The effect of ferric-based chemical phosphorus removal dosing location on downstream liquid and solid stream processes

By

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Abstract

The research investigates the impact of ferric-based chemical phosphorus removal dosing locations on the processes of downstream liquid and solid streams in wastewater treatment. It examines how different dosing points affect sludge production, secondary treatment performance, ultraviolet (UV) disinfection efficiency, digestibility and dewaterability of chemical sludge. Through benchscale testing of various dosing scenarios, the study aims to determine the optimal dosing location that meets phosphorus removal goals while minimizing adverse effects on treatment downstream processes. It was found that sludge production increased by 20 percent and 11 percent for chemically enhanced primary treatment and chemical phosphorus removal in secondary treatment, respectively, to achieve an estimated final effluent total phosphorus of 2.5 mg L^{-1}. It was also found that increasing ferric chloride dosing prior to digestion, CEPT, or chemical phosphorus removal in secondary treatment does not significantly affect downstream processes. This research is crucial for wastewater treatment facilities looking to meet regulatory phosphorus limits efficiently without compromising the performance of the existing treatment process.

Acknowledgements

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Nomenclature

Al	aluminum
BMP	bio-methanation potential
CEPT	chemically enhanced primary treatment
CH_4	methane
CO_2	carbon dioxide
CST	capillary suction time
DO	dissolved oxygen
EBPR	enhanced biological phosphorus removal
EPS	extracellular polymeric substances
Fe	iron
g	gram
H_2	hydrogen
H_2S	hydrogen sulfide
HPAC	high performance polyaluminum chloride
HPO	high purity oxygen
L	litre

mg	milligram
N_2	nitrogen
NEWPCC or NE	North End Water Pollution Control Centre
OP or Ortho-P	soluble ortho phosphorus
OUR	oxygen uptake rate
PACl	polyaluminum chloride
PAO	phosphorus accumulating organisms
rpm	rotations per minute
SEWPCC or SE	South End Water Pollution Control Centre
SOUR	specific oxygen uptake rate
SRF	specific resistance to filtration
TN	total nitrogen
TS	total solids
TP	total phosphorus
UV	ultraviolet
UVT	ultraviolet transmittance
VS	volatile solids

WAS	waste activated sludge
WEWPCC or WE	West End Water Pollution Control Centre

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1. Introduction

1.1. Background

The City of Winnipeg (City) is required to meet the Province of Manitoba's effluent limits of 1 mgL^{-1} total phosphorus (TP) and 15 mg L^{-1} total nitrogen (TN) using biological treatment methods at their North End Water Pollution Control Centre (NEWPCC). An upgrade of the existing plant is required to meet this new regulation, but requires years of planning, financing, construction, and commissioning to complete such a large upgrade to the plant. A temporary solution of chemical phosphorus removal is being considered to allow the City to meet the TP effluent limit sooner but must consider the affect on other plant processes.

The current liquid stream treatment at NEWPCC consists of raw sewage pumping, screening, grit removal, primary clarification, secondary treatment using high purity oxygen (HPO) reactors, secondary clarification and ultraviolet (UV) disinfection. Sludge generated in the primary and secondary clarifiers is co-thickened in the primary clarifier prior to anaerobic digestion. Sludge generated at the South End Water Pollution Control Centre (SEWPCC) and West End Water Pollution Control Centre (WEWPCC) is hauled to NEWPCC to be digested along with the NEWPCC sludge. Ferric chloride is added prior to and following digestion to reduce hydrogen sulfide levels, reduce struvite formation, and phosphorus removal. Digested sludge is dewatered using centrifuges prior to disposal. Centrate from the dewatering process is treated with sequencing batch reactors for ammonium removal prior to returning to the main liquid stream treatment. A current simplified process flow diagram of NEWPCC is illustrated in ***Figure 1.1***.

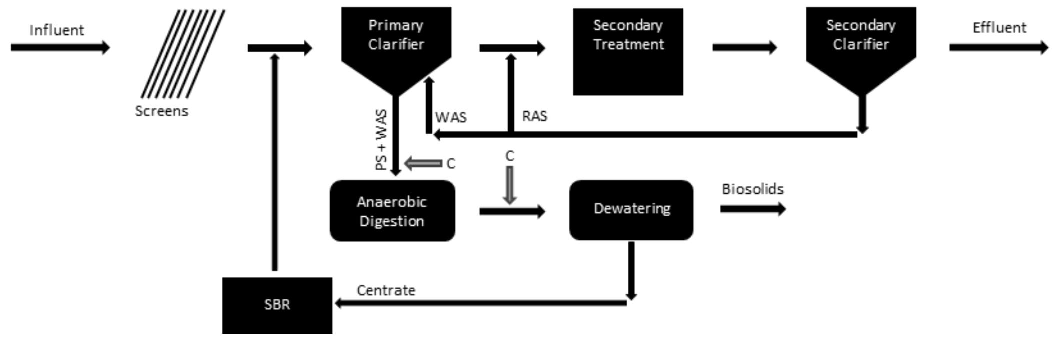

Figure 1.1: NEWPCC Current Process Flow Diagram

SEWPCC is currently undergoing upgrades to meet the licence requirements. The upgrade includes biological nutrient removal, which will increase the phosphorus load in SEWPCC sludge received at NEWPCC. To maintain or decrease phosphorus loads in the final effluent at NEWPCC, without having to complete any major modifications to the current treatment processes, chemical phosphorus removal is being considered. Benchscale testing will help determine the dose required to maximize TP removal in the final effluent without overloading or upsetting downstream liquid and solids stream processes due to chemical phosphorus removal. The three dosing locations being considered for benchscale testing is increasing the current side stream dose prior to digestion, prior to primary clarification for chemically enhanced primary treatment, and prior to secondary treatment for chemical phosphorus removal in the HPO reactors. The current ferric chloride dosing locations outlined in ***Figure 1.1*** will remain in all three scenarios. Benchscale testing will be completed using ferric chloride as NEWPCC already has a receiving and storage facility.

The main disadvantage of chemical phosphorus removal is the increase in sludge produced. NEWPCC's anaerobic digester as nearing capacity, therefore the amount of sludge produced during chemical phosphorus is critical to determine if the anaerobic digesters solids loading rate or solids retention time maintain within the design parameters. NEWPCC has a total of six (6) anaerobic digesters with a total available digestion volume of 38,370 m^3 and an estimated maximum allowable volatile solids (VS) load of 122,784 kg VS d^{-1}. Assuming a VSS/TSS ratio of 0.71 the allowable average and maximum total solids (TS) loading rates are 121,596 kg TSd^{-1} and 172,935 kg TS d^{-1}, respectively (AECOM 2020). The NEWPCC digesters were designed with a minimum solids retention time of 15 days at 35 degrees Celsius, therefore a maximum sludge volume of 2,558 m^3 d^1 can be sent to the digesters.

1.2. Problem Statement and Research Objectives

1. Determining the effect on sludge production with different ferric chloride dosing points to reduce total phosphorus in final effluent;
2. Determining the effect of ferric chloride dosing on secondary treatment by assessing the specific oxygen uptake rate (SOUR);
3. Determining the effect of ferric chloride dosing on ultraviolet (UV) disinfection by assessing the UV transmittance (UVT) of secondary effluent;
4. Determining the effect of chemical sludge on digestibility, including volatile suspended solids destruction and biogas production and composition; and
5. Determining the effect on chemical sludge of dewaterability.

2. Literature Review

2.1. Introduction

Phosphorus is an essential element for living organisms and is a key ingredient in fertilizers for plant growth (Xu, et al. 2015). However, excess phosphorus and nitrogen in lakes, estuaries, and slow-moving streams can lead to eutrophication. A common sign of eutrophication is harmful algal blooms that cause high turbidity, decrease in dissolved oxygen, and increase in hypoxia conditions, all of which limit aquatic life and cause poor water quality (Goel and Motlagh 2014). Sources of phosphorus in surface waters include wastewater effluent, industrial discharge, agricultural runoff and natural runoff (Metcalf & Eddy; AECOM 2014).

Phosphorus levels in wastewater treatment plant influent typical range from 4 mg L^{-1} to 11 mg L^{-1} for municipal wastewater (Metcalf & Eddy; AECOM 2014). Depending on local regulations and receiving waters, wastewater plants are typically required to remove phosphorus prior to discharging.

2.2. Phosphorus Speciation and Analysis

Phosphorus species are classified based on solubility and reactivity, as shown in **Figure *2.1***. Phosphorus can either be soluble or particulate, both of which are further classified by being reactive or non reactive. Reactive phosphorus is mainly orthophosphate. Standard Methods for the Examination of Water and Wastewater outlines the methods for analysis of phosphorus fractions, as outlined in ***Figure 2.2***.

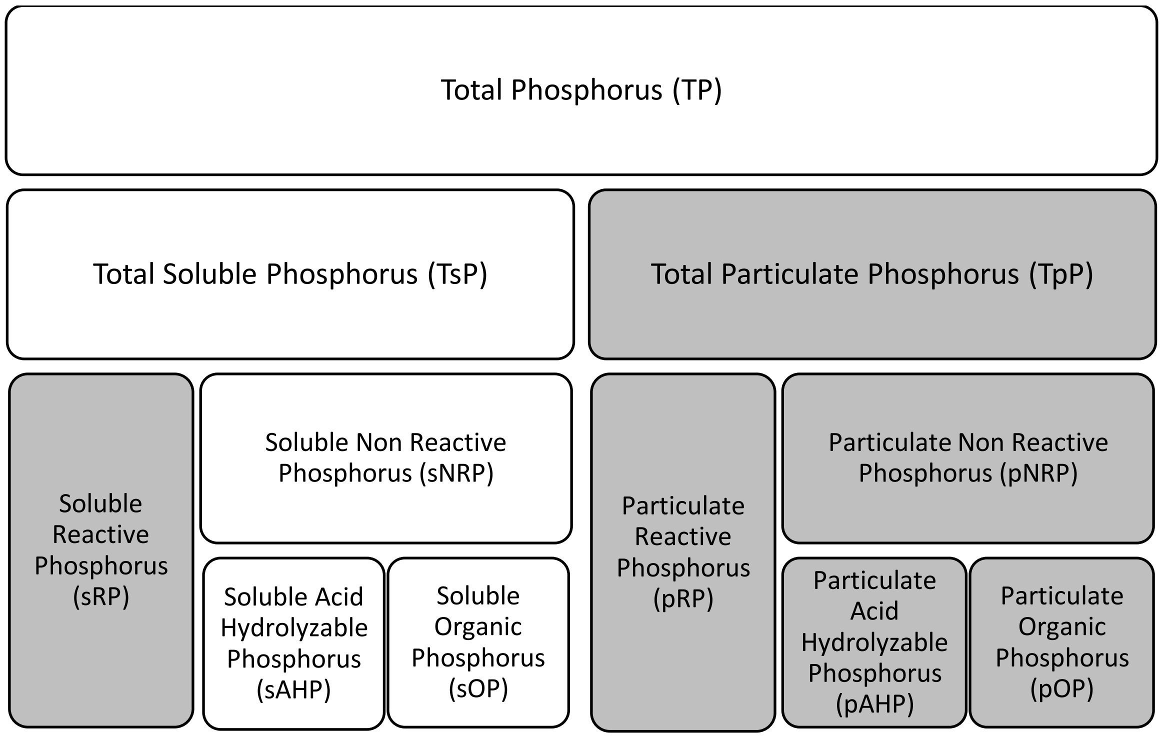

Figure 2.1: Phosphorus Speciation *(Shewa and Dagnew 2020)*

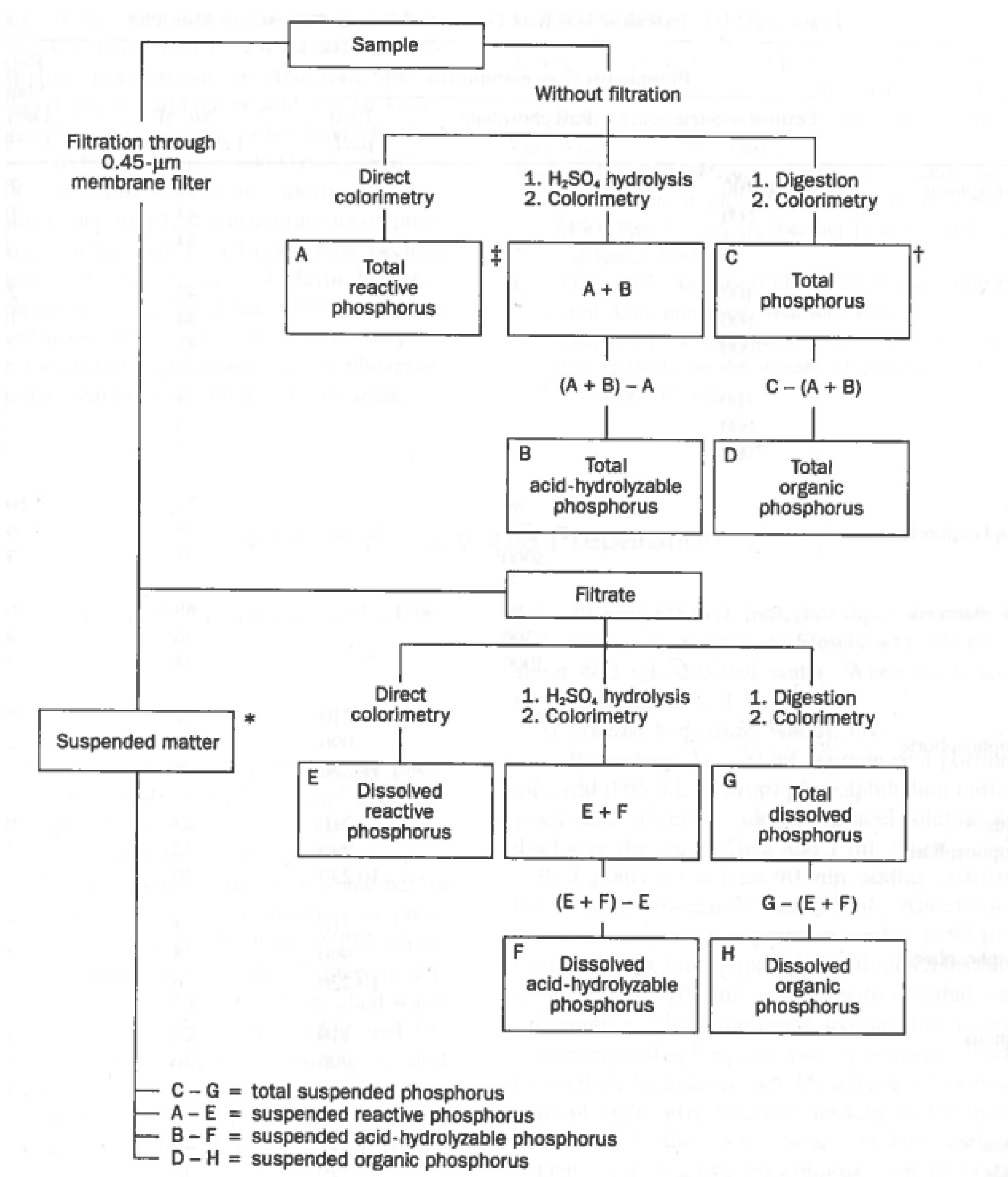

Figure 2.2: Steps for analysis of phosphorus fractions *(APHA, AWWA, WEF 2012)*

2.3. Phosphorus Removal in Wastewater

Phosphorus can be removed from wastewater physically, biologically, chemically, or a combination of the three. Physical phosphorus removal is achieved by sorption or ion exchange. Biological phosphorus removal is typically achieved through enhanced biological phosphorus removal (EBPR) secondary treatment systems, where polyphosphate accumulating organisms (PAOs) are promoted to grow within activated sludge systems. POAs consume phosphorus for cellular growth and maintenance, and also accumulate ortho phosphate in the form of polyphosphate within their cells (Goel and Motlagh 2014). Phosphorus removal efficiency in EBPR systems is affected by temperature, pH, salt, organic loading rate, type of wastewater substrate and aeration control (Yulin Zheng 2023).

Chemical phosphorus removal is achieved by chemical precipitation of phosphorus, particularly soluble reactive phosphorus, mainly ortho phosphate, by the addition of metal salts. This is a reliable and well established method of phosphorus removal. The reaction to precipitate ortho phosphates using ferric chloride is as follows (Kozak, et al. 2010):

$$Fe^{3+} + H_nPO_3^{3-n} \leftrightarrow FePO_4(s) + nH^+$$

The precipitated phosphorus is then removed from the wastewater in sludge by solid liquid separation, mainly clarification or filtration. According to stoichiometry, one mole of iron is needed is needed to precipitate one mole of phosphate, however the reality is there are completing reaction occurring in wastewater and therefore excess ferric chloride is added to ensure complete precipitation of phosphorus occurs (Kozak, et al. 2010). pH, alkalinity, trace elements, mixing, and type of phosphorus present can affect the actual dose required to complete phosphorus precipitation in wastewater (Metcalf & Eddy; AECOM 2014).

2.4. Chemicals for Phosphorus Removal

The two most common metal salts used for chemical phosphorus removal are aluminum (Al) and iron (Fe) based chemicals. Calcium salts, organic polymers, and poly-metal salts can also be used for chemical phosphorus removal but are less commonly used (Yulin Zheng 2023). A number of factors affect the chemical selection including influent phosphorus, suspended solids and alkalinity levels, chemical cost and supply reliability, sludge handling facilities, disposal methods or end use, compatibility with other treatment processes, safety considerations, and pH requirements (Clark and Stephenson 1998).

2.5. Chemical Phosphorus Removal Dosing Locations

There are a number of locations chemicals can be added throughout a wastewater treatment plant for phosphorus removal. Depending on the dosing location, the amount of chemical required to precipitate phosphorus and the effect on downstream processes will differ. Common dosing locations for phosphorus removal include prior to primary clarification, prior to secondary treatment, prior to tertiary treatment, prior to digestion, prior to sludge dewatering, or during side stream treatment, as depicted in **Figure *2.3***. Depending on the dosing location, chemicals added for phosphorus removal can also have the added benefit of odour control.

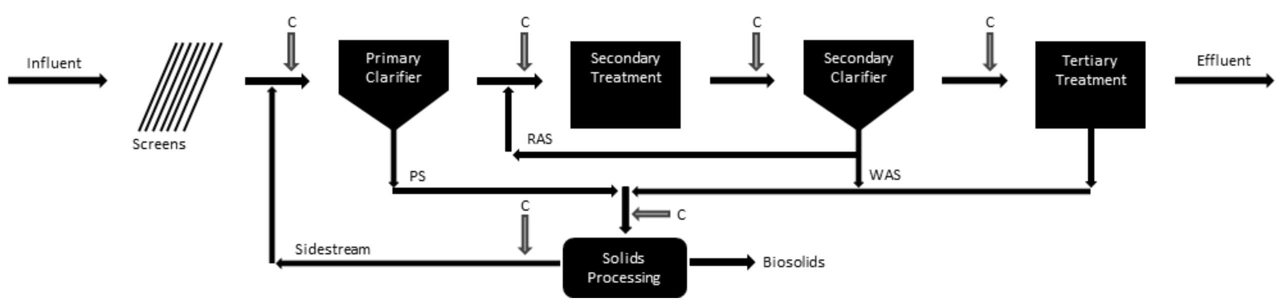

Figure 2.3: Typical chemical dosing locations for chemical phosphorus removal

2.6. Chemical Addition Effects on Primary Sludge

Wastewater treatment plants using primary clarification produce primary sludge due to solid liquid separation in the clarifiers. If chemically enhanced primary treatment (CEPT) is implemented, a coagulant, such as ferric chloride, is added upstream of the primary clarifiers to increase removal of pollutant such as organic carbon and nutrients (Shewa, et al. 2020). Due to the increase in solid separation, wastewater plants using CEPT produce more primary sludge than conventional primary treatment. CEPT sludge also has different characteristics to primary sludge without chemical addition due to the increase in metal salt and organic solids found in CEPT sludge (Ju, et al. 2016).

The following equation can be used estimate the amount of sludge produced for CEPT (Shewa and Dagnew 2020):

$$SP = SSin - SSout + Kprec * D$$

Where:

SP = sludge production (g SS/m^3)
SS_{in} = suspended solids concentration in influent (g SS/m^3)
SS_{out} = suspended solids concentration in effluent (g SS/m^3)
K_{prec} = sludge production coefficient (g SS/g Metal), typically 4-5 for Fe and 6-7 for AL
D = Dosage of coagulant (g $Metal/m^3$)

2.7. Chemical Addition Effects on Activated Sludge

Many wastewater treatment plants use an activated sludge process for secondary treatment to remove organic matter and nutrients (Metcalf & Eddy; AECOM 2014). When a suspended growth process is used, well formed activated sludge flocs are important to allow for efficient solid-liquid separation in secondary clarification, resulting in high quality effluent (Asensi, et al. 2019). Sludge is produced in activated sludge processes due to growth of the microorganisms and the accumulation of refractory organic compounds and minerals (Paul, Laval and Sperandio 2001).

Ferric chloride addition prior to primary clarification or prior to digestion have little to no effect on secondary treatment activated sludge, whereas ferric chloride addition during secondary treatment can have multiple benefits, including improved removal efficiencies, increased reaction rates, and removal of trace metals, but can also impede the nitrification and denitrification process and reduce suspended solids removal (Clark and Stephenson 1998). Ferric chloride addition to secondary treatment also increased the amount of waste activated sludge produced and the characteristics of the sludge.

2.8. Chemical Addition Effects on Ultraviolet Disinfection

Prior to discharge, effluent requires disinfection to partially destroy or inactivate disease causing organisms by chemical addition, commonly chlorine, or a physical process, such as ultraviolet (UV) radiation. UV disinfection is defined as a disinfection process in which UV light with a wavelength between 100 and 400 nanometres is used to inactivate microorganisms (Metcalf & Eddy; AECOM 2014). Inactivation of the microorganisms is achieved by the UV light penetrating the microorganisms cell and damaging the genetic information required for reproduction. (Metcalf & Eddy; AECOM 2014). UV disinfection effectiveness depends on the characteristics of the wastewater being disinfected, including turbidity, and the physical characteristics of the UV disinfection system, including UV power and contact time (Metcalf & Eddy; AECOM 2014). UV transmittance (UVT) is commonly used to determine the ability for wastewater to transmit light through it. The higher the UVT percentage, the better UV disinfection should work. Secondary effluent typically has a UVT ranging from 45 to 70 percent (Metcalf & Eddy; AECOM 2014).

Chemical addition in upstream processes for chemical phosphorus removal can affect the amount of particles present in wastewater effluent and change the effectiveness of the UV disinfection. Ferric chloride addition to primary of secondary treatment can reduce the amount of phosphorus particles and other contaminants, but if overdosed will increase the amount of iron in the effluent being disinfected. Dissolved iron molecules are a strong absorber of UV light, therefore reducing the amount of UV light reaching target microorganisms. Iron also can precipitate on the UV system submerged quartz tube, forming a film and reducing the strength of the UV light (Metcalf & Eddy; AECOM 2014).

A study looking at the effect of ferric chloride addition on water quality found no difference to UVT between wastewater dosed with ferric chloride versus wastewater with no ferric chloride addition, despite having higher total solids when ferric chloride was added. In both cases, UVT was found to be around 75 percent for secondary effluent (Kozak, et al. 2010).

2.9. Chemical Addition Effects on Digestibility

Sludge wasted from the primary and secondary treatment systems is typically anaerobically or aerobically digested to create stabilized biosolids prior to disposal. Aerobic digestion is operated with the presence of oxygen and sludge is oxidized to carbon dioxide and other end products. Anaerobic digestion is more commonly used in wastewater treatment plants and is operated in the absence of oxygen and sludge is converted to methane, carbon dioxide, and other end products (Metcalf & Eddy; AECOM 2014).

The main parameter to determine optimal operation of digestion is reduction of volatile solids from the digester influent to the digester effluent. Anaerobic digesters are typically designed for a minimum volatile solids reduction of 38 percent but can be higher depending on regulatory requirements or intended end use.

A study done by Johnson et al. (2003) found that non-iron dosed sludge had a 44 percent reduction in volatile solids, whereas iron-dosed sludge had a 37 percent reduction in volatile solids, which shows a significant reduction to iron-dosed sludge digestibility (Johnson, Carliell-Marquet and Forster 2003). Ofverstorm et al. (2010) also found a drop of six to 15 percent for volatile solids reduction for ferric chloride dosed sludge versus non-ferric chloride dosed sludge, with the drop increasing with higher ferric chloride doses.

On the contrary, a study by Feng et al. (2016) found that volatile solids reduction increased from 66 percent to 70 percent when bioelectrochemical anaerobic digester feed sludge was dosed with ferric chloride (Feng, Song and Jang 2016). Cheng et al. (2021) also found an increase in volatile solids reduction as the ferric chloride dose to WAS containing aluminum increased to a certain point. The volatile solids reduction increased from six to 29 percent with an increase in ferric chloride dose from 0 to 160 mg L^{-1}. For ferric chloride doses higher than 160 mg L^{-1}, volatile solids reduction dropped to around ten percent (Cheng, et al. 2021). Another study found a minimal difference in volatile solids reduction between ferric chloride dosed sludge and sludge without chemical addition (Zhang, et al. 2013).

2.10. Chemical Addition Effects on Biogas Production

The methane, carbon dioxide, and other gaseous end products produced in anaerobic digestion are commonly referred to as biogas. Biogas typically contains about 65 to 70 percent methane (CH_4) by volume, 25 to 30 percent carbon dioxide (CO_2) by volume, and small amounts of nitrogen (N_2), hydrogen (H_2), and hydrogen sulfide (H_2S), water vapour, and other gases (Metcalf & Eddy; AECOM 2014). Biogas is an energy source and can be used to fuel boilers for heating the digesters or other processes and facilities, or be used in cogeneration or used as renewable natural gas.

Due to the energy content of biogas, many have researched the affects of various conditions to increase biogas production during anaerobic digestion. A study tested co-digestion of microalgae with waste activated sludge (WAS), which found to produce 25 percent more methane than WAS alone (Costa, et al. 2012). Another study was conducted on the addition of metallic wastes (fly ash and copper mining waste) to the anaerobic digestion of sludge, both which increased methane produce by more than 100 percent (Montalvo, et al. 2018). This study also looked at anaerobic digestion pretreatment of aerobic hydrolysis combined with the addition of metallic wastes to the anaerobic digestion, which was found to increase methane production by 162 to 200 percent (Montalvo, et al. 2018).

The affects of chemically treated sludge on anaerobic digestion with regards to the amount of biogas produced and methane content of the biogas has also been researched, with varying results under different conditions. Kindzierski and Hrudey (1985) found that both alum and ferric addition to activated sludge for phosphorus removal resulted in reduced methane production in batch anaerobic digestion (Kindzierski and Hrudey 1985). Similarly, Johnson et al. (2003) found that iron-dosed sludge produced less biogas than non-iron-dosed sludge, but iron-dosed sludge had higher methane content in the biogas produced, resulting in an insignificant difference between iron-dosed and non-iron dosed sludge methane production. The study also found a linear relationship between the gas production and concentration of bound iron in the sludge (Johnson, Carliell-Marquet and Forster 2003). Ojo and Ifelebuegu (2019) also found a 35.7 percent decrease in biogas production in WAS dosed with ferric chloride but did not measure the methane content of the biogas produced (Ojo and Ifelebuegu 2019).

Conversely, a study by Yu et al. found that the addition of ferric chloride to anaerobic digesters treating WAS produced 99% more methane than those without ferric chloride. The study attributed the increase in methane production to the enrichment of *Actinobactricia* for hydrolysis acidification by 16 percent and *Methanosarcina* for methanogenesis by 63 percent with the addition of ferric chloride (Yu, et al. 2015). Zhan et al. (2020) also found that biogas and methane production increase with the addition of ferric chloride. The study also found that methane production peaked with a ferric chloride dose of 234 mg Fe(III) L^{-1}, but higher doses of ferric chloride than that reduced the affect of ferric chloride addition on methane production (Zhan, et al. 2020). Another study confirmed that low doses of ferric chloride to WAS containing aluminum increased methane production by over 30 percent compared to the control with no ferric chloride addition, but high ferric chloride doses resulted in lower methane production than the control (Cheng, et al. 2021).

2.11. Chemical Addition Effects on Dewaterability

Following digestion, sludge is typically dewatered to reduce the water content, resulting in reducing sludge handling and final disposal costs. The dewatering process can be described in two steps, filtration and consolidation, but is difficult to distinguish the two for biological sludge so the term dewaterability is used to describe the rate of both steps (Christensen, et al. 2015). A number of sludge characteristics can affect sludge dewaterability, including conductivity, water hardness, pH, storage, pumping, and treatment processes (Christensen, et al. 2015). Dewaterability is generally measured by specific resistance to filtration (SRF) and capillary suction time (CST). SRF is a complex and labour-intensive test that predicts the solids concentration in dewatered sludge, whereas CST is relatively simple method to predict an increase or decrease in dewaterability but cannot predict final solids concentration (Ghodsi, et al. 2021).

Niu et al. (2013) found a significant increase in dewaterability when sludge was dosed with ferric chloride, polyaluminum chloride (PACl) or high performance PACl (HPAC) prior to SRF testing. These results were attributed to stronger and denser flocs formed with chemical addition. The study found the optimum ferric chloride dose to be 5-10 percent (g ferric chloride per g of dry solids), which decreased the SRF from 1.72×10^{10} m kg^{-1} for raw sludge to 18×10^{10} to 6.82×10^{10} m kg^{-1} (Niu, et al. 2013).

Another study found that the addition of ferric and aluminum salts resulted in improved dewaterability for primary sludge but decreased dewaterability for WAS. It found a 16 and 25 percent increase in dewaterability for primary sludge dosed with 50 mg L^{-1} Al(III) and Fe(III), respectively, and a 73 and 64 percent decrease in dewaterability for WAS dosed with 50 mg L^{-1} Al(III) and Fe(III), respectively. The increase in dewaterability for primary sludge dosed with metal salts were attributed to surface charge chemistry and the disturbance of bonds between water and extracellular polymeric substances (EPS) structures. The decrease in dewaterability for WAS dosed with metal salts was attributed to an increase in water retention capacity and quantity of bound water in the EPS structure (Ojo and Ifelebuegu 2019).

3. Materials and Methods

The three dosing scenarios were each tested in two separate phases; Phase 1: Annual Average Conditions and Phase 2: Maximum Month Conditions. Phase 1 commenced in September 2020 and was completed in November 2020. Phase 2 commenced in March 2021 and was completed in April 2021.

3.1. Phase 1: Annual Average Conditions

3.1.1. Characteristics of Wastewater and Seed Sludge

Wastewater and sludge collected from the NEWPCC and the WEWPCC were collected and immediately transported to the University of Manitoba Environmental Laboratory (refereed to as “the Lab” from here on out), where they were either used immediately for testing and analysis, or stored in 4°C cold chamber or 35°C heated chamber for less than 24 hours prior to being used in the experiment. Samples were collected, transported, and stored in 20 litres containers with minimal headspace. For Phase 1: Annual Average Conditions, wastewater and sludge samples were collected in October 2020, typically when the plant receives close to annual average conditions.

3.1.1.1. Primary Sludge

Primary sludge samples from the NEWPCC were collected from a sample port following the primary sludge transfer pumps directly into the sample container. Samples were taken while the primary sludge transfer pumps were running to ensure a fresh sample. Characteristics of the primary sludge such as pH, alkalinity, total solids, volatile solids, soluble ortho-phosphorus, and total phosphorus were measured prior to conducting the experiment, the results are presented in the associated chapters. Primary sludge samples that were not used immediately once at the Lab were stored in the 4°C cold chamber until used on the same day. Primary sludge combined with WEWPCC sludge and used as the influent for the Scenario 1: Increased Side Stream Chemical Phosphorus Removal jar tests.

3.1.1.2. WEWPCC Sludge

Sludge from the WEWPCC holding tanks prior to being hauled to the NEWPCC for treatment was collected by City of Winnipeg staff immediately prior to pickup and transportation to the Lab. Characteristics of the primary sludge such as pH, alkalinity, total solids, volatile solids, soluble ortho-phosphorus, and total phosphorus were measured prior to conducting the experiment, the results are presented in the associated chapters. WEWPCC sludge samples that were not used immediately once at the Lab were stored in the 4°C cold chamber until used on the same day. WEWPCC sludge combined with primary sludge and used as the influent for the Scenario 1: Increased Side Stream Chemical Phosphorus Removal jar tests. WEWPCC sludge was also mixed with sludge produced in Scenario 2: Chemically Enhanced Primary Treatment and Scenario 3: Chemical Phosphorus Removal in HPO Reactors jar tests and used as digester feed for the bio-methanation potential (BMP) tests. WEWPCC sludge was used to represent both WEWPCC and SEWPCC sludge once SEWPCC is also upgraded to BNR.

3.1.1.3. Primary Influent

Primary influent samples from the NEWPCC were collected from the grit effluent channel through an access hatch using a bucket and rope. Characteristics of the primary influent such as pH, alkalinity, total solids, volatile solids, soluble ortho-phosphorus, and total phosphorus were measured prior to conducting the experiment, the results are presented in the associated chapters. Primary influent samples that were not used immediately once at the Lab were stored in the 4°C cold chamber until used on the same day. Primary influent was used as the influent for the Scenario 2: Chemically Enhanced Primary Treatment jar tests.

