Item	*Power Requirement (KW)*	*Duration of use (hr/day)*	*Energy (KW-hr/d)*
Solid separation			
Solid separator	1.1185	3	3.4
Agitator for reception pit	4	3	12
Supply pump	8	3	24
Fermentation			
Pump, mixing/transfer	50	20	1000
EBPR			
Submersible Aerator/Mixer	5.5927	15.23	85
Blower	7.457	15.23	114
Independent mixer for SAM	3.728	7.77	29
Decant Pump	37	0.25	9.3
SBR Waste pump	7	0.5	3.5
Total Energy (KW-hr)			1280
Total Cost ($/yr)			**$58,967**

*Cost of power is \$0.03748/KW-hr for the first 900 KW-hr and \$0.02983/KW-hr after; Fuel adjustment cost of \$0.01310 applies to each KW-hr used (Griffitt, 2002).

Based on the expected life of each piece of equipment, replacement costs occurring in a 20-year period were estimated (Table 6.8). Salvage value was taken into account for equipment having useful life remaining after the 20-year study period (Table 6.9). Present worth of the total cost of manure management with EBPR was calculated (Table 6.10).

Table 6.8: Estimated replacement costs of equipment over 20 years

Item (Estimated life, years)[*]	*Cost*	*Replacement Year/s, n*	*Costs*[†] *Incurred in Year(n)*		
			n = 7	*N = 13*	*n = 14*
Solid separation					
Agitator for reception pit (7)	$4,500	7,14	$4,500		$4,500
Supply pump (7)	3,930	7,14	3,930		3,930
Fermentation					
Pump, mixing/transfer (7)	2,005	7,14	2,005		2,005
EBPR					
Submersible Aerator/Mixer (13)	29,000	13		$29,000	
Blowers (7)	10,000	7,14	10,000		10,000
Independent mixer (7)	4,000	7,14	4,000		4,000
Decant pump (7)	5,060	7,14	5,060		5,060
SBR Waste pump (7)	3,930	7,14	3,930		3,930
Total			**$33,425**	**$29,000**	**$33,425**

[*]Based on estimates given by suppliers.
[†]Value assessed using straight-line depreciation.

Table 6.9: Estimated salvage value of equipment at the end of year 20

Item	*Cost*	*Last Replacement Year, n*	*Years of useful life remaining at n = 20*	*Value at n = 20*
Solid separation				
Agitator for reception pit	$4,500	14	1	$643
Supply pump	3,930	14	1	$561
Fermentation				
Pump, mixing/transfer	2,005	14	1	$286
EBPR				
Submersible Aerator/Mixer (SAM)	29,000	13	8	$17,846
Blowers (set of two)	10,000	14	1	$1,429
Independent mixer for SAM	4,000	14	1	$571
Decant pump	5,060	14	1	$723
SBR Waste pump	3,930	14	1	$561
Total				**$22,621**

The net present worth of manure management without EBPR was greater than that of manure management with EBPR, i.e., EBPR did not have an economic advantage (Table 6.11). The greatest cost was manure hauling which was considerably lower for manure management with EBPR. Operational costs were the next greatest cost factor for manure management with EBPR, followed by commercial fertilizer requirements.

Table 6.10: Present worth of manure management using P-based applications on the representative farm with EBPR system over 20 years of operation

Expenses and Revenues	*Present Worth (i = 5.7%)*[‡]	
	Cash Outflows	*Cash Inflows*
Investment capital costs	$130,862	
Hauling/Spreading expenses: -$181,505(P/A,i,20)[*]	2,133,516	
Receipts from manure nutrients: $10,131(P/A,i,20)[*]		$119,083
Commercial Fertilizer: -$14,809(P/A,i,20)[*]	174,072	
Power: -$58,967(P/A,i,20)[*]	693,133	
Equipment replacement, year 7: -$33,425(P/F,i,7)[†]	22,675	
Equipment replacement, year 13: -$29,000(P/F,i,13)[†]	14,107	
Equipment replacement, year 14: -$33,425(P/F,i,14)[†]	15,382	
Salvage value of depreciable assets: +$22,621(P/F,i,20)[†]		$7,465
Total	$3,183,748	$126,548
Total Present Worth		-$3,057,200

[*](P/A,i,20) refers to present worth factor for annual payments over the next 20 years.
[†](P/F,1,n) refers to present worth factor for future payment in year n.
[‡]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

Table 6.11: Comparison of cost factors of nutrient management with P-based manure applications on the representative farm with and without EBPR

Expenses and Revenues	*Present Worth (i = 5.7%)*[*]	
	With EBPR	*Without EBPR*
Manure Hauling/Spreading	-$2,133,516	-$2,898,036
Commercial Fertilizer	-174,072	-261,650
Manure Nutrient Sales	119,083	342,170
Capital Costs	-130,862	n/a
Operational (Power) Costs	-693,133	n/a
Future equipment replacement	-52,164	n/a
Salvage value of depreciable assets	7,465	n/a
Total	-$3,057,200	-$2,817,517

[*]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

6.4 Factors affecting EBPR feasibility

Due to the large variations in farm characteristics, many factors affect the feasibility of EBPR. From the cost analysis, it was determined that manure hauling was the greatest expense for manure management both with and without EBPR. Some of the factors that affect manure hauling volumes are the cropping system, the ratio of cows to cropland, and off-farm nutrient utilization options. Further analysis of these three variables was conducted as discussed in the following sections. System performance was also considered a potential factor in the economic feasibility of EBPR. Other factors such as regulatory issues and taxation may also affect EBPR feasibility.

6.4.1 Cropping System

The amount of cropland relative to the herd size determines how much of the resulting manure can be utilized by land application. The cropping system is also a factor since the nutrient requirements are crop specific and can vary widely. Other factors that limit land application are land slope and soil types on which crop yields are dependent. Farmers should also consider previous crop rotations to account for current soil nutrient levels.

Crop rotations on dairy farms are largely dependent on feed rations. A common crop rotation is that of corn silage (summer) and rye (winter). For the representative farm, the total acreage was chosen based on corn silage only (Table 6.12).

Table 6.12: Dairy manure nutrient availability and crop nutrient requirements for corn silage and ryelage

Nutrient	*Manure Nutrient Production*	*Manure Nutrient Availability*[*]	Crop Requirements		
			Corn Silage[†]	*Ryelage*[‡]	*Corn Silage & Ryelage*
			(kg/yr)		
N	79,236	22,759	47,450	11,050	58,500
P_2O_5	32,132	32,132	14,625	6,500	21,125
K_2O	63,900	63,900	14,625	6,500	21,125
N:P[§]		2	7	4	

[*]Accounting for N losses during storage and application. Assume 58% Organic N and 42% NH_3-N and availability coefficients of 0.35 and 0.20, respectively.

[†]Based on 325 ha corn silage.

[‡]Based on fall application to winter rye (325 ha); N, P_2O_5, and K_2O applications of 34, 40, 40 kg/ha (DCR, 1995).

[§]Elemental nutrient ratio.

Adding a winter crop to the original farm scenario results in a greater nutrient demand. However, the N:P requirements are different for spring (corn silage) and winter (ryelage) applications. The N:P ratios for corn silage and ryelage are 7 and 4. The N recommendation is 28 to 34 kg N/ha for fall manure applications to rye, as opposed to 145 kg N/ha applied for corn silage in spring or fall. Rye crop requirements are much greater if applied in the late winter (78 kg/ha). Adding winter rye to the cropping system would increase the amount of manure that could be applied to cropland.

The effect of this cropping system on the economic feasibility of EBPR would depend on how the treatment system would accommodate the two different nutrient ratios. As mentioned earlier, it would be easier to completely remove PO_4 than to target a specific concentration. Increasing the last anaerobic period in the SBR cycle to encourage some PO_4 release is an option but may be too risky from an operational standpoint. Phosphate release can occur rapidly and would be difficult to control once induced. Although the blending ratio could be changed seasonally for different crop nutrient requirements, the system must still be sized for the highest N:P ratio. Therefore, the sizing of the system would not affect the economic viability of EBPR in this cropping system compared to a corn silage only cropping system. Assuming that complete PO_4 would occur in the system, the lower N:P ratio required by rye could be accommodated by blending high P sludge back into the SBR effluent.

6.4.2 Herd to Land Ratio

Herd size affects the economic feasibility of manure treatment. The ability of a farm to accommodate manure is highly dependent on the cropland relative to the herd size. Given the crop nutrient requirements and nutrient production on the representative farm, it was determined that the manure from one cow would meet the P needs on 0.89 ha of corn silage (Table 5.5). Similarly, the manure from 1.13 cows could be applied on one ha if applied on a P-basis (Table 5.5). Based on this land capacity, cropland and herd size (for the representative farm) required for P-based manure applications without excess manure were estimated.

Given the herd size of the representative farm, the costs of the two manure management scenarios were determined for different amounts of cropland (Table 6.13 and 6.14). The cropland was assumed to be 100% corn silage as on the representative farm.

Table 6.13: Total cost of manure management with P-based manure applications and representative herd size (805 cows) without EBPR treatment for varying amounts of cropland

Cropland (ha)	*Yearly Expenses/Receipts*			*Present Worth[*] (i=5.7%)[†]*
	Commercial Fertilizer Cost	*Manure Nutrient Sales*	*Hauling/ Spreading Cost*	
715	$48,971	$0	$92,446	-$1,662,296
500	34,245	16,044	177,378	-2,298,947
400	27,396	23,510	216,902	-2,595,271
325	22,259	29,110	246,546	-2,817,511
163	11,164	41,205	310,575	-3,297,556
81	5,548	47,327	342,985	-3,540,547

[*]Higher present worth (less negative) indicates less cost to the farmer.
[†]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

Table 6.14: Cost of manure management for P-based manure applications and representative herd size (805 cows) with EBPR treatment and varying amounts of cropland

Cropland (ha)	*Yearly Expenses/Receipts*			*Present Worth[*] (i=5.7%)[†]*
	Commercial Fertilizer Cost	*Manure Nutrient Sales*	*Hauling/ Spreading Cost*	
715	$48,973	$0	$181,505	-$3,577,864
600	38,899	2,985	181,505	-3,424,361
500	30,139	5,584	181,505	-3,290,841
400	21,379	8,182	181,505	-3,157,333
325	14,809	10,131	181,505	-3,057,195
163	618	14,340	181,505	-2,840,911
81	0	16,471	181,505	-2,808,598

[*]Higher present worth (less negative) indicates less cost to the farmer.
[†]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

Based on the characteristics of the representative farm, EBPR was the more cost effective option when cropland was 270 ha and below (Figure 6.1). Above 270 ha, the cost of manure management with EBPR was greater than manure management without EBPR.

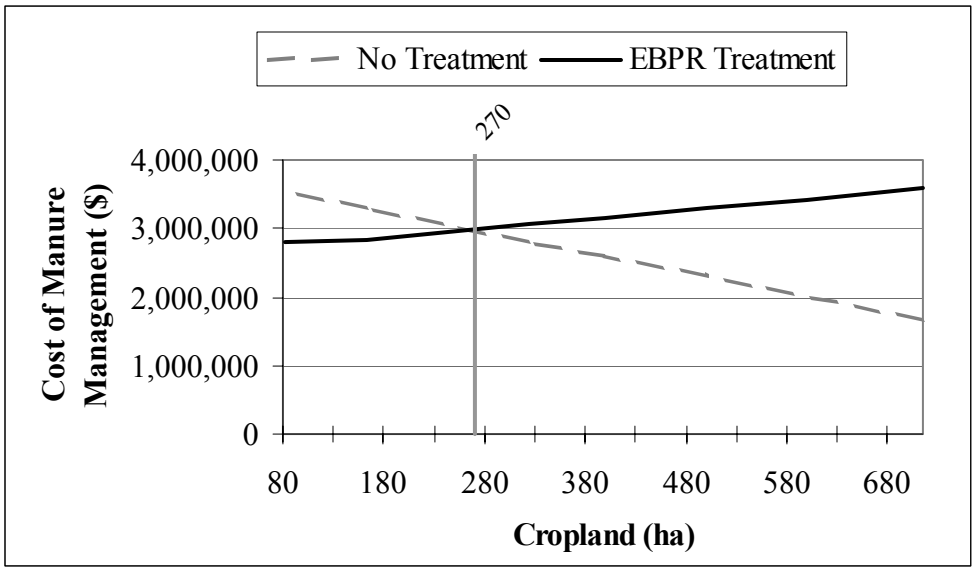

Figure 6.1: Cost of manure management (negative present worth) with P-based manure applications and the representative herd size (805 cows) with and without manure treatment for varying amounts of cropland.

6.4.3 Utilization of Excess Manure Nutrients

It was assumed that there were nearby farms to which the dairy farmer could haul excess manure. The availability of such farms is highly variable and depends on regional cropping systems and farm management practices. If regional outlets for manure nutrients are available, the proximity of these farms would have a significant impact on the cost of manure hauling (Table 6.15).

Table 6.15: Total cost (present worth) manure hauling for farm with no manure treatment for varying haul distances

Haul Distance	*Hauling Cost*[*]	*Hauling/Spreading*		*Present Worth (i=5.7%)*[†]
		Total Cost	*Present Worth*	
100	$154,099	$246,546	-$2,898,036	-$2,817,517
125	$218,286	$310,732	-$3,652,522	-$3,572,002
150	$282,473	$374,919	-$4,407,007	-$4,326,488
175	$346,659	$439,105	-$5,161,493	-$5,080,973
200	$410,846	$503,292	-$5,915,978	-$5,835,459

[*]Hauling cost for 25,856 m^3 of manure assuming \$0.0993/m^3 for each loaded km exceeding 100 km.
[†]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

It was assumed that receiving farmers would be located within 100 km and that a single haul would be the same cost within that distance. Given a cost of \$ 0.10/ton_m for every loaded km over 100 km (Bosch et al., 1997) and a manure density of 993 kg/m^3, it was assumed that manure hauling cost \$0.0993/m^3 for every loaded km over 100. At greater haul distances, EBPR becomes more economical (Tables 6.15 and 6.16). At haul distances of 117 km and above, manure management with EBPR is more economical than manure management without EBPR for a farm with 805 cows (Figure 6.2).

Table 6.16: Total cost (present worth) of manure hauling with EBPR treatment for varying hauling distances

Haul Distance	*Hauling Cost*[*]		*Hauling/Spreading*		*Present Worth (i=5.7%)*[§]
	Solid Separated[†]	*SBR Solids*[‡]	*Total Cost*	*Present Worth*	
100	\$38,976	\$50,084	\$181,505	-\$2,133,516	-\$3,057,200
125	\$52,643	\$70,945	\$216,034	-\$2,539,388	-\$3,463,071
150	\$66,311	\$91,806	\$250,563	-\$2,945,259	-\$3,868,942
175	\$79,978	\$112,667	\$285,092	-\$3,351,130	-\$4,274,813
200	\$93,646	\$133,529	\$319,621	-\$3,757,001	-\$4,680,685

[*]Hauling was based on weight (\$0.10/tonm).
[†]Density of solid separated solids was 836 kg/m^3 resulting in a hauling cost of \$0.0836/m^3.
[‡]Density of SBR wasted solids assumed that of untreated manure (993 kg/m^3) for hauling cost estimation.
[§]Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

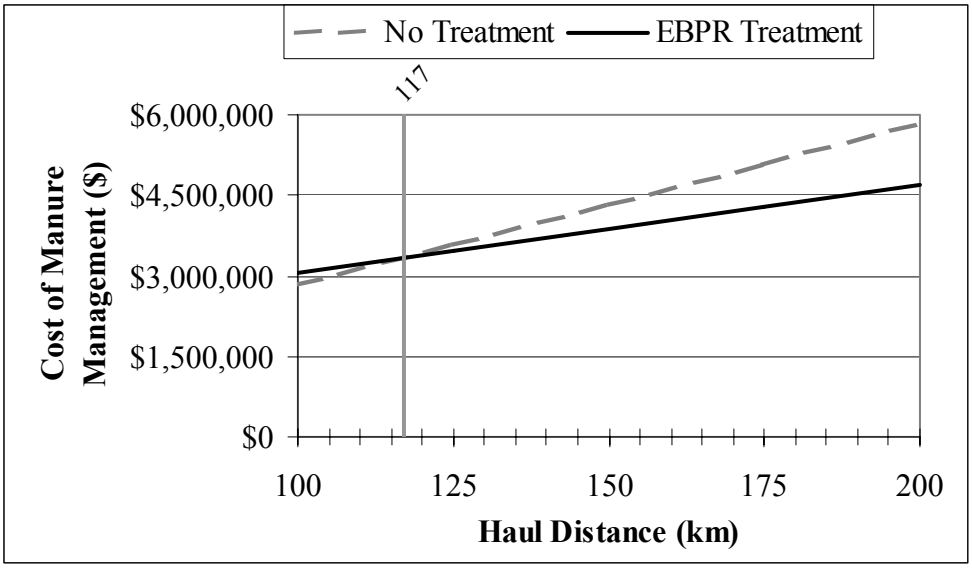

Figure 6.2: Total cost of manure management (negative present worth) with P-based manure applications for the representative herd size (805 cows) with and without EBPR treatment versus hauling distance.