3.1.1.4. Mixed Liquor

Mixed liquor samples from the NEWPCC were collected from each of the three trains channels. Samples were collected using a bucket and rope. Characteristics of the mixed liquor such as pH, alkalinity, total solids, volatile solids, soluble ortho-phosphorus, and total phosphorus were measured prior to conducting the experiment, the results are presented in the associated chapters. Mixed liquor samples that were not used immediately once at the Lab were stored in the 4°C cold chamber until used on the same day. Mixed liquor was used as the influent for the Scenario 3: Chemical Phosphorus Removal in HPO Reactors jar tests. Settled biomass from the mixed liquor was also used for the SOUR tests on supernatant produced in Scenario 2: Chemically Enhanced Primary Treatment jar tests.

3.1.1.5. Digested Sludge

Digested sludge samples from the NEWPCC were collected from a sample port following the anaerobic digesters directly into the sample container. Characteristics of the digested sludge such as pH, alkalinity, total solids, volatile solids, soluble ortho-phosphorus, and total phosphorus were measured prior to conducting the experiment, the results are presented in the associated chapters. Digested sludge samples that were not used immediately once at the Lab were stored in the 35°C heated chamber until used on the same day. Digested sludge was used as digester inoculum for all three scenario's BMP tests.

3.1.2. Experimental Set Up

3.1.2.1. Scenario 1: Increased Side Stream Chemical Phosphorus Removal

3.1.2.1.1. Ferric Chloride

Stock solution of ferric chloride was prepared using a sample of ferric chloride collected from the NEWPCC in February 2020. A stock solution of 10,000 mg Fe L^{-1} was used for Scenario 1.

3.1.2.1.2. Jar Test

Jar tests were conducted using Phipps & Bird PB-900 Series Programmable Jar Testers and 1,000 mL glass beakers. BioWin modelling was completed by AECOM to predict the ferric chloride dose required to maintain soluble phosphorus concentration in the centrate below 20 mg PO_4-P L^{-1} (AECOM 2020). The four ferric chloride doses tested were 0, 135, 250, and 500 mg Fe L^{-1} of sludge; the control dose, the current dose for hydrogen sulfide control, half the BioWin predicted dose, and the BioWin predicted dose, respectively. NEWPCC primary sludge and WEWPCC sludge samples were combined at a ratio of 7:3 to replicate the conditions of the plant once SEWPCC upgrades are complete. 1,000 mL of the sludge mixture was added to four beakers and placed in the jar test machine and stir paddles were lowered. The specified dosa of ferric chloride was added to the beakers and the stir paddles were set to 200 rpm for 5 minutes, followed by 15 minutes at 80 rpm. Directly following the 20 minutes of reaction time, sludge from each beaker was sampled for soluble ortho-phosphorus and total phosphorus analysis and BMP testing. A total of four sets of jar tests were completed: with no pH adjustment, a duplicate of no pH adjustment, with pH adjusted to 6, and with pH adjusted to 7. On runs with pH adjustment, the pH was adjusted during the rapid mix using 5M NaOH.

3.1.2.1.3. BMP Tests

Bio-methanation potential (BMP) tests were conducted on sludge produced in the jar tests using the Challenge Technology AER-800 Respirometer. Each reactor bottle was seeded with 464.3 mL of digested sludge and 35.7 mL of sludge from each jar test was added, for a total sludge volume of 500 mL, to replicate the annual average digester volumetric loading of 0.07 m^3/m^3*d at the NEWPCC. The bottles were placed in a water bath maintained at 36°C. Bottles were mixed using magnetic mixers set at 270 rpm. Biogas produced during the 15 day test was automatically logged every minute. Biogas was sampled for composition testing on day 2, 5, 7, 12, and 14 for the 15 day BMP test.

3.1.2.1.4. Post Digestion Ferric Chloride Dosing

If the soluble ortho-phosphorus concentration in the centrate was above the 20 mg PO_4-P L^{-1} objective, a second ferric dose after digestion would be conducted to reach the desired centrate concentration. 200 mL of each digested sludge was transferred to a glass beaker and placed on Cole-Parmer IKA 3907500 Ultra-Flat Lab Disc Magnetic Stirrer for magnetic mixing. The necessary ferric chloride dose was added to each sample and stirred for 7.5 minutes. Directly following the reaction time, the samples were analyzed again.

3.1.2.1.5. Capillary Suction Time Tests

Duplicate capillary suction time (CST) tests were completed on all samples after digestion and again after the second ferric dose to determine the affect on dewaterability.

3.1.2.2. Scenario 2: Chemically Enhanced Primary Treatment

3.1.2.2.1. Ferric Chloride

The same 1,000 mg Fe L^{-1} stock solution used in Scenario 1 was used for Scenario 2.

3.1.2.2.2. Jar Test

Jar tests were conducted using Phipps & Bird PB-900 Series Programmable Jar Testers and 1,000 mL glass beakers. The four ferric chloride doses tested were 0, 8, 14, and 18 mg Fe L^{-1} of primary influent; the control dose, and doses based on prior testing and BioWin modeling (AECOM 2020). 1,000 mL of primary influent was added to four beakers and placed in the jar test machine and stir paddles were lowered. The specified dosage of ferric chloride was added to the beakers and the stir paddles were set to 40 rpm for 7.5 minutes, followed by 30 minutes of settling. Directly following the 30 minutes of settling, sludge volume was recorded and supernatant from each beaker was sampled for further analysis. Supernatant was then removed from each beaker using a peristaltic pump. Sludge produced in the jar tests was sampled for analysis and BMP testing.

3.1.2.2.3. BMP Tests

Sludge produced in the jar tests and WEWPCC sludge samples were combined at a ratio of 7:3 to replicate the conditions of the plant once SEWPCC upgrades are complete. BMP tests were then conducted on the mixed sludge using the Challenge Technology AER-800 Respirometer. Each reactor bottle was seeded with 464.3 mL of digested sludge and 35.7 mL of the WEWPCC and jar test sludge mixture was added, for a total sludge volume of 500 mL, to replicate the annual average digester volumetric loading of 0.07 m^3/m^3*d at the NEWPCC. The bottles were placed in a water bath maintained at 36°C. Bottles were mixed using magnetic mixers set at 270 rpm. Biogas produced during the 15 day test was automatically logged every minute. Biogas was sampled for composition testing on day 2, 5, 7, 11, and 14 for the 15 day BMP test.

3.1.2.2.4. Capillary Suction Time Tests

Duplicate capillary suction time (CST) tests were completed on all samples after digestion to determine the affect on dewaterability.

3.1.2.2.5. Specific Oxygen Update Rate Tests

Specific oxygen uptake rate tests were completed on supernatant samples from all jar tests. Mixed liquor from all 3 NEWPCC trains were collected and combined in equal parts. Two litres of the mixed liquor were settled for 30 minutes and then 800 mL of the settled biomass was collected for the SOUR test. The biomass was aerated prior to the SOUR test to ensure biomass was not in a state of starvation. 20 mL of biomass was combined with 380 mL of supernatant from each jar test and further aerated until reaching a dissolved oxygen (DO) level of 8 mg L^{-1}. The biomass and supernatant mixture were then transferred to a 350 mL BOD bottle and a DO probe was inserted to record the drop in DO every 30 seconds until the DO reached 1 mg L^{-1}. DO versus time was plotted and a trendline was plotted on the linear portion. The absolute value of the trendline slope is the samples oxygen uptake rate (OUR) in mg O_2/L∗h. OUR is then divided by the volatile solids of the biomass used in the test to determine the SOUR in mg O_2/g VS∗h.

3.1.2.3. Scenario 3: Chemical Phosphorus Removal in HPO Reactors

3.1.2.3.1. Ferric Chloride

The same 1,000 mg Fe L^{-1} stock solution used in Scenario 1 and 2 was used for Scenario 3.

3.1.2.3.2. Jar Test

Jar tests were conducted using Phipps & Bird PB-900 Series Programmable Jar Testers and 1,000 mL glass beakers. The four ferric chloride doses tested were 0, 10, 15, and 20 mg Fe L^{-1} of mixed liquor; the control dose, and doses based on prior testing and BioWin modeling (AECOM 2020). 1,000 mL of mixed liquor was added to four beakers and placed in the jar test machine and stir paddles were lowered. The specified dosage of ferric chloride was added to the beakers and the stir paddles were set to 40 rpm for 7.5 minutes, followed by 30 minutes of settling. Directly following the 30 minutes of settling, sludge volume was recorded and supernatant from each beaker was sampled for further analysis. Supernatant was then removed from each beaker using a peristaltic pump. Sludge produced in the jar tests was sampled for analysis and BMP testing.

3.1.2.3.3. BMP Tests

Sludge produced in the jar tests were combined with primary sludge at a ratio of 45:55. The jar test and primary sludge mixture and WEWPCC sludge samples were then combined at a ratio of 7:3 to replicate the conditions of the plant once SEWPCC upgrades are complete. BMP tests were then conducted on the mixed sludge using the Challenge Technology AER-800 Respirometer. Each reactor bottle was seeded with 464.3 mL of digested sludge and 35.7 mL of the WEWPCCs, jar test, and primary sludge mixture was added, for a total sludge volume of 500 mL, to replicate the annual average digester volumetric loading of 0.07 $m^3/m^3 * d$ at the NEWPCC. The bottles were placed in a water bath maintained at 36°C. Bottles were mixed using magnetic mixers set at 270 rpm. Biogas produced during the 15 day test was automatically logged every minute. Biogas was sampled for composition testing on day 2, 5, 9, and 12 for the 15 day BMP test.

3.1.2.3.4. Capillary Suction Time Tests

Duplicate capillary suction time (CST) tests were completed on all samples after digestion to determine the affect on dewaterability.

3.1.3. Analytical Methods

3.1.3.1. Liquid Phase Analysis

3.1.3.1.1. pH

pH was monitored during jar test using a portable pH meter.

3.1.3.1.2. Alkalinity

Alkalinity was measured using standard methods section 2320 B (APHA, AWWA, WEF 2012).

3.1.3.1.3. Total Solids

Total solids was measured using standard methods section 2540 D (APHA, AWWA, WEF 2012).

3.1.3.1.4. Volatile Solids

Volatile solids was measured using standard methods section 2540 E (APHA, AWWA, WEF 2012).

3.1.3.1.5. Soluble ortho-phosphorus

Soluble ortho-phosphorus was measured using standard methods section 4500-P G (APHA, AWWA, WEF 2012).

3.1.3.1.6. Total Phosphorus

Total phosphorus was measured using standard methods section 4500-P H (APHA, AWWA, WEF 2012).

3.1.3.1.7. Specific oxygen uptake rate

Specific oxygen uptake rate (SOUR) was measured using standard methods section 2710 B (APHA, AWWA, WEF 2012).

3.1.3.2. Solids Phase Analysis

3.1.3.2.1. Capillary suction time

CST was measured according to standard methods sections 2710 G (APHA, AWWA, WEF 2012).

3.1.3.3. Gas Phase Analysis

3.1.3.3.1. Biogas composition

Biogas composition was measured according to standard methods 2720 C (APHA, AWWA, WEF 2012) with 490 Micro GC (Agilent Technologies).

3.2. Phase 2: Maximum Month Conditions

3.2.1. Characteristics of Wastewater and Seed Sludge

Wastewater and sludge collected from the NEWPCC and the WEWPCC were collected and immediately transported to the University of Manitoba Environmental Laboratory (refereed to as “the Lab” from hereon out), where they were either used immediately for testing and analysis, or stored in 4°C cold chamber or 35°C heated chamber for less than 24 hours prior to being used in the experiment. Samples were collected, transported, and stored in 20 litres containers with minimal headspace. For Phase 1: Maximum Month Conditions, wastewater and sludge samples were collected in March 2021, as spring melt caused the plant to receive higher flows than typical.

3.2.1.1. Primary Sludge

Primary sludge samples were collected, analyzed, and stored in the same manner as previously described for annual average conditions.

3.2.1.2. WEWPCC Sludge

WEWPCC sludge samples were collected, analyzed, and stored in the same manner as previously described for annual average conditions.

3.2.1.3. Primary Influent

Primary influent samples were collected, analyzed, and stored in the same manner as previously described for annual average conditions.

3.2.1.4. Mixed Liquor

Mixed liquor samples from the NEWPCC were collected from each of the three trains channels. Samples were collected using a bucket and rope. Characteristics of the mixed liquor such as pH, alkalinity, total solids, volatile solids, soluble ortho-phosphorus, and total phosphorus were measured prior to conducting the experiment, the results are presented in the associated chapters. Mixed liquor samples that were not used immediately once at the Lab were stored in the 4°C cold chamber until used on the same day. Despite mixed liquor samples being used within a few hours of being received at the Lab, it was observed that the soluble ortho-phosphorus significantly changed during storage and mixing conditions. To most accurately mimic actual conditions at the NEWPCC, mixed liquor samples were taken from each of the three train channels and jar tests were immediately conducted at the NEWPCC. Sludge produced in the jar tests was then transported to the Lab for analysis and BMP tests. Mixed liquor was used as the influent for the Scenario 3: Chemical Phosphorus Removal in HPO Reactors jar tests.

3.2.1.5. Digested Sludge

Digested sludge samples were collected, analyzed, and stored in the same manner as previously described for annual average conditions.

3.2.2. Experimental Set Up

3.2.2.1. Scenario 1: Increased Side Stream Chemical Phosphorus Removal

3.2.2.1.1. Ferric Chloride

Stock solution of ferric chloride was prepared using a sample of ferric chloride collected from the NEWPCC in March 2021. A stock solution of 10,000 mg Fe L^{-1} was used for Scenario 1.

3.2.2.1.2. Jar Test

Jar tests were conducted using Phipps & Bird PB-900 Series Programmable Jar Testers and 1,000 mL glass beakers. The four ferric chloride doses tested were the same as annual average conditions; 0, 135, 250, and 500 mg Fe L^{-1} of sludge; the control dose, the current dose for hydrogen sulfide control, half the BioWin predicted dose, and the BioWin predicted dose, respectively. NEWPCC primary sludge and WEWPCC sludge samples were combined at a ratio of 3:1 to replicate the max month conditions of the plant once SEWPCC upgrades are complete. 1,000 mL of the sludge mixture was added to four beakers and placed in the jar test machine and stir paddles were lowered. The specified dosage of ferric chloride was added to the beakers and the stir paddles were set to 200 rpm for 5 minutes, followed by 15 minutes at 80 rpm. Directly following the 20 minutes of reaction time, sludge from each beaker was sampled for soluble ortho-phosphorus and total phosphorus analysis and BMP testing. A total of four sets of jar tests were completed: with no pH adjustment, a duplicate of no pH adjustment, with pH adjusted to 6, and with pH adjusted to 7. On runs with pH adjustment, the pH was adjusted during the rapid mix using 5M NaOH.

3.2.2.1.3. BMP Tests

BMP tests were conducted on sludge produced in the jar tests using the Challenge Technology AER-800 Respirometer. Each reactor bottle was seeded with 450.0 mL of digested sludge and 50.0 mL of sludge from each jar test was added, for a total sludge volume of 500 mL, to replicate the annual average digester volumetric loading of 0.10 m^3/m^3*d at the NEWPCC. The bottles were placed in a water bath maintained at 36°C. Bottles were mixed using magnetic mixers set at 270 rpm. Biogas produced during the 15 day test was automatically logged every minute. Biogas was sampled for composition testing on day 1, 3, 5, 7, 10, 12, and 14 for the 15 day BMP test.

3.2.2.1.4. Post Digestion Ferric Chloride Dosing

If the soluble ortho-phosphorus concentration in the centrate was above the 20 mg PO_4-P L^{-1} objective, a second ferric dose after digestion would be conducted to reach the desired centrate concentration. 200 mL of each digested sludge was transferred to a glass beaker and placed on Cole-Parmer IKA 3907500 Ultra-Flat Lab Disc Magnetic Stirrer for magnetic mixing. The necessary ferric chloride dose was added to each sample and stirred for 7.5 minutes. Directly following the reaction time, the samples were analyzed again.

3.2.2.1.5. Capillary Suction Time Tests

CST tests were not completed for maximum month conditions due to time constraints.

3.2.2.2. Scenario 2: Chemically Enhanced Primary Treatment

3.2.2.2.1. Ferric Chloride

The same 1,000 mg Fe L^{-1} stock solution used in Scenario 1 was used for Scenario 2.

3.2.2.2.2. Jar Test

Jar tests were conducted using Phipps & Bird PB-900 Series Programmable Jar Testers and 2,000 mL jar test containers. The three ferric chloride doses tested were 0, 10, and 20 mg Fe L^{-1} of primary influent; the control dose, and doses based on prior testing and BioWin modeling (AECOM 2020). 2,000 mL of primary influent was added to three containers and placed in the jar test machine and stir paddles were lowered. The specified dosage of ferric chloride was added to the beakers and the stir paddles were set to 40 rpm for 7.5 minutes. Directly following the 7.5 minutes of reaction time, the contents of each beaker was transferred to a 2,000 mL graduated cylinder for 60 minutes of settling. Directly following the 60 minutes of settling, sludge volume was recorded and supernatant from each cylinder was sampled for further analysis. Supernatant was then removed from each cylinder using a peristaltic pump. Sludge produced in the jar tests was sampled for analysis and BMP testing.

3.2.2.2.3. BMP Tests

Sludge produced in the jar tests and WEWPCC sludge samples were combined at a ratio of 3:1 to replicate the maximum month conditions of the plant once SEWPCC upgrades are complete. BMP tests were then conducted on the mixed sludge using the Challenge Technology AER-800

Respirometer. Each reactor bottle was seeded with 450.0 mL of digested sludge and 50.0 mL of the WEWPCC and jar test sludge mixture was added, for a total sludge volume of 500 mL, to replicate the annual average digester volumetric loading of 0.10 m^3/m^3*d at the NEWPCC. The bottles were placed in a water bath maintained at 36°C. Bottles were mixed using magnetic mixers set at 270 rpm. Biogas produced during the 15 day test was automatically logged every minute. Biogas was sampled for composition testing on day 1, 4, 6, 8, 11, and 13 for the 15 day BMP test.

3.2.2.2.4. Capillary Suction Time Tests

CST tests were not completed for maximum month conditions due to time constraints.

3.2.2.2.5. SOUR Tests

SOUR tests were not completed in Phase 2 due to time constraints.

3.2.2.3. Scenario 3: Chemical Phosphorus Removal in HPO Reactors

3.2.2.3.1. Ferric Chloride

The same 1,000 mg Fe L^{-1} stock solution used in Scenario 1 and 2 was used for Scenario 3.

3.2.2.3.2. Jar Test

Jar tests were conducted using Phipps & Bird PB-900 Series Programmable Jar Testers and 1,000 mL glass beakers. The four ferric chloride doses tested were 0, 4, and 5 mg Fe L^{-1} of mixed liquor; the control dose, and doses based on prior testing and BioWin modeling. 1,000 mL of mixed liquor was added to four beakers and placed in the jar test machine and stir paddles were lowered. The specified dosage of ferric chloride was added to the beakers and the stir paddles were set to 40 rpm for 7.5 minutes. Directly following the 7.5 minutes of reaction time, the contents of each beaker was transferred to a 1,000 mL graduated cylinder for 60 minutes of settling. Directly following the 60 minutes of settling, sludge volume was recorded and supernatant from each beaker was sampled for further analysis. Supernatant was then removed from each beaker using a peristaltic pump. Sludge produced in the jar tests was sampled for analysis and BMP testing.

3.2.2.3.3. BMP Tests

Sludge produced in the jar tests were combined with primary sludge at a ratio of 36:64. The jar test and primary sludge mixture and WEWPCC sludge samples were then combined at a ratio of 3:1 to replicate the maximum month conditions of the plant once SEWPCC upgrades are complete. BMP tests were then conducted on the mixed sludge using the Challenge Technology AER-800 Respirometer. Each reactor bottle was seeded with 450.0 mL of digested sludge and 50.0 mL of the WEWPCCs, jar test, and primary sludge mixture was added, for a total sludge volume of 500 mL, to replicate the annual average digester volumetric loading of 0.10 $m^3/m^3{*}d$ at the NEWPCC. The bottles were placed in a water bath maintained at 36°C. Bottles were mixed using magnetic mixers set at 270 rpm. Biogas produced during the 15 day test was automatically logged every minute. Biogas was sampled for composition testing on day 1, 4, 6, 8, 11, and 13 for the 15 day BMP test.

3.2.2.3.4. Capillary Suction Time Tests

CST tests were not completed for maximum month conditions due to time constraints.

3.2.3. Analytical Methods

3.2.3.1. Liquid Phase Analysis

Liquid phase analysis was completed in the same manner as previously described for annual average conditions.

3.2.3.2. Solids Phase Analysis

Solid phase analysis was completed in the same manner as previously described for annual average conditions.

3.2.3.3. Gas Phase Analysis

Gas phase analysis was completed in the same manner as previously described for annual average conditions.

4. Results and Discussion

4.1. Phase 1: Annual Average Conditions

4.1.1. Scenario 1: Increased Side Stream Chemical Phosphorus Removal

4.1.1.1. Jar Test

Primary sludge samples collected from the NEWPCC (NE) and sludge collected from the WEWPCC (WE) sludge holding tank were analyzed upon arrival to the Lab and presented in ***Table 4.1***. The NE primary sludge and the WE holding tank sludge were combined at a ratio of 7:3. Characteristics of the mixture of NE primary sludge and WE sludge were analyzed and presented in ***Table 4.1***.

Table 4.1: Annual Average Scenario 1 Raw Sample Characteristics

Parameter	Unit	NE Primary Sludge	WE Sludge	NE Primary Sludge + WE Sludge
pH		5.8	5.0	5.6
Alkalinity	mg $CaCO_3$ L^{-1}	840	420	1,020
TS	mg L^{-1}	26,832	32,458	28,526
VS	mg L^{-1}	21,990	27,844	23,526
Ortho-P	mg L^{-1}	77.1	483.0	207.9
TP	mg L^{-1}	85.3	589.5	216.0

Jar testing was completed on the mixture of NE primary sludge and WE holding tank sludge for four different ferric doses based on previously determined doses using BioWin to predict a soluble ortho-phosphorus concentration of 20 mg L^{-1} in the centrate. The four ferric doses prior to digestion were 0, 135, 250, and 500 mg Fe L^{-1} of sludge; the control dose, the current dose for hydrogen sulfide control, half the BioWin predicted dose, and the BioWin predicted dose, respectively (AECOM 2020). A reaction time of 5 minutes rapid mixing (200 rpm) and 15 minutes of slow mixing (80 rpm) was used for all doses. A total of four sets of jar tests were completed: with no pH adjustment, a duplicate of no pH adjustment, with pH adjusted to 6, and with pH adjusted to 7. The results of the four sets of jar tests are presented in **Figure 4.1**, **Table *4.2***, **Table *4.3***, and **Table *4.4***, with the no pH adjustment shown as the average of the duplicate sets.

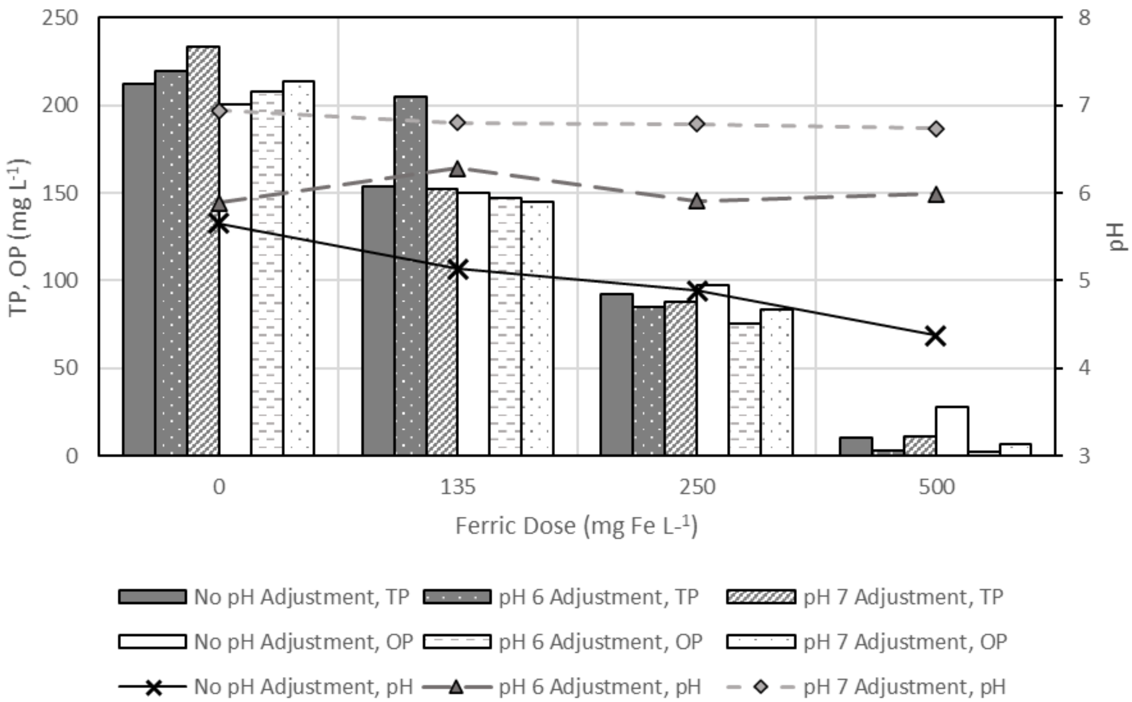

Figure 4.1: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 1 Jar Tests

As seen in **Figure 4.1**, pH drops from 5.7 to 4.4 as ferric chloride dose increases from the control dose to 500 mg L^{-1}. This was stabilized in the tests with pH control during rapid mixing. It does not appear the pH drop affected the phosphorus removal as TP and OP are relatively consistent for sludge with no pH adjustment, pH adjusted to 6 and pH adjusted to 7.

Table 4.2: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 1 Jar Tests - No pH Adjustment

Parameter	Unit	D0	D135	D250	D500
Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
pH		5.7	5.1	4.9	4.4
Ortho-P	mg L^{-1}	200.7	150.3	97.0	27.7
TP	mg L^{-1}	212.1	153.5	92.1	9.90

Inconsistencies between TP and OP results were found, particularly for tests with no pH adjustment for the 250 and 500 mg L^{-1} doses, as results show soluble ortho phosphorus higher than total phosphorus, which is not possible. Soluble ortho phosphorus tests were rerun to ensure proper calibration of the flow injection analysis, with similar results. The cause of this inconsistency was not determined but is suspected to be because of delays between sampling and testing for total phosphorus.

Table 4.3: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 1 Jar Tests - pH Adjusted to 6

Parameter	Unit	D0 (pH 6)	D135 (pH 6)	D250 (pH 6)	D500 (pH 6)
Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
pH		5.9	6.3	5.9	6.0
Ortho-P	mg L^{-1}	208.0	146.8	75.6	1.90
TP	mg L^{-1}	219.7	205.0	85.0	3.20

Table 4.4: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 1 Jar Tests - pH Adjusted to 7

Parameter	Unit	D0 (pH 7)	D135 (pH 7)	D250 (pH 7)	D500 (pH 7)
Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
pH		6.9	6.8	6.8	6.7
Ortho-P	mg L^{-1}	214.0	145.2	83.2	6.70
TP	mg L^{-1}	233.6	152.5	87.9	11.1

4.1.1.2. BMP Test

After the 20 minutes of reaction time, 35.7 mL of the sludge from the jar test was added to 464.3 mL of NE digested sludge to replicate the current digester volumetric loading of 0.07 m^3/m^3*d based on historical data for the NE. The characteristics of the digested sludge sampled from the NEWPCC used as inoculum for the BMP test is presented in ***Table 4.5***.

Table 4.5: Annual Average Scenario 1 Digester Inoculum Raw Characteristics

Parameter	Unit	NE Digested Sludge
pH		7.1
Alkalinity	mg $CaCO_3$ L^{-1}	2,680
TS	mg L^{-1}	13,274
VS	mg L^{-1}	8,550
Ortho-P	mg L^{-1}	97.2
TP	mg L^{-1}	101.4

Characteristics of the sludge pre and post-digestion are provided in **Table 4.6**, **Table 4.7**, and **Table 4.8**.

Table 4.6: Pre- and Post-Digestion Sludge Characteristics for Annual Average Scenario 1 BMP Test - No pH Adjustment

	Parameter	Unit	D0	D135	D250	D500
	Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
Pre-Digestion	**pH**		-	-	-	-
	Alkalinity	mg $CaCO_3$ L^{-1}	2,640	2,690	2,640	2,620
	TS	mg L^{-1}	14,558	13,937	14,343	13,961
	VS	mg L^{-1}	9,768	9,296	9,663	9,436
	Ortho-P	mg L^{-1}	94.0	83.4	84.1	69.8
	TP	mg L^{-1}	109.9	109.4	101.1	94.09
Post-Digestion	**pH**		7.3	7.2	7.2	7.3
	Alkalinity	mg $CaCO_3$ L^{-1}	3,490	3,340	3,440	3,270
	TS	mg L^{-1}	12,405	11,830	12,595	12,437
	VS	mg L^{-1}	7,543	7,032	7,420	7,260
	Ortho-P	mg L^{-1}	86.3	85.4	83.6	74.9*
	TP	mg L^{-1}	111.1	98.7	99.7	98.6

Table 4.7: Pre- and Post-Digestion Sludge Characteristics for Annual Average Scenario 1 BMP Test - pH Adjusted to 6

	Parameter	Unit	D0 (pH 6)	D135 (pH 6)	D250 (pH 6)	D500 (pH 6)
	Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
Pre-Digestion	**pH**		-	-	-	-
	Alkalinity	mg $CaCO_3$ L^{-1}	2,720	2,700	2,640	2,600
	TS	mg L^{-1}	13,846	13,130	13,084	13,354
	VS	mg L^{-1}	9,370	8,896	8,904	8,788
	Ortho-P	mg L^{-1}	90.2	82.4	56	61
	TP	mg L^{-1}	110.1	103.3	100.1	67.5
Post-Digestion	**pH**		7.6	7.3	7.4	7.4
	Alkalinity	mg $CaCO_3$ L^{-1}	3,440	3,480	3,400	3,400
	TS	mg L^{-1}	12,770	11,430	11,900	11,990
	VS	mg L^{-1}	7,373	6,840	7,320	7,273
	Ortho-P	mg L^{-1}	61.2	82.5	87.3	81.9
	TP	mg L^{-1}	73.5	105.1	101.5	96.7

Table 4.8: Pre- and Post-Digestion Sludge Characteristics for Annual Average Scenario 1 BMP Test - pH Adjusted to 7

	Parameter	Unit	D0 (pH 7)	D135 (pH 7)	D250 (pH 7)	D500 (pH 7)
	Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
Pre-Digestion	**pH**		-	-	-	-
	Alkalinity	mg $CaCO_3$ L^{-1}	2,600	2,700	2,680	2,700
	TS	mg L^{-1}	13,678	14,268	13,954	14,050
	VS	mg L^{-1}	9,178	9,546	9,362	9,198
	Ortho-P	mg L^{-1}	88	57.6	76.4	63
	TP	mg L^{-1}	111.6	79.3	105.5	99.2
Post-Digestion	**pH**		7.4	7.3	7.3	7.3
	Alkalinity	mg $CaCO_3$ L^{-1}	3,380	3,320	3,340	3,380
	TS	mg L^{-1}	11,410	12,373	12,427	12,277
	VS	mg L^{-1}	6,983	7,690	7,667	7,527
	Ortho-P	mg L^{-1}	84.6	90	83.1	89.7
	TP	mg L^{-1}	103.1	106.8	99.6	94.4

Total phosphorus, soluble ortho-phosphorus and pH for the sludge post-digestion are shown in **Figure 4.2**. Total phosphorus marginally decreases as ferric chloride dose increases, whereas soluble ortho phosphorus remains consistent across all doses. Based on these results, pH adjustment prior to digestion does not significantly affect the pH post-digestion and all post-digestions pH levels are within the ideal pH level for mesophilic digestion (WEF, ASCE, EWRI 2010). However, this may not be the case if the digesters are constantly feed with sludge with low pH in a full scale application, as the pH buffer due to the alkalinity in the digesters may eventually be diminished.

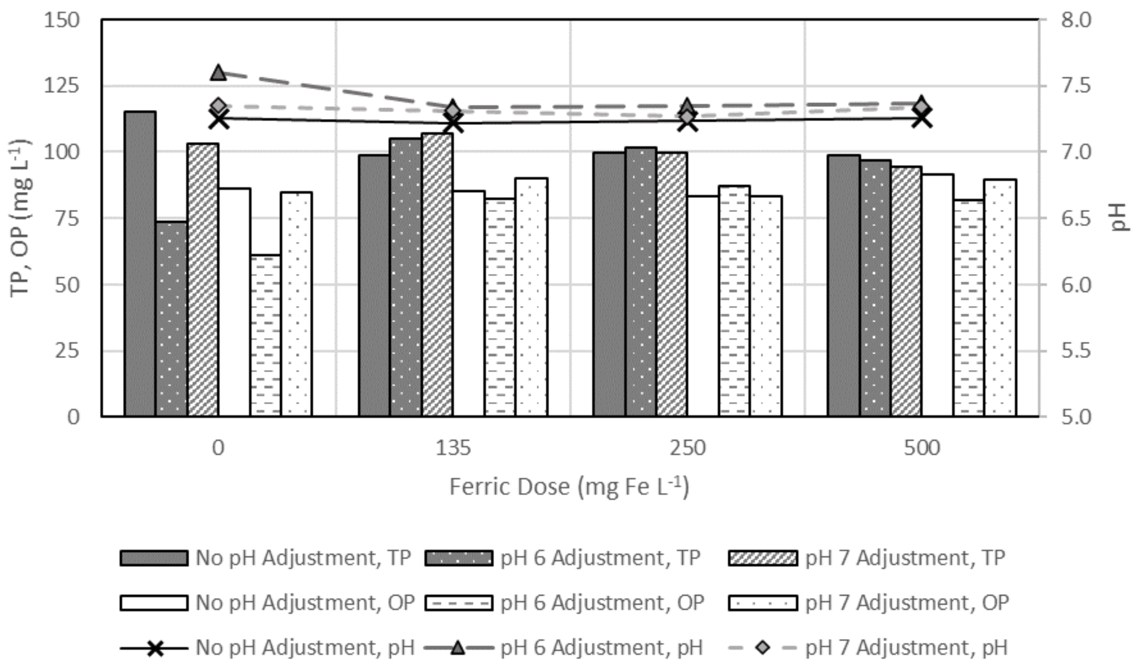

Figure 4.2: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 1 Post-Digestion

Total solids destruction and volatile solids destruction during digestion are shown in **Figure 4.3**. For all doses, with or without pH adjustment, volatile solids destruction is between 17 and 25 percent, which is well below the typical operational range of 45 to 55 percent for mesophilic digesters (WEF, ASCE, EWRI 2010).

These results contradict the results of Ofverstorm, Sapkaite and Dauknys (2010), where a reduction in volatile solids destruction was observed when ferric chloride was dosed to a mixture of primary sludge and waste activated sludge prior to digestion.

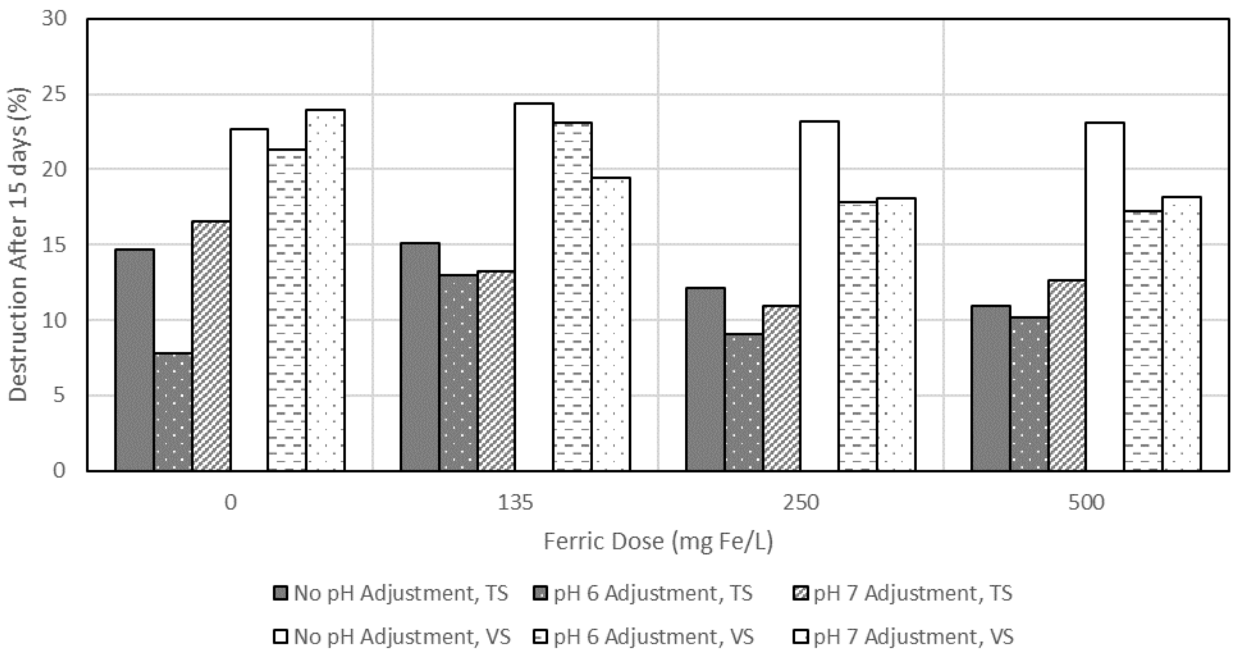

Figure 4.3: Total and Volatile Solids Destruction Annual Average Scenario 1 Post-Digestion

Biogas produced during the 15 day BMP test was automatically logged every minute. Cumulative biogas production during the BMP test are shown in ***Figure 4.4***, ***Figure 4.5***, and ***Figure 4.6***.

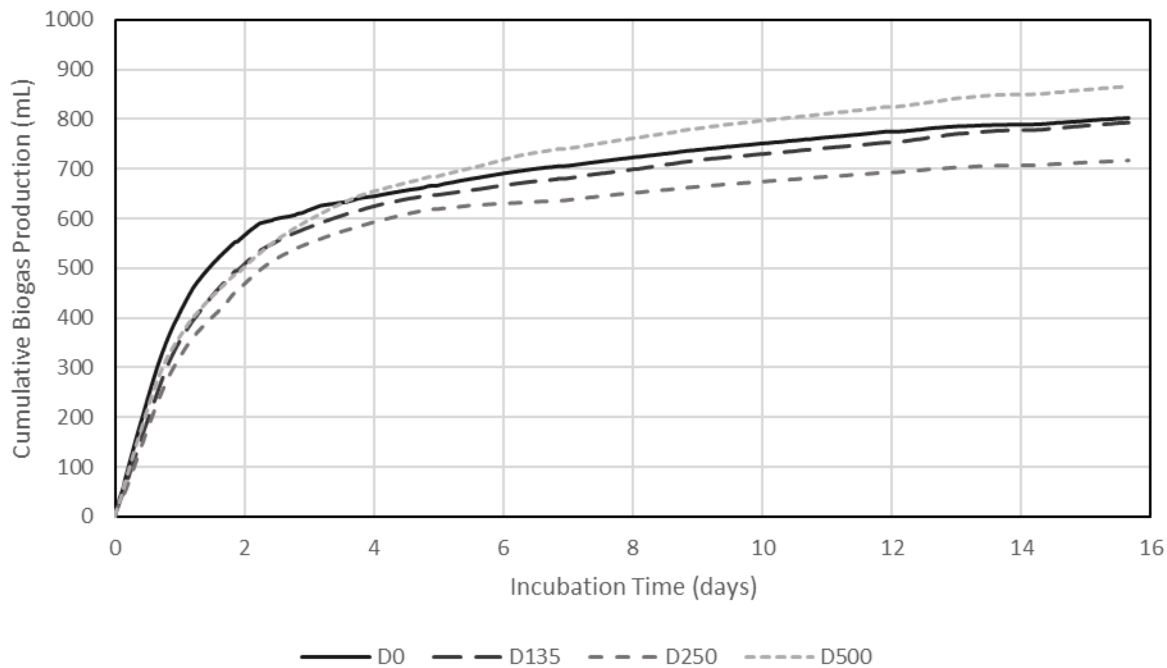

Figure 4.4: Annual Average Scenario 1 Cumulative Biogas Production - No pH Adjustment

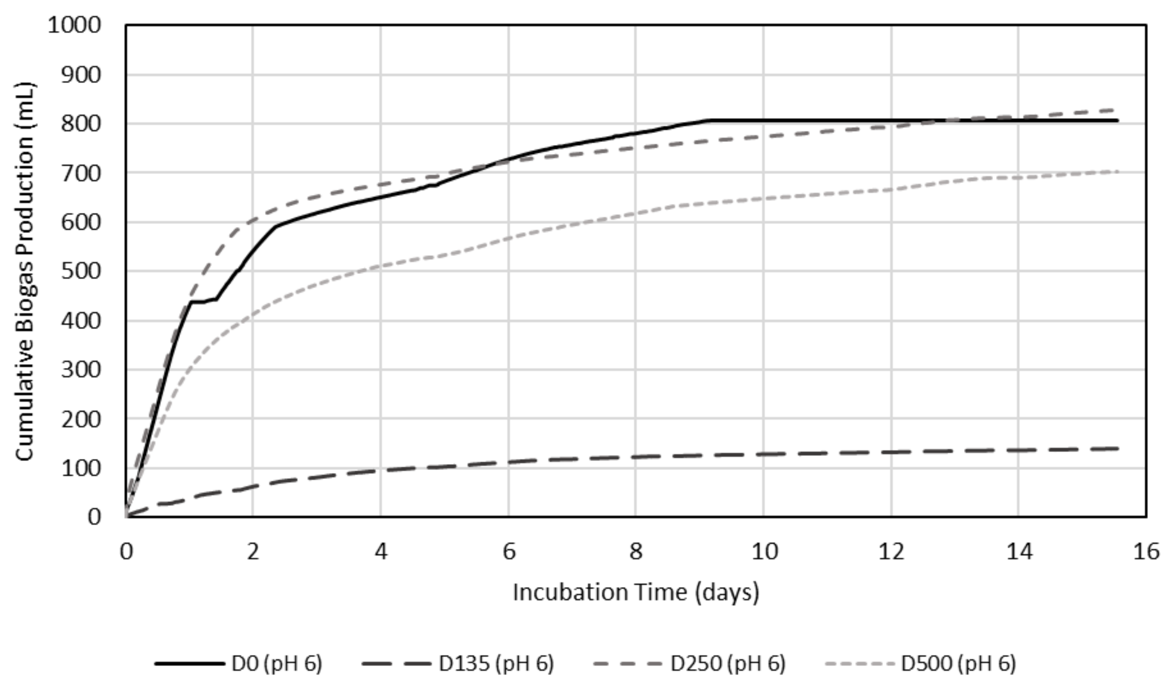

Figure 4.5: Annual Average Scenario 1 Cumulative Biogas Production – pH Adjusted to 6

As seen in **Figure 4.5** and **Figure 4.6**, the respirometer channels for D135 for both pH adjusted to 6 and 7 had an issue. As other parameters were not affected, it is believed that it was an issue with logging biogas production, not the actual digestion setup. D0 (pH 6) shows a period of minimal biogas production during day 1 due to due to a clog in the respirometer tubing. D0 (pH 6) has no biogas production following day 9 due to a leak in the bottle seal. This is confirmed by the low methane content in the headspace tested on days 12 and 14, shown in **Figure 4.8**.

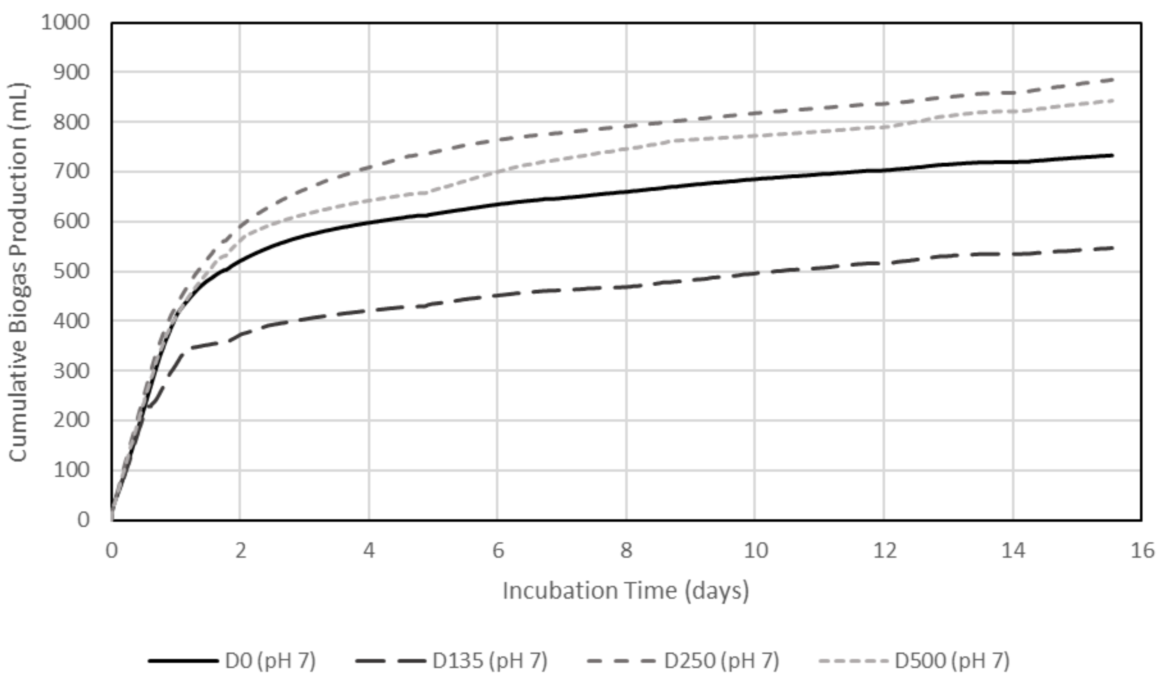

Figure 4.6: Annual Average Scenario 1 Cumulative Biogas Production – pH Adjusted to 7

Biogas composition was very consistent across all ferric chloride doses tested, as shown in **Figure 4.7**, **Figure 4.8**, and **Figure 4.9**. The methane content of biogas for sludge with no pH adjustment was consistently around 60 percent throughout the entire 15 day digestion process, whereas the sludge with pH adjusted to 6 or 7 were considerably higher at 70 percent. Despite the pH adjustment appearing to not affect the characteristics of the pre and post digestion sludge and biogas production, the composition of the biogas produced does appear to be affected. There does not appear to be a difference between pH 6 or 7, therefore if pH adjustment is used in a full scale application, maintaining a pH of 6 should be adequate to receive the benefit of increased methane production.

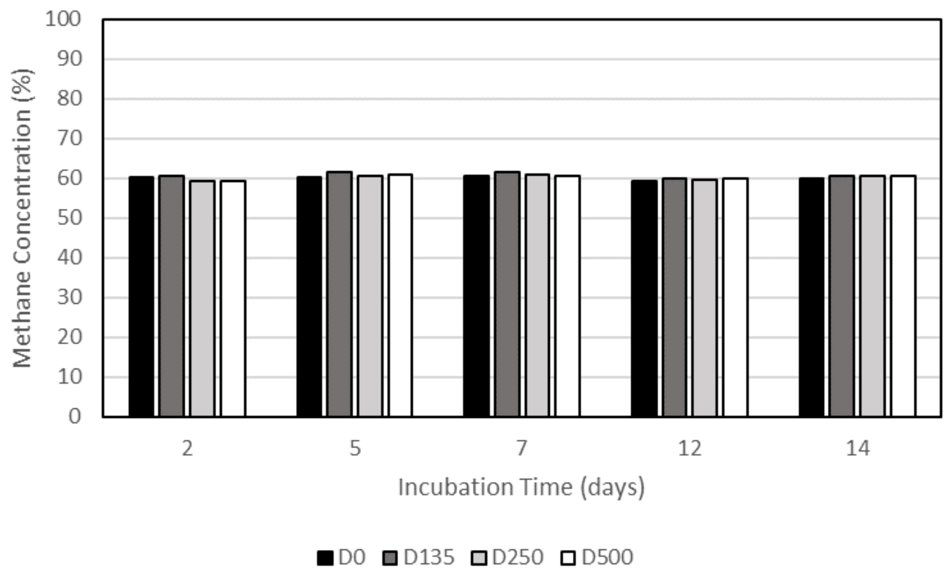

Figure 4.7: Annual Average Scenario 1 Biogas Methane Content - No pH Adjustment

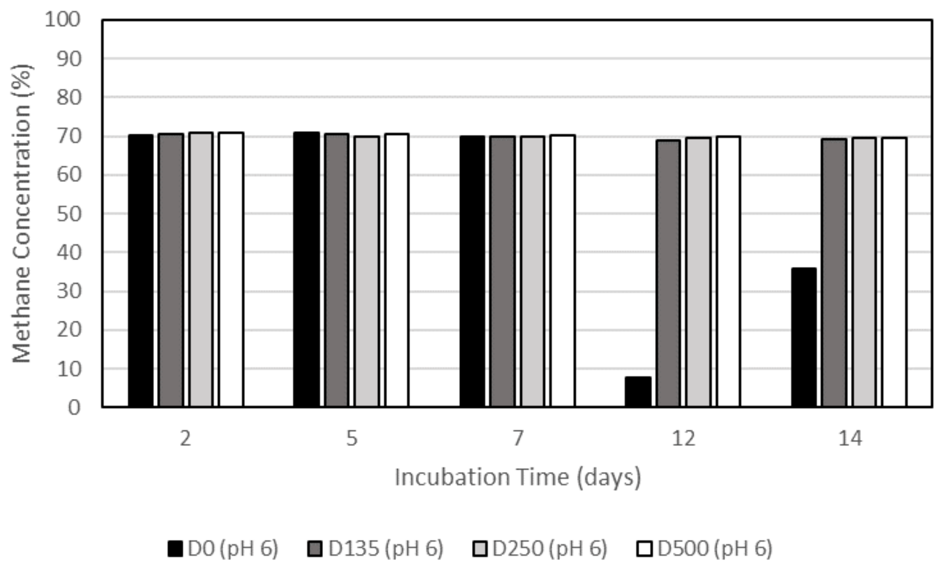

Figure 4.8: Annual Average Scenario 1 Biogas Methane Content - pH Adjusted to 6

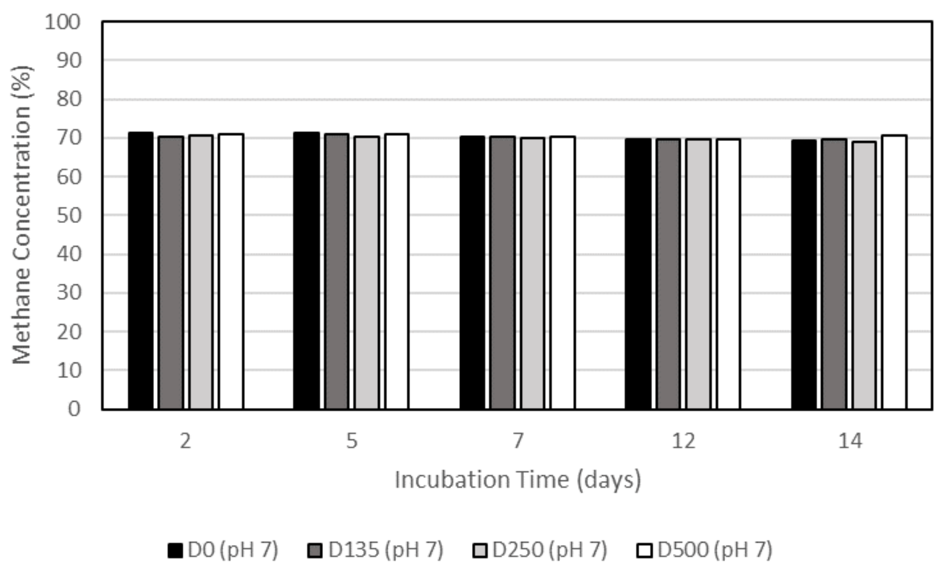

Figure 4.9: Annual Average Scenario 1 Biogas Methane Content - pH Adjusted to 7

The average methane content of the biogas produced throughout the 15 day digestion period is summarized in **Table 4.9**. D0 (pH 6) is the average for the first 9 days of digestion instead of the full 15 due to the leak previously mentioned.

Table 4.9: Annual Average Scenario 1 Biogas Composition

	Ferric Dose to Sludge	Unit	Methane	Other
No pH Adjustment				
D0	0 mg Fe L^{-1}	%	60.09	39.91
D135	135 mg Fe L^{-1}	%	60.83	39.17
D250	250 mg Fe L^{-1}	%	60.29	39.71
D500	500 mg Fe L^{-1}	%	60.21	39.79
Adjustment to pH 6				
D0 (pH 6)	0 mg Fe L^{-1}	%	70.24	29.76
D135 (pH 6)	135 mg Fe L^{-1}	%	69.75	30.25
D250 (pH 6)	250 mg Fe L^{-1}	%	69.91	30.09
D500 (pH 6)	500 mg Fe L^{-1}	%	70.17	29.83
Adjustment to pH 7				
D0 (pH 7)	0 mg Fe L^{-1}	%	70.33	29.67
D135 (pH 7)	135 mg Fe L^{-1}	%	70.20	29.80
D250 (pH 7)	250 mg Fe L^{-1}	%	69.90	30.10
D500 (pH 7)	500 mg Fe L^{-1}	%	70.43	29.57

Methane yield was determined based off biogas production, average methane concentration and volatile solids loading to the digester. In all tests, it does not appear that ferric chloride dose affects methane yield, as shown in **Figure 4.10**, **Figure 4.11**, and **Figure 4.12**. However, methane yield is higher for sludge with pH adjustment versus sludge without pH adjustment.

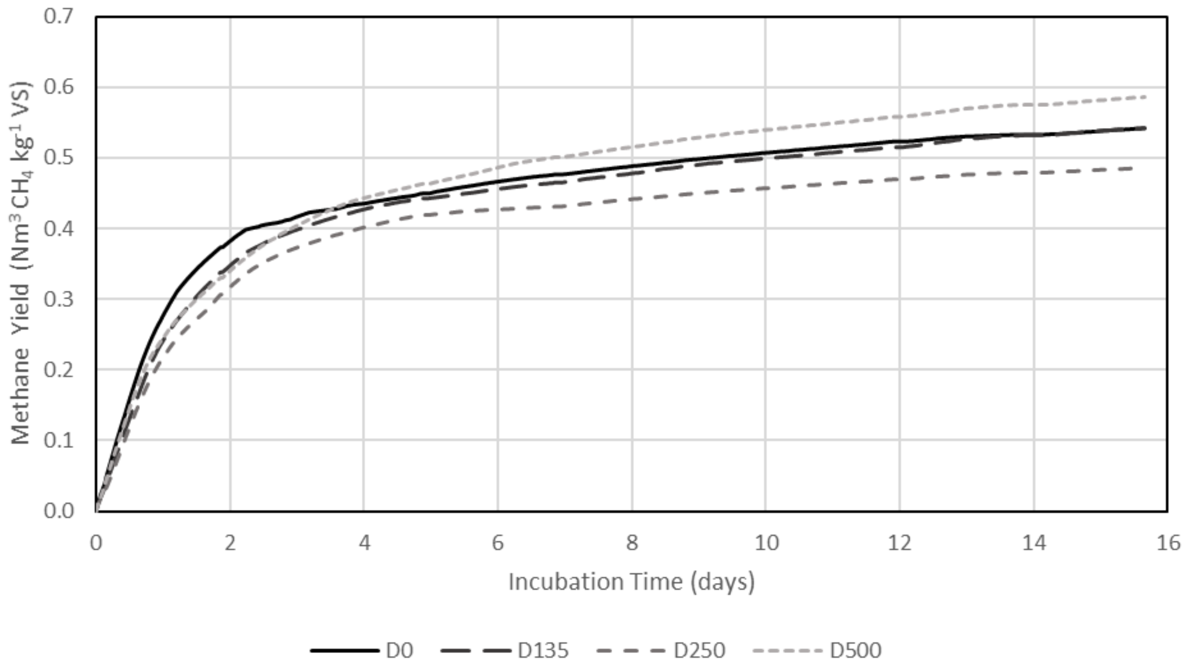

Figure 4.10: Annual Average Scenario 1 Cumulative Methane Yield - No pH Adjustment

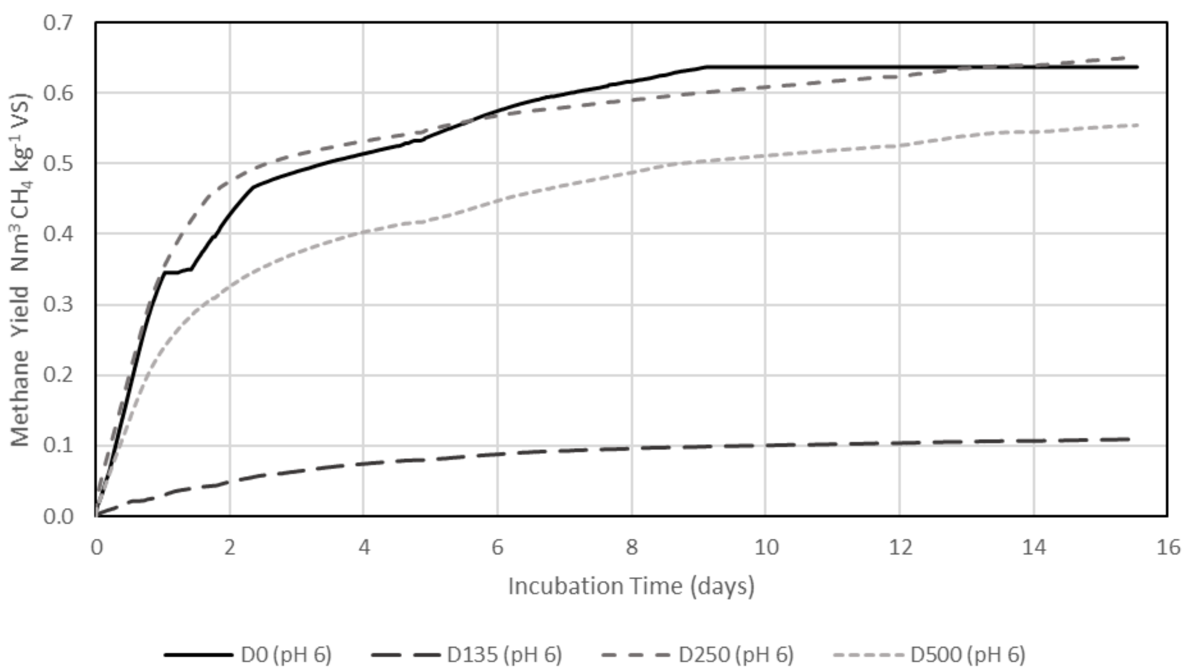

Figure 4.11: Annual Average Scenario 1 Cumulative Methane Yield - pH Adjusted to 6

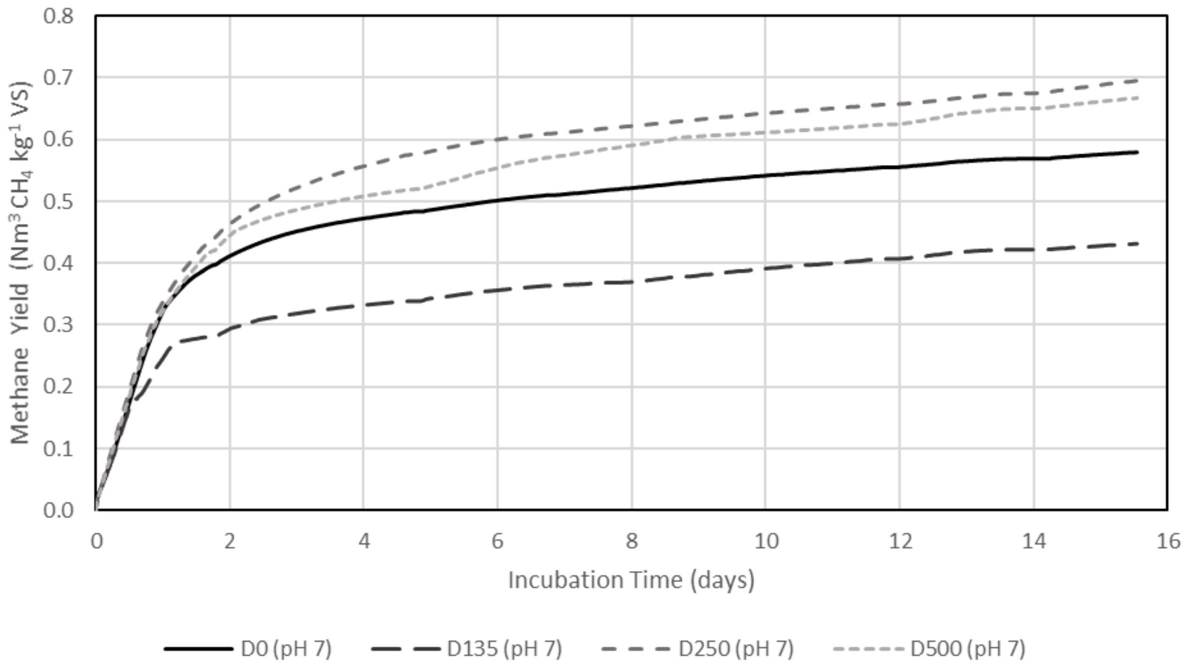

Figure 4.12: Annual Average Scenario 1 Cumulative Methane Yield - pH Adjusted to 7

The overall methane yield not being affected by ferric chloride dosing is in line with the findings of Johnson, et al. (2003), although that study found a decrease in biogas production and increase in methane content, the other methane yield was unaffected by the ferric chloride dosing in secondary treatment.

4.1.1.3. Post Digestion Ferric Chloride Dosing

As the objective for Scenario 1 dosing was to reach a soluble ortho phosphorus concentration of around 20 mg PO_4-P L^{-1} in the centrate, a second ferric dosing after digestion was necessary. A dose of 200 mg Fe L^{-1} of digested sludge was added to all samples. After a reaction time of 7.5 minutes, all samples were analyzed again. **Figure 4.13** shows the soluble ortho phosphorus and pH of the samples after the second ferric dose.

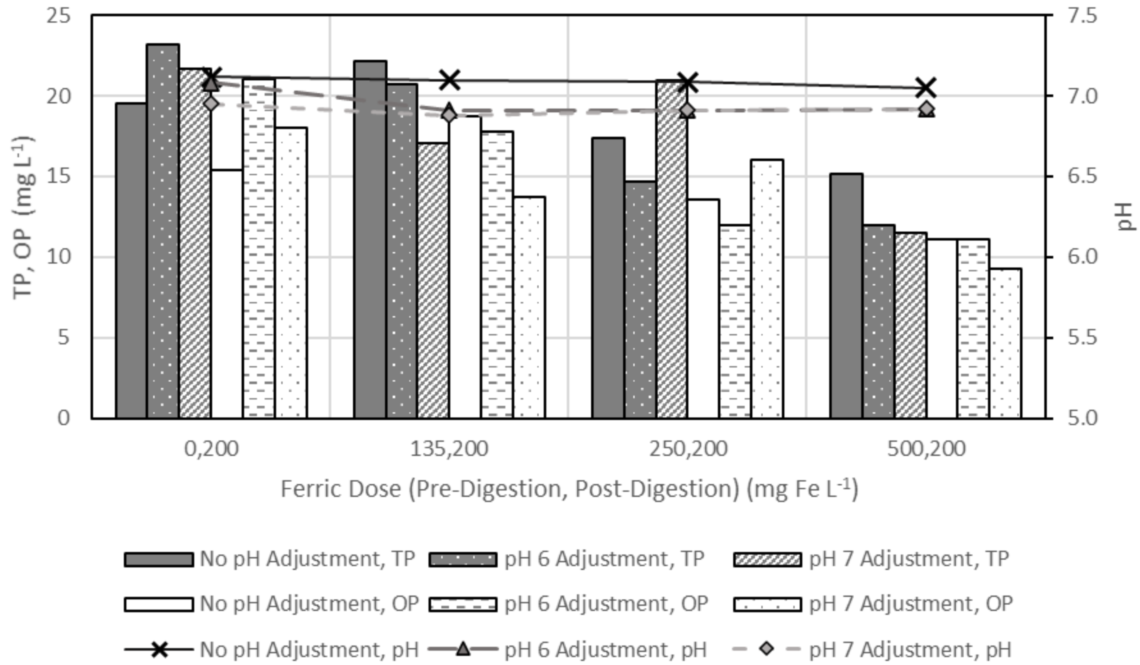

Figure 4.13: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 1 After Second Ferric Dose of 200 mg Fe L^{-1}

The 200 mg L^{-1} ferric chloride dose was required to achieve the soluble ortho phosphorus concentration of 20 mg PO_4-P L^{-1} in the centrate for samples with 0 and 135 mg/L ferric chloride doses prior to digestion, but a lower post digestion dose could have been used for samples with 250 and 500 mg L^{-1} ferric chloride prior to digestion and still reach the intended 20 mg PO_4-P L^{-1} in the centrate. Post digestion ferric chloride doses were adjusted in Phase 2: Max Month Conditions to achieve a more consistent final soluble ortho phosphorus concentration in the centrate.

4.1.1.4. Capillary Suction Time Tests

Duplicate capillary suction time (CST) tests were completed on all samples after digestion and again after the post digestion ferric dose to determine the affect on dewaterability. **Table 4.10** and **Table 4.11** outlines the average CST for each sample after digestion and after the post digestion ferric dose, respectively.