One of the most variable factors in managing excess manure nutrients is the nutrient need of neighboring farms. For the initial cost comparison, it was assumed that the receiving farmer would be willing to pay for all of the nutrients contained in the manure. If a farmer is only in need of one of the nutrients, it is unlikely that he/she will pay for the worth of the other nutrients contained in the manure. Due to the variability in farming operations (e.g., crop rotation, residual soil nutrients, crop yields), typical nutrient requirements of receiving farms could not be estimated. To evaluate the impact of nutrient needs of receiving farms, the costs of manure management were estimated assuming the farmer would only pay for a fraction of the nutrients contained in the manure (Tables 6.17 and 6.18).

Table 6.17: Total cost (present worth) of manure hauling for farm with no manure treatment for varying percent sales of excess manure nutrients

Percent Sales of Nutrients	*Cash Inflow from Nutrients*		*Present Worth (i=5.7%)**
	Cost	*Present Worth*	
100	$29,110	-$342,170	-$2,817,517
75	21,832	-256,627	-2,903,059
50	14,555	-171,085	-2,988,602
25	7,277	-85,542	-3,074,144
0	0	0	-3,159,686

*Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

Table 6.18: Total cost (present worth) of manure hauling with EBPR treatment for varying percent sales of excess manure nutrients

Percent Sales of Nutrients	*Cash Inflow from Nutrients*		*Present Worth (i=5.7%)**
	Cost	*Present Worth*	
100	$10,131	-$119,083	-$3,057,200
75	7,598	-89,313	-3,086,971
50	5,065	-59,542	-3,116,741
25	2,533	-29,771	-3,146,512
0	0	0	-3,176,283

*Discount rate calculated based on an interest rate of 8% and inflation equal to 2.2% (Appendix E).

The fraction of nutrient worth realized from the sale of manure has a greater effect on the total cost of manure management for a farm not employing treatment (Figure 6.3) as indicated by the greater slope. The cash inflow from the sale of manure nutrients does not affect the

economic feasibility of EBPR with respect to manure management without manure treatment. If no excess manure is sold, manure management is still more costly with EBPR than without. This does not, however, take into account additional expenses incurred by off-farm manure utilization. Different hauling distances would also affect the cost of off-farm manure utilization.

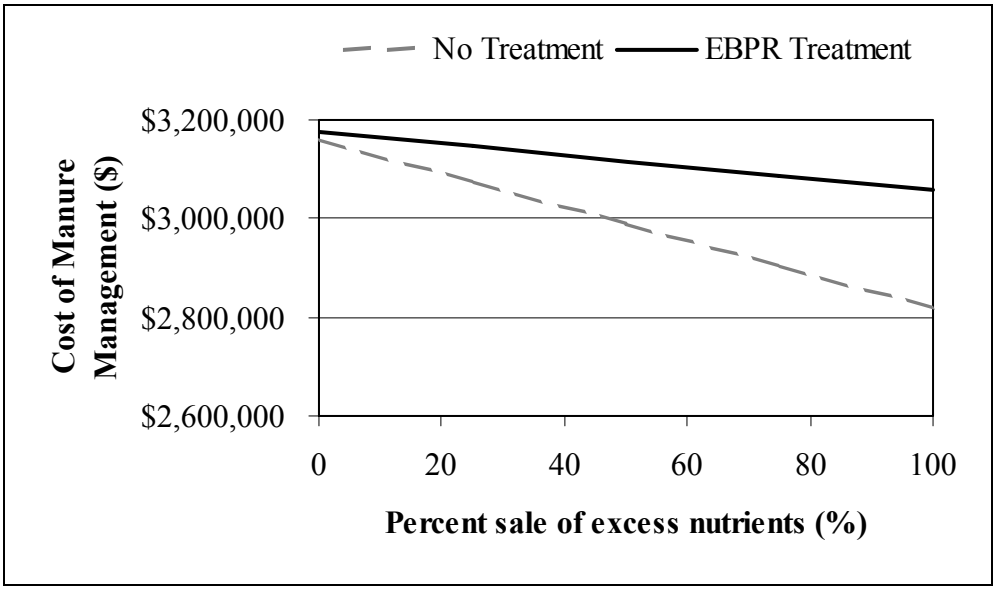

Figure 6.3: Total cost of manure management for P-based applications and representative herd size (805 cows) with and without EBPR versus percent sale of excess manure nutrients.

6.4.4 System Performance

All calculations were based on complete PO_4 removal. While complete PO_4 removal has been demonstrated in practice for municipal wastewater treatment, EBPR application to dairy manure may not be as effective. After PO_4 is completely removed in the final aeration period of an SBR, the wastewater must settle so that effluent can be decanted from the top of the reactor. During this settling period, the DO concentration drops and the reactor slowly becomes anaerobic. If this period is too long, then PAO heterotrophs will release PO_4 under anaerobic conditions. Since dairy manure has a high solids content, it may be difficult to settle solids without experiencing some PO_4 release. Settling capabilities of such treated dairy manure and the timing of secondary PO_4 release would have to be determined experimentally.

A greater fraction of the dairy manure could be treated in anticipation of secondary PO_4 release or less optimal settling prior to decant. In the design of the treatment system, it was

estimated that 83% of the solid separated manure would be treated to result in an N:P ratio of 7. Based on the same manure characteristics, the greatest acceptable PO_4 release was determined. If the entire manure volume was treated (no blending), the greatest PO_4-P release that would still maintain an approximate N:P nutrient ratio of 7 was 13 mg/L.

Another factor related to nutrient recovery from the treatment system is the effect of storage on the manure nutrient content. Nitrogen losses have been accounted for in the availability coefficients. Phosphorus and potassium are often concentrated in solids during storage and are conserved in the system (Converse et al., 2000).

6.4.5 Other Factors

As no two farming operations are the same, there is great difficulty in evaluating a technology for the dairy industry as a whole. Data from different studies were used in estimating manure and wastewater characteristics (Table 5.1). It would be beneficial to use manure from a single operation to estimate and, more importantly, compare the effects of various manure handling practices on manure characteristics. Operational characteristics, such as diet, can have a significant effect on excess nutrient production. Manure from cows fed a low P ration had 41 and 35% less total P (percent DM) in liquid and solid fractions of solid separated manure than cows fed a high P diet (Knowlton, 2002). It is expected that the capital costs of the SBR would not vary significantly between two similarly sized dairy operations. Manure collection methods, on the other hand, would affect treatment components. The amount of flushwater (or lack thereof) used in manure collection would affect the size of the treatment system. Since the capital costs of the SBR system were not a major factor in the economic feasibility, no further evaluation on the effects of flushwater was completed.

Regulatory issues

All calculations were done based on P-based manure applications. Although these regulations are not yet in place for dairy farms, there is a trend towards increased environmental restrictions on farm waste management. As with taxation and many cost share programs, regulatory issues vary from state to state and are a significant factor in regional variations in farm management practices. Such differences will affect the application of new practices and technologies such as agricultural wastewater treatment. Economic incentives for practices

supporting natural resource conservation may affect the economic viability of biological manure treatment.

Effects of taxation on farm economics

Due to the complexity of taxation laws and their dependence on operation-specific finances, tax write-offs were not taken into account in the economic analysis. Tax credits and deductions for farm related expenses can affect the economic feasibility of implementing new on-farm technologies such as EBPR. Farmers can receive a federal tax credit of up to 25% of expenditures for non-depreciable expenses that support soil and water conservation (Harris et al., 1998). (This tax credit has to be applied after taking into account any applicable cost share benefits.) For a farmer who does not have any taxes to pay (no gross income), such programs are of no benefit. The credit cannot be carried over into subsequent years.

State tax incentives are highly variable and addressing these was beyond the scope of the project. Virginia gives farmers opportunities to obtain conservation credits against taxes. These can be carried forward five years to the benefit of a farmer experiencing years with no gross income (Tax Code of Virginia, 2002).

6.5 Summary

Based on the representative farm, the cost (as present worth) of manure management over a 20-year period with EBPR ($4,349,326) was greater than manure management without EBPR ($4,005,288). Costs were compared for varying herd to land ratios, manure hauling distances, and returns from excess manure disposal. It was found that EBPR had an economic advantage for an 805-cow herd if the cropland available for manure application was less than 270 ha. For an average hauling distance over 117 km, EBPR had an economic advantage. Receipts for excess manure nutrients did not affect the economic feasibility of EBPR. Due to the variability of manure utilization/disposal options, the cost of manure management without receiving farmers available to purchase manure could not be fully addressed. Other variables that could not be quantitatively addressed include cropping systems, treatment system performance, regulatory standards, tax incentives, and cost sharing.

Future environmental pressure and economic constraints will continue to transform the dairy industry. The question is, how much change/regulation will be absorbed through incorporation of new technologies. Some dairy farmers having trouble meeting nutrient regulations may be able to continue their business with the help of new technologies. Farms with higher herd size to cropland ratios are more likely to use treatment as a means to meet regulations requiring P-based applications.

Chapter 7: Summary and Conclusions

7.1 Summary

Enhanced biological phosphorus removal (EBPR) was investigated as a means of nutrient management on dairy farms. Laboratory analysis was conducted to determine the volatile fatty acid (VFA) production from fermentation of dairy manure in laboratory scale fermenters. The EBPR component of the BioWin model was evaluated. A sensitivity analysis was conducted to determine the parameters to which phosphate (PO_4) output was most sensitive. A sequencing batch reactor (SBR) was designed to treat dairy manure through EBPR. Dairy manure characteristics were estimated based on pretreatment with solid separation and fermentation. Desired effluent characteristics were based on the crop nutrient requirements of a representative dairy farm with a herd of 700 lactating cows and 325 ha of corn silage. System components required to incorporate EBPR into the existing farm nutrient management operation were selected. An economic analysis was conducted to determine the feasibility of EBPR for dairy farms using P-based manure applications on cropland. It was assumed that excess manure would be hauled from the dairy farm to a receiving farm in need of crop nutrients. Manure treatment with EBPR would result in considerable reduction of manure hauling. The cost of EBPR was compared to manure management without EBPR over a 20-year period.

7.2 Results

1. Fermentation of solid separated dairy manure resulted in VFA production of 15.3% of the influent chemical oxygen demand (COD). Total VFA-COD production consisted of acetic (57%), propionic (23%), and butyric (20%) acids.

2. Peak VFA concentrations were achieved after 3 to 4 days of fermentation.

3. The BioWin parameters to which PO_4-P was most sensitive were maximum specific growth rate ($\mu_{MAX,ZBP}$), growth yield (Y_{ZBP}), aerobic phosphate uptake rate per unit PHB utilized for growth ($f_{P/PHB,AER}$), PHB yield per unit VFA uptake (Y_{PHB}), PO_4 release per unit VFA uptake ($f_{P/AC}$), and the fraction of phosphate taken up which can be released (Y_{PP-LO}).

4. The cost of manure management over a 20-year period with and without EBPR was $3,057,200 and $2,817,517, respectively.

5. Manure management with EBPR was the more cost effective option for a herd of 805 dairy cows when cropland available for manure application was 270 ha or less.

6. Manure management with EBPR was more cost effective than manure management without EBPR at haul distances of 117 km and above.

7. The cost of manure management over a 20-year period was $4,518,611 and $4,491,705 for manure management with and without EBPR and no sale of excess manure nutrients.

7.3 Conclusions

1. Prefermentation of dairy manure is required to enable EBPR.

2. BioWin could not be used for treatment system design without calibration and/or parameter determination.

3. Mechanical aeration cannot meet aeration needs due to the high oxygen requirements and small volumes of dairy manure. Specification of an adequate aeration system would require experimental analysis to determine oxygen requirements and oxygen transfer capabilities in liquid dairy manure.

4. Phosphate removal efficiency in an SBR is a critical factor in selecting blending fractions for treated and untreated wastewater.

5. Solids handling options of high-P sludge need to be further evaluated as solids handling may pose an operational barrier in the application of EBPR on dairy farms.

6. Enhanced biological P removal was less cost effective than manure management without EBPR for the representative farm with 805 dairy cows and 325 ha of corn silage.

7. The economic feasibility of EBPR on dairy farms is most dependent on the herd size to cropland ratio and the dairy farm's proximity to other farms with cropland in need of excess nutrients.

7.4 Engineering Significance

Increased pressure on livestock operations may require enforcement of P-based manure applications for land application of all animal manures. This research was a preliminary evaluation of EBPR for manure management on dairy farms. Although this study does not provide the information necessary for complete EBPR process design, critical design issues were identified to direct future research efforts. It was found that selecting an appropriate aeration

system and determining the fate of high-P sludge were the most limiting factors in EBPR treatment system design.

Fermentation potential for dairy manure was determined, emphasizing the importance of pretreatment in applying EBPR to dairy manure. The BioWin model was evaluated and the most critical growth parameters (with respect to EBPR) were identified. Due to the numerous growth parameters in biological wastewater treatment models, a full evaluation of each parameter value is difficult and time consuming. Identification of the most critical EBPR parameters can assist modelers in focusing their attention on the most crucial model components.

An EBPR system was designed based on treatment requirements estimated through process simulation and design calculation. Although precise treatment requirements must be determined through experimental analysis, design factors were identified through approximation of process requirements. A complete treatment process was conceptualized for a representative dairy farm. This enabled identification of critical factors such as pretreatment and solids handling that must be considered when incorporating manure treatment systems in existing manure management practices.

Resource availability and farm characteristics are significant factors in adoption of municipal wastewater treatment practices to agricultural wastes. Through economic analysis, it was determined that the ratio of herd size to cropland and manure hauling distance had the greatest effect on the economic feasibility of EBPR for dairy farms. It was determined that economic feasibility of EBPR would be significantly affected by government subsidies and tax benefits. Such regionally varying factors can be considered in greater detail for specific farms where regionally dependent factors can be identified.

7.5 Recommendations

Experimental determination of microbial growth parameters is necessary for modeling EBPR processes. Determination of maximum specific growth rate ($\mu_{MAX,ZBP}$), growth yield (Y_{ZBP}), aerobic phosphate uptake rate per unit PHB utilized for growth ($f_{P/PHB,AER}$), PHB yield per unit VFA uptake (Y_{PHB}), phosphate release per unit VFA uptake ($f_{P/AC}$), and the fraction of phosphate taken up which can be released (Y_{PP-LO}) would assist in improving reliability of EBPR

models. Determining these parameters for pretreated dairy manure in an SBR would be most beneficial for optimizing full-scale systems for dairy farms.

In this research, it was determined that fermentation of dairy manure could supply VFA to support EBPR. The effects of seasonally fluctuating temperatures on fermentation should be investigated for design of a prefermentation system. The fermenter specified for this operation was a large volume due to the one-day sludge retention time (SRT) of the SBR. Increasing the number of decants per day would enable smaller volumes to be removed in a given cycle period. Smaller volumes for reactors should be considered to reduce system costs and space requirements at dairy farms. Aeration systems (which may limit the minimum size of the SBR) should also be evaluated to determine their ability to meet oxygen requirements.

Investigation of composting sludge from the treatment system should also be considered. If sufficient composting outlets are in close proximity to the operation, this may be the most beneficial option for solids handling. Space requirements for a composting operation must also be considered. The nutrient composition and water content of sludge and separated solids must be determined in order to select the correct compost amendments. Crop residues from neighboring farm operations or other fiber residues from nearby processing facilities may be acquired at little or no cost to the dairy farmer.

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Appendix A: Fermentation Potential Results

The sampling and analysis schedule for the fermentation experiment and corresponding integration sequences is given in Table A.1. Results from volatile fatty acid (VFA) analysis of control samples are then presented, followed by data from manure sample analysis. Data from VFA analysis are presented for acetic, propionic, and butyric acids, respectively. For each VFA, results for manure from cows 1 through 4 are given. Bold values indicate those that were averaged to determine peak concentrations.

Table A.1: Fermenter sampling and analysis schedule

Day of sampling period	*Date*	*Integration Sequence*[†]
0	2/7/2002	1
1	2/8/2002	1
2	2/9/2002	1
3	2/10/2002	2
4	2/11/2002	3
5	2/12/2002	3
6	2/13/2002	4
7	2/14/2002	5
8[*]	2/15/2002	na
9[*]	2/16/2002	na
10[*]	2/17/2002	na
11	2/18/2002	7
12	2/19/2002	7
13	2/20/2002	9

[*]No samples were taken on these days because analysis indicated VFA concentrations had peaked. Sampling was continued after further analysis revealed that VFA peaks were not clearly defined for some samples.

[†]Integration sequences correspond to recalibration of gas chromatograph.

Table A.2: Concentrations (mg/L) of control samples

Day	Acetic	Propionic	Butyric
0	120	111	103
0	126	118	112
Average	123	115	108
1	107	107	98
1	92	93	89
1	90	90	86
1	77	69	69
1	96	97	96
1	93	94	94
Average	93	92	89
7	83	84	84
7	87	88	88
Average	85	86	86

Table A.3: Percent decrease of VFAs in control samples between day zero and days one and seven

Day	Decrease in VFA concentration from day zero (%)		
	Acetic	Propionic	Butyric
1	24.8	19.9	17.5
7	30.9	24.9	20.0

Table A.4: Acetic acid results from gas chromatography analysis of fermented dairy manure from cow 1.

Cow[*]	*Sample Name*	*Acetic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
1	Day0Cow1 2/11/02	24	475	507	3	0	0
1	Day0Cow1 2/11/02	22	433	462	3	0	0
1A	Day1Cow1A 2/08/02	63	1258	1342	1	1	19
1A	Day1Cow1A 2/08/02	53	1066	1137	1	1	19
1A	Day1Cow1A 2/13/02	53	1064	1135	4	1	19
1A	Day1Cow1A 2/13/02	53	1069	1141	4	1	19
1A	Day2Cow1A 2/10/02	78	1552	1656	2	2	42
1A	Day2Cow1A 2/10/02	60	1208	1289	2	2	42
1A	Day2Cow1A 2/11/02	52	1036	1106	3	2	42
1A	Day2Cow1A 2/11/02	57	1140	1216	3	2	42
1A	Day2Cow1A 2/11/02	51	1027	1095	3	2	42
1A	Day3Cow1A 2/13/02	128	2565	**2737**	4	3	71

1A	Day3Cow1A 2/13/02	122	2440	**2603**	4	3	71
1A	Day4Cow1A 2/13/02	130	2599	**2773**	4	4	90.5
1A	Day4Cow1A 2/13/02	114	2284	**2437**	4	4	90.5
1A	Day5Cow1A 2/13/02	82	1644	1755	4	5	116
1A	Day5Cow1A 2/13/02	80	1591	1697	4	5	116
1	Day0Cow1 2/11/02	24	475	507	3	0	0
1	Day0Cow1 2/11/02	22	433	462	3	0	0
1B	Day1Cow1B 2/08/02	62	1247	1331	1	1	19
1B	Day1Cow1B 2/08/02	58	1157	1234	1	1	19
1B	Day2Cow1B 2/10/02	70	1396	1490	2	2	42
1B	Day2Cow1B 2/10/02	71	1420	1515	2	2	42
1B	Day3Cow1B 2/13/02	105	2109	**2250**	4	3	71
1B	Day3Cow1B 2/13/02	100	2005	**2140**	4	3	71
1B	Day4Cow1B 2/13/02	107	2143	**2286**	4	4	90.5
1B	Day4Cow1B 2/13/02	94	1887	**2013**	4	4	90.5
1B	Day5Cow1B 2/13/02	65	1308	1395	4	5	116
1B	Day5Cow1B 2/13/02	67	1332	1421	4	5	116
1	Day0Cow1 2/11/02	24	475	507	3	0	0
1	Day0Cow1 2/11/02	22	433	462	3	0	0
1C	Day1Cow1C 2/08/02	43	870	928	1	1	19
1C	Day1Cow1C 2/08/02	44	887	946	1	1	19
1C	Day2Cow1C 2/10/02	72	1437	**1533**	2	2	42
1C	Day2Cow1C 2/10/02	77	1546	**1650**	2	2	42
1C	Day3Cow1C 2/14/02	24	483	516	5	3	71
1C	Day3Cow1C 2/14/02	26	526	562	5	3	71
1C	Day4Cow1C 2/14/02	22	435	464	5	4	90.5
1C	Day4Cow1C 2/14/02	20	405	432	5	4	90.5
1C	Day5Cow1C 2/14/02	20	401	428	5	5	116
1C	Day5Cow1C 2/14/02	19	376	401	5	5	116
1C	Day6Cow1C 2/14/02	24	480	513	5	6	142
1C	Day6Cow1C 2/14/02	22	440	470	5	6	142

[*]All samples listed here came from cow 1. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
[†]Accounts for sample dilution of 1:20 prior to fermentation.
[‡]Conversion for acetic acid is 1.067 mg COD/mg acetic acid.
[§]Gas chromatograph recalibrated for each sequence.

Table A.5: Acetic acid results from gas chromatography analysis of fermented dairy manure from cow 2.

Cow[*]	*Sample Name*	*Acetic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
2A	Day2Cow2A 2/14/02	19	374	399	5	2	42
2A	Day2Cow2A 2/14/02	18	369	393	5	2	42
2A	Day3Cow2A 2/14/02	25	494	527	5	3	71
2A	Day3Cow2A 2/14/02	24	470	502	5	3	71
2A	Day4Cow2A 2/14/02	22	439	469	5	4	90.5
2A	Day1Cow2A 2/08/02	45	892	952	1	1	19
2A	Day1Cow2A 2/08/02	40	804	858	1	1	19
2A	Day4Cow2A 2/18/02	112	2238	2388	7	4	90.5
2A	Day4Cow2A 2/18/02	107	2133	2276	7	4	90.5
2A	Day5Cow2A 2/18/02	121	2418	2580	7	5	116
2A	Day5Cow2A 2/18/02	124	2482	2648	7	5	116
2A	Day6Cow2A 2/18/02	130	2596	2770	7	6	142
2A	Day7Cow2A 2/18/02	132	2640	2817	7	7	168
2A	Day7Cow2A 2/18/02	136	2723	2905	7	7	168
2A	Day3Cow2A 2/18/02	95	1899	2026	7	3	71
2A	Day11Cow2A 2/18/02	175	3502	3737	7	11	263
2A	Day11Cow2A 2/18/02	161	3222	3438	7	11	263
2A	Day6Cow2A 2/18/02	128	2559	2730	7	6	142
2A	Day6Cow2A 2/18/02	131	2612	2787	7	6	142
2A	Day11Cow2A 2/18/02	163	3250	3468	7	11	263
2A	Day12Cow2A 2/20/02	229	4587	4894	9	12	280
2A	Day12Cow2A 2/20/02	140	2804	2992	9	12	280
2A	Day12Cow2A 2/20/02	137	2732	2915	9	12	280
2A	Day12Cow2A 2/20/02	203	4051	4323	9	12	280
2A	Day12Cow2A 2/20/02	207	4148	4425	9	12	280
2B	Day1Cow2B 2/08/02	35	707	755	1	1	19
2B	Day1Cow2B 2/08/02	35	698	745	1	1	19
2B	Day5Cow2B 2/18/02	85	1692	1805	7	5	116
2B	Day5Cow2B 2/18/02	79	1575	1680	7	5	116
2B	Day6Cow2B 2/18/02	61	1227	1309	7	6	142
2B	Day6Cow2B 2/18/02	71	1428	1524	7	6	142
2B	Day7Cow2B 2/18/02	97	1947	2077	7	7	168
2B	Day7Cow2B 2/18/02	96	1922	2051	7	7	168
2B	Day11Cow2B 2/18/02	113	2253	2404	7	11	263
2B	Day11Cow2B 2/18/02	120	2408	2569	7	11	263
2B	Day12Cow2B 2/20/02	87	1749	1866	9	12	280

2B	Day12Cow2B 2/20/02	84	1680	1793	9	12	280
2C	Day1Cow2C 2/08/02	32	647	691	1	1	19
2C	Day1Cow2C 2/08/02	27	539	576	1	1	19
2C	Day5Cow2C 2/18/02	73	1467	1565	7	5	116
2C	Day5Cow2C 2/18/02	81	1610	1718	7	5	116
2C	Day6Cow2C 2/18/02	80	1598	1705	7	6	142
2C	Day6Cow2C 2/18/02	93	1863	1988	7	6	142
2C	Day11Cow2C 2/18/02	129	2582	2755	7	11	263
2C	Day11Cow2C 2/18/02	130	2594	2768	7	11	263
2C	Day7Cow2C 2/18/02	110	2192	2339	7	7	168
2C	Day7Cow2C 2/18/02	96	1930	2059	7	7	168
2C	Day7Cow2C 2/18/02	100	1991	2124	7	7	168
2C	Day12Cow2C 2/20/02	105	2098	2238	9	12	280
2C	Day12Cow2C 2/20/02	101	2028	2164	9	12	280

*All samples listed here came from cow 2. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for acetic acid is 1.067 mg COD/mg acetic acid.
§Gas chromatograph recalibrated for each sequence.

Table A.6: Acetic acid results from gas chromatography analysis of fermented dairy manure from cow 3.

Cow[*]	*Sample Name*	*Acetic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
3	Day0Cow3 2/11/02	50	1004	1072	3	0	0
3	Day0Cow3 2/11/02	57	1146	1222	3	0	0
3A	Day1Cow3A 2/08/02	36	723	772	1	1	19
3A	Day1Cow3A 2/08/02	37	747	797	1	1	19
3A	Day5Cow3A 2/18/02	65	1306	1394	7	5	116
3A	Day5Cow3A 2/18/02	68	1359	1451	7	5	116
3A	Day6Cow3A 2/18/02	73	1456	1553	7	6	142
3A	Day6Cow3A 2/18/02	74	1477	1576	7	6	142
3A	Day7Cow3A 2/18/02	92	1846	**1969**	7	7	168
3A	Day7Cow3A 2/18/02	93	1866	**1991**	7	7	168
3	Day0Cow3 2/11/02	50	1004	1072	3	0	0
3	Day0Cow3 2/11/02	57	1146	1222	3	0	0
3B	Day1Cow3B 2/08/02	30	605	646	1	1	19
3B	Day1Cow3B 2/08/02	25	502	536	1	1	19
3	Day0Cow3 2/11/02	50	1004	1072	3	0	0
3	Day0Cow3 2/11/02	57	1146	1222	3	0	0
3C	Day1Cow3C 2/08/02	21	421	449	1	1	19

3C	Day1Cow3C 2/08/02	22	447	477	1	1	19

*All samples listed here came from cow 3. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for acetic acid is 1.067 mg COD/mg acetic acid.
§Gas chromatograph recalibrated for each sequence.

Table A.7: Acetic acid results from gas chromatography analysis of fermented dairy manure from cow 4

Cow[*]	*Sample Name*	*Acetic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
4	Day0Cow4 2/11/02	49	977	1042	3	0	0
4	Day0Cow4 2/11/02	42	846	902	3	0	0
4A	Day1Cow4A 2/08/02	35	708	756	1	1	19
4A	Day1Cow4A 2/08/02	37	731	780	1	1	19
4	Day0Cow4 2/11/02	49	977	1042	3	0	0
4	Day0Cow4 2/11/02	42	846	902	3	0	0
4B	Day1Cow4B 2/11/02	52	1031	1100	3	1	19
4B	Day1Cow4B 2/11/02	49	985	1051	3	1	19
4	Day0Cow4 2/11/02	49	977	1042	3	0	0
4	Day0Cow4 2/11/02	42	846	902	3	0	0
4C	Day1Cow4C 2/11/02	44	886	945	3	1	19
4C	Day1Cow4C 2/11/02	44	887	946	3	1	19

*All samples listed here came from cow 4. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for acetic acid is 1.067 mg COD/mg acetic acid.
§Gas chromatograph recalibrated for each sequence.

Table A.8: Propionic acid results from gas chromatography analysis of fermented dairy manure from cow 1.

Cow[*]	*Sample Name*	*Propionic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
1	Day0Cow1 2/11/02	9	184	278	3	0	0
1	Day0Cow1 2/11/02	8	150	227	3	0	0
1A	Day1Cow1A 2/08/02	23	453	684	1	1	19
1A	Day1Cow1A 2/08/02	16	329	497	1	1	19
1A	Day1Cow1A 2/13/02	17	337	508	4	1	19
1A	Day1Cow1A 2/13/02	17	335	506	4	1	19
1A	Day2Cow1A 2/10/02	21	413	624	2	2	42

1A	Day2Cow1A 2/10/02	17	344	520	2	2	42
1A	Day2Cow1A 2/11/02	14	289	436	3	2	42
1A	Day2Cow1A 2/11/02	16	314	474	3	2	42
1A	Day2Cow1A 2/11/02	13	266	402	3	2	42
1A	Day3Cow1A 2/13/02	43	852	**1287**	4	3	71
1A	Day3Cow1A 2/13/02	38	759	**1147**	4	3	71
1A	Day4Cow1A 2/13/02	43	854	1289	4	4	90.5
1A	Day4Cow1A 2/13/02	37	731	1104	4	4	90.5
1A	Day5Cow1A 2/13/02	26	518	783	4	5	116
1A	Day5Cow1A 2/13/02	25	508	767	4	5	116
1	Day0Cow1 2/11/02	9	184	278	3	0	0
1	Day0Cow1 2/11/02	8	150	227	3	0	0
1B	Day1Cow1B 2/08/02	18	369	557	1	1	19
1B	Day1Cow1B 2/08/02	17	334	505	1	1	19
1B	Day2Cow1B 2/10/02	19	379	572	2	2	42
1B	Day2Cow1B 2/10/02	19	386	582	2	2	42
1B	Day3Cow1B 2/13/02	32	643	970	4	3	71
1B	Day3Cow1B 2/13/02	31	612	925	4	3	71
1B	Day4Cow1B 2/13/02	35	709	**1071**	4	4	90.5
1B	Day4Cow1B 2/13/02	32	642	**970**	4	4	90.5
1B	Day5Cow1B 2/13/02	22	435	657	4	5	116
1B	Day5Cow1B 2/13/02	22	438	661	4	5	116
1	Day0Cow1 2/11/02	9	184	278	3	0	0
1	Day0Cow1 2/11/02	8	150	227	3	0	0
1C	Day1Cow1C 2/08/02	14	289	436	1	1	19
1C	Day1Cow1C 2/08/02	13	264	398	1	1	19
1C	Day2Cow1C 2/10/02	20	402	608	2	2	42
1C	Day2Cow1C 2/10/02	19	384	579	2	2	42
1C	Day3Cow1C 2/14/02	22	443	670	5	3	71
1C	Day3Cow1C 2/14/02	24	477	721	5	3	71
1C	Day4Cow1C 2/14/02	22	442	667	5	4	90.5
1C	Day4Cow1C 2/14/02	22	431	651	5	4	90.5
1C	Day5Cow1C 2/14/02	23	469	708	5	5	116
1C	Day5Cow1C 2/14/02	22	440	665	5	5	116
1C	Day6Cow1C 2/14/02	30	610	**920**	5	6	142
1C	Day6Cow1C 2/14/02	28	566	**855**	5	6	142

[*]All samples listed here came from cow 1. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
[†]Accounts for sample dilution of 1:20 prior to fermentation.
[‡]Conversion for propionic acid is 1.51 mg COD/mg propionic acid.
[§]Gas chromatograph recalibrated for each sequence.

Table A.9: Propionic acid results from gas chromatography analysis of fermented dairy manure from cow 2.

Cow[*]	*Sample Name*	*Propionic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
2	Day0Cow2 2/11/02	14	271	409	3	0	0
2	Day0Cow2 2/11/02	12	247	373	3	0	0
2A	Day1Cow2A 2/08/02	12	235	355	1	1	19
2A	Day1Cow2A 2/08/02	10	203	307	1	1	19
2A	Day2Cow2A 2/14/02	16	321	485	5	2	42
2A	Day2Cow2A 2/14/02	16	311	470	5	2	42
2A	Day3Cow2A 2/14/02	25	495	747	5	3	71
2A	Day3Cow2A 2/14/02	23	467	705	5	3	71
2A	Day3Cow2A 2/18/02	25	490	740	7	3	71
2A	Day4Cow2A 2/14/02	24	482	728	5	4	90.5
2A	Day4Cow2A 2/18/02	30	590	892	7	4	90.5
2A	Day4Cow2A 2/18/02	27	550	830	7	4	90.5
2A	Day5Cow2A 2/18/02	32	644	972	7	5	116
2A	Day5Cow2A 2/18/02	33	660	996	7	5	116
2A	Day6Cow2A 2/18/02	35	693	1047	7	6	142
2A	Day6Cow2A 2/18/02	33	663	1002	7	6	142
2A	Day6Cow2A 2/18/02	34	678	1023	7	6	142
2A	Day7Cow2A 2/18/02	35	709	1071	7	7	168
2A	Day7Cow2A 2/18/02	35	709	1071	7	7	168
2A	Day11Cow2A 2/18/02	44	889	1343	7	11	263
2A	Day11Cow2A 2/18/02	42	841	1270	7	11	263
2A	Day11Cow2A 2/18/02	43	864	1305	7	11	263
2A	Day12Cow2A 2/20/02	72	1434	**2165**	9	12	280
2A	Day12Cow2A 2/20/02	104	2084	**3147**	9	12	280
2A	Day12Cow2A 2/20/02	48	959	**1448**	9	12	280
2A	Day12Cow2A 2/20/02	47	940	**1420**	9	12	280
2A	Day12Cow2A 2/20/02	67	1346	**2032**	9	12	280
2	Day0Cow2 2/11/02	14	271	409	3	0	0
2	Day0Cow2 2/11/02	12	247	373	3	0	0
2B	Day1Cow2B 2/08/02	8	163	246	1	1	19
2B	Day1Cow2B 2/08/02	8	165	249	1	1	19
2B	Day5Cow2B 2/18/02	23	456	689	7	5	116
2B	Day5Cow2B 2/18/02	20	402	607	7	5	116
2B	Day6Cow2B 2/18/02	16	324	489	7	6	142
2B	Day6Cow2B 2/18/02	18	364	549	7	6	142
2B	Day7Cow2B 2/18/02	25	495	748	7	7	168

2B	Day7Cow2B 2/18/02	24	485	732	7	7	168
2B	Day11Cow2B 2/18/02	25	501	757	7	11	263
2B	Day11Cow2B 2/18/02	29	582	879	7	11	263
2B	Day12Cow2B 2/20/02	30	603	**910**	9	12	280
2B	Day12Cow2B 2/20/02	28	568	**857**	9	12	280
2	Day0Cow2 2/11/02	14	271	409	3	0	0
2	Day0Cow2 2/11/02	12	247	373	3	0	0
2C	Day1Cow2C 2/08/02	9	175	264	1	1	19
2C	Day1Cow2C 2/08/02	7	150	226	1	1	19
2C	Day5Cow2C 2/18/02	18	364	550	7	5	116
2C	Day5Cow2C 2/18/02	22	437	660	7	5	116
2C	Day6Cow2C 2/18/02	19	383	578	7	6	142
2C	Day6Cow2C 2/18/02	23	458	692	7	6	142
2C	Day7Cow2C 2/18/02	26	526	794	7	7	168
2C	Day7Cow2C 2/18/02	23	451	681	7	7	168
2C	Day7Cow2C 2/18/02	27	549	829	7	7	168
2C	Day11Cow2C 2/18/02	32	648	979	7	11	263
2C	Day11Cow2C 2/18/02	34	677	1022	7	11	263
2C	Day12Cow2C 2/20/02	33	661	**998**	9	12	280
2C	Day12Cow2C 2/20/02	36	720	**1086**	9	12	280

*All samples listed here came from cow 2. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for propionic acid is 1.51 mg COD/mg propionic acid.
§Gas chromatograph recalibrated for each sequence.