Table 4.10: Annual Average Scenario 1 Capillary Suction Times After Digestion

Ferric Dose Before Digestion	Unit	No pH Adjustment	pH 6 Adjustment	pH 7 Adjustment
0 mg Fe L^{-1}	sec	229	238	228
135 mg Fe L^{-1}	sec	238	245	218
250 mg Fe L^{-1}	sec	223	227	217
500 mg Fe L^{-1}	sec	239	214	207

Table 4.11: Annual Average Scenario 1 Capillary Suction Times After Post Digestion Ferric Chloride Dose

Ferric Dose Before Digestion	Ferric Dose After Digestion	Unit	No pH Adjustment	pH 6 Adjustment	pH 7 Adjustment
0 mg Fe L^{-1}	200 mg Fe L^{-1}	sec	134	141	110
135 mg Fe L^{-1}	200 mg Fe L^{-1}	sec	147	111	100
250 mg Fe L^{-1}	200 mg Fe L^{-1}	sec	135	112	105
500 mg Fe L^{-1}	200 mg Fe L^{-1}	sec	115	103	110

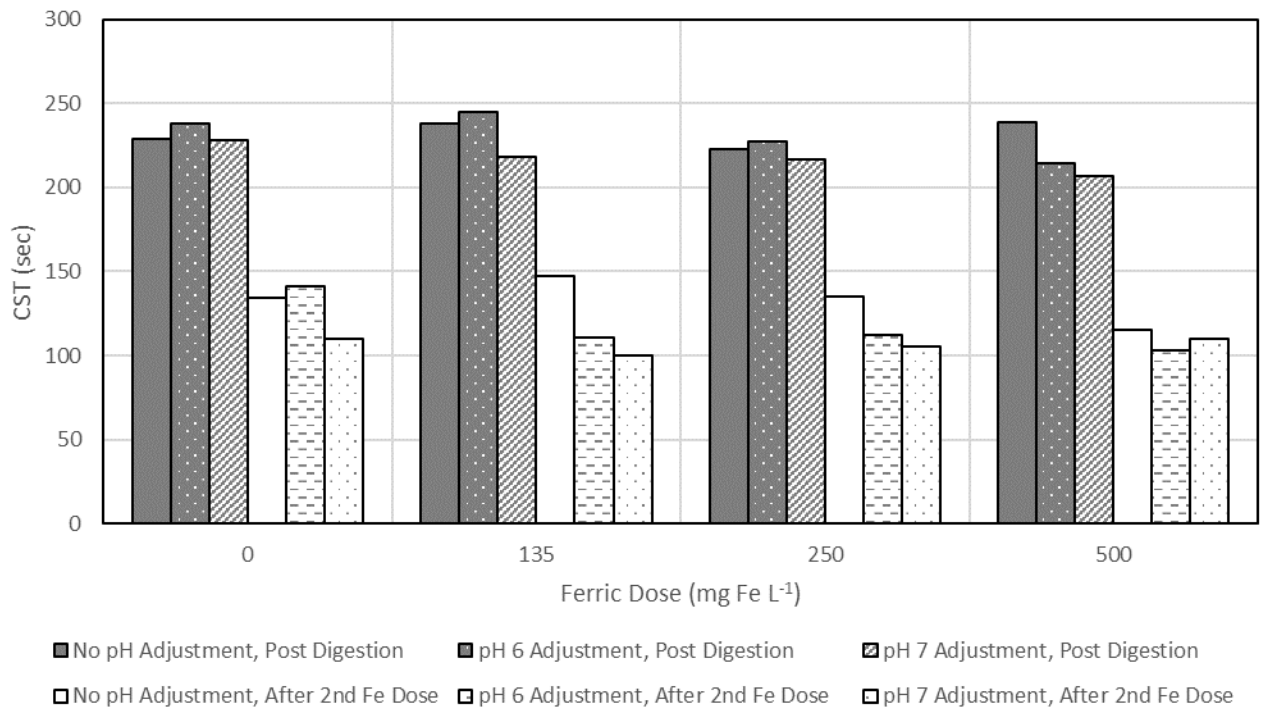

Figure 4.14: Annual Average Scenario 1 Capillary Suction Times

As depicted in **Figure 4.14**, CST is not affected by the pre digestion ferric chloride dose. The post digestion ferric chloride dose greatly decreases the CST for all samples, equating to an increase in dewaterability.

Ojo and Ifelebuegu (2019) found up to a 25 percent increase in primary sludge dewaterability when dosed with ferric chloride pre digestion, and up to a 75 percent decrease in WAS dewaterability when dosed with ferric chloride pre digestion, which suggests that the co-thickened primary sludge at NEWPCC balances out the increase in primary sludge and decreased in WAS dewaterability, resulting in no significant impact on dewaterability on post digestion sludge.

4.1.2. Scenario 2: Chemically Enhanced Primary Treatment

4.1.2.1. Initial Jar Test

Initial jar testing was conducted on the NE primary influent to determine the mixing regime and ferric chloride dose to be used for Scenario 2 Annual Average Conditions testing. The six initial ferric chloride doses tested were 0, 5, 10, 15, 20 and 30 mg Fe L^{-1} of primary influent, along with the three mixing regimes of 1 minute rapid (100 rpm) followed by 7.5 minutes of slow mixing (40 rpm), 2 minutes rapid (100 rpm) followed by 15 minutes of slow mixing (40 rpm), and 5 minutes rapid (100 rpm) followed by 30 minutes of slow mixing (40 rpm). After 15 minutes of settling, supernatant was sampled for soluble ortho phosphorus testing. **Figure 4.15** outlines the soluble ortho phosphorus for the six ferric chloride doses following the three mixing regimes and the average ratio for ferric dosed to soluble ortho phosphorus removed. The mixing regime did not have a significant impact on the soluble ortho phosphorus concentration. The ratio of ferric dosed to ortho phosphorus removed is approximately 3.5 mg Fe / mg soluble ortho phosphorus removed for the linear portion of the graph between 5 and 15 mg Fe L^{-1} of primary influent.

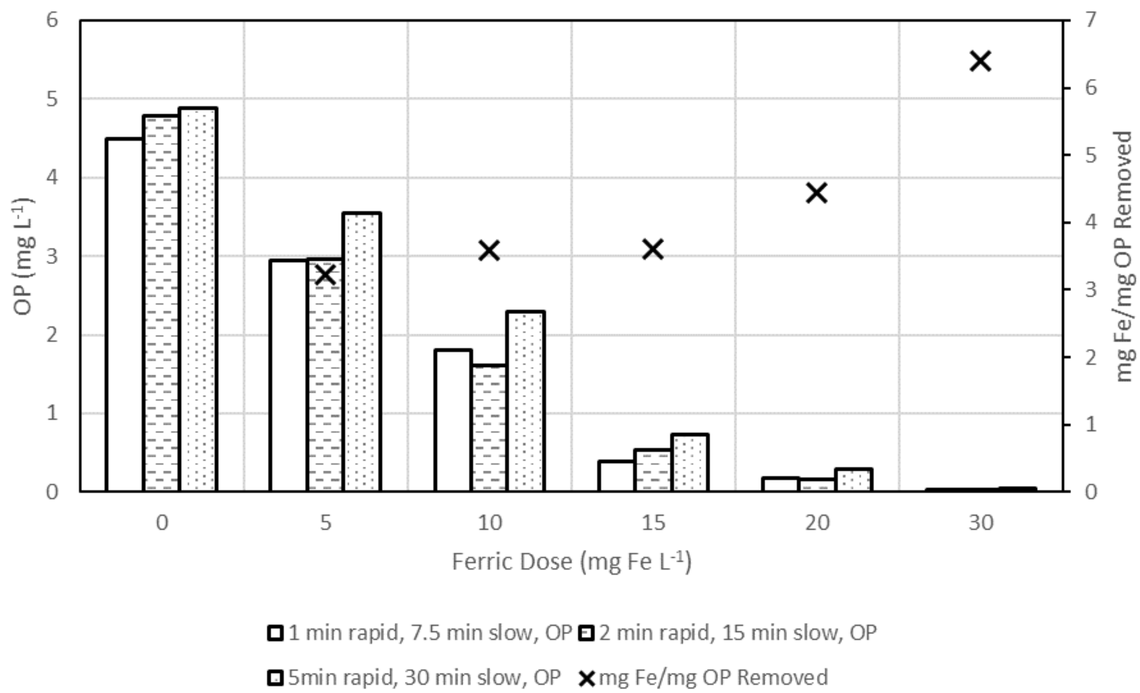

Figure 4.15: Annual Average Scenario 2 Initial Jar Test

4.1.2.2. Jar Test

Primary influent samples collected from the NE were analyzed upon arrival to the Lab and presented in **Table 4.12**.

Table 4.12: Annual Average Scenario 2 Raw Sample Characteristics

Parameter	Unit	NE Primary Influent
pH		7.12
Alkalinity	mg $CaCO_3$ L^{-1}	280
TS	mg L^{-1}	1,032
VS	mg L^{-1}	528
Ortho-P	mg L^{-1}	4.64
TP	mg L^{-1}	4.88

Jar testing was completed on the NE primary influent for four different ferric doses based on initial jar testing and previously determined doses using BioWin to predict a total phosphorus concentration of 2.5 mg TP L^{-1} in the final effluent (AECOM 2020). The four ferric doses used were 0, 8, 14, and 18 mg Fe L^{-1} of primary influent; the control dose, the predicted dose based on initial testing to reach 2.5 mg TP L^{-1} in the final effluent, the predicted dose based on initial testing to reach 1 mg TP L^{-1} in the final effluent, and the BioWin predicted dose to reach 1 mg TP L^{-1} in the final effluent, respectively (AECOM 2020). A reaction time of 7.5 minutes of slow mixing (40 rpm) was used for all doses. After 30 minutes of settling, the volume of settled sludge was recorded and sampled for further testing and analysis. Supernatant was sampled immediately following the 30 minutes of settling for further analysis, with results shown in **Table *4.13*** and **Figure 4.16**.

Table 4.13: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 2 Jar Test Supernatant

Parameter	Unit	D0	D8	D14	D18
Ferric Dose	mg L^{-1}	0	8	14	18
pH		7.12	6.96	6.85	6.79
Alkalinity	mg $CaCO_3$ L^{-1}	290	270	220	220
Ortho-P	mg L^{-1}	4.82	2.14	0.76	0.15
TP	mg L^{-1}	4.90	2.44	1.20	0.44

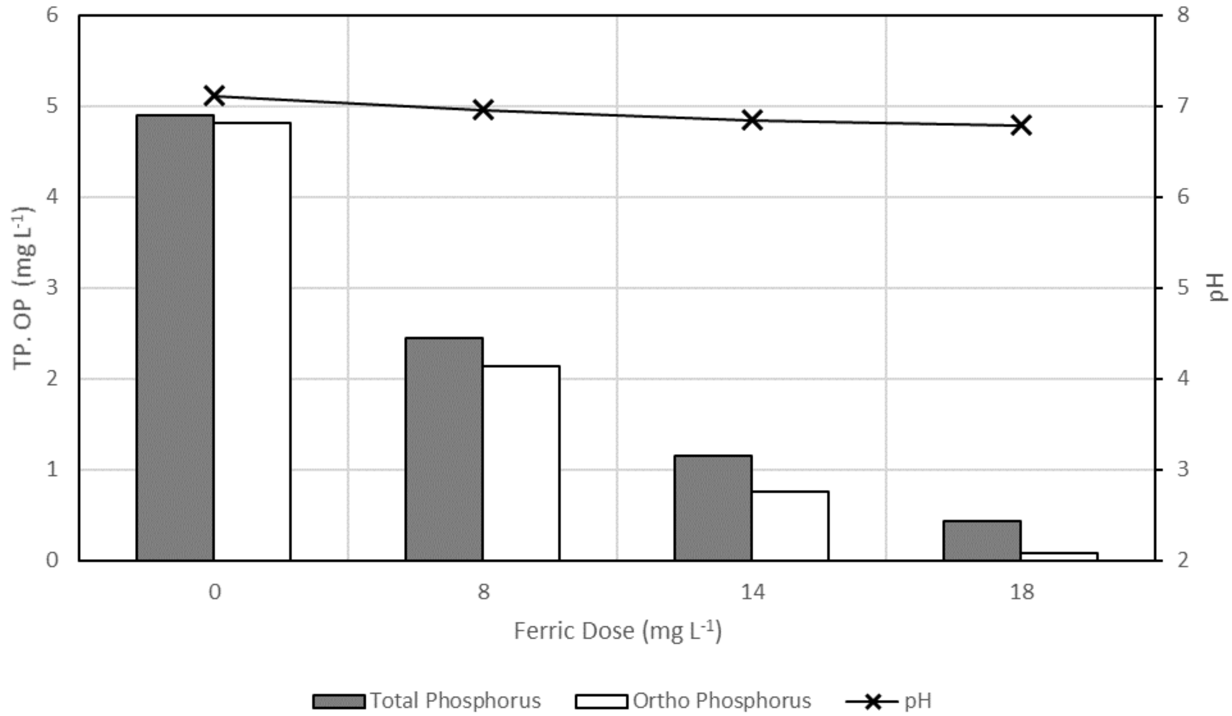

Figure 4.16: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 2 Jar Tests

The volume of settled sludge increased as well as the total sludge produced as the ferric dose increased, as shown in **Figure 4.17**.

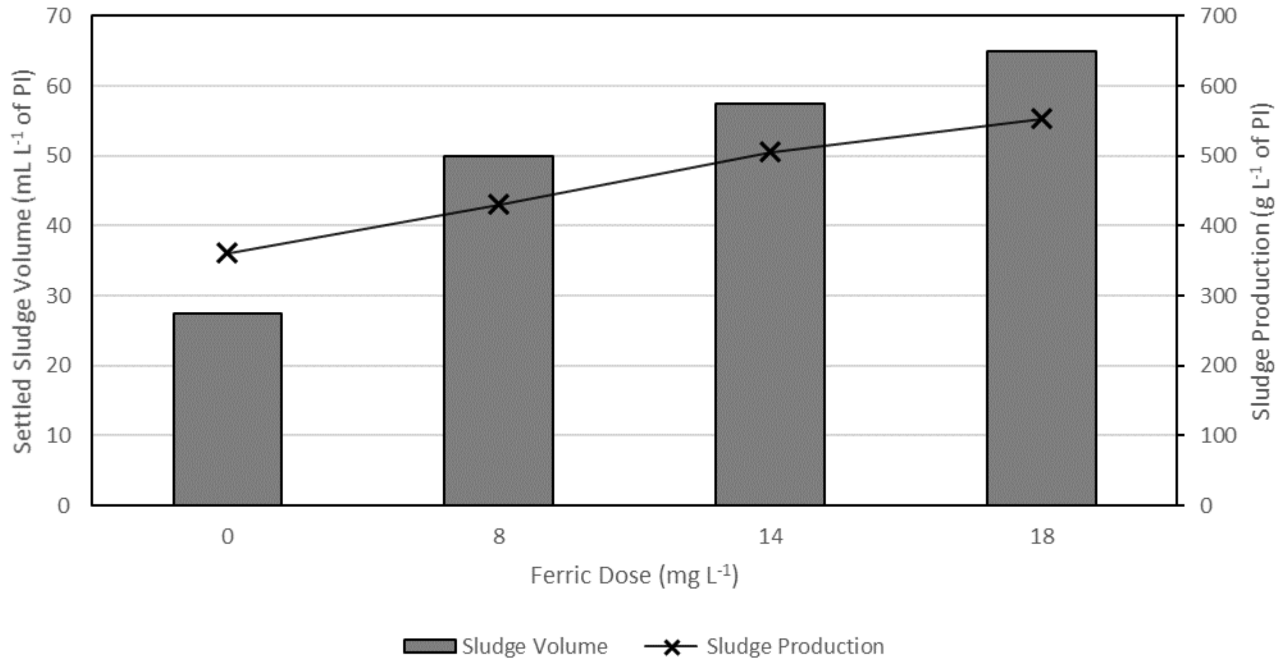

Figure 4.17: Annual Average Scenario 2 Sludge Volume and Production

4.1.2.3. BMP Test

Sludge produced from each jar test was mixed with the WE sludge sampled from the holding tank at a ratio of 7:3. The mixed sludge was then added to digester inoculum at a volumetric loading rate of 0.07 $m^3/m^3{*}d$ to replicate the current digester volumetric loading of 0.07 $m^3/m^3{*}d$ based on historical data for the NE. The characteristics of the WE sludge sampled from the holding tank and digested sludge sampled from the NE used as inoculum for the BMP test is presented in **Table 4.14**.

Table 4.14: Annual Average Scenario 2 WE Sludge and Digester Inoculum Raw Characteristics

Parameter	Unit	WE Sludge	NE Digested Sludge
pH		5.32	7.34
Alkalinity	mg $CaCO_3$ L^{-1}	660	2,680
TS	mg L^{-1}	38,086	13,954
VS	mg L^{-1}	32,972	8,890
Ortho-P	mg L^{-1}	496	63.2
TP	mg L^{-1}	541	76.2

Characteristics of the sludge pre and post-digestion are provided in **Table *4.15***.

Table 4.15: Pre- and Post-Digestion Sludge Characteristics for Annual Average Scenario 2 BMP Test

	Parameter	Unit	D0	D8	D14	D18
	Ferric Dose	mg L^{-1}	0	8	14	18
Pre-Digestion	**pH**		7.18	7.20	7.14	7.16
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-	-
	TS	mg L^{-1}	13,733	13,411	12,861	12,917
	VS	mg L^{-1}	9,101	8,925	8,526	8,565
	Ortho-P	mg L^{-1}	70.6	70.8	68.5	67.5
	TP	mg L^{-1}	-	-	-	-
Post-Digestion	**pH**		7.21	7.22	7.26	7.27
	Alkalinity	mg $CaCO_3$ L^{-1}	3,410	3,400	3,370	3,300
	TS	mg L^{-1}	11,840	11,695	10,989	10,989
	VS	mg L^{-1}	7,161	7,036	6,537	6,584
	Ortho-P	mg L^{-1}	83.2	82.9	80.5	78.9
	TP	mg L^{-1}	-	-	-	-

Soluble ortho-phosphorus and pH for the sludge post-digestion are shown in **Figure 4.18**. Soluble ortho phosphorus decreases as ferric chloride dose increases, whereas pH is consistent for all ferric chloride doses.

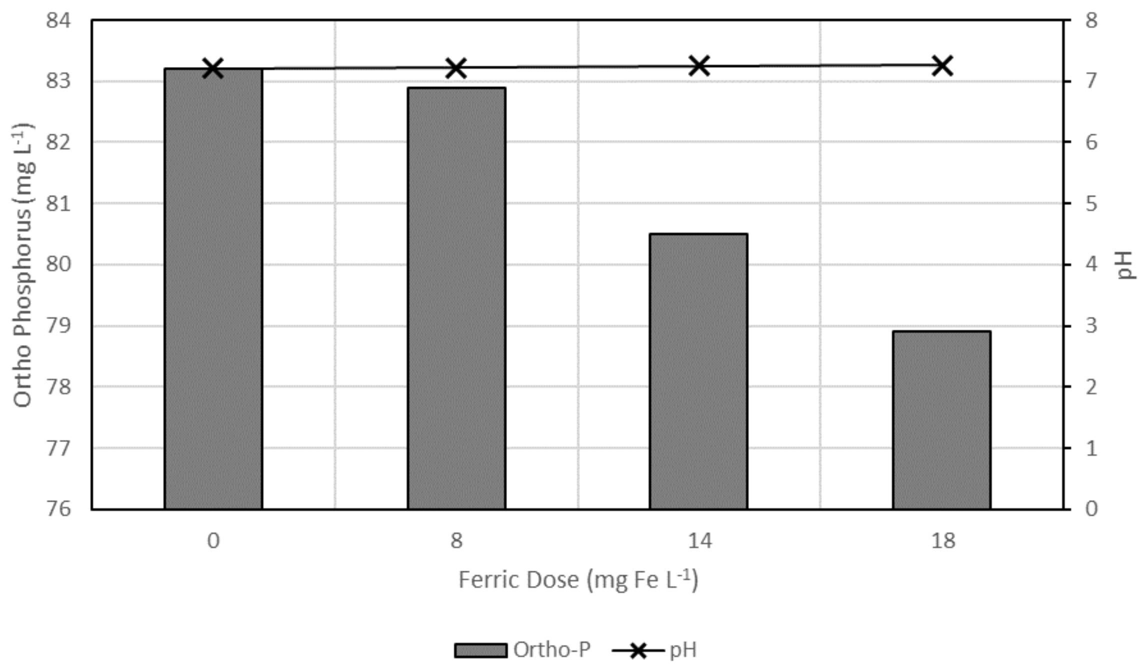

Figure 4.18: Soluble Ortho-Phosphorus and pH for Annual Average Scenario 2 Post-Digestion

Total solids destruction and volatile solids destruction during digestion are shown in **Figure 4.19**. For all doses, volatile solids destruction is between 20 and 25 percent, which is well below the typical operational range of 45 to 55 percent for mesophilic digesters (WEF, ASCE, EWRI 2010).

These results contradict the results of Feng, Song and Jang (2016), where an increase in volatile solids destruction during digestion was observed for sludge produced in CEPT.

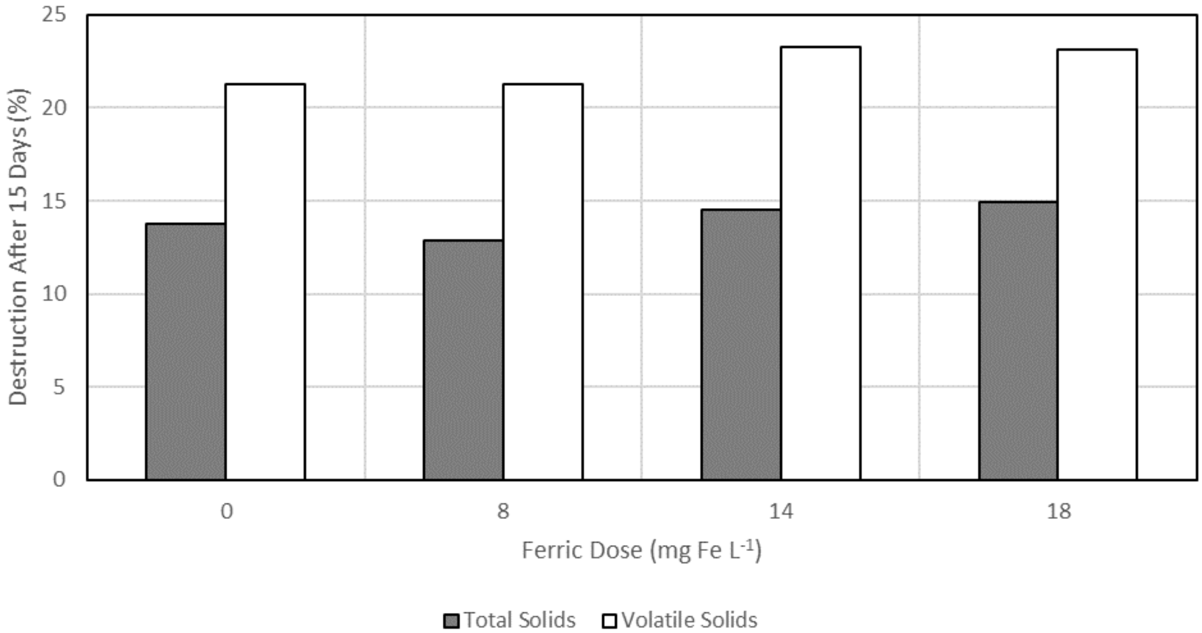

Figure 4.19: Total and Volatile Solids Destruction Annual Average Scenario 2 Post-Digestion

Biogas produced during the 15 day BMP test was automatically logged every minute.

Cumulative biogas production during the BMP test is shown in **Figure 4.20**.

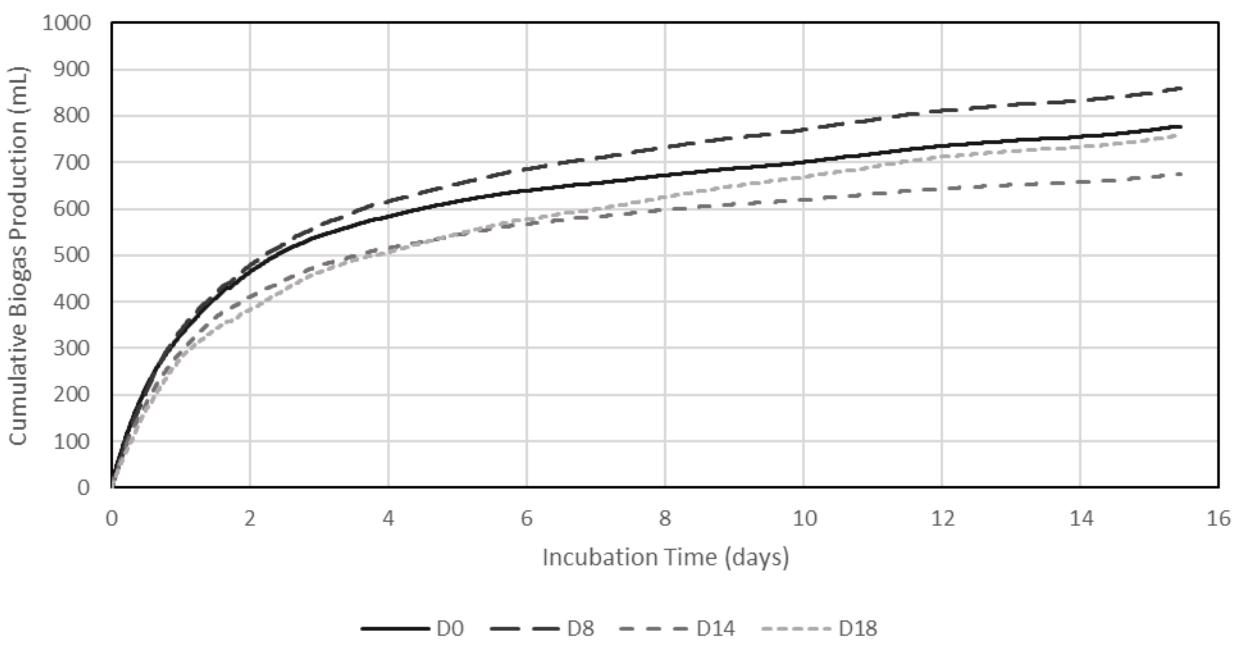

Figure 4.20: Annual Average Scenario 2 Cumulative Biogas Production

Biogas composition was very consistent across all ferric chloride doses tested, as shown in **Figure 4.21**.

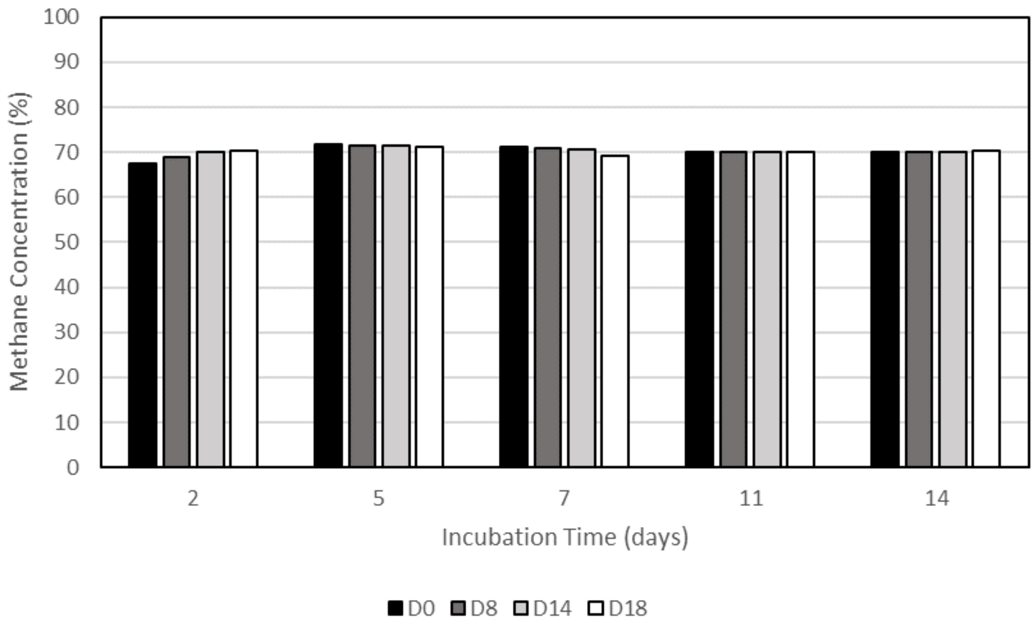

Figure 4.21: Annual Average Scenario 2 Biogas Methane Content

Table 4.16: Annual Average Scenario 2 Biogas Composition

	Ferric Dose to Primary Influent	Unit	Methane	Other
No pH Adjustment				
D0	0 mg Fe L^{-1}	%	70.11	29.89
D8	8 mg Fe L^{-1}	%	70.19	29.81
D14	14 mg Fe L^{-1}	%	70.43	29.57
D18	14 mg Fe L^{-1}	%	70.26	29.74

Methane yield was determined based off biogas production, average methane concentration and volatile solids loading to the digester. In all tests, it does not appear that ferric chloride dose significantly affects methane yield, as shown in **Figure 4.22**.

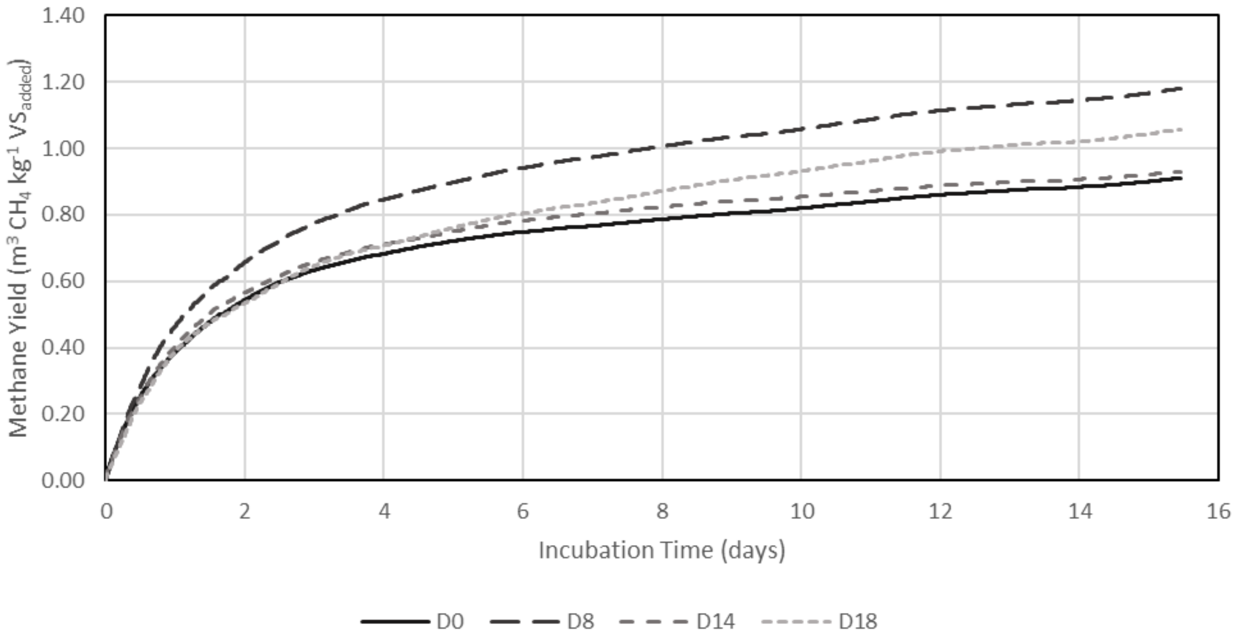

Figure 4.22: Annual Average Scenario 2 Cumulative Methane Yield

The overall methane yield not being affected by ferric chloride dosing is in line with the findings of Johnson, et al. (2003), although that study found a decrease in biogas production and increase in methane content, the other methane yield was unaffected by the ferric chloride dosing in secondary treatment.

4.1.2.4. Capillary Suction Time Tests

CST tests were completed on all samples after digestion to determine the affect on dewaterability. **Table 4.17** outlines the average CST for each sample after digestion. As shown in **Figure 4.23**, CST increases as ferric chloride dose to primary influent increases, suggesting that dewaterability decreases with chemically enhanced primary treatment.