Table A.10: Propionic acid results from gas chromatography analysis of fermented dairy manure from cow 3.

Cow[*]	*Sample Name*	*Propionic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
3	Day0Cow3 2/11/02	19	375	566	3	0	0
3	Day0Cow3 2/11/02	20	403	609	3	0	0
3A	Day1Cow3A 2/08/02	9	188	284	1	1	19
3A	Day1Cow3A 2/08/02	9	179	271	1	1	19
3A	Day5Cow3A 2/18/02	19	377	570	7	5	116
3A	Day5Cow3A 2/18/02	18	360	544	7	5	116
3A	Day6Cow3A 2/18/02	18	369	557	7	6	142
3A	Day6Cow3A 2/18/02	17	349	527	7	6	142
3A	Day7Cow3A 2/18/02	24	473	**714**	7	7	168
3A	Day7Cow3A 2/18/02	27	549	**830**	7	7	168
3	Day0Cow3 2/11/02	19	375	566	3	0	0

3	Day0Cow3 2/11/02	20	403	609	3	0	0
3B	Day1Cow3B 2/08/02	7	136	205	1	1	19
3B	Day1Cow3B 2/08/02	5	101	153	1	1	19
3	Day0Cow3 2/11/02	19	375	566	3	0	0
3	Day0Cow3 2/11/02	20	403	609	3	0	0
3C	Day1Cow3C 2/08/02	5	103	155	1	1	19
3C	Day1Cow3C 2/08/02	5	104	157	1	1	19

*All samples listed here came from cow 3. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for propionic acid is 1.51 mg COD/mg propionic acid.
§Gas chromatograph recalibrated for each sequence.

Table A.11: Propionic acid results from gas chromatography analysis of fermented dairy manure from cow 4.

Cow[*]	*Sample Name*	*Propionic Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
4	Day0Cow4 2/11/02	11	227	344	3	0	0
4	Day0Cow4 2/11/02	10	196	296	3	0	0
4A	Day1Cow4A 2/08/02	6	120	181	1	1	19
4A	Day1Cow4A 2/08/02	6	122	184	1	1	19
4	Day0Cow4 2/11/02	11	227	344	3	1	0
4	Day0Cow4 2/11/02	10	196	296	3	1	0
4B	Day1Cow4B 2/11/02	14	287	433	3	1	19
4B	Day1Cow4B 2/11/02	12	237	357	3	1	19
4	Day0Cow4 2/11/02	11	227	344	3	0	0
4	Day0Cow4 2/11/02	10	196	296	3	0	0
4C	Day1Cow4C 2/11/02	9	174	263	3	1	19
4C	Day1Cow4C 2/11/02	9	188	284	3	1	19

*All samples listed here came from cow 4. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for propionic acid is 1.51 mg COD/mg propionic acid.
§Gas chromatograph recalibrated for each sequence.

Table A.12: Butyric acid results from gas chromatography analysis of fermented dairy manure from cow 1

Cow[*]	*Sample Name*	*Butyric Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
1	Day0Cow1 2/11/02	5	98	178	3	0	0
1	Day0Cow1 2/11/02	4	89	161	3	0	0
1A	Day1Cow1A 2/08/02	20	399	725	1	1	19
1A	Day1Cow1A 2/08/02	11	221	401	1	1	19
1A	Day1Cow1A 2/13/02	12	237	430	4	1	19
1A	Day1Cow1A 2/13/02	12	234	424	4	1	19
1A	Day2Cow1A 2/10/02	18	358	650	2	2	42
1A	Day2Cow1A 2/10/02	16	322	585	2	2	42
1A	Day2Cow1A 2/11/02	14	271	492	3	2	42
1A	Day2Cow1A 2/11/02	12	231	420	3	2	42
1A	Day3Cow1A 2/13/02	41	816	**1481**	4	3	71
1A	Day3Cow1A 2/13/02	37	732	**1329**	4	3	71
1A	Day4Cow1A 2/13/02	35	709	1287	4	4	90.5
1A	Day4Cow1A 2/13/02	29	584	1061	4	4	90.5
1A	Day5Cow1A 2/13/02	19	381	692	4	5	116
1A	Day5Cow1A 2/13/02	19	373	678	4	5	116
1	Day0Cow1 2/11/02	5	98	178	3	0	0
1	Day0Cow1 2/11/02	4	89	161	3	0	0
1B	Day1Cow1B 2/08/02	11	228	414	1	1	19
1B	Day1Cow1B 2/08/02	11	212	384	1	1	19
1B	Day2Cow1B 2/10/02	17	349	634	2	2	42
1B	Day2Cow1B 2/10/02	18	355	645	2	2	42
1B	Day3Cow1B 2/13/02	31	622	**1130**	4	3	71
1B	Day3Cow1B 2/13/02	31	622	**1130**	4	3	71
1B	Day4Cow1B 2/13/02	31	613	1113	4	4	90.5
1B	Day4Cow1B 2/13/02	28	552	1002	4	4	90.5
1B	Day5Cow1B 2/13/02	17	338	615	4	5	116
1B	Day5Cow1B 2/13/02	17	335	608	4	5	116
1	Day0Cow1 2/11/02	5	98	178	3	0	0
1	Day0Cow1 2/11/02	4	89	161	3	0	0
1C	Day1Cow1C 2/08/02	10	191	347	1	1	19
1C	Day1Cow1C 2/08/02	8	153	278	1	1	19
1C	Day2Cow1C 2/10/02	15	300	546	2	2	42
1C	Day2Cow1C 2/10/02	15	308	559	2	2	42
1C	Day3Cow1C 2/14/02	24	483	**877**	5	3	71
1C	Day3Cow1C 2/14/02	26	526	**956**	5	3	71

1C	Day4Cow1C 2/14/02	22	435	790	5	4	90.5
1C	Day4Cow1C 2/14/02	20	405	736	5	4	90.5
1C	Day5Cow1C 2/14/02	20	401	728	5	5	116
1C	Day5Cow1C 2/14/02	19	376	683	5	5	116
1C	Day6Cow1C 2/14/02	24	480	873	5	6	142
1C	Day6Cow1C 2/14/02	22	440	799	5	6	142

*All samples listed here came from cow 1. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
†Accounts for sample dilution of 1:20 prior to fermentation.
‡Conversion for butyric acid is 1.816 mg COD/mg butyric acid.
§Gas chromatograph recalibrated for each sequence.

Table A.13: Butyric acid results from gas chromatography analysis of fermented dairy manure from cow 2

Cow[*]	*Sample Name*	*Butyric Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
2	Day0Cow2 2/11/02	8	164	298	3	0	0
2	Day0Cow2 2/11/02	7	149	270	3	0	0
2A	Day1Cow2A 2/08/02	8	153	277	1	1	19
2A	Day1Cow2A 2/08/02	6	128	232	1	1	19
2A	Day2Cow2A 2/14/02	19	374	679	5	2	42
2A	Day2Cow2A 2/14/02	18	369	669	5	2	42
2A	Day3Cow2A 2/14/02	25	494	897	5	3	71
2A	Day3Cow2A 2/14/02	24	470	854	5	3	71
2A	Day3Cow2A 2/18/02	25	507	920	7	3	71
2A	Day4Cow2A 2/14/02	22	439	798	5	4	90.5
2A	Day4Cow2A 2/18/02	27	534	970	7	4	90.5
2A	Day4Cow2A 2/18/02	24	480	871	7	4	90.5
2A	Day5Cow2A 2/18/02	25	499	906	7	5	116
2A	Day5Cow2A 2/18/02	25	505	918	7	5	116
2A	Day6Cow2A 2/18/02	23	454	825	7	6	142
2A	Day6Cow2A 2/18/02	23	461	836	7	6	142
2A	Day6Cow2A 2/18/02	23	466	846	7	6	142
2A	Day7Cow2A 2/18/02	21	429	779	7	7	168
2A	Day7Cow2A 2/18/02	20	394	715	7	7	168
2A	Day11Cow2A 2/18/02	25	494	898	7	11	263
2A	Day11Cow2A 2/18/02	24	488	886	7	11	263
2A	Day11Cow2A 2/18/02	27	533	969	7	11	263
2A	Day12Cow2A 2/20/02	79	1580	**2870**	9	12	280
2A	Day12Cow2A 2/20/02	30	597	**1085**	9	12	280
2A	Day12Cow2A 2/20/02	33	661	**1201**	9	12	280

2A	Day12Cow2A 2/20/02	45	901	**1636**	9	12	280
2A	Day12Cow2A 2/20/02	45	905	**1644**	9	12	280
2	Day0Cow2 2/11/02	8	164	298	3	0	0
2	Day0Cow2 2/11/02	7	149	270	3	0	0
2B	Day1Cow2B 2/08/02	3	59	107	1	1	19
2B	Day1Cow2B 2/08/02	3	66	120	1	1	19
2B	Day5Cow2B 2/18/02	12	247	448	7	5	116
2B	Day5Cow2B 2/18/02	29	573	1040	7	5	116
2B	Day6Cow2B 2/18/02	11	220	399	7	6	142
2B	Day6Cow2B 2/18/02	13	251	456	7	6	142
2B	Day7Cow2B 2/18/02	14	273	495	7	7	168
2B	Day7Cow2B 2/18/02	11	219	397	7	7	168
2B	Day11Cow2B 2/18/02	12	238	433	7	11	263
2B	Day11Cow2B 2/18/02	13	266	483	7	11	263
2B	Day12Cow2B 2/20/02	23	469	**852**	9	12	280
2B	Day12Cow2B 2/20/02	21	429	**779**	9	12	280
2	Day0Cow2 2/11/02	8	164	298	3	0	0
2	Day0Cow2 2/11/02	7	149	270	3	0	0
2C	Day1Cow2C 2/08/02	5	98	178	1	1	19
2C	Day1Cow2C 2/08/02	4	83	151	1	1	19
2C	Day5Cow2C 2/18/02	10	208	378	7	5	116
2C	Day5Cow2C 2/18/02	15	295	535	7	5	116
2C	Day6Cow2C 2/18/02	10	199	362	7	6	142
2C	Day6Cow2C 2/18/02	12	232	421	7	6	142
2C	Day7Cow2C 2/18/02	14	277	502	7	7	168
2C	Day7Cow2C 2/18/02	12	234	424	7	7	168
2C	Day7Cow2C 2/18/02	17	335	608	7	7	168
2C	Day11Cow2C 2/18/02	15	295	535	7	11	263
2C	Day11Cow2C 2/18/02	15	307	557	7	11	263
2C	Day12Cow2C 2/20/02	27	548	**996**	9	12	280
2C	Day12Cow2C 2/20/02	26	511	**928**	9	12	280

[*]All samples listed here came from cow 2. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
[†]Accounts for sample dilution of 1:20 prior to fermentation.
[‡]Conversion for butyric acid is 1.816 mg COD/mg butyric acid.
[§]Gas chromatograph recalibrated for each sequence.

Table A.14: Butyric acid results from gas chromatography analysis of fermented dairy manure from cow 3

Cow[*]	*Sample Name*	*Butyric Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
3	Day0Cow3 2/11/02	15	291	529	3	0	0
3	Day0Cow3 2/11/02	17	334	606	3	0	0
3A	Day1Cow3A 2/08/02	7	148	269	1	1	19
3A	Day1Cow3A 2/08/02	6	130	236	1	1	19
3A	Day5Cow3A 2/18/02	24	488	887	7	5	116
3A	Day5Cow3A 2/18/02	23	465	844	7	5	116
3A	Day6Cow3A 2/18/02	21	416	755	7	6	142
3A	Day6Cow3A 2/18/02	21	415	754	7	6	142
3A	Day7Cow3A 2/18/02	30	608	**1105**	7	7	168
3A	Day7Cow3A 2/18/02	25	494	**897**	7	7	168
3	Day0Cow3 2/11/02	15	291	529	3	0	0
3	Day0Cow3 2/11/02	17	334	606	3	0	0
3B	Day1Cow3B 2/08/02	5	109	198	1	1	19
3B	Day1Cow3B 2/08/02	4	90	163	1	1	19
3	Day0Cow3 2/11/02	15	291	529	3	0	0
3	Day0Cow3 2/11/02	17	334	606	3	0	0
3C	Day1Cow3C 2/08/02	4	75	137	1	1	19
3C	Day1Cow3C 2/08/02	4	79	143	1	1	19

[*]All samples listed here came from cow 3. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
[†]Accounts for sample dilution of- 1:20 prior to fermentation.
[‡]Conversion for butyric acid is 1.816 mg COD/mg butyric acid.
[§]Gas chromatograph recalibrated for each sequence.

Table A.15: Butyric acid results from gas chromatography analysis of fermented dairy manure from cow 4

Cow[*]	*Sample Name*	*Butyric Acid (mg/L)*			*Integration Sequence*[§]	*Time*	
		Sample	*w/ dilution factor*[†]	*As COD*[‡]		*Day*	*Hour*
4	Day0Cow4 2/11/02	10	195	355	3	0	0
4	Day0Cow4 2/11/02	8	165	300	3	0	0
4A	Day1Cow4A 2/08/02	6	112	203	1	1	19
4A	Day1Cow4A 2/08/02	6	110	200	1	1	19
4	Day0Cow4 2/11/02	10	195	355	3	0	0
4	Day0Cow4 2/11/02	8	165	300	3	0	0
4B	Day1Cow4B 2/11/02	12	243	442	3	1	19
4B	Day1Cow4B 2/11/02	10	191	346	3	1	19
4	Day0Cow4 2/11/02	10	195	355	3	0	0
4	Day0Cow4 2/11/02	8	165	300	3	0	0
4C	Day1Cow4C 2/11/02	8	150	273	3	1	19
4C	Day1Cow4C 2/11/02	8	150	273	3	1	19

[*]All samples listed here came from cow 4. Manure from each cow was fermented in triplicate as designated by letters A, B, and C.
[†]Accounts for sample dilution of 1:20 prior to fermentation.
[‡]Conversion for butyric acid is 1.816 mg COD/mg butyric acid.
[§]Gas chromatograph recalibrated for each sequence.

Appendix B: BioWin Simulation Settings

B.1 SBR Calculations

To simulate an SBR with variable flow in BioWin, a flow schedule must be entered. Influent and wastage flow rates were calculated based on equations [4.1] and [4.2]. Since settling began after 22.5 hours of the one-day cycle (Table B.1), the total time devoted to fill and react was 22.5 hours and the effective reaction time (ξ) was 93.75% (22.5/24*100) of the total cycle.

Table B.1: Cycle time devoted to fill plus react

Cycle	Begin	End	Time (hrs)
Fill/React	0.0	22.5	22.5
Settle	22.5	23.5	1.0
Decant	23.5	24.0	0.5
Total Time			24.0

The influent flow rate was calculated based on the desired SRT and effective HRT (τ_e) which were selected to be three and two days, respectively. The daily flow rate (F) was calculated:

$$F = \frac{\xi \cdot V}{\tau_e} = \frac{0.9375 \cdot 3.5L}{2d} = 1.64L/d$$

Since the SBR was fed four times per day, the total volume added per fill period was 0.41 L. A fill period of 0.1 h (6 min) was selected and the corresponding flow rate (F_{fill}) was calculated:

$$F_{fill} = \frac{0.41L}{0.1h} = 98.4L/d$$

The resulting BioWin fill schedule consisted of four 6-min fill periods at a flow rate of 98.4 L/d. The wastage rate (F_w) was calculate using equation [4.2]:

$$F_W = \frac{\xi \cdot V}{\Theta_{ce}} = \frac{0.9375 \cdot 3.5L}{3d} = 1.09L/d$$

The flow rate used for influent wastewater (98.4 L/d) was also used for wastage. The SBR was wasted once per day. The corresponding wastage time was calculated:

$$T_{waste} = \frac{1.09L}{98.4L/d} = 16\,\text{min}$$

The SBR was wasted once per day for 16 min at a flow rate of 98.4 L/d. BioWin simulates decanting from SBR based on a flow rate or a minimum decant volume. The minimum decant volume is the percent of the total volume which remains after reactor wastage and decant. The minimum decant volume option was used for these simulations. The minimum decant volume as a percent of the total fill volume was calculated:

$$V_{\min(\%)} = \left[1 - \frac{V_{added}}{V_{total}}\right] \times 100 = \left[1 - \frac{1.64L}{3.5L}\right] \times 100 = 53.1\%$$

B.2 BioWin Inputs

Table B.2: BioWin cycle times for baseline simulation

Step	*Start time*	*End time*	*Duration (h)*
SBR fill 1	0:00	0:06	0.1
Mix	0:00	23:00	23.0
Anaerobic react 1	0:00	2:00	2.0
Aerobic react 1	2:00	6:00	4.0
SBR fill 2	6:00	6:06	0.1
Anaerobic react 2	6:00	8:00	2.0
Aerobic react 2	8:00	12:00	4.0
SBR fill 3	12:00	12:06	0.1
Anaerobic react 3	12:00	14:00	2.0
Aerobic react 3	14:00	18:00	4.0
SBR fill 4	18:00	18:06	0.1
Anaerobic react 4	18:00	20:00	2.0
Aerobic react 4	20:00	23:00	3.0
Waste	22:44	23:00	0.27
Settle (end mixing)	23:00	24:00	1.0
Decant	23:40	24:00	0.3

Table B.3: BioWin model inputs – Wastage rate itinerary

Start time		*Flowrate*
(min)	(h)	(L/d)
0	0	0.00E+00
1364	22.73333	98.4
1380	23	0.00E+00

Table B.4: BioWin model inputs - Aeration itinerary

Start time		*DO Setpoint*
(min)	*(h)*	*(mg/L)*
0	0	0
120	2	2
360	6	0
480	8	2
720	12	0
840	14	2
1080	18	0
1200	20	2
1379	22.98333	0

Table B.5: BioWin model inputs - Variable stream influent schedule

Time	*Flow*	*Concentration*											
		X_{sp}	X_{sc}	X_i	S_{bsc}	S_{bsa}	S_{us}	ISS	Alk.	PO_4-P	X_{on}	NH_3-N	N_{os}
(h)	(L/d)	(mg/L)							(mmol/L)	(mg P/L)	(mg N/L)		
0.0	98.44	1492	1719	983	1565	593	748	800	57	88	46.9	498	56
0.1	0.00	0	0	0	0	0	0	0	0	0	0	0	0
6.0	98.44	1492	1719	983	1565	593	748	800	57	88	46.9	498	56
6.1	0.00	0	0	0	0	0	0	0	0	0	0	0	0
12.0	98.44	1492	1719	983	1565	593	748	800	57	88	46.9	498	56
12.1	0.00	0	0	0	0	0	0	0	0	0	0	0	0
18.0	98.44	1492	1719	983	1565	593	748	800	57	88	46.9	498	56
18.1	0.00	0	0	0	0	0	0	0	0	0	0	0	0

B.3 Settings for Baseline 2

Aeration settings for BL_2 were based on PO_4 removal (incomplete) required to meet the N:P crop nutrient requirements. Crop nutrient recommendations for corn silage (DCR, 1995) were used to determine target nutrient content of the SBR effluent. Assuming average soil productivity and medium to high soil test levels for P, the N:P ratio was determined (Table B.6).

Table B.6: Nutrient requirements for corn silage (DCR, 1995)

Nutrient	*Requirement*
N (kg/ha)	146
P (kg/ha)	20
N:P	7

It was estimated that 15 mg/L NH_4-N would be consumed during treatment in the SBR and that all soluble organic N (N_{os}-N) would be consumed. The nutrient availability coefficient (due to losses from storage and land application) was 0.2 for NH_4-N resulting in a crop availability of 96.6 mg/L for NH_4-N (Table B.7). Based on the NH_4-N crop availability and the target N:P ratio, the desired PO_4-P effluent concentration was 14 (96.6/7) mg PO_4-P/L. It was assumed that only soluble nutrients (not those bound to solid particles) were conserved in the SBR treatment.

Table B.7: Nutrient availability after SBR treatment, storage, and application

Nutrient	*Before Treatment*	*After Treatment*	*Crop Availability*
NH_4-N (mg/L)	498	483	96.6
N_{os}-N (mg/L)	56	0	0
PO_4-P	88	14	14

The DO setpoint was decreased (from 2 to 1 mg/L) and the last anaerobic period was lengthened by 15 minutes to meet the effluent PO_4-P goal of 14 mg P/L (Table B.8).

Table B.8: Aeration settings for BL_2 – Incomplete PO_4 removal

Start time		*DO Setpoint*
(min)	*(h)*	*(mg/L)*
0	0	0
120	2	1
360	6	0
480	8	1
720	12	0
840	14	1
1080	18	0
1200	20	1
1335	22.25	0

Appendix C: Sensitivity Analysis Results

Model outputs and relative sensitivities are presented for each parameter evaluated in three different sets of simulations. Results are presented by each set of simulations beginning with preliminary simulations (C.1) followed by complete PO_4 removal (C.2) and incomplete PO_4 removal simulations (C.3). Results for preliminary simulations (C.1) are grouped by organisms: non-PAO heterotrophs, PAO heterotrophs, and autotrophs. Bolded numbers indicate baseline parameter values.

C.1 Preliminary Simulation

Non-PAO Heterotrophs
Kinetic Growth Parameters

Table C.1: Model response to changes in $\mu_{MAX,ZBH}$

$\mu_{MAX,ZBH}$ (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
10.00	2186	348.5	165.1	3062	5.39	23.1	0.01	476.9	0.05
9.00	2205	354.4	167.0	3089	5.41	24.5	0.01	476.9	0.06
7.80	2208	356.5	167.3	3095	5.41	26.1	0.01	476.9	0.06
6.60	2194	353.8	166.2	3078	5.40	30.5	0.01	477.1	0.06
6.00	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
5.40	2212	361.2	168.0	3106	5.41	34.8	0.01	477.1	0.06
4.20	2216	367.3	169.2	3118	5.42	42.4	0.01	477.2	0.06
3.00	2172	359.5	166.8	3070	5.43	61.9	0.01	477.5	0.06
0.98	0	386.7	170.0	4689	3.62	1565.0	0.01	535.4	0.1

Table C.2: Model response to changes in $K_{S,ZBH}$

$K_{S,ZBH}$ (mg COD/L)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
300	2218	365.9	169.4	3121	5.43	42.6	0.01	477.3	0.06
260	2216	365.0	169.1	3116	5.42	36.6	0.01	477.0	0.06
220	2209	364.8	168.4	3105	5.42	33.0	0.01	477.0	0.06
200	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
180	2209	355.7	164.1	3096	5.30	29.1	0.01	477.0	0.06
140	2218	358.4	167.7	3108	5.39	25.0	0.01	476.8	0.06
100	2221	355.1	167.6	3107	5.39	21.4	0.01	476.8	0.06
4	2227	346.4	166.5	3089	5.39	3.2	0.01	475.0	0.05

Table C.3: Model response to changes in b_{ZBH}

b_{ZBH} (d^{-1})	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.6200	1438	375.3	168.0	2922	5.75	62.6	0.01	498.5	0.07
0.3672	1920	379.9	170.5	3010	5.66	46.8	0.01	487.8	0.07
0.3182	1996	358.3	166.0	2988	5.56	36.2	0.01	483.4	0.06
0.2693	2144	364.2	168.2	3077	5.47	35.0	0.01	479.4	0.06
0.2448	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.2203	2288	357.2	167.9	3141	5.34	28.9	0.01	474.6	0.06
0.1714	2432	346.0	167.0	3193	5.23	24.8	0.01	469.1	0.06
0.1224	2665	353.2	171.1	3350	5.11	20.8	0.01	462.9	0.05

Table C.4: Model responses to changes in $\eta_{HYD,AX}$

$h_{HYD,AX}$	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.0	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.9	2202	358.8	166.7	3091	5.39	30.9	0.01	477.0	0.06
0.7	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.5	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06
0.4	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06

Table C.5: Model response to changes in $\eta_{HYD,AN}$

$\eta_{HYD,AN}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
0.75	2266	376.8	171.9	3136	5.48	28.9	0.01	477.2	0.06
0.65	2253	370.2	170.4	3131	5.44	29.0	0.01	477.0	0.06
0.55	2209	359.3	167.1	3090	5.41	32.7	0.01	477.2	0.06
0.50	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.45	2184	353.6	165.9	3077	5.39	32.5	0.01	477.0	0.06
0.35	2169	353.5	166.2	3089	5.38	35.3	0.01	477.1	0.06
0.25	2157	352.3	165.9	3106	5.34	37.2	0.01	477.1	0.06
0.10	2118	351.8	165.4	3123	5.30	41.3	0.02	477.3	0.06

Table C.6: Model response to changes in $\eta_{AX,ZBH}$

$\eta_{AX,ZBH}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
0.555	2212	362.2	168.2	3107	5.41	33.1	0.01	477.1	0.06
0.481	2196	357.2	166.6	3084	5.40	30.9	0.01	477.0	0.06
0.407	2211	361.3	168.0	3105	5.41	31.0	0.01	477.0	0.06
0.370	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.333	2205	360.7	167.6	3097	5.41	32.4	0.01	477.0	0.06
0.259	2208	359.7	167.6	3100	5.41	32.3	0.01	477.0	0.06
0.185	2214	361.1	168.1	3108	5.41	32.8	0.01	477.0	0.06

Table C.7: Model response to changes in K_H

K_H (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
4.215	2270	361.7	168.6	3060	5.51	17.2	0.01	476.9	0.06
3.653	2235	351.0	165.5	3039	5.45	22.0	0.01	476.9	0.06
3.091	2222	357.4	166.8	3078	5.42	28.2	0.01	476.9	0.06
2.81	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
2.529	2178	360.1	167.3	3117	5.37	36.9	0.01	477.2	0.06
1.967	2096	372.5	169.7	3250	5.22	44.6	0.01	477.8	0.06
1.405	1815	393.1	174.2	3764	4.63	45.1	0.01	477.5	0.07

Table C.8: Model response to changes in $K_{S,HYD}$

$K_{S,HYD}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
0.225	2170	367.6	169.6	3169.6	5.35	34.8	0.01	477.1	0.06
0.195	2191	363.6	168.8	3146.9	5.36	33.9	0.01	477.1	0.06
0.165	2190	358.7	167.0	3099.6	5.39	32.0	0.01	477.0	0.06
0.150	2212	361.5	168.0	3105.8	5.41	32.4	0.01	477.0	0.06
0.135	2233	365.3	169.1	3112.1	5.43	29.5	0.01	476.9	0.06
0.105	2234	356.4	166.8	3062.5	5.45	26.1	0.01	476.9	0.06
0.075	2258	354.9	167.1	3046.0	5.49	22.3	0.01	477.2	0.06

Table C.9: Model response to changes in K_{ADS}

K_{ADS}	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
1.200	2238	353.1	166.1	3114	5.33	31.5	0.01	474.9	0.06
1.040	2214	359.5	167.7	3128	5.36	31.4	0.01	475.6	0.06
0.880	2228	361.7	168.3	3121	5.39	33.3	0.01	476.6	0.06
0.800	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.720	2182	359.4	167.0	3075	5.43	32.9	0.01	477.8	0.06
0.560	2190	368.7	169.9	3100	5.48	32.6	0.01	479.0	0.06
0.400	2173	362.7	167.9	3075	5.46	32.7	0.01	479.0	0.06

Table C.10: Model response to changes in $K_{R,AMMON}$

$K_{R,AMMON}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
0.160	2177	345.4	164.2	3051	5.38	27.6	0.02	477.1	0.06
0.120	2209	357.2	167.6	3100	5.41	30.2	0.01	477.2	0.06
0.104	2187	351.1	165.9	3068	5.41	29.1	0.01	477.1	0.06
0.088	2207	359.2	167.6	3098	5.41	31.0	0.01	477.1	0.06
0.080	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.072	2225	366.9	169.3	3125	5.42	33.3	0.01	477.0	0.06
0.056	2257	379.2	172.6	3172	5.44	36.5	0.01	476.9	0.06
0.040	2256	375.7	171.6	3166	5.42	36.7	0.01	476.5	0.06

Non-PAO heterotrophs
Stoichiometric growth parameters

Table C.11: Model response to changes in $Y_{ZBH,AER}$

$Y_{ZBH,AER}$ (mg COD/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
0.7200	4804	129.0	166.1	4681	3.55	15.4	0.01	364.5	0.48
0.6300	3892	214.9	166.0	4124	4.02	16.2	0.01	403.6	0.08
0.5460	3173	295.2	168.4	3713	4.54	20.4	0.01	435.7	0.08
0.4620	2491	343.8	166.7	3274	5.09	26.6	0.01	463.8	0.06
0.4200	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.3780	1939	376.8	169.6	2941	5.77	34.6	0.01	489.7	0.05
0.2940	1415	373.5	167.4	2618	6.39	36.2	0.01	512.1	0.05
0.2100	891	375.8	166.9	2651	6.30	33.6	0.01	529.0	0.04

Table C.12: Model response to changes in $Y_{ZBH,ANA}$

$Y_{ZBH,ANA}$ (mg COD/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{BH}	Z_{BP}	*Total P*	*VSS*	*Total P/ VSS (%)*	S_{BSC}	S_{BSA}	NH_3	PO_4
0.15	2213	360.7	168.0	3107	5.41	32.7	0.01	477.1	0.06
0.13	2193	354.2	166.1	3078	5.40	31.0	0.01	477.0	0.06
0.11	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06
0.10	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.09	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.07	2213	361.2	168.5	3107	5.42	30.8	0.01	477.0	0.06
0.05	2203	359.3	167.3	3094	5.41	33.0	0.01	477.1	0.06

Table C.13: Model response to changes in $f_{N,ZBH}$

$f_{N,ZBH}$ (mg N/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{BH}	Z_{BP}	Total P	VSS	Total P/ VSS (%)	S_{BSC}	S_{BSA}	NH_3	PO_4
0.1020	2216	361.5	168.2	3110	5.41	33.1	0.01	426.7	0.06
0.0884	2224	364.2	169.0	3123	5.41	32.6	0.01	446.8	0.06
0.0748	2209	357.0	167.3	3099	5.40	33.0	0.01	467.0	0.06
0.0680	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0612	2200	358.9	167.0	3090	5.41	32.4	0.01	487.1	0.06
0.0476	2223	364.9	169.1	3123	5.42	31.0	0.01	507.3	0.06
0.0340	2214	363.7	168.7	3112	5.42	31.7	0.01	527.5	0.06

Table C.14: Model response to changes in $f_{N,ZE,ZBH}$

$f_{N,ZE,ZBH}$ (mg N/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{BH}	Z_{BP}	Total P	VSS	Total P/ VSS (%)	S_{BSC}	S_{BSA}	NH_3	PO_4
0.1020	2207	360.7	167.8	3100	5.41	32.8	0.01	474.7	0.06
0.0884	2200	358.2	167.0	3090	5.41	33.1	0.01	475.7	0.06
0.0748	2195	357.1	166.6	3083	5.40	32.5	0.01	476.6	0.06
0.0680	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0612	2213	360.7	168.0	3106	5.41	32.7	0.01	477.5	0.06
0.0476	2214	362.7	168.4	3110	5.42	32.6	0.01	478.5	0.06
0.0340	2216	361.5	168.1	3110	5.41	31.2	0.01	479.3	0.06
0.0300	2204	360.7	167.6	3097	5.41	30.9	0.01	479.6	0.06

Table C.15: Model response to changes in $f_{P,ZBH}$

$f_{P,ZBH}$ (mg P/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{BH}	Z_{BP}	Total P	VSS	Total P/ VSS (%)	S_{BSC}	S_{BSA}	NH_3	PO_4
0.0315	2284	278.5	168.7	3081	5.47	21.2	0.01	478.2	0.06
0.0273	2239	319.5	168.3	3088	5.45	21.4	0.01	477.4	0.06
0.0231	2202	347.2	166.8	3080	5.42	31.0	0.01	477.2	0.06
0.0210	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0189	2214	370.7	168.3	3116	5.40	33.4	0.01	476.9	0.06
0.0147	2207	374.3	168.0	3108	5.41	31.5	0.01	476.6	0.05
0.0105	2199	375.7	167.0	3095	5.40	28.1	0.01	476.3	0.05

Table C.16: Model response to changes in $f_{N,ZE,ZBP}$

$f_{N,ZE,ZBP}$ (mg P/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{BH}	Z_{BP}	Total P	VSS	Total P/ VSS (%)	S_{BSC}	S_{BSA}	NH_3	PO_4
0.0315	2214	361.0	184.6	3108	5.94	31.1	0.01	477.1	0.06
0.0273	2212	359.5	177.3	3104	5.71	33.8	0.01	477.1	0.06
0.0231	2205	358.7	170.2	3096	5.50	31.1	0.01	477.0	0.06
0.0210	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0189	2193	357.6	163.3	3080	5.30	33.2	0.01	477.1	0.06
0.0147	2204	361.6	158.0	3097	5.10	33.0	0.01	477.0	0.06
0.0105	2224	367.1	153.2	3125	4.90	33.0	0.01	477.1	0.06
0.0100	2200	360.8	150.5	3091	4.87	33.0	0.01	477.1	0.06