Table 4.17: Annual Average Scenario 2 Capillary Suction Times After Digestion

	Ferric Dose to Primary Influent	Unit	CST
D0	0 mg Fe L^{-1}	sec	218
D8	8 mg Fe L^{-1}	sec	222
D14	14 mg Fe L^{-1}	sec	263
D18	18 mg Fe L^{-1}	sec	272

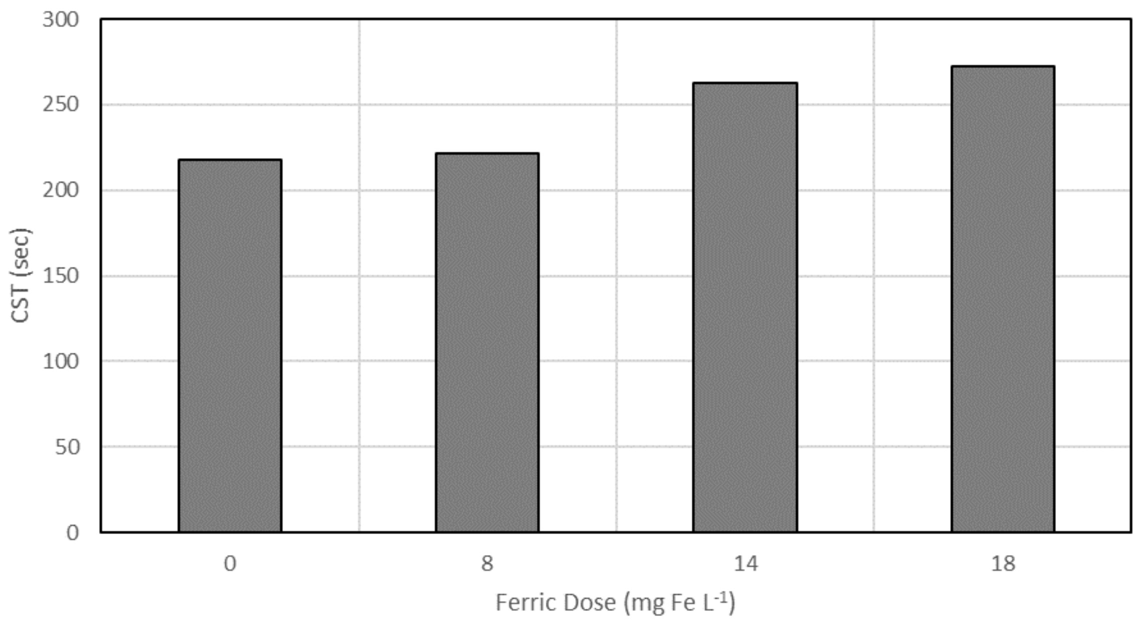

Figure 4.23: Annual Average Scenario 2 Capillary Suction Times

4.1.2.5. Specific Oxygen Uptake Rate Test

Specific oxygen uptake rate tests were completed on supernatant samples from all jar tests. Mixed liquor from all 3 NE trains were collected and combined in equal parts. Two litres of the mixed liquor were settled for 30 minutes and then 800 mL of the settled biomass was collected for the OUR test. The biomass was aerated prior to the OUR test to ensure biomass was not in a state of starvation. 20 mL of biomass was combined with 380 mL of supernatant from each jar test and further aerated until reaching a dissolved oxygen (DO) level of 8 mgL^{-1}. The biomass and supernatant mixture were then transferred to a 350 mL BOD bottle and a DO probe was inserted to record the drop in DO every 30 seconds until the DO reached 1 mg L^{-1}. DO versus time was plotted and a trendline was plotted on the linear portion. As shown in **Figure 4.24**, the SOUR decreases as the ferric dose increases. The reduction is SOUR indicates chemically enhanced primary treatment could negatively affect the secondary treatment process efficiency.

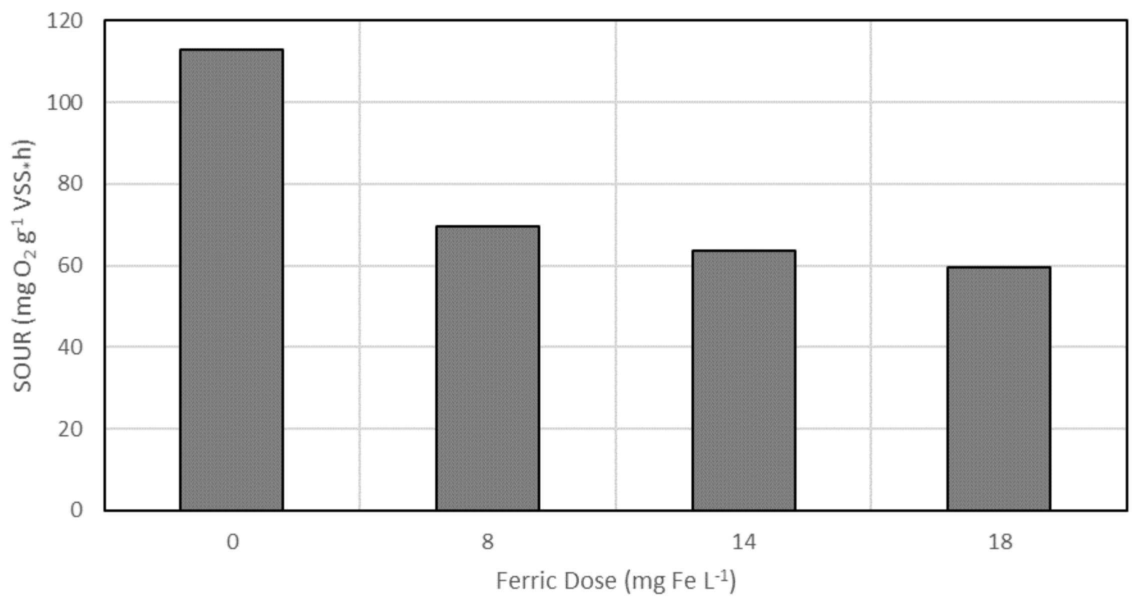

Figure 4.24: Annual Average Scenario 2 SOUR

4.1.3. Scenario 3: Chemical Phosphorus Removal in HPO Reactors

4.1.3.1. Initial Jar Test

Initial jar testing was conducted on the NE mixed liquor to determine the mixing regime and ferric chloride dose to be used for Scenario 3 Annual Average Conditions testing. The four initial ferric chloride doses tested were 0, 10, 20, and 30 mg Fe L^{-1} of primary influent, along with the three mixing regimes of 7.5 minutes of slow mixing (40 rpm), 15 minutes of slow mixing (40 rpm), and 30 minutes of slow mixing (40 rpm). After 30 minutes of settling, supernatant was sampled for soluble ortho phosphorus testing. **Figure 4.25** outlines the soluble ortho phosphorus for the four ferric chloride doses following the three mixing regimes and the average ratio for ferric dosed to soluble ortho phosphorus removed. The mixing regime did not have a significant impact on the soluble ortho phosphorus concentration.

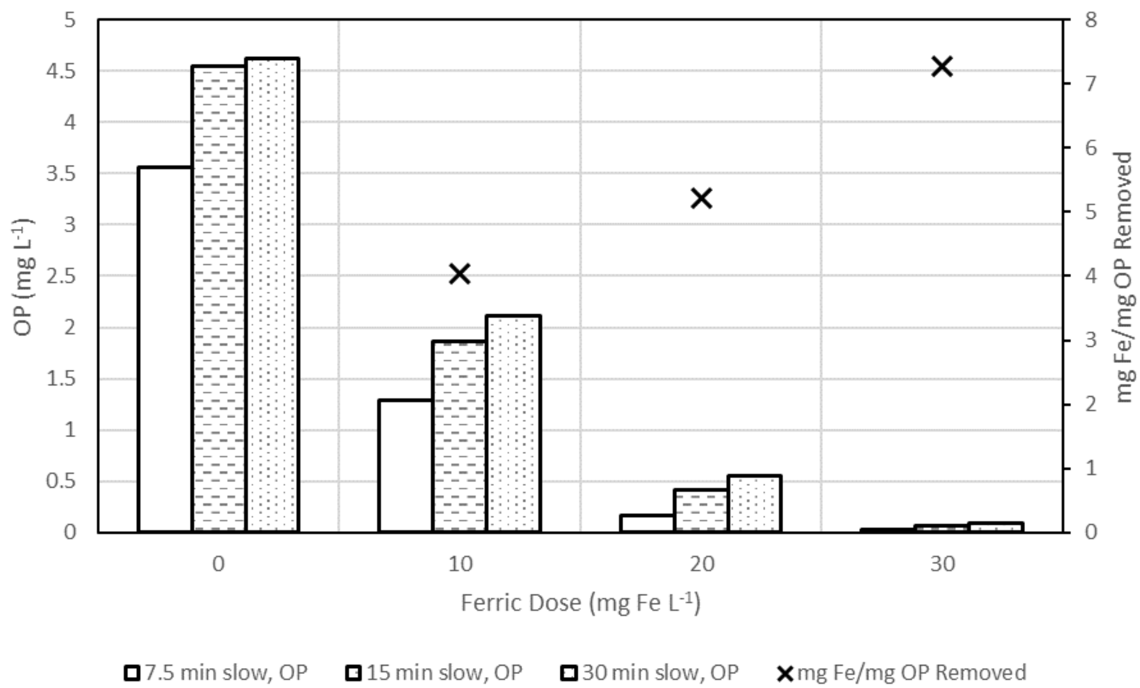

Figure 4.25: Annual Average Scenario 2 Initial Jar Test

4.1.3.2. Jar Test

Mixed liquor from the NE was collected from each train and combined in equal parts for testing. Mixed liquor samples collected from the NE were analyzed upon arrival to the Lab and presented in **Table 4.18**.

Table 4.18: Annual Average Scenario 3 Raw Sample Characteristics

Parameter	Unit	NE Mixed Liquor Mixture
pH		6.55
Alkalinity	mg $CaCO_3$ L^{-1}	220
TS	mg L^{-1}	3,006
VS	mg L^{-1}	2,202
Ortho-P	mg L^{-1}	11.6
TP	mg L^{-1}	11.7

Jar testing was completed on the NE mixed liquor for four different ferric doses based on initial testing and previously determined doses using BioWin to predict a total phosphorus concentration of 2.5 mg TP L^{-1} in the final effluent. The four ferric doses used were 0, 10, 15, and 20 mg Fe L^{-1} of mixed liquor; the control dose, the predicted dose based on initial testing to reach 2.5 mg TP L^{-1} in the final effluent, the BioWin predicted dose to reach 2.5 mg TP L^{-1} in the final effluent, and the predicted dose based on initial testing to reach 1 mg TP L^{-1} in the final effluent, respectively (AECOM 2020). A reaction time of 7.5 minutes of slow mixing (40 rpm) was used for all doses. After 30 minutes of settling, the volume of settled sludge was recorded and sampled for further testing and analysis. Supernatant was sampled immediately following the 30 minutes of settling for further analysis, with results shown in **Table 4.19** and **Figure 4.26**.

Table 4.19: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 3 Jar Test Supernatant

Parameter	Unit	D0	D10	D15	D20
Ferric Dose	mg L^{-1}	0	10	15	20
pH		6.70	6.59	6.54	6.47
Alkalinity	mg $CaCO_3$ L^{-1}	220	210	200	190
Ortho-P	mg L^{-1}	5.47	2.67	1.53	0.679
TP	mg L^{-1}	9.12	3.95	2.47	1.46

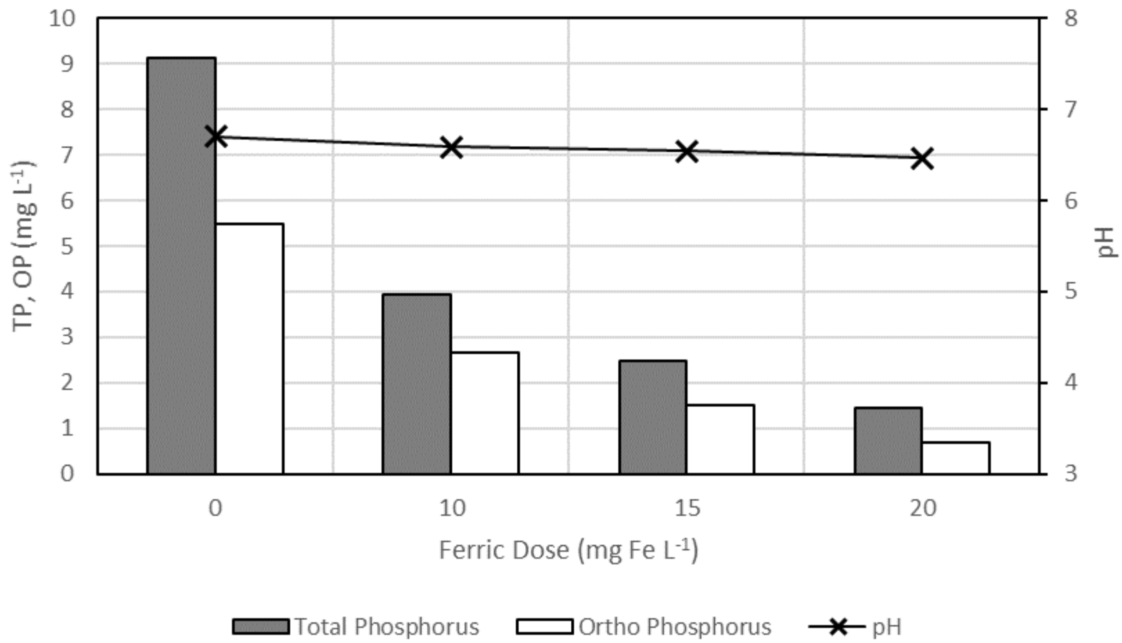

Figure 4.26: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Annual Average Scenario 3 Jar Tests

The volume of settled sludge increased as well as the total sludge produced as the ferric dose increased, as shown in **Figure 4.27**.

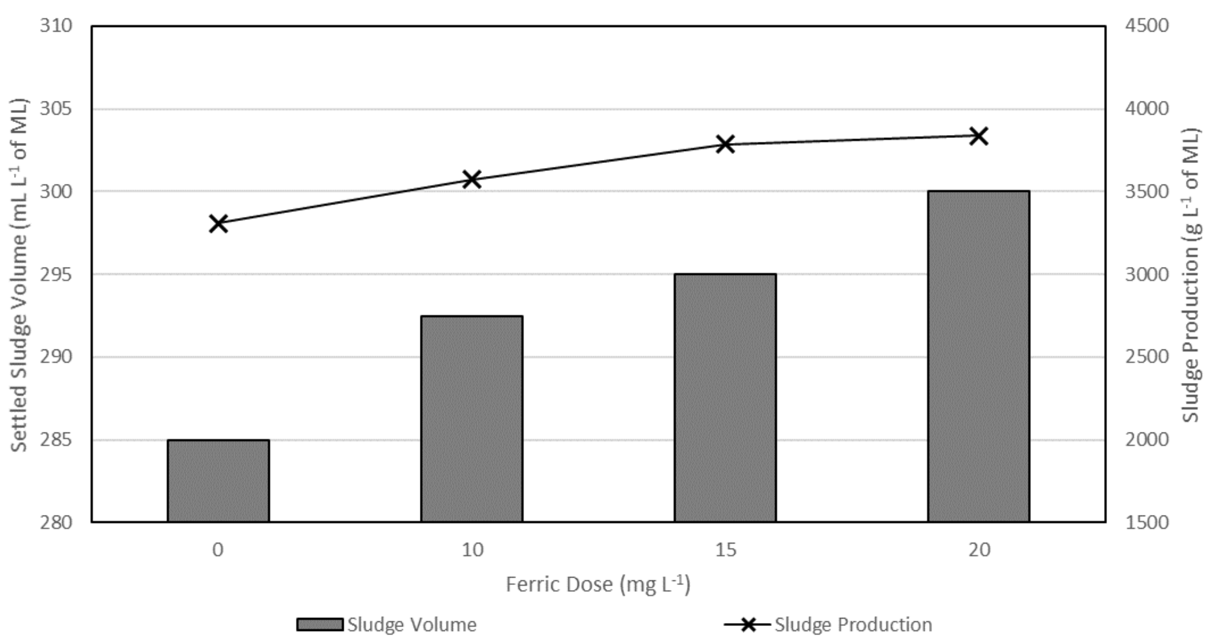

Figure 4.27: Annual Average Scenario 2 Sludge Volume and Production

4.1.3.3. UVT Test

Ultraviolet transmittance (UVT) was measured on all supernatant samples, as shown in **Figure 4.28**. The increase in UVT correspond with an increase in UV disinfection efficiency, therefore chemical phosphorus removal at the HPO reactors is anticipated to have a positive impact on downstream UV disinfection.

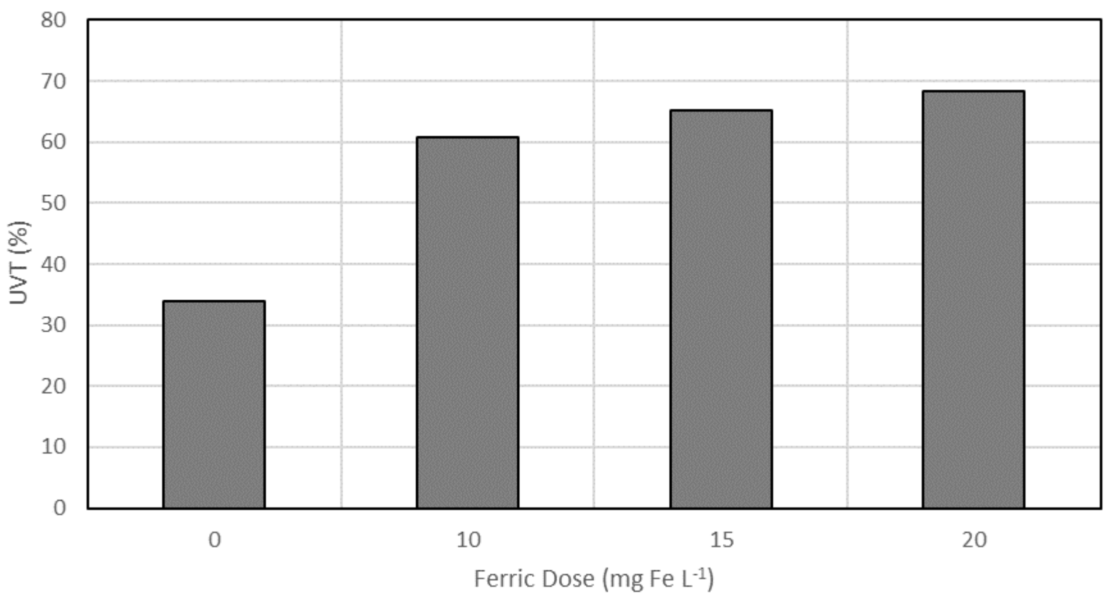

Figure 4.28: Annual Average Scenario 3 Supernatant Ultraviolet Transmittance

These results differ from those found by Kozak, et al. (2010), where no difference in UVT was found between secondary effluent during ferric-based chemical phosphorus removal periods and without. UVT can increase with ferric chloride addition due to the increased organics removal but can be inhibited if residual iron is present in the secondary effluent, which would suggest that there was minimal residual ferric in the jar test supernatant (Metcalf & Eddy; AECOM 2014).

4.1.3.4. BMP Test

Sludge produced from each jar test was mixed with the NE primary sludge at a ratio of 45:55. That sludge mixture was then mixed with WE sludge sampled from the holding tank at a ratio of 7:3. The mixed sludge was then added to digester inoculum at a volumetric loading rate of 0.07 m^3/m^3*d to replicate the current annual average digester volumetric loading based on historical data for the NE. The characteristics of the NE primary sludge, WE sludge sampled from the holding tank and digested sludge sampled from the NE used as inoculum for the BMP test is presented in **Table 4.20**.

Table 4.20: Annual Average Scenario 3 NE Primary Sludge, WE Sludge and Digester Inoculum Raw Characteristics

Parameter	Unit	NE Primary Sludge	WE Sludge	NE Digested Sludge
pH		6.07	5.32	7.37
Alkalinity	mg $CaCO_3$ L^{-1}	1180	620	2680
TS	mg L^{-1}	29,044	35,166	12,720
VS	mg L^{-1}	22,880	29,992	8,112
Ortho-P	mg L^{-1}	84.3	555	69.4
TP	mg L^{-1}	83.4	569	31.6

Once again, inconsistencies between TP and OP results were found, as results show soluble ortho phosphorus higher than total phosphorus, which is not possible. Soluble ortho phosphorus tests were rerun to ensure proper calibration of the flow injection analysis, with similar results. The cause of this inconsistency was not determined but is suspected to be because of delays between sampling and testing for total phosphorus.

Characteristics of the sludge pre and post-digestion are provided in **Table *4.21***.

Table 4.21: Pre- and Post-Digestion Sludge Characteristics for Annual Average Scenario 3 BMP Test

	Parameter	Unit	D0	D10	D15	D20
	Ferric Dose	mg L^{-1}	0	10	15	20
Pre-Digestion	**pH**		7.30	7.27	7.26	7.30
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-	-
	TS	mg L^{-1}	13,217	13,320	13,329	13,245
	VS	mg L^{-1}	8,660	8,858	8,829	8,715
	Ortho-P	mg L^{-1}	76.2	77.4	79.0	78.0
	TP	mg L^{-1}	-	-	-	-
Post-Digestion	**pH**		7.12	7.15	7.14	7.17
	Alkalinity	mg $CaCO_3$ L^{-1}	3,370	3,480	3,490	3,520
	TS	mg L^{-1}	11,525	11,682	11,727	11,593
	VS	mg L^{-1}	6,933	7,021	7,053	6,962
	Ortho-P	mg L^{-1}	93.2	89.4	86.4	87.7
	TP	mg L^{-1}	-	-	-	-

Soluble ortho-phosphorus and pH for the sludge post-digestion are shown in **Figure 4.29**. Soluble ortho phosphorus decreases as ferric chloride dose increases apart from the highest ferric chloride dose, whereas pH is consistent for all ferric chloride doses.

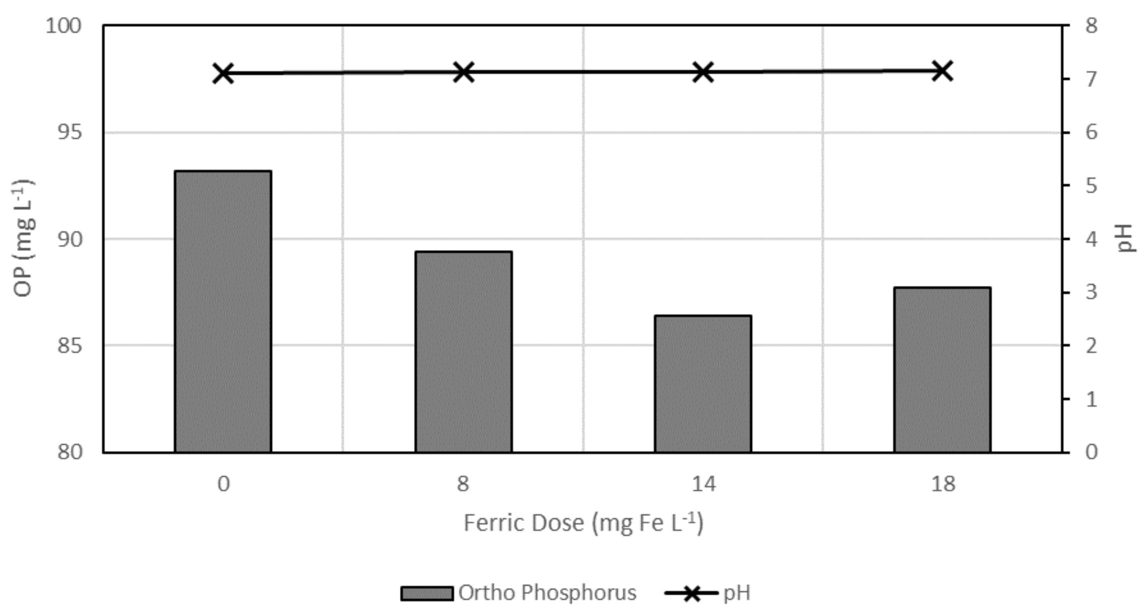

Figure 4.29: Soluble Ortho-Phosphorus and pH for Annual Average Scenario 3 Post-Digestion

Total solids destruction and volatile solids destruction during digestion are shown in **Figure 4.30**. For all doses, volatile solids destruction is around 20 percent, which is well below the typical operational range of 45 to 55 percent for mesophilic digesters (WEF, ASCE, EWRI 2010).

These results are in line with the results of Zhang, et al. (2013), where no significant change to solids destruction was observed in the digestion process between samples dosed with ferric chloride in the secondary treatment system and those without ferric chloride dosing.

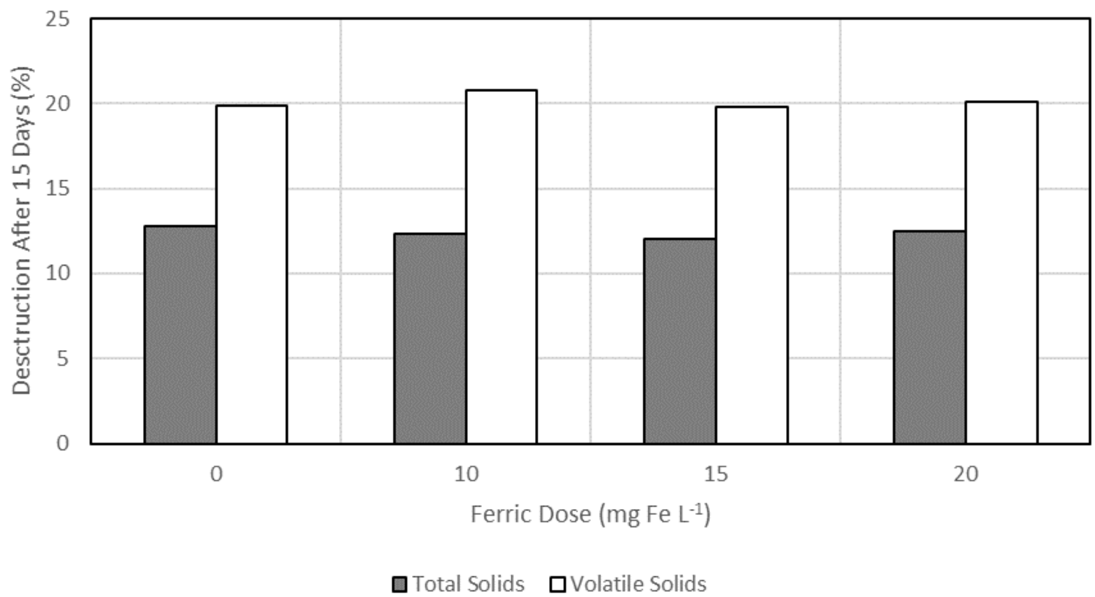

Figure 4.30: Total and Volatile Solids Destruction Annual Average Scenario 3 Post-Digestion

Biogas produced during the 15 day BMP test was automatically logged every minute. Cumulative biogas production during the BMP test is shown in **Figure 4.31**.

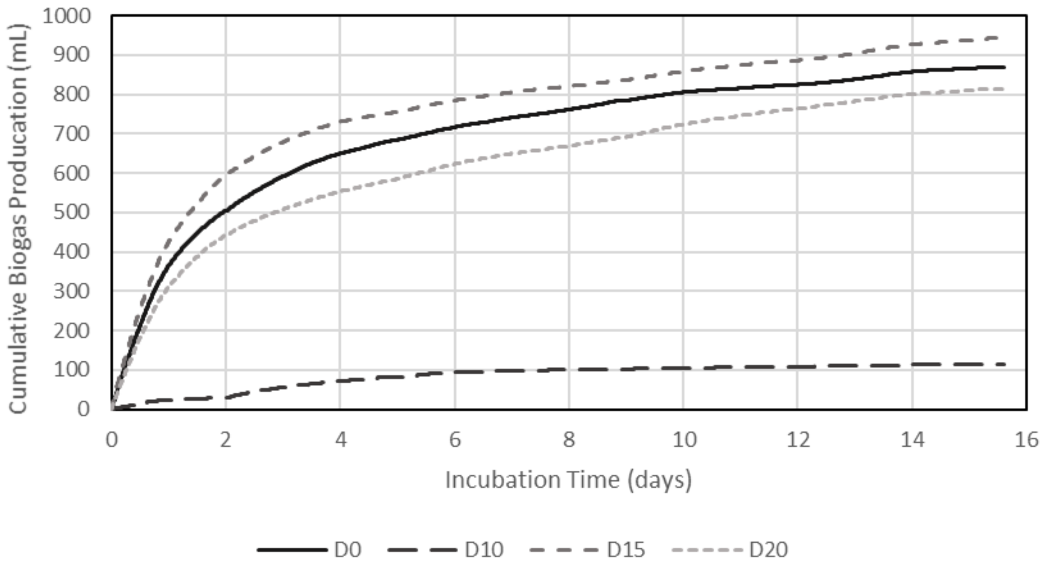

Figure 4.31: Annual Average Scenario 3 Cumulative Biogas Production

As seen in **Figure 4.31**, the respirometer channel for D10 had an issue. As other parameters were not affected, it is believed that it was an issue with logging biogas production, not the actual digestion setup.

Biogas composition was very consistent across all ferric chloride doses tested, as shown in **Figure 4.32**.

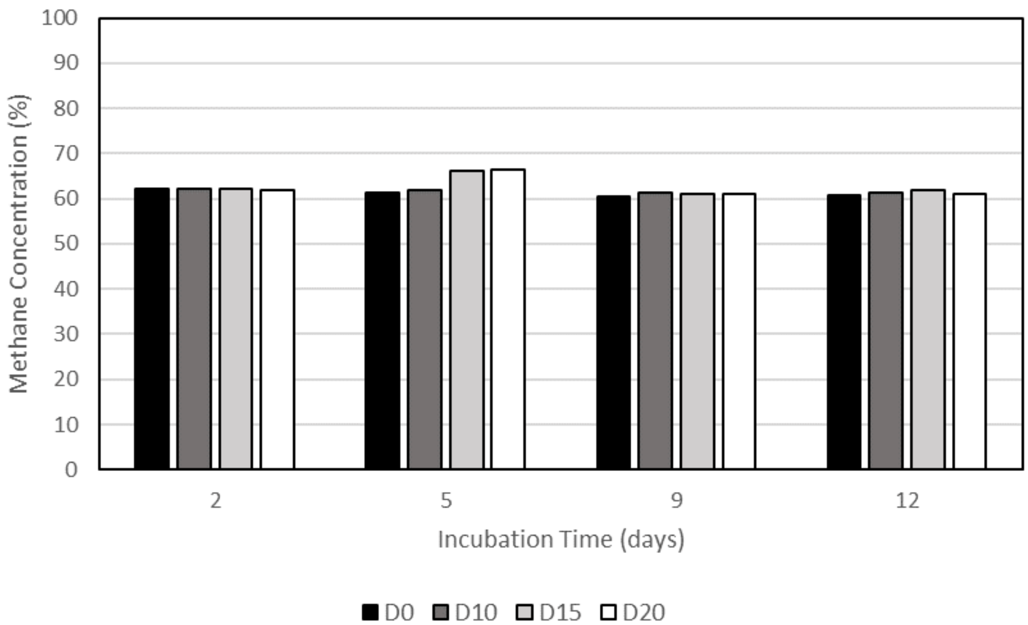

Figure 4.32: Annual Average Scenario 3 Biogas Methane Content

Table 4.22: Annual Average Scenario 3 Biogas Composition

	Ferric Dose to Primary Influent	Unit	Methane	Other
No pH Adjustment				
D0	0 mg Fe L^{-1}	%	61.13	38.87
D10	10 mg Fe L^{-1}	%	61.61	38.39
D15	15 mg Fe L^{-1}	%	62.75	37.25
D20	20 mg Fe L^{-1}	%	62.58	37.42

Methane yield was determined based off biogas production, average methane concentration and volatile solids loading to the digester. It does not appear that ferric chloride dose significantly affects methane yield, as shown in **Figure 4.33**.

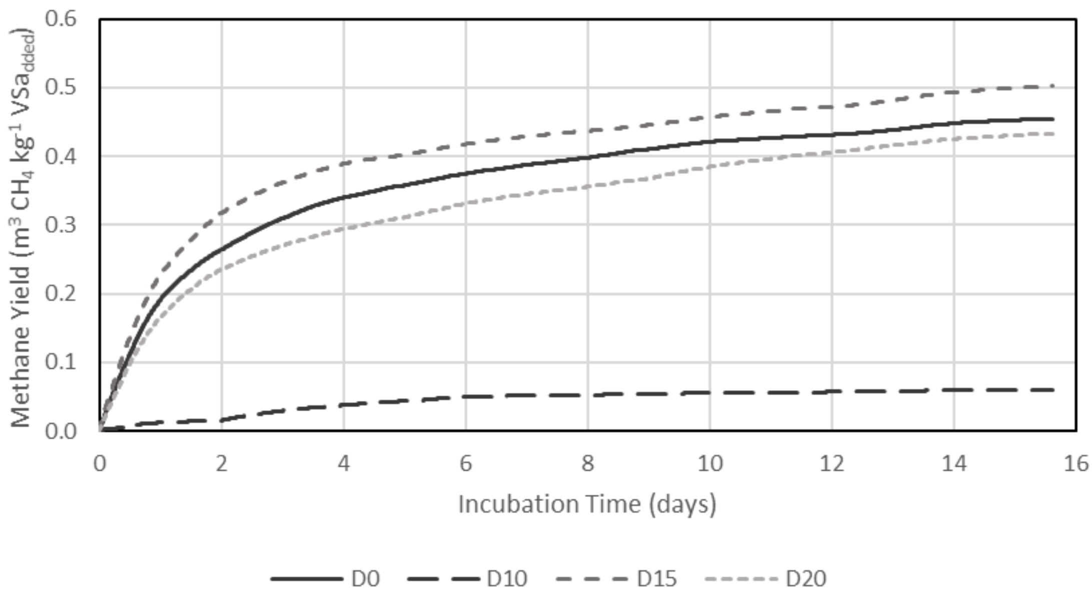

Figure 4.33: Annual Average Scenario 3 Cumulative Methane Yield

The overall methane yield not being affected by ferric chloride dosing is in line with the findings of Johnson, et al. (2003), although that study found a decrease in biogas production and increase in methane content, the other methane yield was unaffected by the ferric chloride dosing in secondary treatment.