Table C.17: Model response to changes in $f_{ZE,ZBH}$

$f_{ZE,ZBH}$	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.1200	2203	363.8	169.2	3139	5.39	32.8	0.01	475.7	0.06
0.1040	2198	359.0	167.3	3113	5.37	30.8	0.01	476.0	0.06
0.0880	2212	361.0	168.0	3114	5.40	30.9	0.01	476.7	0.06
0.0800	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0720	2225	362.9	168.7	3114	5.42	30.9	0.01	477.3	0.06
0.0560	2222	361.2	168.0	3093	5.43	32.6	0.01	478.0	0.06
0.0400	2222	361.2	167.5	3077	5.44	31.1	0.01	478.4	0.06

Table C.18: Model response to changes in $f_{CV,ZBH}$

$f_{CV,ZBH}$ (mg COD/mg VSS)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
2.2200	2179	345.6	164.3	2117	7.76	27.2	0.02	476.8	0.05
1.9240	2183	348.6	165.1	2412	6.85	27.4	0.02	476.8	0.05
1.6280	2194	357.9	166.6	2825	5.90	30.7	0.01	477.0	0.05
1.4800	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
1.3320	2229	369.6	169.9	3453	4.92	34.4	0.01	477.2	0.06
1.0360	2276	389.0	174.3	4461	3.91	37.7	0.01	477.5	0.1
0.7400	2217	361.7	168.2	5969	2.82	39.3	0.01	477.4	0.24

Table C.19: Model response to changes in $Y_{ZBH,ANOX}$

$Y_{ZBH,ANOX}$ (mg COD/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.6660	2202	358.7	167.1	3092	5.40	33.1	0.01	477.1	0.06
0.6045	2210	360.8	167.8	3103	5.41	31.0	0.01	477.1	0.06
0.5239	2193	354.2	166.1	3078	5.40	31.0	0.01	477.0	0.06
0.4433	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06
0.4030	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.3627	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.2821	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.2015	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06

Table C.20: Model response to changes in ADS_{MAX}

ADS_{MAX}	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.5000	2227	361.2	168.1	3119	5.39	32.8	0.01	476.4	0.06
1.3000	2225	360.6	168.0	3117	5.39	32.9	0.01	476.6	0.06
1.1000	2228	363.9	169.0	3126	5.41	32.6	0.01	476.9	0.06
1.0000	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.9000	2211	362.6	168.6	3108	5.43	33.0	0.01	477.4	0.06
0.7000	2190	362.5	168.1	3089	5.44	32.8	0.01	478.0	0.06
0.5000	2189	369.3	169.8	3100	5.48	30.5	0.01	478.7	0.06

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Table C.21: Model response to changes in $\mu_{MAX,ZBP}$

$\mu_{MAX,ZBP}$ (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
3.340	2179	456.6	190.2	3061	6.22	101.8	0	474.5	0.06
1.425	2206	426.4	174.7	3090	5.66	68.2	0.01	475.1	0.06
1.235	2185	402.1	169.5	3058	5.54	60.5	0.01	475.7	0.06
1.045	2201	379.4	168.0	3086	5.44	44.8	0.01	476.4	0.05
0.950	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.855	2190	316.2	163.0	3068	5.31	15.7	0.02	477.8	2.57
0.665	2469	0.0	138.2	2895	4.77	13.5	0	481.2	52.09
0.475	2461	0.0	137.9	2886	4.78	13.6	0	481.2	52.09

Table C.22: Model response to changes in $K_{S,ZBP}$

$K_{S,ZBP}$ (mg COD/L)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.15	2186	333.0	164.5	3086	5.33	15.9	0.02	477.3	0.11
0.13	2211	351.7	167.8	3108	5.40	23.4	0.02	477.3	0.06
0.11	2212	357.7	167.9	3106	5.40	31.0	0.01	477.2	0.06
0.10	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.09	2192	357.7	166.7	3075	5.42	33.5	0.01	476.8	0.05
0.07	2188	363.2	166.3	3066	5.42	38.7	0.01	476.7	0.06
0.05	2214	381.5	169.2	3103	5.45	46.3	0.01	476.5	0.06

Table C.23: Model response to changes in μ_{PLIM}

μ_{PLIM} (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.63	2202	377.6	167.0	3080	5.42	31.3	0.01	475.8	0.06
0.55	2198	369.4	166.6	3079	5.41	33.3	0.01	476.4	0.06
0.46	2210	365.9	168.0	3102	5.42	33.2	0.01	476.9	0.06
0.42	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.38	2225	360.6	169.4	3127	5.42	32.5	0.2	477.3	0.06
0.29	2220	348.9	168.6	3122	5.40	30.4	0.02	477.8	0.06
0.21	2209	336.7	166.9	3108	5.37	29.6	0.02	478.8	0.06

Table C.24: Model response to changes in $K_{S,PLIM}$

$K_{S,PLIM}$ (mg COD/L)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.08	2210	359.1	167.9	3104	5.41	30.8	0.01	477.1	0.06
0.075	2203	359.0	167.5	3096	5.41	32.8	0.01	477.2	0.06
0.066	2213	360.8	167.9	3107	5.40	33.4	0.01	477.1	0.06
0.055	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.050	2191	354.9	166.1	3075	5.40	33.4	0.01	477.1	0.06
0.045	2225	365.9	169.0	3123	5.41	30.9	0.01	476.9	0.06
0.035	2198	359.8	166.5	3085	5.40	33.0	0.01	476.9	0.06

Table C.25: Model response to changes in b_{ZBP}

b_{ZBP} (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.060	2210	338.4	167.7	3097	5.41	23.5	0.02	477.8	0.07
0.052	2202	344.9	167.0	3089	5.41	24.9	0.02	477.3	0.06
0.044	2222	360.7	168.8	3120	5.41	30.4	0.02	477.2	0.05
0.040	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.036	2200	360.9	167.0	3089	5.41	33.5	0.01	476.8	0.05
0.028	2195	371.6	167.0	3086	5.41	35.7	0.01	476.5	0.05
0.020	2212	384.0	168.7	3111	5.42	38.6	0.01	476.0	0.05

Table C.26: Model response to changes in $b_{ZBP,AN}$

$b_{ZBP,AN}$ (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.045	2234	367.9	169.9	3135	5.42	30.7	0.01	476.9	0.07
0.039	2215	364.4	168.6	3111	5.42	33.0	0.01	477.1	0.07
0.033	2219	360.2	168.3	3113	5.41	33.1	0.01	477.1	0.06
0.030	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.027	2211	359.9	167.8	3104	5.41	32.5	0.01	477.0	0.06
0.021	2209	360.1	168.0	3103	5.41	33.0	0.01	477.1	0.05
0.015	2201	355.6	166.8	3089	5.40	33.0	0.01	477.1	0.05

Table C.27: Model response to changes in K_{VFA}

K_{vFA} (mg COD mg COD-1 d-1)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
9.00	2203	360.8	167.3	3097	5.40	32.2	0.01	477.1	0.06
7.80	2214	359.9	167.5	3108	5.39	31.0	0.01	477.0	0.06
6.60	2211	360.0	167.8	3104	5.41	33.1	0.01	477.1	0.06
6.00	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
5.40	2216	362.8	168.7	3111	5.42	31.1	0.02	477.0	0.06
4.20	2200	344.6	166.2	3071	5.41	26.3	0.02	476.9	0.06
3.00	2302	267.5	168.0	3064	5.48	15.1	0.02	477.5	0.12

Table C.28: Model response to changes in $\eta_{AX,ZBP}$

$\eta_{AX,ZBP}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.60	2200	357.9	166.8	3089	5.40	33.1	0.01	447.1	0.06
0.52	2190	354.9	166.1	3074	5.40	30.9	0.01	477.0	0.06
0.44	2217	362.5	168.5	3112	5.41	33.0	0.01	477.1	0.06
0.40	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.36	2209	360.4	167.7	3100	5.41	32.5	0.01	477.0	0.06
0.28	2226	364.1	169.0	3125	5.41	32.7	0.01	477.1	0.06
0.20	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06

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Table C.29: Model response to changes in Y_{ZBP}

Y_{ZBP} (mg COD/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.959	2196	474.8	162.7	3173	5.13	15.8	0.01	469.2	1.45
0.831	2232	453.3	168.3	3204	5.25	22.4	0.01	472.1	0.07
0.703	2216	392.1	168.0	3134	5.36	28.1	0.01	475.3	0.06
0.639	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.575	2187	322.5	166.7	3044	5.47	33.5	0.02	478.6	0.05
0.447	2206	262.7	168.8	3015	5.60	38.9	0.02	482.2	0.05
0.320	2244	165.2	168.2	2941	5.72	34.3	0.02	484.7	0.04

Table C.30: Model response to changes in $f_{P/PHB,AER}$

$f_{P/PHB,AER}$ (mg P/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.425	2219	282.9	171.4	3162	5.42	56.8	0.03	482.1	0.06
1.235	2219	314.9	171.5	3149	5.45	52.0	0.03	480.4	0.06
1.045	2209	340.7	168.4	3112	5.41	40.5	0.02	478.2	0.05
0.950	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.855	2234	383.3	169.4	3127	5.42	19.8	0.01	475.9	0.06
0.665	2461	0.0	137.9	2886	4.78	13.6	0	481.2	52.09
0.475	2469	0.0	138.2	2895	4.77	13.5	0	481.2	52.09

Table C.31: Model response to changes in $f_{P/PHB,ANOX}$

$f_{P/PHB,ANOX}$ (mg P/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.525	2204	359.2	167.4	3095	5.41	33.1	0.01	477.1	0.06
0.455	2225	363.5	169.0	3123	5.41	33.1	0.01	477.1	0.06
0.385	2212	361.4	167.9	3106	5.41	32.9	0.01	477.1	0.06
0.350	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.315	2215	360.6	167.7	3108	5.39	30.9	0.01	477.0	0.06
0.245	2204	360.0	167.4	3095	5.41	30.9	0.01	477.0	0.06
0.175	2213	359.9	167.9	3106	5.41	32.2	0.01	477.0	0.06

Table C.32: Model response to changes in Y_{PHB}

Y_{PHB} (mg COD/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.000	2192	372.0	166.9	3134	5.32	41.4	0.02	476.2	0.06
0.978	2199	370.4	166.7	3133	5.32	40.7	0.02	476.4	0.06
0.889	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.800	2206	340.0	167.1	3053	5.47	15.9	0.01	477.5	0.09
0.622	2414	45.7	141.0	2884	4.89	13.5	0	481.1	51.74
0.445	2469	0.0	138.2	2895	4.77	13.5	0	481.2	52.09

Table C.33: Model response to changes in $f_{N,ZBP}$

$f_{N,ZBP}$ (mg N/mg COD)	Concentration (mg/L)								
	Mixed Liquor					Decant			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.105	2207	360.6	167.8	3099	5.41	33.6	0.01	468.7	0.06
0.091	2203	359.0	167.3	3093	5.41	33.1	0.01	472.1	0.06
0.077	2222	363.9	168.9	3120	5.41	32.4	0.01	475.4	0.06
0.070	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.063	2213	362.7	168.4	3109	5.42	33.6	0.01	478.8	0.06
0.049	2205	358.9	167.4	3096	5.41	33.1	0.01	482.2	0.06
0.035	2221	364.3	168.9	3120	5.41	33.4	0.01	485.5	0.06

Table C.34: Model response to changes in $f_{N,ZE,ZBP}$

$f_{N,ZE,ZBP}$ (mg N/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.105	2200	357.8	166.9	3089	5.40	33.1	0.01	476.9	0.06
0.091	2209	361.8	167.9	3103	5.41	33.1	0.01	477.0	0.06
0.077	2218	362.6	168.5	3114	5.41	33.1	0.01	477.0	0.06
0.070	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.063	2219	362.9	168.7	3115	5.41	32.8	0.01	477.1	0.06
0.049	2205	360.0	167.6	3097	5.41	30.9	0.01	477.1	0.06
0.035	2224	364.0	169.0	3122	5.41	30.8	0.01	477.2	0.06
0.030	2223	363.4	168.9	3121	5.41	33.4	0.01	477.3	0.06

Table C.35: Model response to changes in $f_{N,SE,ZBP}$

$f_{N,SE,ZBP}$ (mg N/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.105	2214	360.5	168.0	3107	5.41	33.1	0.01	477.1	0.06
0.091	2218	362.2	168.3	3113	5.41	33.1	0.01	477.1	0.06
0.077	2221	363.0	168.7	3118	5.41	33.1	0.01	477.1	0.06
0.070	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.063	2209	359.8	167.6	3101	5.40	33.0	0.01	477.1	0.06
0.049	2201	358.9	167.2	3092	5.41	31.0	0.01	477.0	0.06
0.035	2203	359.1	167.3	3093	5.41	31.0	0.01	477.0	0.06

Table C.36: Model response to changes in $f_{P,ZBP}$

$f_{P,ZBP}$ (mg P/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.032	2194	342.2	165.2	3066	5.39	30.7	0.01	477.2	0.06
0.027	2220	359.9	169.0	3113	5.43	30.4	0.01	477.0	0.06
0.023	2211	360.3	168.0	3104	5.41	30.7	0.01	477.0	0.06
0.021	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.019	2212	363.5	168.3	3107	5.42	33.7	0.01	477.1	0.06
0.015	2217	367.1	168.7	3117	5.41	34.0	0.01	477.0	0.06
0.011	2206	366.7	167.9	3105	5.41	33.3	0.01	476.9	0.06

Table C.37: Model response to changes in $f_{P,ZE,ZBP}$

$f_{P,ZE,ZBP}$ (mg P/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.032	2209	361.8	167.9	3103	5.41	31.0	0.01	477.0	0.06
0.027	2212	361.8	168.0	3106	5.41	33.1	0.01	477.2	0.06
0.023	2211	361.6	167.9	3104	5.41	33.1	0.01	477.1	0.06
0.021	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.019	2218	362.8	168.5	3113	5.41	33.1	0.01	477.1	0.06
0.015	2215	361.5	168.2	3109	5.41	30.9	0.01	477.0	0.05
0.011	2196	357.2	166.6	3084	5.40	30.9	0.01	477.0	0.06
0.010	2207	361.3	167.9	3100	5.42	33.0	0.01	477.1	0.06

Table C.38: Model response to changes in $f_{ZE,ZBP}$

$f_{ZE,ZBP}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.375	2216	362.0	168.3	3115	5.40	33.1	0.01	476.9	0.06
0.325	2216	362.9	168.5	3114	5.41	31.0	0.01	476.9	0.06
0.275	2213	361.4	167.9	3107	5.40	30.9	0.01	477.0	0.06
0.250	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.225	2204	360.1	167.6	3096	5.41	32.8	0.01	477.1	0.06
0.175	2223	365.4	169.1	3121	5.42	32.7	0.01	477.2	0.06
0.125	2212	361.5	168.0	3103	5.42	30.9	0.01	477.2	0.06

Table C.39: Model response to changes in $f_{SE,ZBP}$

$f_{SE,ZBP}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.300	2222	364.8	169.0	3121	5.41	33.6	0.01	477.1	0.06
0.260	2205	359.3	167.2	3095	5.40	32.9	0.01	477.1	0.06
0.220	2213	361.7	168.0	3107	5.41	30.8	0.01	476.9	0.06
0.200	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.180	2209	359.8	167.6	3101	5.40	33.0	0.01	477.1	0.06
0.140	2201	358.9	167.2	3092	5.41	31.0	0.01	477.0	0.06
0.100	2203	359.1	167.3	3093	5.41	31.0	0.01	477.0	0.06

Table C.40: Model response to changes in $f_{P/AC}$

$f_{P/AC}$ *(mg P/mg VFA-COD)*	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.735	2469	0.0	138.2	2895	4.77	13.5	0	481.2	52.09
0.637	2461	0.0	137.9	2886	4.78	13.5	0	481.2	52.09
0.539	2237	359.1	168.6	3107	5.43	15.6	0.01	476.2	0.22
0.490	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.441	2196	349.5	167.6	3104	5.40	41.5	0.02	478.1	0.06
0.343	2200	311.2	168.7	3130	5.39	51.4	0.03	480.5	0.06
0.245	2210	257.6	169.5	3164	5.36	56.8	0.04	483.5	0.05

Table C.41: Model response to changes in $f_{CV,ZBP}$

$f_{CV,ZBP}$ *(mg COD/mg VSS)*	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
2.130	2218	360.9	168.3	3027	5.56	30.8	0.01	477.0	0.05
1.846	2214	359.5	167.8	3048	5.51	30.8	0.01	477.0	0.06
1.562	2220	363.7	168.8	3094	5.46	31.0	0.01	477.0	0.06
1.420	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
1.278	2203	360.7	167.5	3122	5.36	30.8	0.01	476.9	0.06
0.994	2215	362.0	168.2	3219	5.23	33.2	0.01	477.1	0.06
0.710	2230	369.8	169.9	3395	5.01	34.4	0.01	477.2	0.06

Table C.42: Model response to changes in $Y_{PP\text{-}LO}$

YPP-LO	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.000	2182	361.1	166.1	3074	5.40	33.5	0.01	476.8	0.06
0.940	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.846	2328	241.0	168.0	3056	5.50	14.7	0.01	478.2	1.51
0.658	2469	0.0	138.2	2895	4.77	13.5	0.00	481.2	52.09
0.470	2461	0.0	137.9	2886	4.78	13.6	0	481.2	52.09