4.1.3.5. Capillary Suction Time Tests

Duplicate capillary suction time (CST) tests were completed on all samples after digestion to determine the affect on dewaterability. **Table 4.23** outlines the average CST for each sample after digestion. CST is higher for all sludges dosed with ferric chloride as compared to the control dose, indicating chemical phosphorus removal at the HPO reactors could have a negative effect on the downstream dewatering process.

Table 4.23: Annual Average Scenario 3 Capillary Suction Times After Digestion

	Ferric Dose to Primary Influent	Unit	CST
D0	0 mg Fe L^{-1}	sec	214
D10	10 mg Fe L^{-1}	sec	230
D15	15 mg Fe L^{-1}	sec	224
D20	20 mg Fe L^{-1}	sec	221

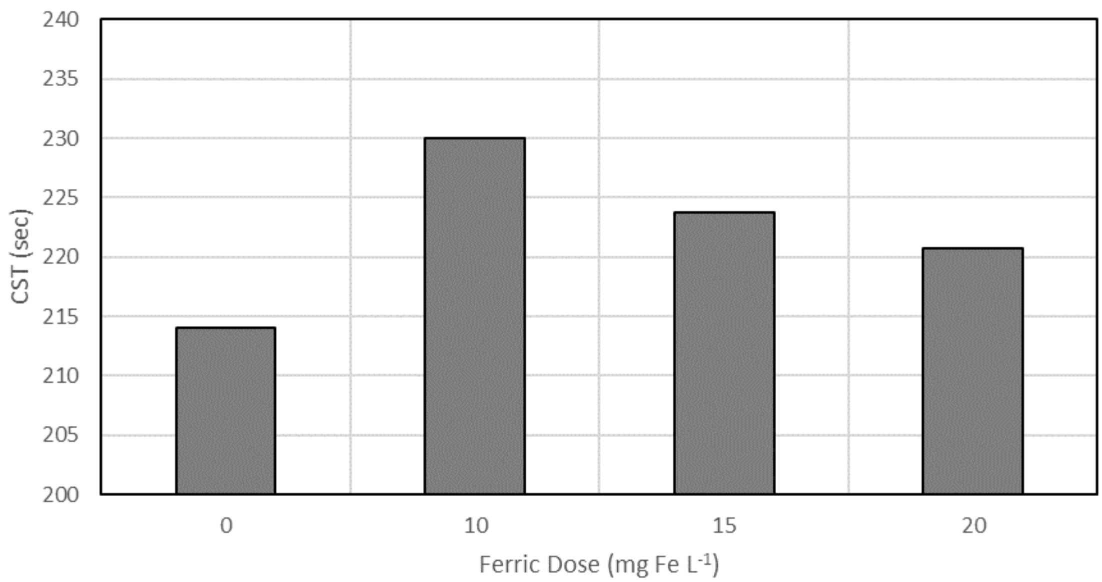

Figure 4.34: Annual Average Scenario 3 Capillary Suction Times

4.2. Phase 2: Maximum Month Conditions

4.2.1. Scenario 1: Increased Side Stream Chemical Phosphorus Removal

4.2.1.1. Jar Test

Primary sludge samples collected from the NE and sludge collected from the WE sludge holding tank were analyzed upon arrival to the Lab and presented in **Table *4.24***. The NE primary sludge and the WE holding tank sludge were combined at a ratio of 3:1. Characteristics of the mixture of NE primary sludge and WE sludge were analyzed and presented in **Table *4.24***. Total phosphorus was not analysed for Scenario 1 Max Month Conditions due to time restraints, inconsistencies found in Annual Average Conditions analysis, and the goal of Scenario 1 being an ortho phosphorus concentration, not total phosphorus.

Table 4.24: Maximum Month Scenario 1 Raw Sample Characteristics

Parameter	Unit	NE Primary Sludge	WE Sludge	NE Primary Sludge + WE Sludge
pH		6.38	5.60	5.88
Alkalinity	mg $CaCO_3$ L^{-1}	4040	740	2180
TS	mg L^{-1}	23,878	44,008	47,626
VS	mg L^{-1}	15,512	35,464	32,462
Ortho-P	mg L^{-1}	34.2	383.5	174
TP	mg L^{-1}	-	-	-

Jar testing was completed on the mixture of NE primary sludge and WE holding tank sludge for four different ferric doses based on previously determined doses using BioWin to predict a soluble ortho-phosphorus concentration of 20 mg L^{-1} in the centrate. The four ferric doses prior to digestion were 0, 135, 250, and 500 mg Fe L^{-1} of sludge; the control dose, the current dose for hydrogen sulfide control, half the BioWin predicted dose, and the BioWin predicted dose, respectively (AECOM 2020). A reaction time of 5 minutes rapid mixing (200 rpm) and 15 minutes of slow mixing (80 rpm) was used for all doses. A total of four sets of jar tests were completed: with no pH adjustment, a duplicate of no pH adjustment, with pH adjusted to 6, and with pH adjusted to 7. The results of the four sets of jar tests are presented in **Figure 4.35**, **Table *4.25***, **Table *4.26***, and **Table *4.27***, with the no pH adjustment shown as the average of the duplicate sets.

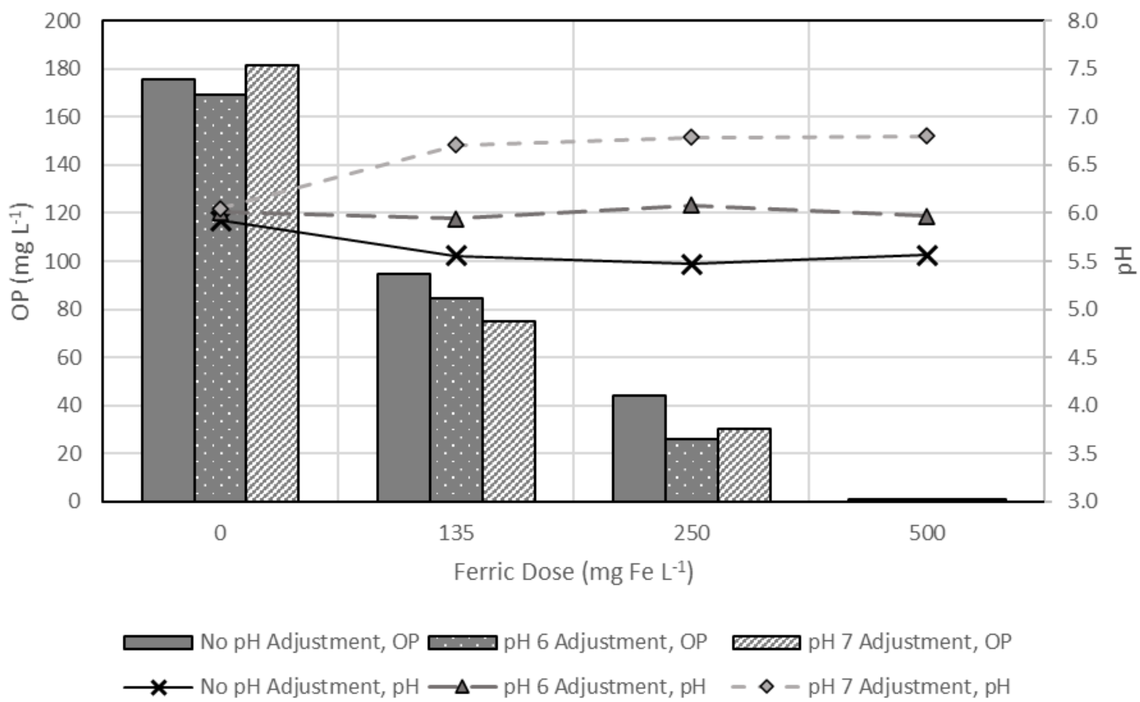

Figure 4.35: Soluble Ortho-Phosphorus and pH for Maximum Month Scenario 1 Jar Tests

Table 4.25: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Maximum Month Scenario 1 Jar Tests - No pH Adjustment

Parameter	Unit	D0	D135	D250	D500
Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
pH		5.93	5.56	5.47	5.57
Ortho-P	mg L^{-1}	175.6	94.9	44.3	0.89
TP	mg L^{-1}	-	-	-	-

Table 4.26: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Maximum Month Scenario 1 Jar Tests - pH Adjusted to 6

Parameter	Unit	D0 (pH 6)	D135 (pH 6)	D250 (pH 6)	D500 (pH 6)
Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
pH		6.01	5.94	6.08	5.97
Ortho-P	mg L^{-1}	169.4	84.8	25.8	0.746
TP	mg L^{-1}	-	-	-	-

Table 4.27: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Maximum Month Scenario 1 Jar Tests - pH Adjusted to 7

Parameter	Unit	D0 (pH 7)	D135 (pH 7)	D250 (pH 7)	D500 (pH 7)
Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
pH		6.05	6.71	6.79	6.80
Ortho-P	mg L^{-1}	181.6	75.0	30.0	0.71
TP	mg L^{-1}	-	-	-	-

4.2.1.2. BMP Test

After the 20 minutes of reaction time, 50.0 mL of the sludge from the jar test was added to 450.0 mL of NE digested sludge to replicate the current digester volumetric loading of 0.10 $m^3/m^3{*}d$ based on historical data for the NE for maximum month. The characteristics of the digested sludge sampled from the NEWPCC used as inoculum for the BMP test is presented in **Table 4.28**.

Table 4.28: Maximum Month Scenario 1 Digester Inoculum Raw Characteristics

Parameter	Unit	NE Digested Sludge
pH		7.23
Alkalinity	mg $CaCO_3$ L^{-1}	2940
TS	mg L^{-1}	15,384
VS	mg L^{-1}	8,552
Ortho-P	mg L^{-1}	37.2
TP	mg L^{-1}	-

Characteristics of the sludge pre and post-digestion are provided in **Table 4.29**, **Table 4.30**, and **Table 4.31**.

Table 4.29: Pre- and Post-Digestion Sludge Characteristics for Maximum Month Scenario 1 BMP Test - No pH Adjustment

	Parameter	Unit	D0	D135	D250	D500
	Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
Pre-Digestion	pH		7.29	7.26	7.26	7.25
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-	-
	TS	mg L^{-1}	17,432	17,236	17,273	17,571
	VS	mg L^{-1}	9,996	9,794	9,821	10,006
	Ortho-P	mg L^{-1}	52.0	45.5	39.5	28.1
	TP	mg L^{-1}	-	-	-	-
Post-Digestion	pH		7.20	7.14	7.13	7.17
	Alkalinity	mg $CaCO_3$ L^{-1}	3,690	3,650	3,680	3,650
	TS	mg L^{-1}	14,655	14,738	14,892	15,033
	VS	mg L^{-1}	7,463	7,650	7,590	7,713
	Ortho-P	mg L^{-1}	65.9	59.5	53.9	42.4
	TP	mg L^{-1}	-	-	-	-

Table 4.30: Pre- and Post-Digestion Sludge Characteristics for Maximum Month Scenario 1 BMP Test - pH Adjusted to 6

	Parameter	Unit	D0 (pH 6)	D135 (pH 6)	D250 (pH 6)	D500 (pH 6)
	Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
Pre-Digestion	pH		7.32	7.28	7.27	7.28
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-	-
	TS	mg L^{-1}	18,412	18,376	18,328	18,582
	VS	mg L^{-1}	10,410	10,162	10,270	10,504
	Ortho-P	mg L^{-1}	47.4	41.4	36.0	27.4
	TP	mg L^{-1}	-	-	-	-
Post-Digestion	pH		7.10	7.09	7.16	7.10
	Alkalinity	mg $CaCO_3$ L^{-1}	3780	3740	3800	3840
	TS	mg L^{-1}	15,867	15,490	15,837	16,303
	VS	mg L^{-1}	7,837	7,620	7,787	7,860
	Ortho-P	mg L^{-1}	65.2	60.4	53.8	45.6
	TP	mg L^{-1}	-	-	-	-

Table 4.31: Pre- and Post-Digestion Sludge Characteristics for Maximum Month Scenario 1 BMP Test - pH Adjusted to 7

	Parameter	Unit	D0 (pH 7)	D135 (pH 7)	D250 (pH 7)	D500 (pH 7)
	Ferric Dose (prior to digestion)	mg L^{-1}	0	135	250	500
Pre-Digestion	**pH**		7.27	7.37	7.38	7.40
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-	-
	TS	mg L^{-1}	18,526	18,880	18,756	18,700
	VS	mg L^{-1}	10,486	10,936	10,806	10,508
	Ortho-P	mg L^{-1}	49.8	39.8	34.6	26.6
	TP	mg L^{-1}	-	-	-	-
Post-Digestion	**pH**		7.14	7.15	7.10	7.10
	Alkalinity	mg $CaCO_3$ L^{-1}	3,760	3,860	3,900	3,840
	TS	mg L^{-1}	15,647	16,403	15,763	15,900
	VS	mg L^{-1}	7,523	8,010	7,627	7,443
	Ortho-P	mg L^{-1}	66.8	56.6	56.4	45.2
	TP	mg L^{-1}	-	-	-	-

Soluble ortho-phosphorus and pH for the sludge post-digestion are shown in **Figure 4.36**. Soluble ortho phosphorus decreases with the increase of pre-digestion ferric chloride dose, however it does not appear to be affected with or without pH adjustment. pH adjustment prior to digestion does not significantly affect the pH post-digestion and all post-digestions pH levels are within the ideal pH level for mesophilic digestion (WEF, ASCE, EWRI 2010). However, this may not be the case if the digesters are constantly feed with sludge with low pH in a full scale application, as the pH buffer due to the alkalinity in the digesters may eventually be diminished.

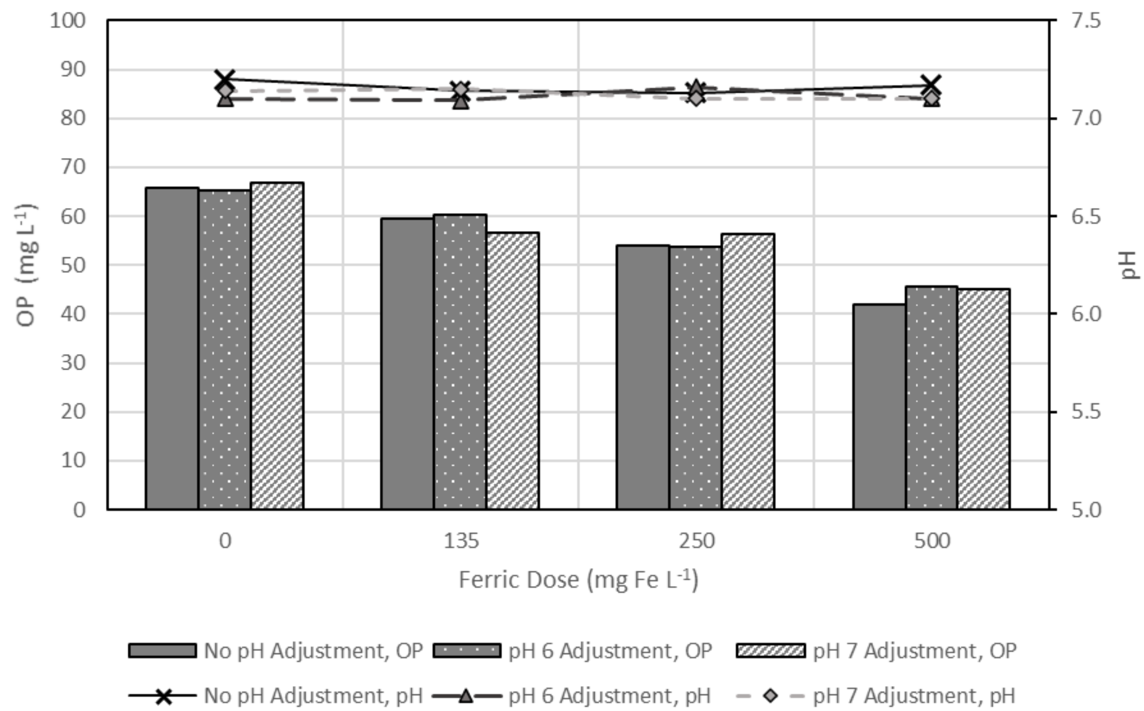

Figure 4.36: Soluble Ortho-Phosphorus and pH for Maximum Month Scenario 1 Post-Digestion

Total solids destruction and volatile solids destruction during digestion are shown in **Figure 4.37**. For all doses, with or without pH adjustment, volatile solids destruction is between 22 and 30 percent, which is well below the typical operational range of 45 to 55 percent for mesophilic digesters (WEF, ASCE, EWRI 2010). Total solids destruction does not appear to be affected by pH adjustment sludge prior to digestion, whereas volatile solids destruction increases with increasing pH sludge prior to digestion.

These results contradict the results of Ofverstorm, Sapkaite and Dauknys (2010), where a reduction in volatile solids destruction was observed when ferric chloride was dosed to a mixture of primary sludge and waste activated sludge prior to digestion.

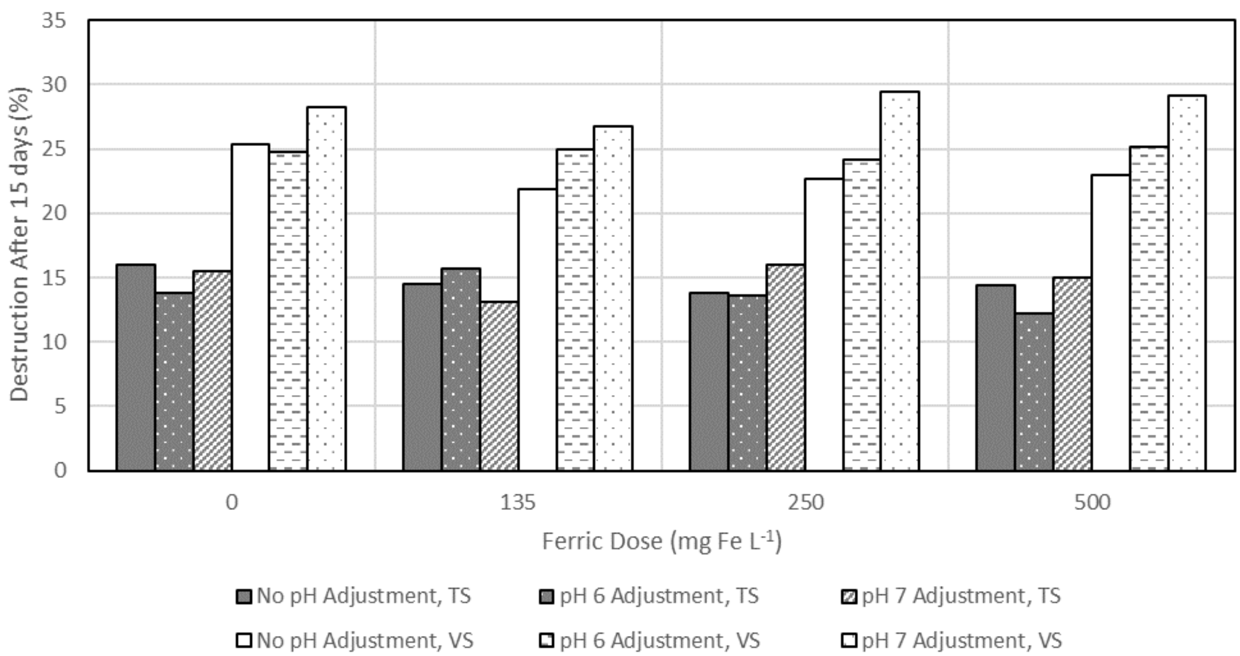

Figure 4.37: Total and Volatile Solids Destruction Maximum Month Scenario 1 Post-Digestion

Biogas produced during the 15 day BMP test was automatically logged every minute. Cumulative biogas production during the BMP test are shown in **Figure 4.38**, **Figure 4.39**, and **Figure 4.40**. There was a power outage at the Lab on day 2 of the BMP test, which is why no biogas production was logged for that period of time.

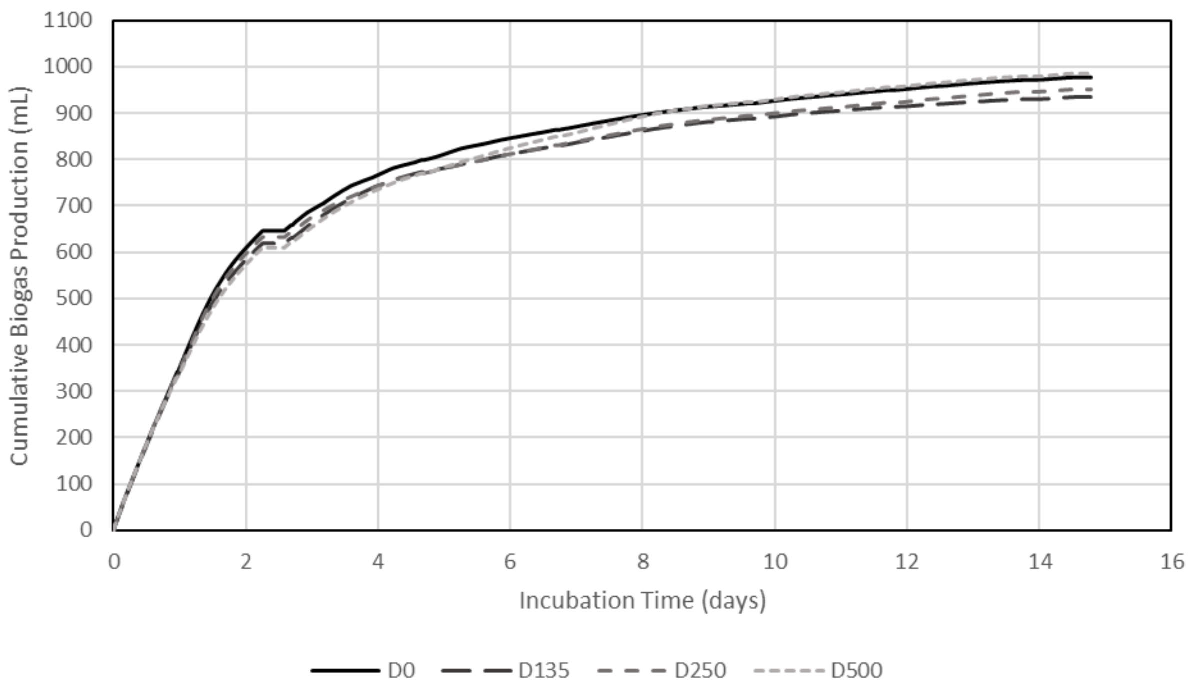

Figure 4.38: Maximum Month Scenario 1 Cumulative Biogas Production - No pH Adjustment

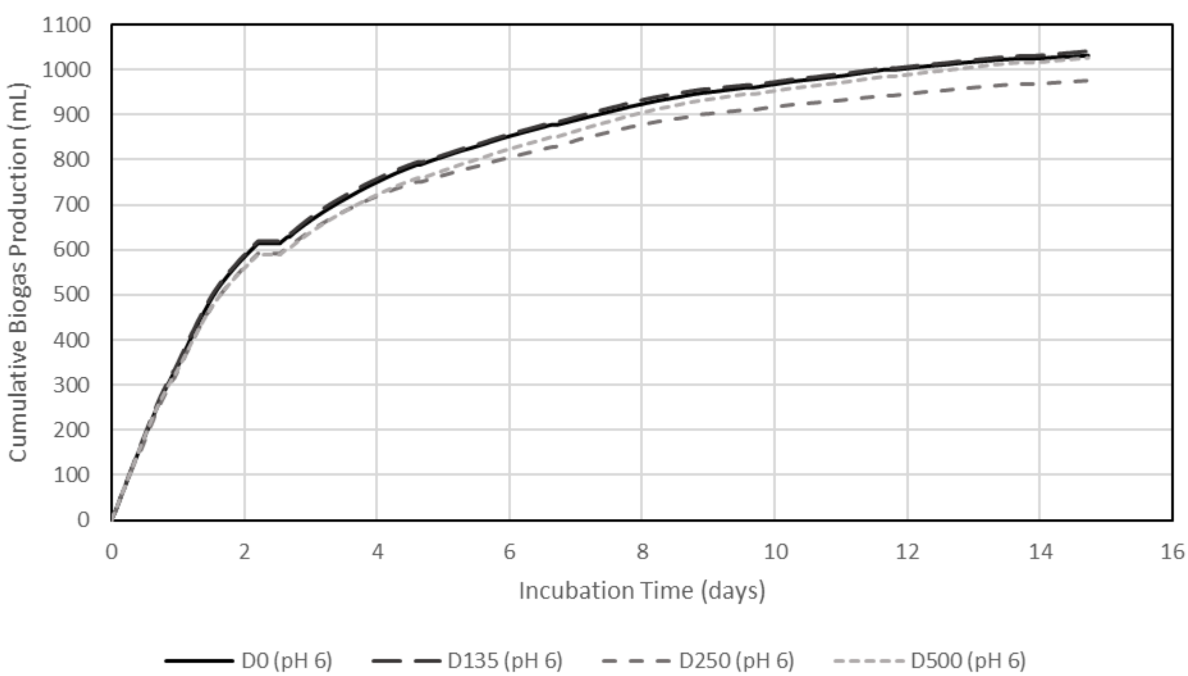

Figure 4.39: Maximum Month Scenario 1 Cumulative Biogas Production – pH Adjusted to 6

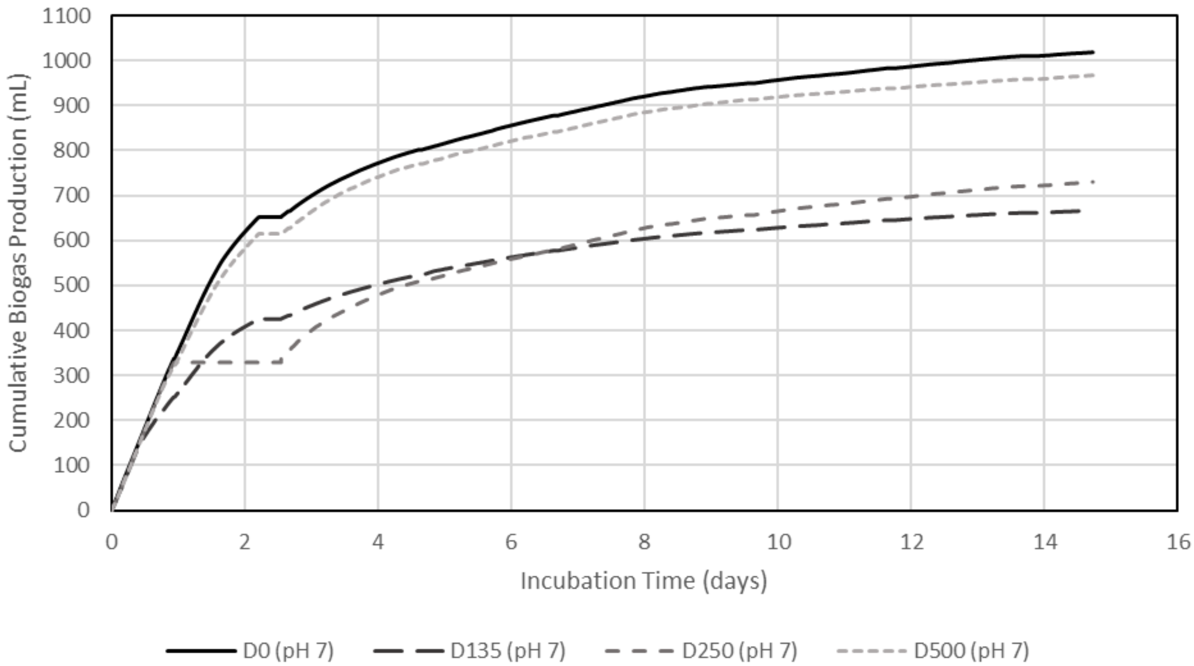

Figure 4.40: Maximum Month Scenario 1 Cumulative Biogas Production – pH Adjusted to 7

The respirometer was incorrectly installed on D250 (pH 7) following biogas composition testing on day 1 of the BMP test and was not corrected till later on day 2, which is why there is a period showing no biogas production in **Figure *4.40***. Other than that period, the biogas production for D250 (pH 7) follows similar slopes of D0 (pH 7) and D500 (pH 7). D135 (pH 7) appears to have a logging issue, similar to what was seen in Scenario 1 Annual Average Conditions, despite the replacement of tubing and parts on the respirometer to fix the problem.

Biogas composition was very consistent across all ferric chloride doses tested, as shown in **Figure 4.41**, **Figure 4.42**, and **Figure 4.43**. The methane content of biogas for sludge with and without pH adjustment was consistently around 60 to 65 percent throughout the 15 day digestion process.

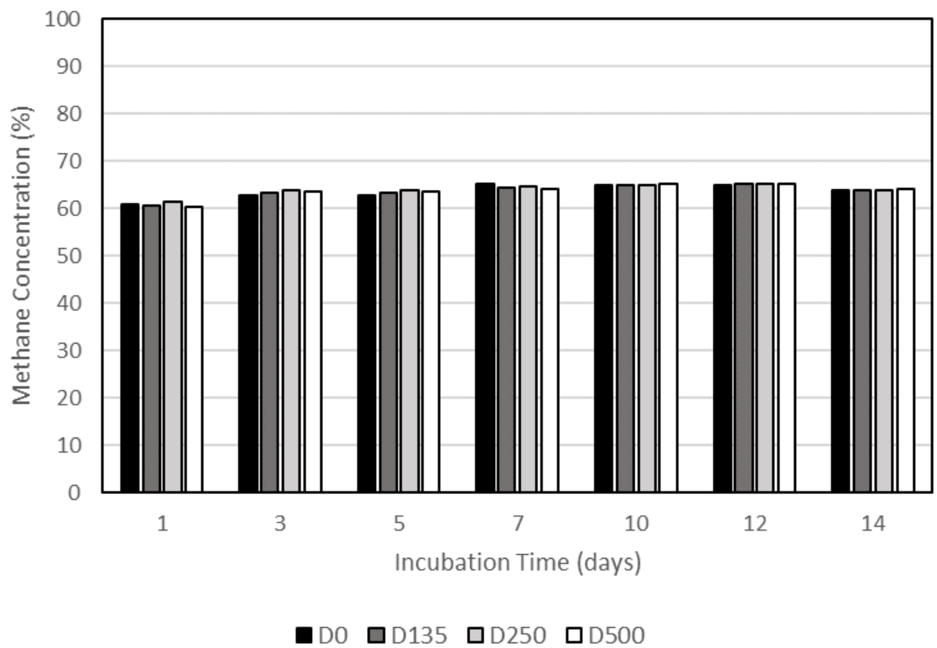

Figure 4.41: Maximum Month Scenario 1 Biogas Methane Content - No pH Adjustment

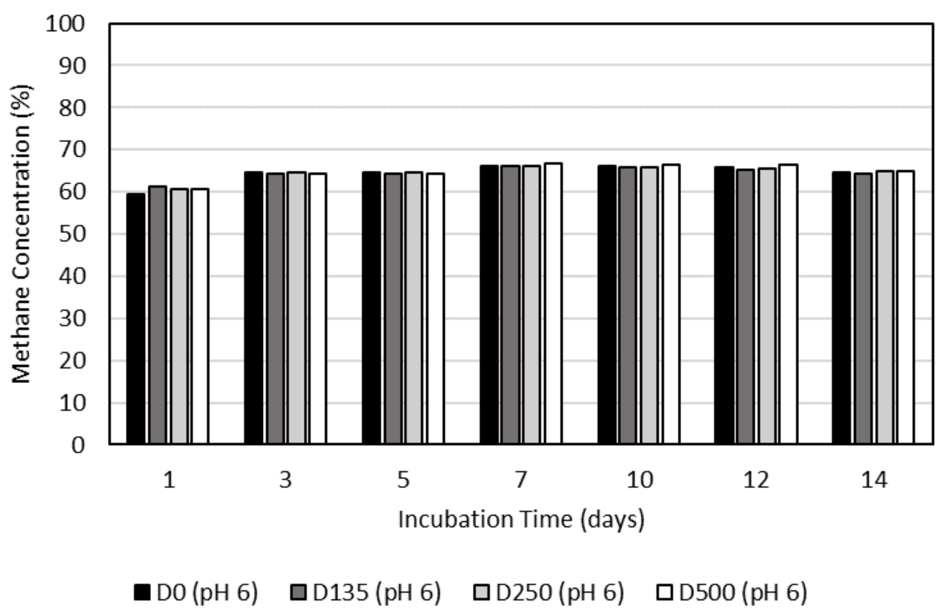

Figure 4.42: Maximum Month Scenario 1 Biogas Methane Content - pH Adjusted to 6

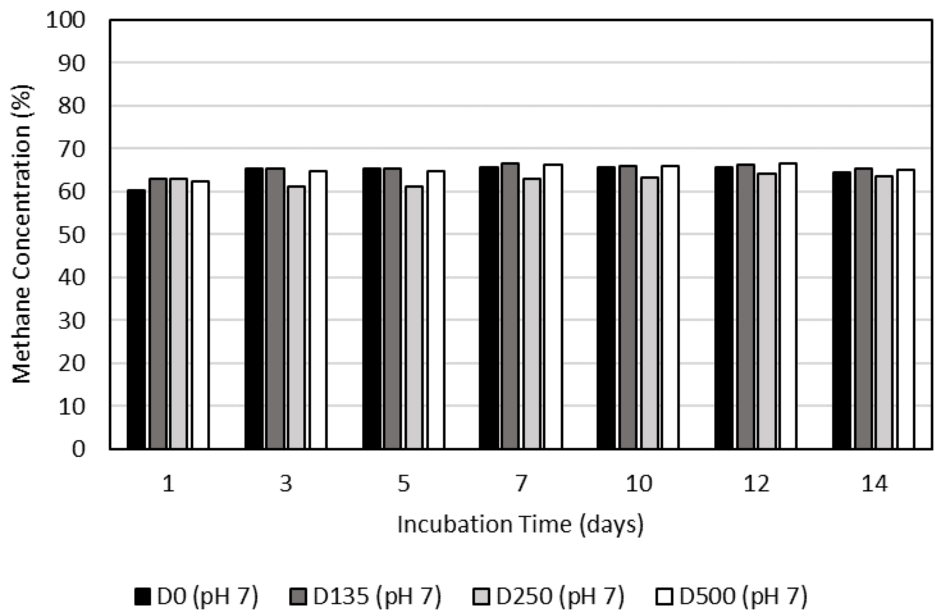

Figure 4.43: Maximum Month Scenario 1 Biogas Methane Content - pH Adjusted to 7

The average methane content of the biogas produced throughout the 15 day digestion period is summarized in **Table *4.32***. The error that occurred on D250 (pH 7) after the first biogas composition test did seem to affect the methane concentration slightly for the remainer of the digestion process.

Table 4.32: Maximum Month Scenario 1 Biogas Composition

	Ferric Dose to Sludge	Unit	Methane	Other
No pH Adjustment				
D0	0 mg Fe L^{-1}	%	63.67	36.33
D135	135 mg Fe L^{-1}	%	63.68	36.32
D250	250 mg Fe L^{-1}	%	63.96	36.04
D500	500 mg Fe L^{-1}	%	63.81	36.19
Adjustment to pH 6				
D0 (pH 6)	0 mg Fe L^{-1}	%	64.41	35.59
D135 (pH 6)	135 mg Fe L^{-1}	%	64.51	35.49
D250 (pH 6)	250 mg Fe L^{-1}	%	64.60	35.40
D500 (pH 6)	500 mg Fe L^{-1}	%	64.83	35.17
Adjustment to pH 7				
D0 (pH 7)	0 mg Fe L^{-1}	%	64.60	35.40
D135 (pH 7)	135 mg Fe L^{-1}	%	65.39	34.61
D250 (pH 7)	250 mg Fe L^{-1}	%	62.76	37.24
D500 (pH 7)	500 mg Fe L^{-1}	%	65.07	34.93

Methane yield was determined based off biogas production, average methane concentration and volatile solids loading to the digester. In all tests, it does not appear that ferric chloride dose affects methane yield, as shown in **Figure 4.44**, **Figure 4.45**, and **Figure 4.46**. However, methane yield is slightly higher for sludge with pH adjustment versus sludge without pH adjustment.

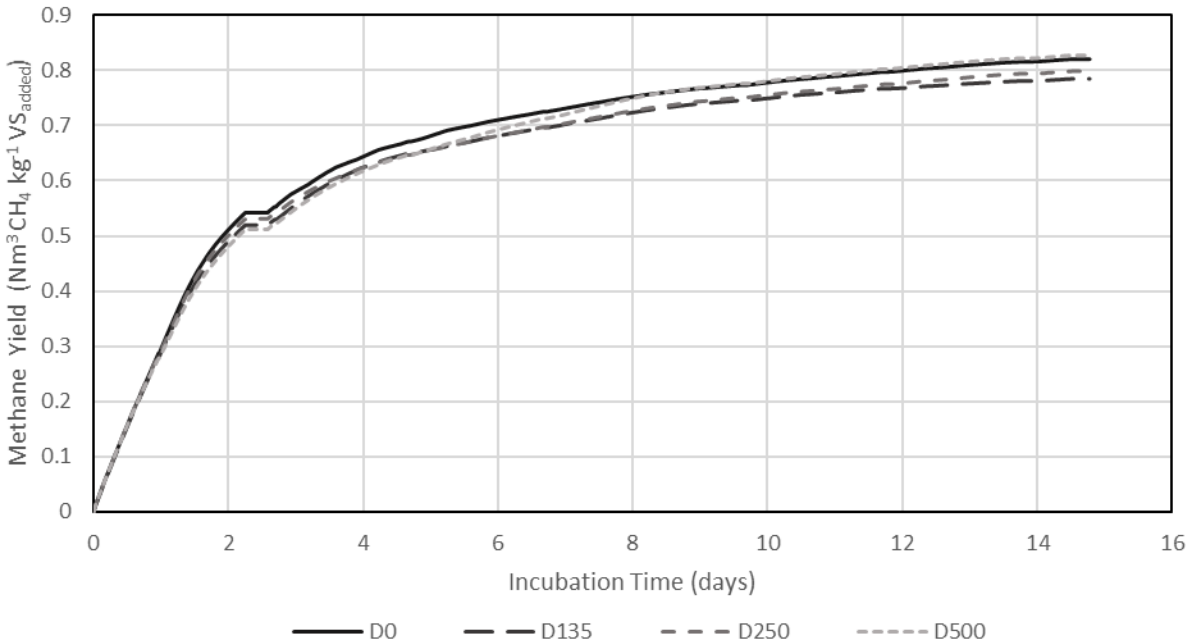

Figure 4.44: Maximum Month Scenario 1 Cumulative Methane Yield - No pH Adjustment

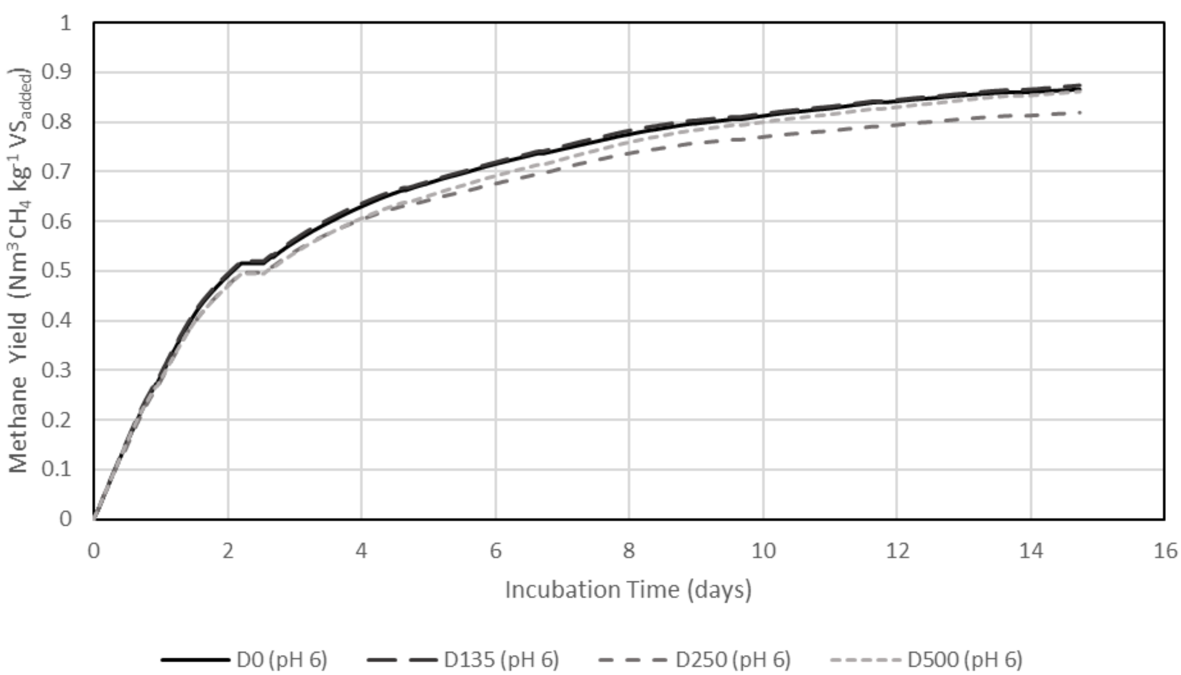

Figure 4.45: Annual Average Scenario 1 Cumulative Methane Yield - pH Adjusted to 6

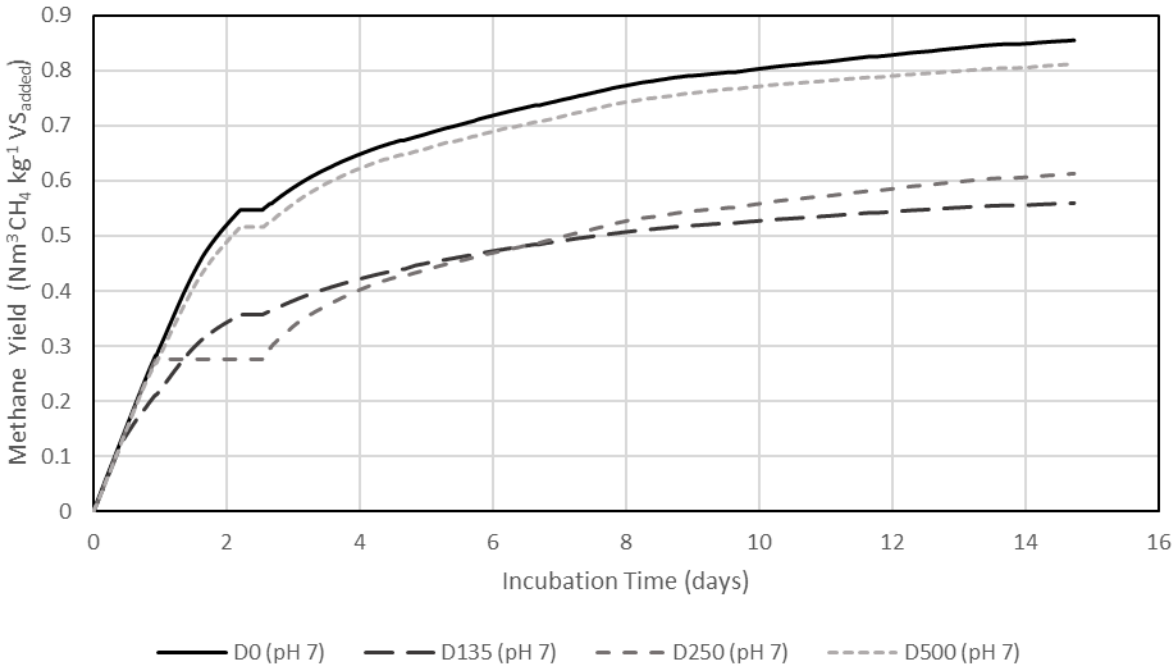

Figure 4.46: Annual Average Scenario 1 Cumulative Methane Yield - pH Adjusted to 7

As with Phase 1: Annual Average Conditions, the overall methane yield not being affected by ferric chloride dosing is in line with the findings of Johnson, et al. (2003), although that study found a decrease in biogas production and increase in methane content, the other methane yield was unaffected by the ferric chloride dosing in secondary treatment.

4.2.1.3. Post Digestion Ferric Chloride Dosing

As the objective for Scenario 1 dosing was to reach a soluble ortho phosphorus concentration of approximately 20 mg PO_4-P L^{-1} in the centrate, a second ferric dosing after digestion was necessary. A dose of 100, 80, 65, and 45 mg Fe L^{-1} of digested sludge was added to the samples with a pre-digestion dose of 0, 135, 250, and 500 mg Fe L^{-1} of sludge, respectively. After a reaction time of 7.5 minutes, all samples were analyzed again. **Figure 4.47** shows the soluble ortho phosphorus and pH of the samples after the second ferric dose.

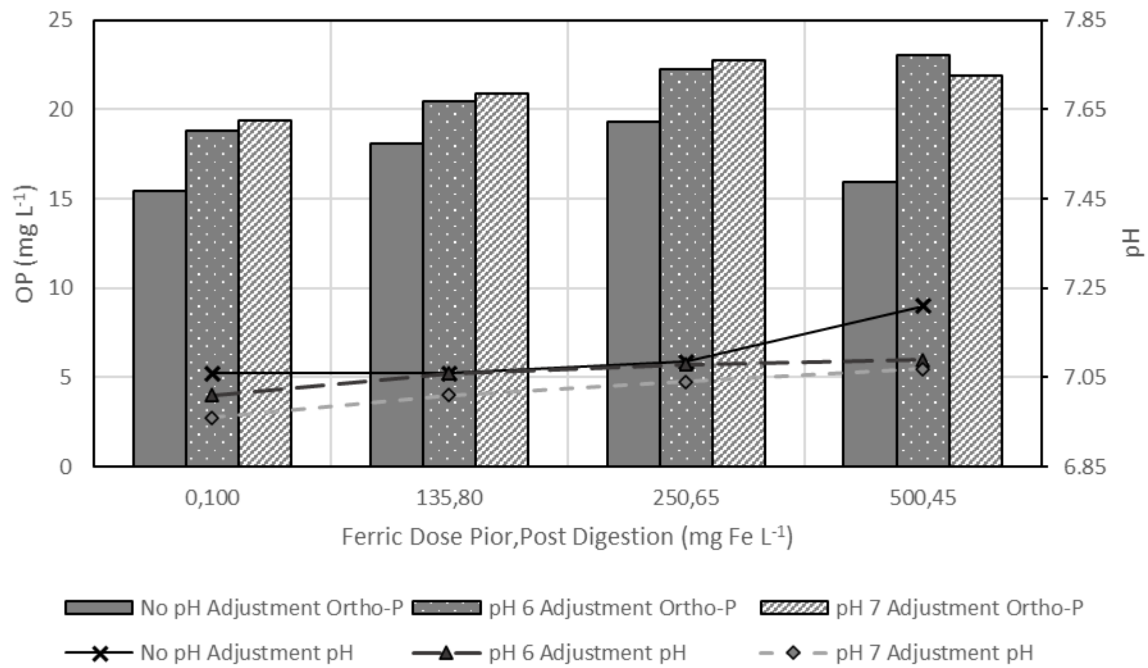

Figure 4.47: Soluble Ortho-Phosphorus and pH for Maximum Month Scenario 1 After Second Ferric Dose

4.1.1. Scenario 2: Chemically Enhanced Primary Treatment

4.1.1.1. Jar Test

Primary influent samples collected from the NE were analyzed upon arrival to the Lab and presented in **Table 4.33**.

Table 4.33: Annual Average Scenario 2 Raw Sample Characteristics

Parameter	Unit	NE Primary Influent
pH		7.06
Alkalinity	mg $CaCO_3$ L^{-1}	300
TS	mg L^{-1}	1,480
VS	mg L^{-1}	680
Ortho-P	mg L^{-1}	4.31
TP	mg L^{-1}	4.56

Jar testing was completed on the NE primary influent for three different ferric doses based on initial testing completed in Phase 1 Annual Average Conditions to determine the anticipated ratio for ferric chloride dose to ortho phosphorus removed and previously determined doses using BioWin to predict a total phosphorus concentration of 2.5 mg TP L^{-1} in the final effluent (AECOM 2020). The three ferric doses used were 0, 10 and 20 mg Fe L^{-1} of primary influent; the control dose, the predicted dose based on initial testing to reach 2.5 mg TP L^{-1} in the final effluent, the predicted dose based on initial testing to reach 1 mg TP L^{-1} in the final effluent, which is also the BioWin predicted dose to reach 2.5 mg TP L^{-1} in the final effluent, respectively (AECOM 2020). A reaction time of 7.5 minutes of slow mixing (40 rpm) was used for all doses. After 60 minutes of settling, the volume of settled sludge was recorded and sampled for further testing and analysis. Supernatant was sampled immediately following the 60 minutes of settling for further analysis, with results shown in **Table 4.34** and **Figure 4.48**.

Table 4.34: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Maximum Month Scenario 2 Jar Test Supernatant

Parameter	Unit	D0	D10	D20
Ferric Dose	mg L^{-1}	0	10	20
pH		7.22	7.19	7.19
Alkalinity	mg $CaCO_3$ L^{-1}	300	260	235
Ortho-P	mg L^{-1}	4.92	1.62	0.22
TP	mg L^{-1}	4.87	1.47	0.35

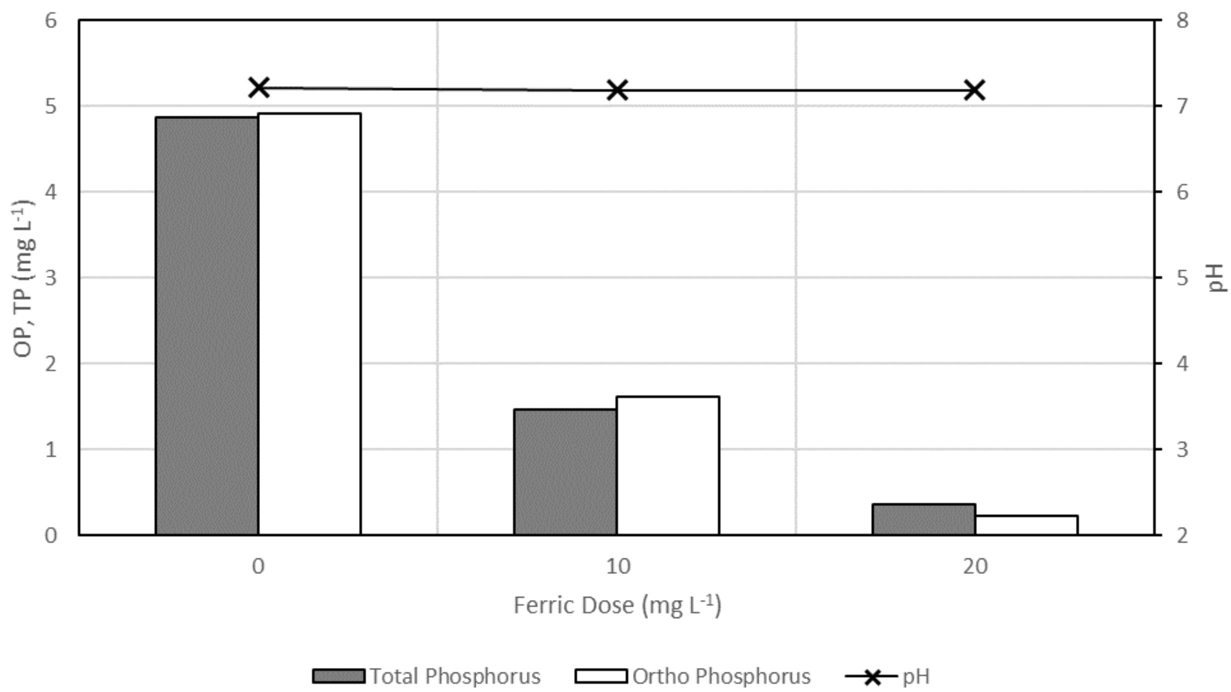

Figure 4.48: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Maximum Month Scenario 2 Jar Tests

Inconsistencies between TP and OP results were found as results show soluble ortho phosphorus higher than total phosphorus, which is not possible. Soluble ortho phosphors tests were rerun to ensure proper calibration of the flow injection analysis, with similar results. The cause of this inconsistency was not determined but is suspected to be because of delays between sampling and testing for total phosphorus.

The volume of settled sludge increased as well as the total sludge produced as the ferric dose increased, as shown in **Figure 4.49**.

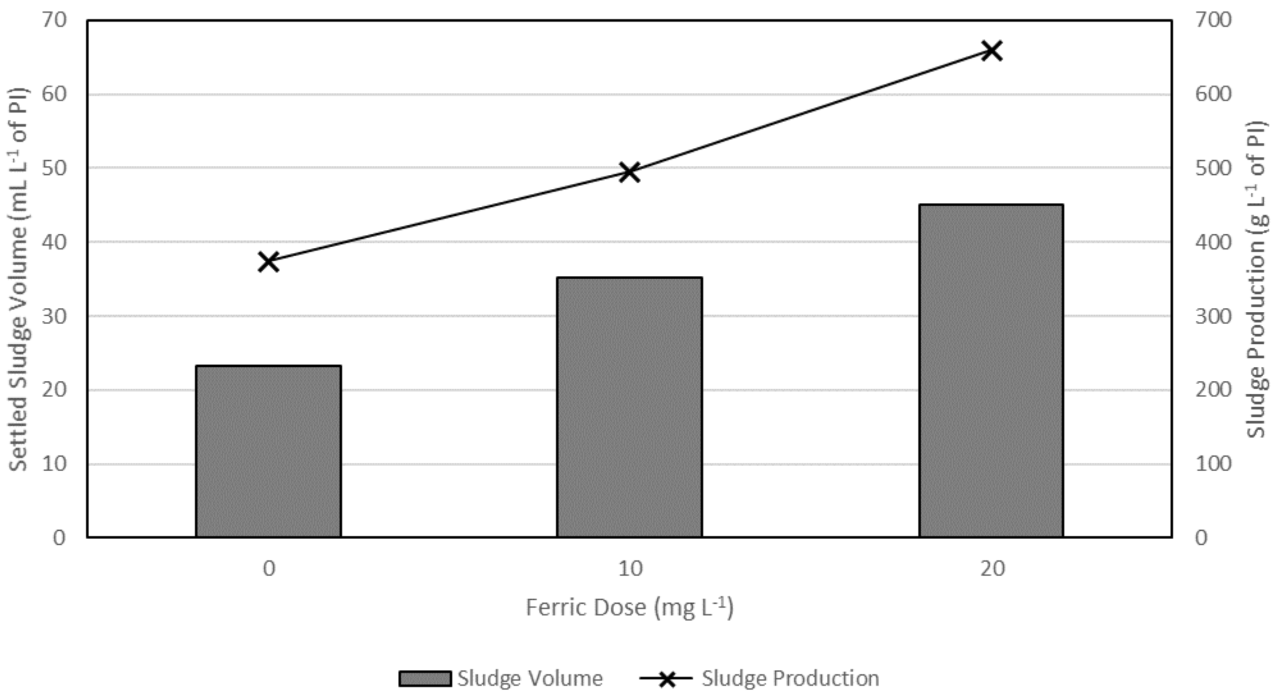

Figure 4.49: Maximum Month Scenario 2 Sludge Volume and Production

4.1.1.2. BMP Test

Sludge produced from each jar test was mixed with the WE sludge sampled from the holding tank at a ratio of 3:1. The mixed sludge was then added to digester inoculum at a volumetric loading rate of 0.10 m^3/m^3*d to replicate the current digester volumetric loading during maximum month conditions. The characteristics of the WE sludge sampled from the holding tank and digested sludge sampled from the NE used as inoculum for the BMP test is presented in **Table 4.35**.

Table 4.35: Maximum Month Scenario 2 WE Sludge and Digester Inoculum Raw Characteristics

Parameter	Unit	WE Sludge	NE Digested Sludge
pH		5.60	7.23
Alkalinity	mg $CaCO_3$ L^{-1}	740	2,940
TS	mg L^{-1}	44,008	15,384
VS	mg L^{-1}	35,464	8,552
Ortho-P	mg L^{-1}	384	37.2
TP	mg L^{-1}	-	-

Characteristics of the sludge pre and post-digestion are provided in **Table *4.36***.

Table 4.36: Pre- and Post-Digestion Sludge Characteristics for Maximum Month Scenario 2 BMP Test

	Parameter	Unit	D0	D10	D20
	Ferric Dose	mg L^{-1}	0	10	20
Pre-Digestion	**pH**		-	-	-
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-
	TS	mg L^{-1}	15,564	14,759	15,029
	VS	mg L^{-1}	8,782	8,316	8,476
	Ortho-P	mg L^{-1}	43.1	40.2	37.1
	TP	mg L^{-1}	-	-	-
Post-Digestion	**pH**		7.21	7.18	7.18
	Alkalinity	mg $CaCO_3$ L^{-1}	3,730	3,710	3,710
	TS	mg L^{-1}	13,636	13,184	13,523
	VS	mg L^{-1}	6,906	6,694	6,797
	Ortho-P	mg L^{-1}	60.3	57.7	52.4
	TP	mg L^{-1}	-	-	-

Soluble ortho-phosphorus and pH for the sludge post-digestion are shown in **Figure *4.50***. Soluble ortho phosphorus decreases as ferric chloride dose increases, whereas pH is consistent for all ferric chloride doses.

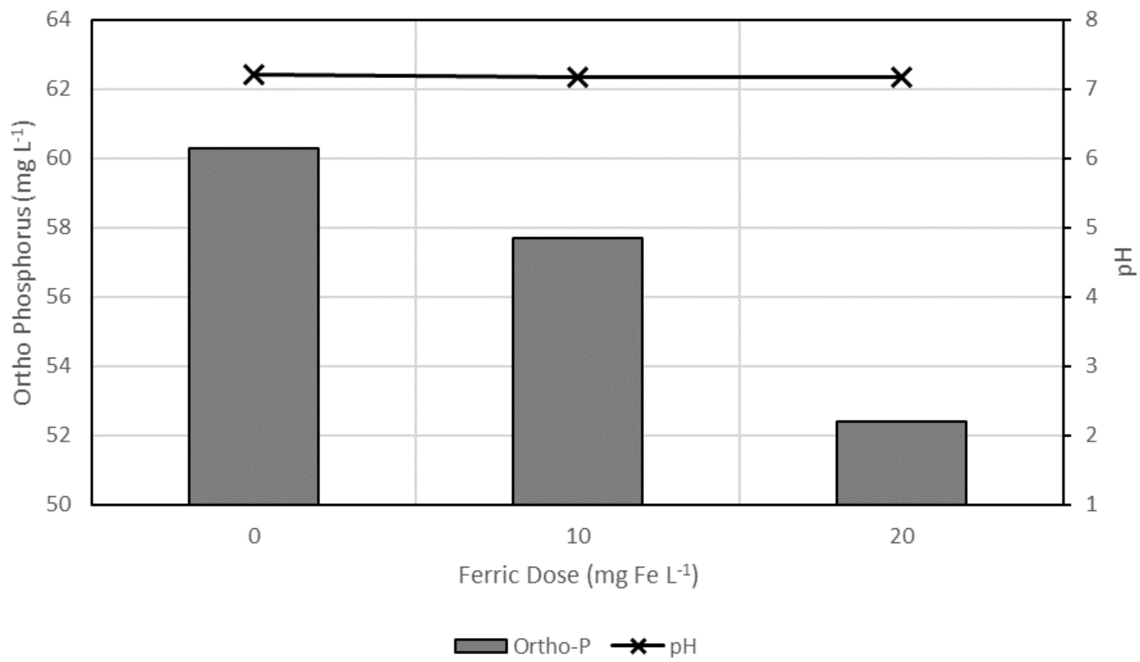

Figure 4.50: Soluble Ortho-Phosphorus and pH for Maximum Month Scenario 2 Post-Digestion

Total solids destruction and volatile solids destruction during digestion are shown in **Figure *4.51***. For all doses, volatile solids destruction is around 20 percent, which is well below the typical operational range of 45 to 55 percent for mesophilic digesters (WEF, ASCE, EWRI 2010).

These results contradict the results of Feng, Song and Jang (2016), where an increase in volatile solids destruction during digestion was observed for sludge produced in CEPT.

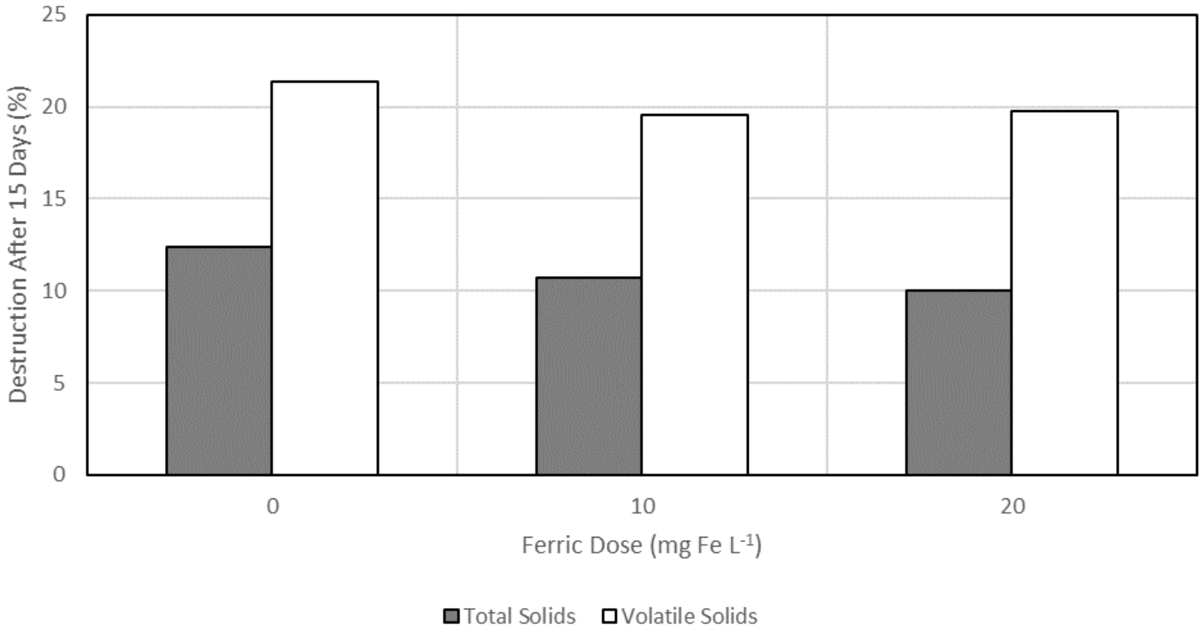

Figure 4.51: Total and Volatile Solids Destruction Maximum Month Scenario 2 Post-Digestion

Biogas produced during the 15 day BMP test was automatically logged every minute.

Cumulative biogas production during the BMP test is shown in **Figure 4.52**.

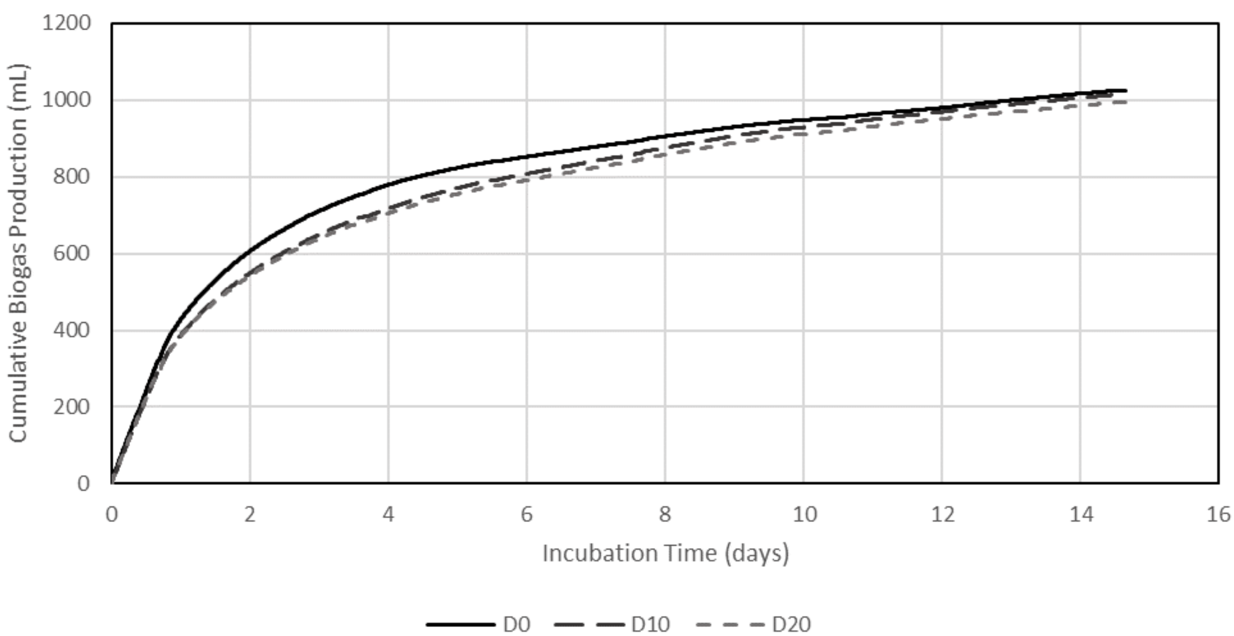

Figure 4.52: Maximum Month Scenario 2 Cumulative Biogas Production

Biogas composition was very consistent across all ferric chloride doses tested, as shown in **Figure 4.53** and **Table *4.37***.