Autotrophs
Kinetic Growth Parameters

Table C.43: Model outputs to changes in μ_{ZBA}

$\mu_{MAX,ZBA}$ (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
2.300	2221	363.4	168.9	3118	5.42	31.0	0.01	477.0	0.06
1.152	2202	360.1	167.4	3094	5.41	33.1	0.01	477.1	0.06
0.998	2221	362.5	168.9	3118	5.42	31.0	0.01	477.0	0.06
0.845	2202	359.5	167.2	3092	5.41	30.7	0.01	477.0	0.06
0.768	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.691	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.538	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.384	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06
0.144	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06

Table C.44: Model response to changes in $K_{S,NH4}$

KS,NH4 (mg N/L)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
8.4	2213	360.5	168.0	3107	5.41	31.0	0.01	477.0	0.06
1.50	2216	361.8	168.3	3111	5.41	31.1	0.01	477.0	0.06
1.30	2212	361.4	168.1	3107	5.41	33.1	0.01	477.1	0.06
1.10	2225	364.6	169.0	3124	5.41	33.1	0.01	477.1	0.06
1.00	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.90	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.70	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.50	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06
0.06	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06

Table C.45: Model response to changes in b_{ZBA}

b_{ZBA} (d-1)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.1680	2206	359.6	167.5	3098	5.41	33.2	0.01	477.1	0.06
0.1080	2204	360.2	167.6	3096	5.41	31.0	0.01	477.0	0.06
0.0936	2204	360.0	167.6	3096	5.41	31.2	0.01	477.0	0.06
0.0792	2218	362.3	168.6	3114	5.41	33.1	0.01	477.1	0.06
0.0720	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0648	2205	360.7	167.6	3097	5.41	32.4	0.01	477.0	0.06
0.0504	2208	359.7	167.6	3100	5.41	32.3	0.01	477.0	0.06
0.0360	2213	360.8	168.0	3107	5.41	30.8	0.01	477.0	0.06
0.0048	2211	361.6	168.0	3105	5.41	33.5	0.01	477.1	0.06

Autotrophs
Stoichiometric Growth Parameters

Table C.46: Model response to changes in Y_{ZBA}

YZBA (mg COD/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.350	2215	361.1	168.0	3109	5.41	33.2	0.01	477.1	0.06
0.225	2215	362.9	168.5	3111	5.42	31.1	0.01	477.0	0.06
0.195	2215	362.3	168.6	3112	5.42	33.1	0.01	477.1	0.06
0.165	2193	354.2	166.1	3078	5.40	32.5	0.01	477.0	0.06
0.150	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.135	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.105	2213	361.1	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.075	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06
0.060	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06

Table C.47: Model response to changes in $f_{N,ZBA}$

$f_{N,ZBA}$ *(mg N/mg COD)*	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.1020	2207	359.8	167.4	3098	5.40	30.9	0.01	477.0	0.06
0.0884	2211	361.0	167.9	3104	5.41	33.1	0.01	477.1	0.06
0.0748	2205	360.2	167.5	3097	5.41	31.2	0.01	477.0	0.06
0.0680	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0612	2214	361.2	168.1	3108	5.41	30.9	0.01	477.0	0.06
0.0476	2211	360.5	167.8	3104	5.41	33.0	0.01	477.1	0.06
0.0340	2209	362.0	168.0	3103	5.41	33.5	0.01	477.1	0.06

Table C.48: Model response to changes in $f_{N,ZE,ZBA}$

$f_{N,ZE,ZBA}$ (mg N/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.1020	2221	363.4	168.9	3119	5.41	30.9	0.01	477.0	0.06
0.0884	2203	359.8	167.2	3094	5.40	32.9	0.01	477.1	0.06
0.0748	2193	354.2	166.1	3078	5.40	31.0	0.01	477.0	0.06
0.0680	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0612	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.0476	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.0340	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06
0.0300	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06

Table C.49: Model response to changes in ($f_{P,ZBA}$)

$f_{P,ZBA}$ (mg P/mg COD)	*Values of state variables (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.0315	2203	359.8	167.2	3094	5.40	32.9	0.01	477.1	0.06
0.0273	2193	354.2	166.1	3078	5.40	31.0	0.01	477.0	0.06
0.0231	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06
0.0210	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0189	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.0147	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.0105	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06

Table C.50: Model response to changes in ($f_{P,ZE,ZBA}$)

$f_{P,ZE,ZBA}$ (mg P/mg COD)	*Values of state variables (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.0315	2211	359.2	167.9	3104	5.41	33.1	0.01	477.1	0.06
0.0273	2207	360.7	167.7	3099	5.41	30.9	0.01	477.0	0.06
0.0231	2210	362.6	168.2	3106	5.42	32.4	0.01	477.0	0.06
0.0210	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.0189	2213	361.5	168.0	3107	5.41	31.0	0.01	477.0	0.06
0.0147	2203	359.4	167.3	3094	5.41	33.1	0.01	477.1	0.06
0.0105	2218	362.7	168.6	3114	5.41	30.9	0.01	477.0	0.06
0.0100	2215	361.3	168.1	3109	5.41	33.4	0.01	477.1	0.06

Table C.51: Model response to changes in $f_{ZE,ZBA}$

$f_{ZE,ZBA}$	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.120	2203	359.8	167.2	3094	5.40	32.9	0.01	477.1	0.06
0.104	2193	354.2	166.1	3078	5.40	31.0	0.01	477.0	0.06
0.088	2205	360.0	167.5	3097	5.41	33.9	0.01	477.0	0.06
0.080	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
0.072	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.056	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.040	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06

Table C.52: Model response to changes in $f_{CV,ZBA}$

$f_{CV,ZBA}$ *(mg COD/mg VSS)*	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
2.130	2203	359.8	167.2	3094	5.40	32.9	0.01	477.1	0.06
1.846	2193	354.2	166.1	3078	5.40	31.0	0.01	477.0	0.06
1.562	2205	360.0	167.5	3097	5.41	30.9	0.01	477.0	0.06
1.420	2212	361.5	168.0	3106	5.41	32.4	0.01	477.0	0.06
1.278	2202	358.8	166.9	3091	5.40	30.9	0.01	477.0	0.06
0.994	2213	361.5	168.1	3107	5.41	30.8	0.01	477.0	0.06
0.710	2203	359.3	167.4	3094	5.41	33.0	0.01	477.1	0.06

C.2 Complete PO_4 Removal (BL_1)

Table C.53: Model outputs for changes in $\mu_{MAX,ZBP}$

$\mu_{max,zbp}$ (d^{-1})	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh} (mg/L)	Z_{bp} (mg/L)	Total P (mg/L)	VSS (mg/L)	Total P/ VSS (%)	S_{bsc} (mg/L)	S_{bsa} (mg/L)	NH_3 (mg/L)	PO_4 (mg/L)
3.340	2099	447.1	176.3	2919	6.0	122.5	0.00	474.8	0.03
1.425	2126	408.5	164.8	2943	5.6	74.9	0.01	476.6	0.03
1.235	2134	396.4	165.3	2954	5.6	57.7	0.01	476.7	0.03
1.045	2145	370.7	163.4	2968	5.5	39.9	0.01	477.4	0.03
0.950	2154	352.9	163.1	2980	5.5	25.0	0.01	478.3	0.03
0.855	2165	319.7	161.3	2989	5.4	14.7	0.02	479.4	3.68
0.665	2425	0.0	136.8	2804	4.9	12.8	0.00	482.3	52.4
0.475	2425	0.0	136.8	2804	4.9	12.8	0.00	479.0	52.4

Table C.54: Relative sensitivity of model outputs to $\mu_{MAX,ZBP}$

$\mu_{max,zbp}$ (d^{-1})	*Relative sensitivity*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
3.340	-0.010	0.106	0.032	-0.008	0.041	1.551	-0.352	-0.003	-0.073
1.425	-0.025	0.315	0.021	-0.025	0.046	3.992	-1.178	-0.007	-0.159
1.235	-0.030	0.411	0.045	-0.029	0.075	4.359	-1.544	-0.011	-0.460
1.045	-0.037	0.505	0.017	-0.040	0.057	5.976	-1.981	-0.017	-0.277
0.855	-0.051	0.939	0.112	-0.031	0.142	4.110	-1.660	-0.024	-1175
0.665	-0.420	3.333	0.537	0.197	0.361	1.630	3.333	-0.028	-5622
0.475	-0.252	2.000	0.322	0.118	0.217	0.980	2.000	-0.003	-3373

Table C.55: Model outputs for changes in $f_{P/AC}$

$f_{P/AC}$ (mg P/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh} (mg/L)	Z_{bp} (mg/L)	Total P (mg/L)	VSS (mg/L)	Total P/ VSS (%)	S_{bsc} (mg/L)	S_{bsa} (mg/L)	NH_3 (mg/L)	PO_4 (mg/L)
0.735	2424	0.01	136.9	2804	4.9	12.6	0.00	455.4	52.4
0.637	2425	0.00	136.8	2804	4.9	12.8	0.00	482.5	52.5
0.539	2175	344.2	162.0	2966	5.5	14.6	0.01	477.7	2.249
0.490	2154	352.9	163.1	2980	5.5	25.0	0.01	478.3	0.031
0.441	2142	343.7	163.1	2989	5.5	35.1	0.02	479.3	0.030
0.343	21367	299.3	163.1	3006	5.4	44.1	0.03	481.6	0.029
0.245	2140	240.5	163.1	3023	5.4	47.5	0.05	484.3	0.027

Table C.56: Relative sensitivity of BioWin model outputs to changes in $f_{P/AC}$

$f_{P/AC}$ (mg P/mg COD)	*Relative sensitivity*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.735	0.251	-2.000	-0.322	-0.118	-0.216	-0.991	-2	-0.096	3369
0.637	0.420	-3.333	-0.537	-0.197	-0.361	-1.63	-3.33	0.029	5622
0.539	0.099	-0.244	-0.068	-0.046	-0.022	-4.14	-2.91	-0.011	714
0.441	0.055	0.260	0.000	-0.031	0.031	-4.02	-2.62	-0.022	0.267
0.343	0.026	0.506	0.000	-0.029	0.028	-2.55	-3.28	-0.023	0.217
0.245	0.012	0.637	0.000	-0.029	0.028	-1.80	-4.29	-0.025	0.253

Table C.57: BioWin model output for varying values of Y_{PHB}

Y_{PHB} (mg COD/mg COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh} (mg/L)	Z_{bp} (mg/L)	Total P (mg/L)	VSS (mg/L)	Total P/ VSS (%)	S_{bsc} (mg/L)	S_{bsa} (mg/L)	NH_3 (mg/L)	PO_4 (mg/L)
1.0000	2150	368.7	163.1	3035	5.4	33.82	0.02	477.7	0.032
0.9779	2150	366.0	163.1	3023	5.4	32.63	0.02	477.8	0.031
0.8890	2154	352.9	163.1	2980	5.5	25.00	0.01	478.3	0.031
0.8001	2159	334.3	162.8	2939	5.5	14.80	0.01	478.9	0.705
0.6223	2425	0.01	136.8	2803	4.9	12.73	0.00	475.8	52.4
0.4445	2422	0.01	136.9	2805	4.9	12.52	0.00	434.2	52.4

Table C.58: Relative sensitivity of BioWin model output to changes in Y_{PHB}

Y_{PHB} (mg COD/mg COD)	*Relative sensitivity*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1	-0.0129	0.360	0.000	0.1464	-0.1438	2.83	3.10	-0.009	0.205
0.9779	-0.0144	0.371	0.000	0.1451	-0.1430	3.06	3.07	-0.010	0.100
0.8001	-0.0251	0.526	0.021	0.1375	-0.1184	4.08	3.57	-0.014	-216.9
0.6223	-0.4199	3.33	0.537	0.1976	0.3606	1.645	3.33	0.017	-5620
0.4445	-0.2492	1.99	0.322	0.1175	0.2168	0.998	2.00	0.184	-3367

Table C.59: BioWin model outputs for varying values of Y_{PP-LO}

Y_{PP-LO}	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh} (mg/L)	Z_{bp} (mg/L)	Total P (mg/L)	VSS (mg/L)	Total P/ VSS (%)	S_{bsc} (mg/L)	S_{bsa} (mg/L)	NH_3 (mg/L)	PO_4 (mg/L)
1.000	2144	364.0	163.1	2984	5.5	28.62	0.01	478.2	0.031
0.940	2154	352.9	163.1	2980	5.5	25.00	0.01	478.3	0.031
0.846	2258	228.3	161.6	2912	5.5	13.95	0.01	479.3	2.99
0.658	2425	0.01	136.8	2803	4.9	12.71	0.00	472.9	52.4
0.470	2422	0.01	136.9	2805	4.9	12.52	0.00	434.5	52.4

Table C.60: Relative sensitivity of BioWin model outputs to changes in Y_{PP-LO}

Y_{PP-LO}	*Relative sensitivity*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.000	-0.070	0.495	0.00	0.022	-0.022	2.27	-0.315	-0.002	-0.091
0.846	-0.487	3.53	0.091	0.228	-0.141	4.42	3.59	-0.021	-951
0.658	-0.420	3.33	0.537	0.198	0.360	1.64	3.33	0.038	-5619
0.470	-0.249	2.00	0.321	0.117	0.217	0.998	2	0.183	-3367

Table C.61: BioWin model output for varying values of $f_{P/PHB,AER}$

$f_{P/PHB,AER}$ *(mg COD/mg COD)*	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh} (mg/L)	Z_{bp} (mg/L)	Total P (mg/L)	VSS (mg/L)	Total P/ VSS (%)	S_{bsc} (mg/L)	S_{bsa} (mg/L)	NH_3 (mg/L)	PO_4 (mg/L)
1.425	2144	263.7	163.1	3009	5.4	46.50	0.04	483	0.031
1.235	2145	296.5	163.1	2999	5.4	42.35	0.03	481	0.031
1.045	2149	333.3	163.1	2986	5.5	33.24	0.02	479	0.030
0.950	2154	352.9	163.1	2980	5.5	25.00	0.01	478	0.031
0.855	2160	369.8	162.7	2974	5.5	14.79	0.01	477	0.871
0.665	2425	0.01	136.8	2804	4.9	12.75	0.00	478	52.4
0.475	2423	0.00	136.9	2804	4.9	12.57	0.00	446	52.4

Table C.62: Relative sensitivity of BioWin model outputs to changes in $f_{P/PHB,AER}$

$f_{P/PHB,AER}$ (mg COD/mg COD)	*Relative Sensitivity*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
1.425	-0.009	-0.505	0.000	0.020	-0.019	1.72	3.07	0.020	-0.021
1.235	-0.014	-0.533	0.000	0.021	-0.020	2.31	3.00	0.022	-0.038
1.045	-0.020	-0.553	0.000	0.020	-0.019	3.30	2.87	0.024	-0.380
0.855	-0.031	-0.481	0.026	0.020	0.006	4.08	3.33	0.023	-270.1
0.665	-0.420	3.333	0.537	0.198	0.361	1.63	3.33	-0.001	-5621
0.475	-0.250	2.000	0.322	0.118	0.217	0.99	2.00	0.133	-3368

Table C.63: BioWin model outputs for varying values of Y_{ZBP}

Y_{ZBP} (g COD/g COD)	*Concentration (mg/L)*								
	Mixed Liquor					*Decant*			
	Z_{bh} (mg/L)	Z_{bp} (mg/L)	Total P (mg/L)	VSS (mg/L)	Total P/ VSS (%)	S_{bsc} (mg/L)	S_{bsa} (mg/L)	NH_3 (mg/L)	PO_4 (mg/L)
0.959	2166	491	162.4	3103	5.2	14.7	0.01	471.2	1.447
0.831	2161	441	163.1	3059	5.3	15.8	0.01	473.7	0.033
0.703	2156	383	163.1	3007	5.4	21.9	0.01	476.7	0.031
0.639	2154	353	163.1	2980	5.5	25.0	0.01	478.3	0.031
0.575	2151	322	163.1	2952	5.5	28.0	0.02	479.9	0.030
0.447	2150	255	163.1	2893	5.6	33.4	0.02	483.1	0.026
0.320	2203	155	163.1	2823	5.8	28.6	0.02	485.5	0.024

Table C.64: Relative sensitivity of BioWin model outputs to changes in Y_{ZBP}

Y_{ZBP} (g COD/g COD)	*Relative sensitivity*								
	Mixed Liquor					*Decant*			
	Z_{bh}	Z_{bp}	Total P	VSS	Total P/ VSS (%)	S_{bsc}	S_{bsa}	NH_3	PO_4
0.959	0.012	0.780	-0.009	0.082	-0.087	-0.821	-0.412	-0.030	91.1
0.831	0.012	0.833	0.000	0.088	-0.086	-1.222	-0.518	-0.032	0.239
0.703	0.012	0.856	0.000	0.091	-0.090	-1.227	-0.448	-0.032	0.087
0.575	0.010	0.883	0.000	0.093	-0.094	-1.212	-0.475	-0.034	0.383
0.447	0.006	0.927	0.000	0.097	-0.100	-1.117	-0.533	-0.034	0.500
0.320	-0.046	1.124	0.000	0.105	-0.111	-0.286	-0.189	-0.030	0.450