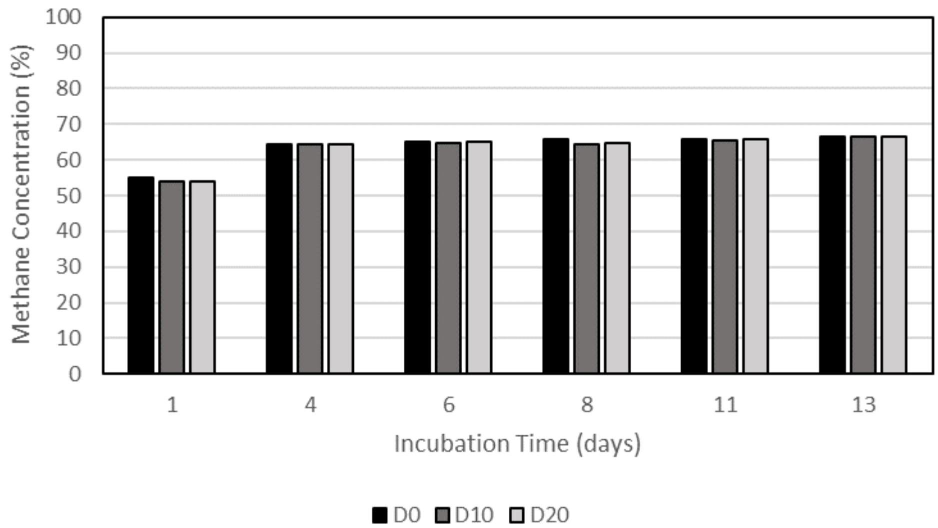

Figure 4.53: Maximum Month Scenario 2 Biogas Methane Content

Table 4.37: Maximum Month Scenario 2 Biogas Composition

	Ferric Dose to Primary Influent	Unit	Methane	Other
No pH Adjustment				
D0	0 mg Fe L^{-1}	%	63.78	36.22
D10	10 mg Fe L^{-1}	%	63.22	36.78
D20	20 mg Fe L^{-1}	%	63.41	36.59

Methane yield was determined based off biogas production, average methane concentration and volatile solids loading to the digester. In all tests, it does not appear that ferric chloride dose affects methane yield, as shown in **Figure 4.54**.

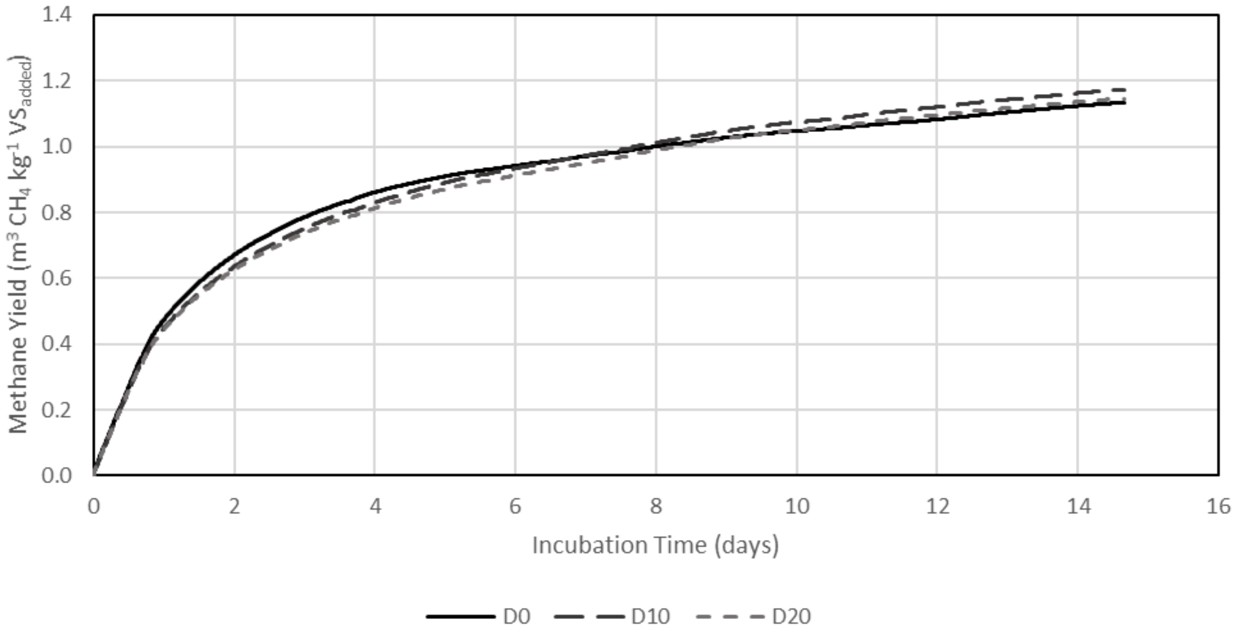

Figure 4.54: Maximum Month Scenario 2 Cumulative Methane Yield

As with Phase 1: Annual Average Conditions, the overall methane yield not being affected by ferric chloride dosing is in line with the findings of Johnson, et al. (2003), although that study found a decrease in biogas production and increase in methane content, the other methane yield was unaffected by the ferric chloride dosing in secondary treatment.

4.1.2. Scenario 3: Chemical Phosphorus Removal in HPO Reactors

4.1.2.1. Jar Test

Mixed liquor from the NE was collected from each train and combined in equal parts for testing. Mixed liquor samples collected from the NE were analyzed upon arrival to the Lab and presented in **Table 4.38**.

Table 4.38: Maximum Month Scenario 3 Raw Sample Characteristics

Parameter	Unit	NE Mixed Liquor Mixture
pH		6.58
Alkalinity	mg $CaCO_3$ L^{-1}	290
TS	mg L^{-1}	3,272
VS	mg L^{-1}	2,276
Ortho-P	mg L^{-1}	1.70
TP	mg L^{-1}	2.58

Jar testing was completed on the NE mixed liquor for three different ferric doses based on initial testing and previously determined doses using BioWin to predict a total phosphorus concentration of 2.5 mg TP L^{-1} in the final effluent (AECOM 2020). The three ferric doses used were 0, 4, and 5 mg Fe L^{-1} of mixed liquor; the control dose, the predicted dose based on initial testing to reach 2.5 mg TP L^{-1} in the final effluent, and the BioWin predicted dose to reach 2.5 mg TP L^{-1} in the final effluent, respectively (AECOM 2020). A reaction time of 7.5 minutes of slow mixing (40 rpm) was used for all doses. After 60 minutes of settling, the volume of settled sludge was recorded and sampled for further testing and analysis. Supernatant was sampled immediately following the 60 minutes of settling for further analysis, with results shown in **Table 4.39** and **Figure 4.55**.

Table 4.39: Soluble Ortho-Phosphorus, Total Phosphorus and pH for Maximum Month Scenario 3 Jar Test Supernatant

Parameter	Unit	D0	D4	D5
Ferric Dose	mg L^{-1}	0	4	5
pH		6.66	6.68	6.67
Alkalinity	mg $CaCO_3$ L^{-1}	299	301	297
Ortho-P	mg L^{-1}	1.94	0.983	0.827
TP	mg L^{-1}	5.81	2.84	2.83

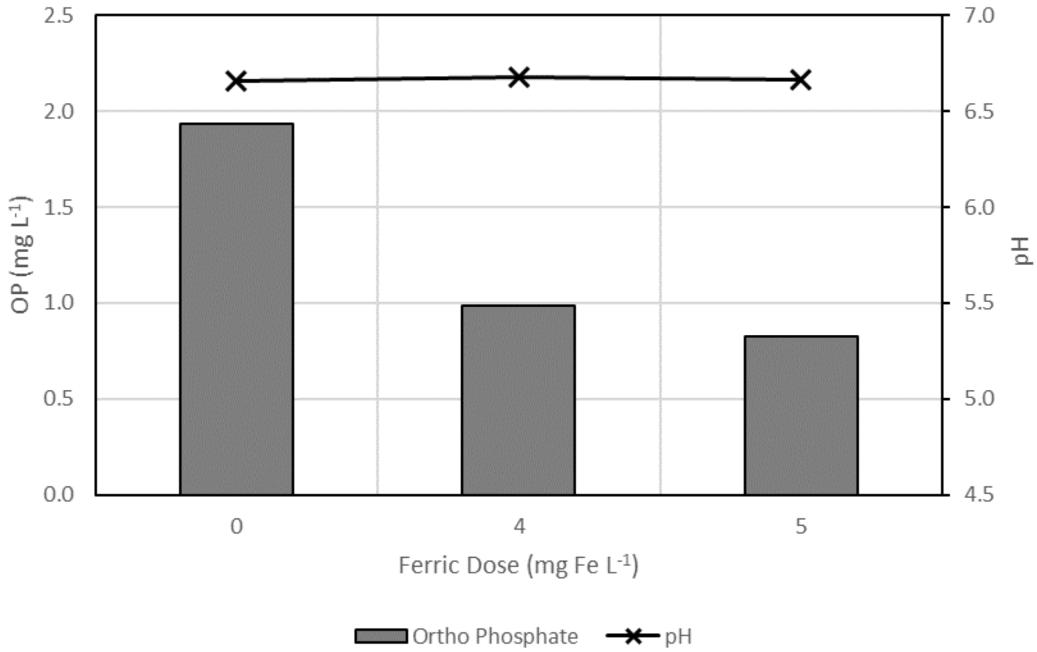

Figure 4.55: Soluble Ortho-Phosphorus and pH for Maximum Month Scenario 3 Jar Tests

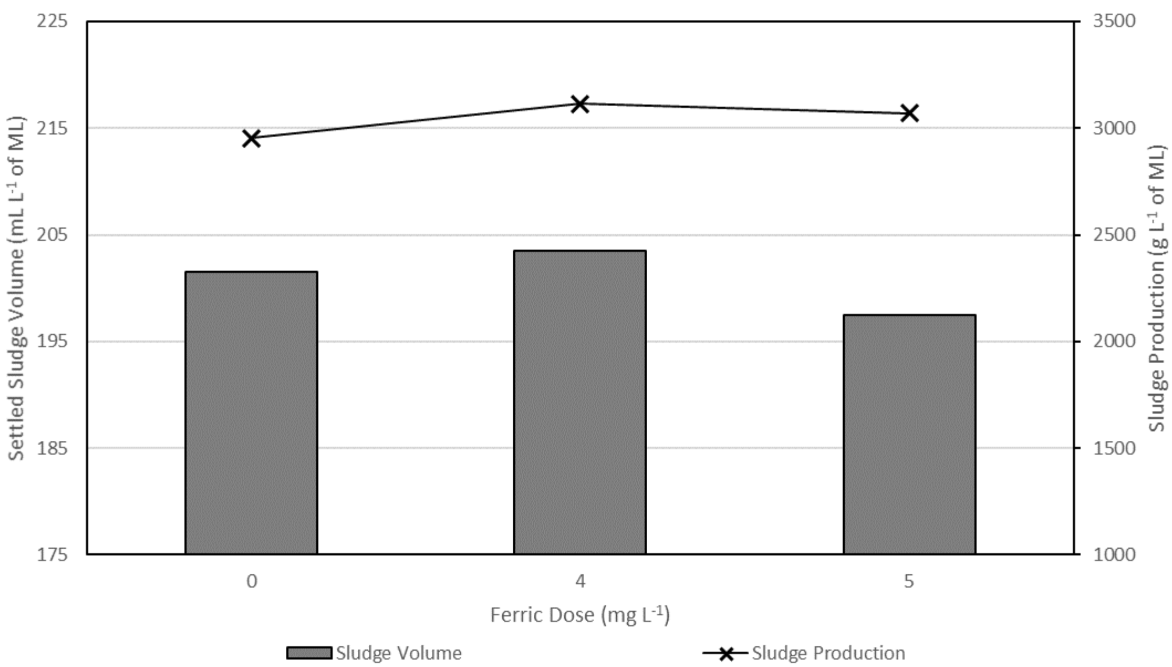

Figure 4.56: Maximum Month Scenario 2 Sludge Volume and Production

4.1.2.2. UVT Test

Ultraviolet transmittance (UVT) was measured on all supernatant samples, as shown in **Figure 4.57**. The increase in UVT correspond with an increase in UV disinfection efficiency, therefore chemical phosphorus removal at the HPO reactors is anticipated to have a positive impact on downstream UV disinfection.

As with Phase 1: Annual Average Conditions, Phase 2: Maximum Month Conditions results differ from those found by Kozak, et al. (2010), where no difference in UVT was found between secondary effluent during ferric-based chemical phosphorus removal periods and without. UVT can increase with ferric chloride addition due to the increased organics removal but can be inhibited if residual iron is present in the secondary effluent, which would suggest that there was minimal residual ferric in the jar test supernatant (Metcalf & Eddy; AECOM 2014).

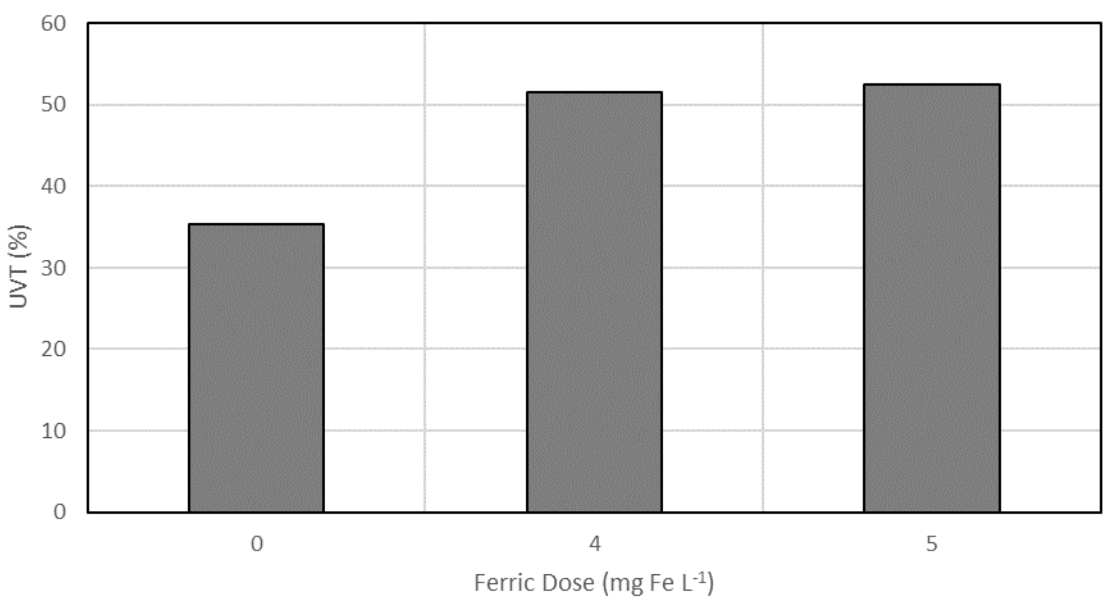

Figure 4.57: Maximum Month Scenario 3 Supernatant Ultraviolet Transmittance

4.1.2.3. BMP Test

Sludge produced from each jar test was mixed with the NE primary sludge at a ratio of 36:64. That sludge mixture was then mixed with WE sludge sampled from the holding tank at a ratio of 3:1. The mixed sludge was then added to digester inoculum at a volumetric loading rate of 0.10 $m^3/m^3 * d$ to replicate the current digester volumetric loading during maximum month conditions. The characteristics of the NE primary sludge, WE sludge sampled from the holding tank and digested sludge sampled from the NE used as inoculum for the BMP test is presented in **Table 4.40**.

Table 4.40: Maximum Month Scenario 3 NE Primary Sludge, WE Sludge and Digester Inoculum Raw Characteristics

Parameter	Unit	NE Primary Sludge	WE Sludge	NE Digested Sludge
pH		-	-	-
Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-
TS	mg L^{-1}	31,066	43,425	13,964
VS	mg L^{-1}	23,266	36,339	7,524
Ortho-P	mg L^{-1}	77.6	388	55.3
TP	mg L^{-1}	-	-	-

Characteristics of the sludge pre and post-digestion are provided in **Table *4.41***.

Table 4.41: Pre- and Post-Digestion Sludge Characteristics for Maximum Month Scenario 3 BMP Test

	Parameter	Unit	D0	D4	D5
	Ferric Dose	mg L^{-1}	0	4	5
Pre-Digestion	**pH**		7.22	7.21	7.23
	Alkalinity	mg $CaCO_3$ L^{-1}	-	-	-
	TS	mg L^{-1}	15,414	15,485	15,529
	VS	mg L^{-1}	9,136	9,198	9,138
	Ortho-P	mg L^{-1}	65.4	63.7	65.0
	TP	mg L^{-1}	-	-	-
Post-Digestion	**pH**		7.09	7.07	7.08
	Alkalinity	mg $CaCO_3$ L^{-1}	4,250	4,270	4,240
	TS	mg L^{-1}	12,816	12,559	12,644
	VS	mg L^{-1}	6,539	6,371	6,450
	Ortho-P	mg L^{-1}	93.8	93.3	93.1
	TP	mg L^{-1}	-	-	-

Soluble ortho-phosphorus and pH for the sludge post-digestion are shown in **Figure *4.58***. Soluble ortho phosphorus decreases slightly as ferric chloride dose increases apart from the highest ferric chloride dose, whereas pH is consistent for all ferric chloride doses.

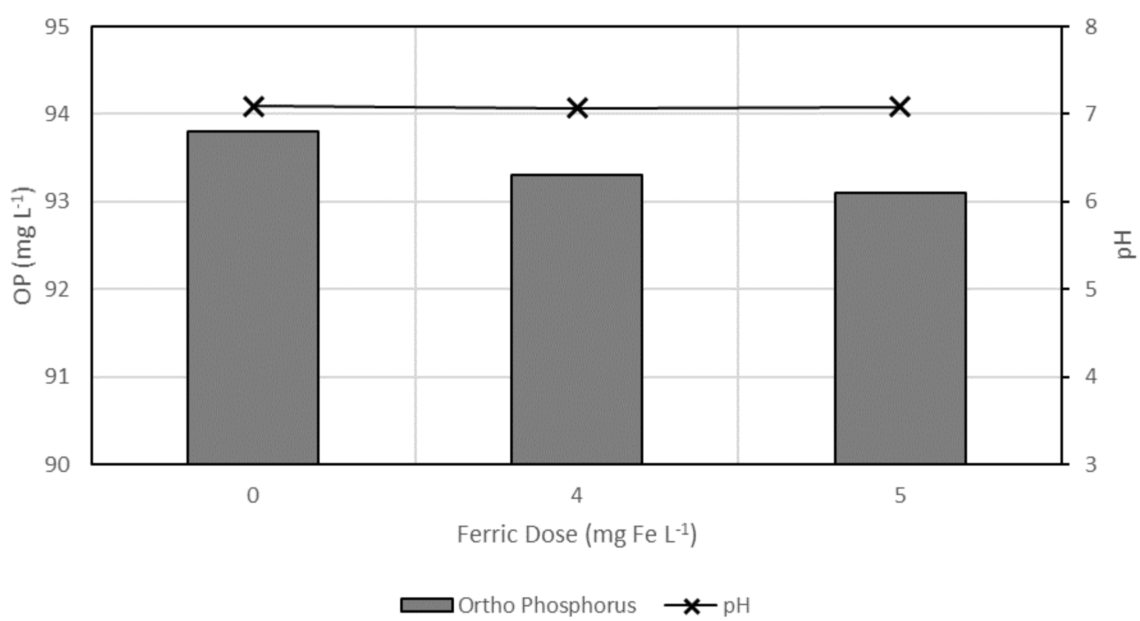

Figure 4.58: Soluble Ortho-Phosphorus and pH for Annual Average Scenario 3 Post-Digestion

Total solids destruction and volatile solids destruction during digestion are shown in **Figure *4.59***. For all doses, volatile solids destruction is around 30 percent, which is well below the typical operational range of 45 to 55 percent for mesophilic digesters (WEF, ASCE, EWRI 2010).

As with annual average conditions in Phase 1, Phase 2: Maximum Month Conditions results are in line with the results of Zhang, et al. (2013), where no significant change to solids destruction was observed in the digestion process between samples dosed with ferric chloride in the secondary treatment system and those without ferric chloride dosing.

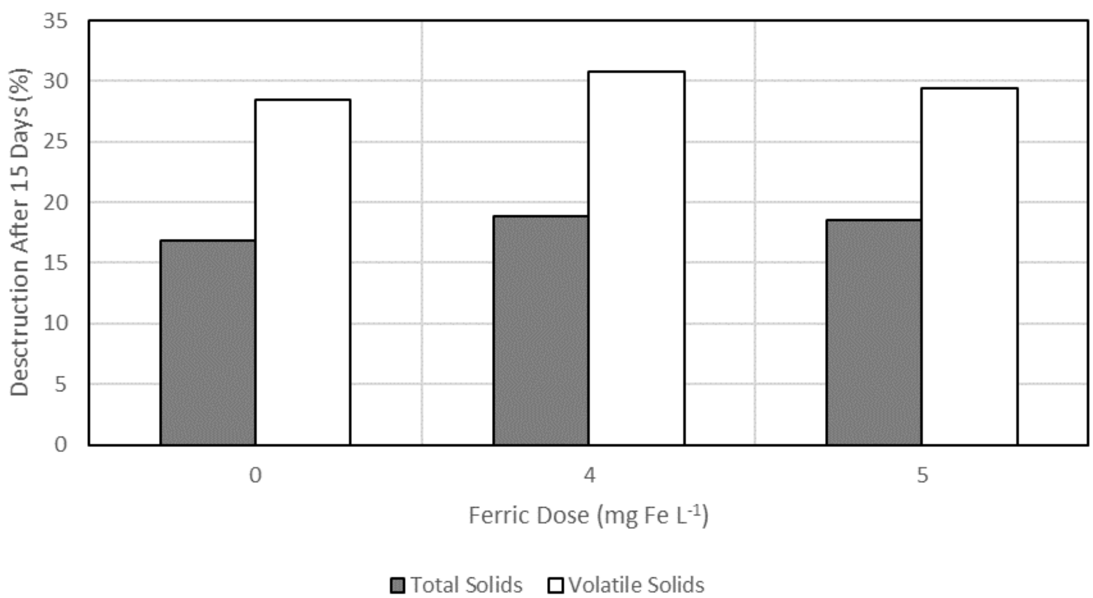

Figure 4.59: Total and Volatile Solids Destruction Maximum Month Scenario 3 Post-Digestion

Biogas produced during the 15 day BMP test was automatically logged every minute. Cumulative biogas production during the BMP test is shown in **Figure 4.60**.

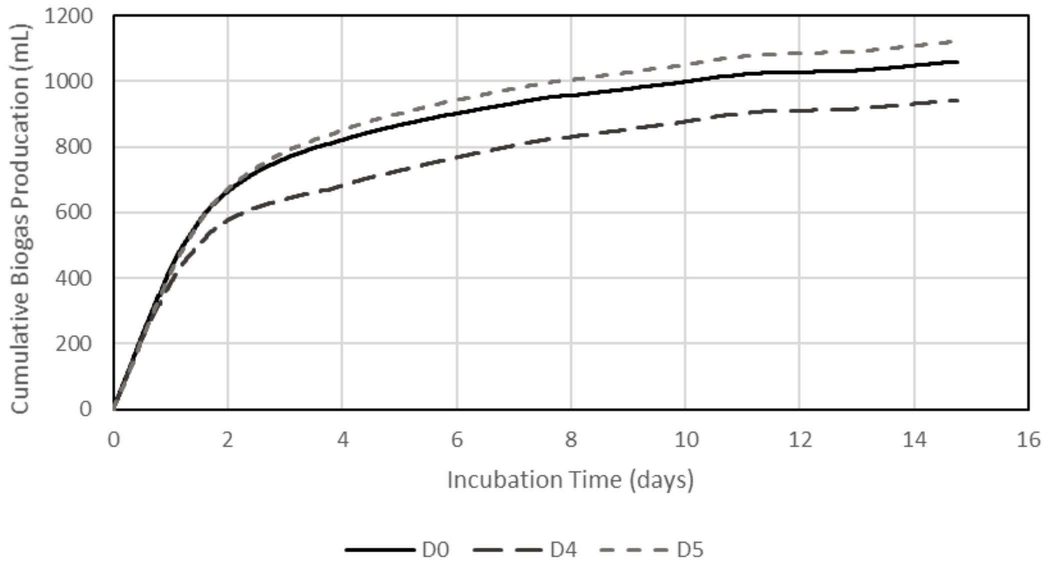

Figure 4.60: Maximum Month Scenario 3 Cumulative Biogas Production

Biogas composition was very consistent across all ferric chloride doses tested, as shown in **Figure 4.61** and **Table *4.42***.

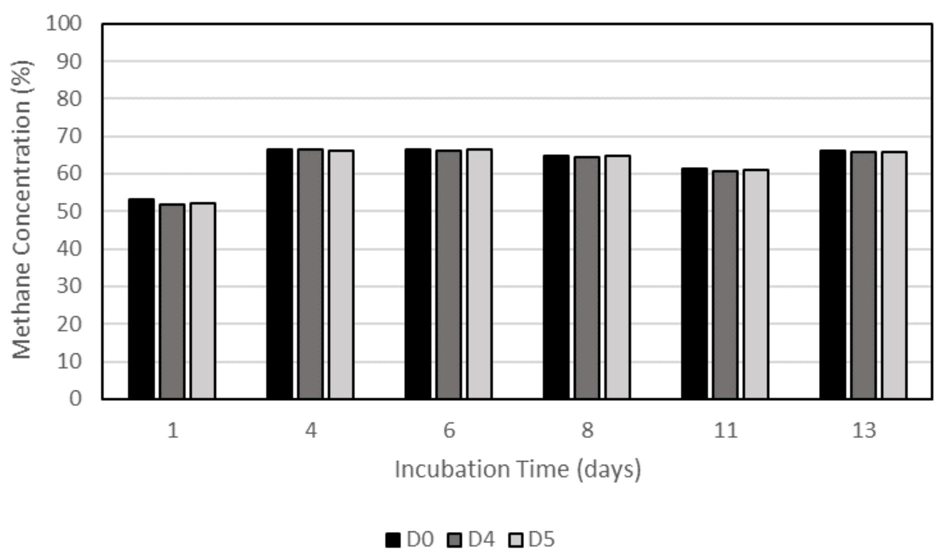

Figure 4.61: Maximum Month Scenario 3 Biogas Methane Content

Table 4.42: Maximum Month Scenario 3 Biogas Composition

	Ferric Dose to Primary Influent	Unit	Methane	Other
No pH Adjustment				
D0	0 mg Fe L^{-1}	%	63.06	36.94
D4	4 mg Fe L^{-1}	%	62.56	37.44
D5	5 mg Fe L^{-1}	%	62.72	37.28

Methane yield was determined based off biogas production, average methane concentration and volatile solids loading to the digester. It does not appear that ferric chloride dose affects methane yield, as shown in **Figure 4.62**.

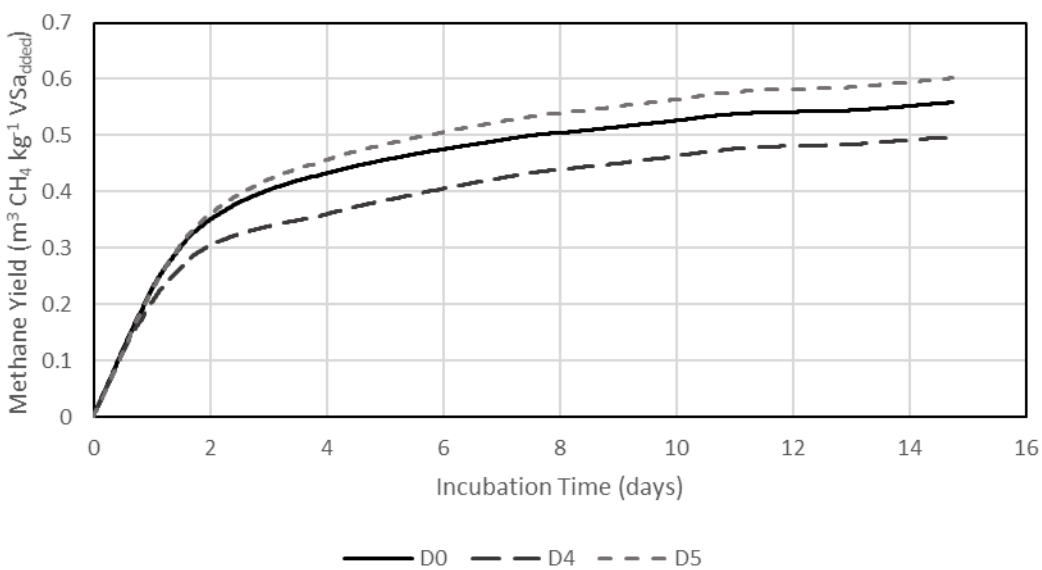

Figure 4.62: Maximum Month Scenario 3 Cumulative Methane Yield

As with Phase 1: Annual Average Conditions, the overall methane yield not being affected by ferric chloride dosing is in line with the findings of Johnson, et al. (2003), although that study found a decrease in biogas production and increase in methane content, the other methane yield was unaffected by the ferric chloride dosing in secondary treatment.

5. Conclusion

The main objective of this research was to compare the affect of chemical phosphorus removal at three different dosing locations on sludge production and secondary objectives were to evaluate downstream effects on liquid and solids stream processes, including secondary treatment, UV disinfection, digestibility, and dewaterability.

5.1. Sludge Production

Increasing the ferric chloride dose pre and post digestion, as tested in Scenario 1, does not increase the amount of sludge produced, but did not decrease the total phosphorus in the final effluent as the goal for this scenario was to maintain the existing soluble phosphorus concentration in centrate being directed to side stream treatment.

Chemically enhanced primary treatment (CEPT), as tested in Scenario 2, was found to require a ferric chloride dose of approximately 8 mg L^{-1} of primary influent during annual average and maximum month conditions to achieve an anticipated final effluent total phosphorus concentration of 2.5 mg L^{-1}, resulting in a 20 percent increase in primary sludge production.

Chemical phosphorus removal in the HPO reactors, as tested in Scenario 3, was found to require a ferric chloride dose of approximately 12 mg L^{-1} of mixed liquor during annual average conditions to achieve an anticipated final effluent total phosphorus concentration of 2.5 mg L^{-1}, resulting in a 11 percent increase in activated sludge production. Ferric chloride dosing was found to not be required during maximum month conditions to achieve an anticipated final effluent total phosphorus concentration of 2.5 mg L^{-1}.

5.2. Secondary Treatment

The effect of ferric chloride addition to primary treatment in Scenario 2 on the downstream secondary treatment was assessed by conducting specific oxygen uptake rate (SOUR) tests on the mixed liquor combined with the primary effluent from Scenario 2 jar tests, which did find a reduction in SOUR for all tests with ferric chloride addition compared to the control. This is likely due to reduced biological activity due to reduced phosphorus loading in the primary effluent dosed with ferric chloride.

5.3. UV Disinfection

The effect of ferric chloride addition to secondary treatment in Scenario 3 on the downstream UV disinfection was assessed by conducting UV transmittance tests on the secondary effluent. UV transmittance increased as ferric chloride dose to the HPO reactors increased, predicting an increase in UV disinfection efficiency when chemical phosphorus removal is implemented in secondary treatment. UVT was likely increased due to the reduction particles in the secondary effluent when ferric chloride was dosed. It is apparent that ferric chloride was not over dosed in the jar tests, as iron is a strong absorber of UV radiation and would reduce UVT if present in the secondary effluent.

5.4. Digestibility

The effect of ferric chloride addition on the downstream anaerobic digestion process was assessed by comparing volatile solids destruction after the 15 day BMP tests, biogas production, and biogas composition for all scenarios. Volatile solids destruction, biogas consumption, and biogas composition was found not to be affected by the increased ferric chloride addition prior to digestion in Scenario 1, the ferric chloride addition to primary treatment in Scenario 2, or the ferric chloride addition to secondary treatment in Scenario 3. Therefore it can be concluded that ferric chloride phosphorus removal does not affect digestibility of chemical sludge.

5.5. Dewaterability

The effect of ferric chloride addition on the downstream centrifuge dewatering process was assessed by comparing capillary suction time (CST) of the digested sludge. The CST was not affected by the increased ferric chloride addition prior to digestion in Scenario 1. The secondary dose of ferric chloride post digestion did decrease CST in all samples compared to CST post digestion prior to the secondary ferric chloride dose. The CST increased with the increase of ferric chloride dose to primary treatment in Scenario 2, ranging from a 2 to 25 percent increase compared to the control dose as ferric chloride dose increased. The CST also increased with the increase of ferric chloride dose to secondary treatment in Scenario 3, ranging from a 3 to 8 percent increase compared to the control dose. Overall, a reduction in dewaterability was found for ferric chloride addition to the liquid stream, which could be mitigated with increased polymer addition, if required.

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