C.3 Incomplete PO_4 Removal (BL_2)

Table C.65: BioWin model outputs for varying values of $\mu_{MAX,ZBP}$

$\mu_{MAX,ZBP}$ (d^{-1})	*Concentration (mg/L)*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	Spbh	S_{bsc}	S_{bsa}	NH_3	PO_4
3.340	2073	442.4	175.5	29.8	155.3	0.00	476.8	0.8
1.425	2117	394.8	164.1	91.5	77.9	0.01	477.7	0.8
1.235	2128	377.1	163.0	117.0	59.1	0.01	478.0	0.8
1.045	2143	331.0	159.0	157.4	52.2	0.02	479.5	8.1
0.950	2154	295.0	156.0	182.6	52.0	0.02	480.7	14.2
0.855	2397	0.00	136.6	0.00	49.7	0.00	483.3	52.9
0.665	2397	0.00	136.6	0.00	49.7	0.00	483.3	52.9
0.475	2397	0.00	136.6	0.00	49.7	0.00	483.3	52.9

Table C.66: Relative sensitivity of BioWin model outputs to changes in $\mu_{MAX,ZBP}$

$\mu_{MAX,ZBP}$ (d^{-1})	*Relative sensitivity*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	Spbh	S_{bsc}	S_{bsa}	NH_3	PO_4
3.340	-0.02	0.20	0.05	-0.33	0.79	-0.36	0.00	-0.4
1.425	-0.03	0.68	0.10	-1.00	1.00	-1.26	-0.01	-1.9
1.235	-0.04	0.93	0.15	-1.20	0.45	-1.69	-0.02	-3.1
1.045	-0.05	1.22	0.20	-1.38	0.04	-2.37	-0.02	-4.3
0.855	-1.13	10.00	1.24	10.00	0.45	9.96	-0.05	-27.2
0.665	-0.38	3.33	0.41	3.33	0.15	3.32	-0.02	-9.1
0.475	-0.23	2.00	0.25	2.00	0.09	1.99	-0.01	-5.4

Table C.67: BioWin model outputs at varying values of $f_{P/AC}$

$f_{P/AC}$ (mg P/mg COD)	*Concentration (mg/L)*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
0.735	2397	0.0	136.6	0.0	49.6	0.00	483.2	52.9
0.637	2397	0.0	136.6	0.0	49.7	0.00	483.3	52.9
0.539	2180	274.7	153.6	141.5	51.7	0.02	480.4	19.0
0.490	2154	295.0	156.0	182.6	52.0	0.02	480.7	14.2
0.441	2134	304.1	158.5	226.1	52.3	0.03	481.2	9.2
0.343	2125	273.8	161.0	308.1	52.5	0.04	483.1	4.2
0.245	2137	213.5	161.7	374.9	52.3	0.06	485.4	2.8
0.147	2207	130.6	162.1	318.3	51.5	0.08	486.0	2.1
0.100	2246	99.9	162.3	261.0	51.1	0.09	485.7	1.6
0.019	2290	68.1	162.6	188.7	50.7	0.09	485.1	1.0

Table C.68: Relative sensitivity of BioWin model outputs to changes in $f_{P/AC}$

$f_{P/AC}$ (mg P/mg COD)	*Relative sensitivity*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
0.735	0.23	-2.00	-0.25	-2.00	-0.09	-1.99	0.01	5.44
0.637	0.38	-3.33	-0.41	-3.33	-0.15	-3.32	0.02	9.06
0.539	0.12	-0.69	-0.15	-2.25	-0.06	-1.57	-0.01	3.38
0.441	0.09	-0.31	-0.16	-2.38	-0.06	-1.85	-0.01	3.57
0.343	0.05	0.24	-0.11	-2.29	-0.03	-2.53	-0.02	2.35
0.245	0.02	0.55	-0.07	-2.11	-0.01	-3.41	-0.02	1.61
0.147	-0.03	0.80	-0.06	-1.06	0.01	-3.83	-0.02	1.22
0.100	-0.05	0.83	-0.05	-0.54	0.02	-3.62	-0.01	1.12
0.019	-0.07	0.80	-0.04	-0.03	0.02	-3.03	-0.01	0.97

Table C.69: BioWin model outputs for varying values of Y_{PHB}

Y_{PHB} (mg COD/mg COD)	*Concentration (mg/L)*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
1.0000	2150	313.5	157.3	253.1	52.1	0.03	480.0	11.6
0.9779	2151	310.3	157.1	238.4	52.0	0.03	480.1	12.0
0.8890	2154	295.0	156.0	182.6	52.0	0.02	480.7	14.2
0.8001	2160	274.1	154.5	132.7	51.9	0.02	481.4	17.2
0.6223	2397	0.0	136.6	0.0	49.6	0.00	483.2	52.9
0.4445	2397	0.0	136.6	0.0	49.5	0.00	480.5	52.9

Table C.70: Relative sensitivity of BioWin model output to changes in Y_{PHB}

Y_{PHB} (mg COD/mg COD)	*Relative sensitivity*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
1.000	-0.01	0.50	0.07	3.09	0.01	2.43	-0.01	-1.49
0.978	-0.01	0.52	0.07	3.06	0.01	2.41	-0.01	-1.53
0.800	-0.03	0.71	0.09	2.74	0.02	2.17	-0.02	-2.06
0.622	-0.38	3.33	0.41	3.33	0.15	3.32	-0.02	-9.06
0.445	-0.23	2.00	0.25	2.00	0.10	1.99	0.00	-5.44

Table C.71: BioWin model outputs for varying values of $Y_{PP\text{-}LO}$

$Y_{PP\text{-}LO}$	*Concentration (mg/L)*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
1.000	2122	338.5	158.1	203.9	52.4	0.02	480.1	10.0
0.940	2154	295.0	156.0	182.6	52.0	0.02	480.7	14.2
0.846	2245	192.4	156.3	98.7	51.0	0.02	481.2	13.6
0.658	2397	0.0	136.6	0.0	49.6	0.00	483.2	52.9
0.470	2397	0.0	136.6	0.0	49.5	0.00	480.5	52.9

Table C.72: Relative sensitivity of BioWin model outputs to changes in $Y_{PP\text{-}LO}$

$Y_{PP\text{-}LO}$	*Relative sensitivity*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
1.000	-0.24	2.31	0.21	1.83	0.14	-0.96	-0.02	-4.67
0.846	-0.42	3.48	-0.02	4.60	0.19	1.45	-0.01	0.43
0.658	-0.38	3.33	0.41	3.33	0.15	3.32	-0.02	-9.06
0.470	-0.23	2.00	0.25	2.00	0.10	1.99	0.00	-5.44

Table C.73: BioWin model outputs for varying values of $f_{P/PHB,AER}$

$f_{P/PHB,AER}$ (mg P/mg COD)	*Concentration (mg/L)*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
1.425	2144	230.2	159.9	326.9	52.2	0.05	484.3	6.4
1.235	2144	257.4	158.9	279.1	52.2	0.04	483.0	8.4
1.045	2149	283.7	157.2	217.1	52.1	0.03	481.4	11.8
0.950	2154	295.0	156.0	182.6	52.0	0.02	480.7	14.2
0.855	2162	302.3	154.4	147.1	51.9	0.02	480.0	17.4
0.665	2397	0.0	136.6	0.0	49.7	0.00	483.2	52.9
0.475	2397	0.0	136.6	0.0	49.5	0.00	480.9	52.9

Table C.74: Relative sensitivity of BioWin model outputs to changes in $f_{P/PHB,AER}$

$f_{P/PHB,AER}$ (mg P/mg COD)	*Relative sensitivity*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
1.425	-0.01	-0.44	0.05	1.58	0.01	2.44	0.02	-1.09
1.235	-0.02	-0.42	0.06	1.76	0.01	2.37	0.02	-1.37
1.045	-0.02	-0.38	0.08	1.89	0.02	2.24	0.02	-1.73
0.855	-0.03	-0.25	0.10	1.95	0.02	2.03	0.01	-2.25
0.665	-0.38	3.33	0.41	3.33	0.15	3.32	-0.02	-9.06
0.475	-0.23	2.00	0.25	2.00	0.10	1.99	0.00	-5.44

Table C.75: BioWin model outputs for varying values of Y_{ZBP}

Y_{ZBP} (mg COD/mg COD)	*Concentration (mg/L)*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
0.914	2171	390.9	153.7	191.3	51.8	0.02	475.3	18.7
0.831	2164	356.4	154.5	189.2	51.8	0.02	477.3	17.1
0.703	2157	316.6	155.5	185.3	51.9	0.02	479.5	15.3
0.639	2154	295.0	156.0	182.6	52.0	0.02	480.7	14.2
0.575	2151	272.0	156.5	179.2	52.0	0.02	481.9	13.2
0.447	2150	218.3	157.6	166.8	52.1	0.03	484.5	11.0
0.320	2207	125.5	158.7	100.8	51.4	0.03	486.1	8.8

Table C.76: Relative sensitivity of BioWin model outputs to changes in Y_{PHB}

Y_{ZBP} (mg COD/mg COD)	*Relative sensitivity*							
	Mixed Liquor				*Decant*			
	Z_{bh}	Z_{bp}	Total P	S_{PHB}	S_{bsc}	S_{bsa}	NH_3	PO_4
0.914	0.02	0.76	-0.03	0.11	-0.01	-0.38	-0.03	0.74
0.831	0.01	0.69	-0.03	0.12	-0.01	-0.37	-0.02	0.67
0.703	0.01	0.73	-0.03	0.15	-0.01	-0.44	-0.02	0.72
0.575	0.01	0.78	-0.03	0.18	-0.01	-0.53	-0.03	0.76
0.447	0.01	0.87	-0.03	0.29	-0.01	-0.65	-0.03	0.76
0.320	-0.05	1.15	-0.03	0.90	0.02	-0.42	-0.02	0.76

Appendix D: Design Calculations

- **Dry matter and water content of combined manure wastewater components**

Mass of dry matter from manure (as excreted):

$$43{,}816kg \times 0.127 = 5{,}565kg$$

Percent dry matter of combined wastewater:

$$\frac{6{,}991kg}{126{,}940kg} \times 100 = 5.51\%$$

Table D.1: Mass fractions used to calculate percent water content and dry matter content after manure collection

Wastewater Component	*Total Mass*	*Mass Fractions*			
		Water Content		*Dry Matter*	
	(kg/d)	*(%)*	*(kg/d)*	*(%)*	*(kg/d)*
Manure*	43,816	87.3	38,251	12.7	5,565
Flush water†	81,539	100	81,539	0	0
Sawdust bedding‡	1,585	10	159	90	1,427
Total	126,940	94.49	119,949	5.51	6,991

*Based on 805 dairy cows, each weighing 635 kg.
†Assuming 1.844 L/d fresh water for every 1 L as excreted manure.
‡Assuming bedding requirement of 1.969 kg d^{-1} cow^{-1}, sawdust density of 192 kg/m^3, and volume reduction of 50 percent during use (MWPS, 1998).

- **Volume of liquid and solid fractions of manure after solid separation**

The dry matter in the solid separator influent manure is equal to the dry matter in the liquid effluent and separated solids:

$$I_M I_{DM\%} = S_M S_{DM\%} + L_M L_{DM\%} \quad [D.1]$$

where I = Influent Manure,
L = Liquid fraction of manure after solid separation,
S = Solid fraction of manure after solid separation,
M = subscript for mass, and
DM% = subscript for percent dry matter content.

The total mass of manure influent to the solid separator is equal to the total mass of separated solids and liquid manure fractions:

$$I_M = S_M + L_M \qquad [D.2]$$

Solving for the mass of the solid manure fraction using equations [D.1] and [D.2]:

$$S_M = \frac{I_M\left(I_{DM\%} - L_{DM\%}\right)}{S_{DM\%} - L_{DM\%}}$$

Table D.2: Mass and volume calculations based on expected dry matter and water content of solid separated manure fractions

Wastewater Component	*Dry Matter (%)*	*Water Content (%)*	*Mass (kg/d)*			*Volume*
			Total	*Dry Matter*	*Water Content*	*(m^3/d)*
Influent	5.51	94.5	126,940.4	6,991	119,949	129.9
Effluent Liquid	2.50	97.5	111,969	2,799	109,170	112.0
Effluent Solids	23.0	77.0	14,971	3,443	11,528	17.9

$$S_M = \frac{126{,}940.4kg\left(5.51 - 2.5\right)}{23 + 2.5} = 14{,}984kg$$

Mass of the liquid fraction:

$$L_M = I_M - S_M$$

$$L_M = 126{,}940kg - 14{,}984kg = 111{,}956kg$$

Assuming the density of the liquid fraction is similar to that of water (approximately 1000 kg/m^3) (NRAES, 1998), the volume of the liquid fraction was determined:

$$L_{volume}\frac{111{,}969kg}{1000kg/m^3} = 112m^3$$

Subtracting this from the influent volume:

$$S_{volume} = 129.9m^3 - 112m^3 = 17.9m^3$$

Based on this volume the density of the solid manure fraction was estimated:

$$\rho_{SolidFraction} = \frac{14{,}971 kg}{17.9 m^3} = 836 kg/m^3$$

- **Aeration schedules for sequencing batch reactor simulations**

Table D.3: Aeration schedule for SBR simulation. Four aeration cycles and continuous feed

Time (hr)	*DO Setpoint (mg/L)*	*Duration Time (hr)*	
		On	*Off*
0	0		2
2	2	4	
6	0		2
8	2	4	
12	0		2
14	2	4	
18	0		2
20	2	3.23	
23.23	0		0.77
Total		15.23	8.77

Table D.4: Aeration schedule for SBR optimization. Eight aeration cycles and continuous feed

Time (hr)	*DO Setpoint (mg/L)*	*Duration Time (hr)*	
		On	*Off*
0	0		1
1	2	2	
3	0		1
4	2	2	
6	0		1
7	2	2	
9	0		1
10	2	2	
12	0		1
13	2	2	
15	0		1
16	2	2	
18	0		1
19	2	2	
21	0		1
22	2	1.23	
23.23	0		0.77
Total		15.23	8.77

Table D.5: Aeration schedule for SBR optimization. Two aeration cycles and continuous feeding

Time (hr)	*DO Setpoint (mg/L)*	*Duration Time (hr)*	
		On	*Off*
0	0		4
4	2	8	
12	0		4
16	2	7.23	
23.23	0		0.77
Total		15.23	8.77

Table D.6: Aeration schedule for four aeration periods with the first starting at hour 1

Time (hr)	*DO Setpoint (mg/L)*	*Duration Time (hr)*	
		On	*Off*
0	0		1
1	2	4	
5	0		2
7	2	4	
11	0		2
13	2	4	
17	0		2
19	2	3.23	
22.23	0		1.77
Total		15.23	8.77

Table D.7: Aeration schedule for two aeration periods with the first starting at hour 1

Time (hr)	*DO Setpoint (mg/L)*	*Duration Time (hr)*	
		On	*Off*
0	0		1
1	2	8	
9	0		4
13	2	7.23	
20.23	0		3.77
Total		15.23	8.77

Appendix E: Economic Analysis Calculations

Estimating interest rate (i) for present worth calculations

Table E.1: Projected GDP inflation for the United States (FAPRI, 2002).

Year	*Inflation (%)*
2001	2.2
2002	1.7
2003	2.3
2004	2.4
2005	2.4
2006	2.5
2007	2.5
2008	2.4
2009	2.3
2010	2.2
2011	2.0
2012	2.0
Average	**2.2**

$$i_{real} = \frac{i_{nominal} - i_{inflation}}{i_{inflation} + 1} \qquad [E.1]$$

where i_{real} = Discount rate (decimal),
$i_{nominal}$ = Loan interest rate (decimal), and
$i_{inflation}$ = Inflation rate (decimal).

Table E.2: Inflation and nominal interest rate used to calculate real interest rate

Rate	*Value (decimal)*	*Source*
Inflation rate	0.022	FAPRI, 2002
Nominal rate*	0.080	Claybaugh, 2002
Real rate	0.057	Equation E.1

*Interest rate for a 7 to 10 year agricultural business loan.

Determining present worth factors

The present worth of annual payments over n years (Sullivan et al., 2000):

$$(P/A,i,n) = \frac{(1+i_{real})^n - 1}{i_{real}(1+i_{real})^n} \quad \text{[E.2]}$$

The present worth of a future payment at interest rate r in year n (Sullivan et al., 2000):

$$(P/F,i,n) = \frac{1}{(1+i_{real})^n} \quad \text{[E.3]}$$

Table E.3: Present worth factors using discrete compounding

Formula (i = 0.057)	*Present Worth Factor n (years)*			
	20	*7*	*13*	*14*
P/A, i, n*	11.75	n/a	n/a	n/a
P/F, i, n†	0.3300	0.6784	0.4864	0.4602

*Present worth of annual payments at interest rate i for n years.

†Present worth of future payment at interest rate i in year n.

Vita

Kristina Anne Yanosek was born on January 8th, 1978 in Alexandria Virginia. She attended Thomas Jefferson High School for Science and Technology and graduated in June 1996. She then pursued a Bachelor of Science degree in Biological Systems Engineering at Virginia Tech. After completing her degree in May 2000, she continued her studies at Virginia Tech to obtain a Master of Science degree in Biological Systems Engineering.