ALTERNATIVE WASTE TREATMENT SYSTEM FOR POULTRY PROCESSING PLANTS

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Alternative Waste Treatment System For Poultry Processing Plants

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Abstract

The objective of this research was to design an alternative wastewater treatment system for turkey processing plants to recover energy and reduce N and P to allowable discharge levels. The objective included: 1. Determine the quantity and quality of biogas produced from the turkey processing wastewater (TPW) and COD reduction efficiency. 2. Design a waste treatment system and validate proof of concept for simultaneous P and N removal with a goal of attaining effluent concentrations of 0.1 mg/L and 4 mg/L, for P and N, respectively.

A lab-scale complete mixed anaerobic digester was used for turkey processing wastewater (TPW) digestion and biogas recovery running for 6 months. Along with the anaerobic digester, a two-sludge system called A^2N-SBR consisting of an anaerobic-anoxic sequencing batch reactor and an attached growth post-nitrification reactor was added for biological nitrogen and phosphorus removal running for 3 months. Biogas production yields of 778 $\pm$ 89 mL/gVS$_{added}$ and 951.30 mL/g COD were obtained through anaerobic digestion. Also, an energy balance was conducted on a pilot scale digester for a turkey processing plant with wastewater production of 2160 m^3/d and using a combined heat and power (CHP) enginefor conversion of biogas to heat and electricity. Although the biogas yield achieved in a complete mixed reactor was relatively lower than yields obtained in previous studies using reactors such as

UASB, still a complete mixed reactor can be a good choice for biogas recovery from TPW and can be used for codigestion with some specific turkey processing byproducts for biogas recovery.

Nitrogen and phosphorus removal in the A^2N-SBR system were 47% and 75%, respectively, and during the study the nitrogen and phosphorus removal mean concentration in effluent did not meet the nutrient limits specified in the objectives. Average TP and TN in the effluent were 3.2 mg/L and 137 mg/L, respectively. Throughout the study, the nitrification reactor biofilm was not completely developed. Incomplete nitrification and poor settling might be the reasons that quality obtained in effluent was low. To improve the process condition in A^2N-SBR, online monitoring of pH, dissolved oxygen (DO) and oxidation reduction potential (ORP) can help to optimize each stage in the SBR and stages duration can be set based on the results.

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A^2N-SBR	Anaerobic-Anoxic/Nitrification Sequencing Batch Reactor
ACR	Anaerobic Contact Reactor
AFFR	Anaerobic Fixed Film Reactor
BNR	Biological Nutrient Removal
BOD	Biological Oxygen Demand
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
rbCOD	Readily Biodegradable Oxygen Demand
sCOD	Soluble Chemical Oxygen Demand
DAF	Dissolved Air Floatation
DNPAO	Denitrifying Polyphosphate Accumulating Organisms
DO	Dissolved Oxygen
EBPR	Enhanced Biological Phosphorous Removal
HRT	Hydraulic Retention Time
LHV	Lower Heating Value
N	Nitrogen
OLAND	Oxygen-Limited Autotrophic Nitrification-Denitrification
ORP	Oxidation-Reduction Potential
P	Phosphorous
PAO	Polyphosphate Accumulating Organism

RAS	Return Activated Sludge
RBC	Rotating Biological Contactor
SBR	Sequencing Batch Reactor
SHARON	Single Reactor System for High Activity Ammonium Removal Over Nitrite
SRT	Solid Retention Time
TAN	Total Ammonia Nitrogen
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorous
TPW	Turkey Processing Wastewater
TS	Total Solids
UASB	Upflow Anaerobic Sludge Bed
UCT	University of Cape Town
VIP	Virginia Initiative Plant
VS	Volatile Solids

1. Background

1.1. Poultry processing industry in US and Virginia

Poultry is a general term referring to any kind of bird raised for the purpose of egg, feather or meat production. It includes chicken, turkey, duck and geese. Chicken and turkey are the most common examples of poultry. Poultry processing includes a series of steps designed to prepare live birds into ready-to-cook whole carcasses, cut-up parts or various forms of deboned meat products (Sams, 2001). A processing plant is a combination of mechanized operations that kill the bird, remove the inedible parts of carcasses, and package and preserve the edible parts for distribution to market. The processing steps include stunning, killing, feather removal, evisceration and chilling (Sams, 2001). Major companies in United States include Perdue Incorporated, Pilgrim's Pride, and Tyson Foods. Turkey production in the US is concentrated in two regions, the South Atlantic and the West North-Central, which account for about 60% of national production (Henry and Rothwell, 1995).

Turkey processing is a vast industry in the State of Virginia. Virginia has the fourth highest turkey production in the United States (USDA, 2010). The amount of production in 2009 was 17,000 thousand heads which is about 7% of the total production in United States (USDA, 2010).

1.2. Waste streams and overview of poultry processing plants

In automated large scale poultry processing plants, birds are hung from shackles, electrically stunned, and then bled. The general process flow of poultry processing plants is illustrated in figure 1-1(Arvanitoyannis and Ladas, 2008).

Beside the finished products which goes to market, poultry processing plants have some byproducts including blood, feathers, offal and deboning residuals which need to be treated before disposal. Table 1-1 shows the characteristics of different poultry processing byproducts.

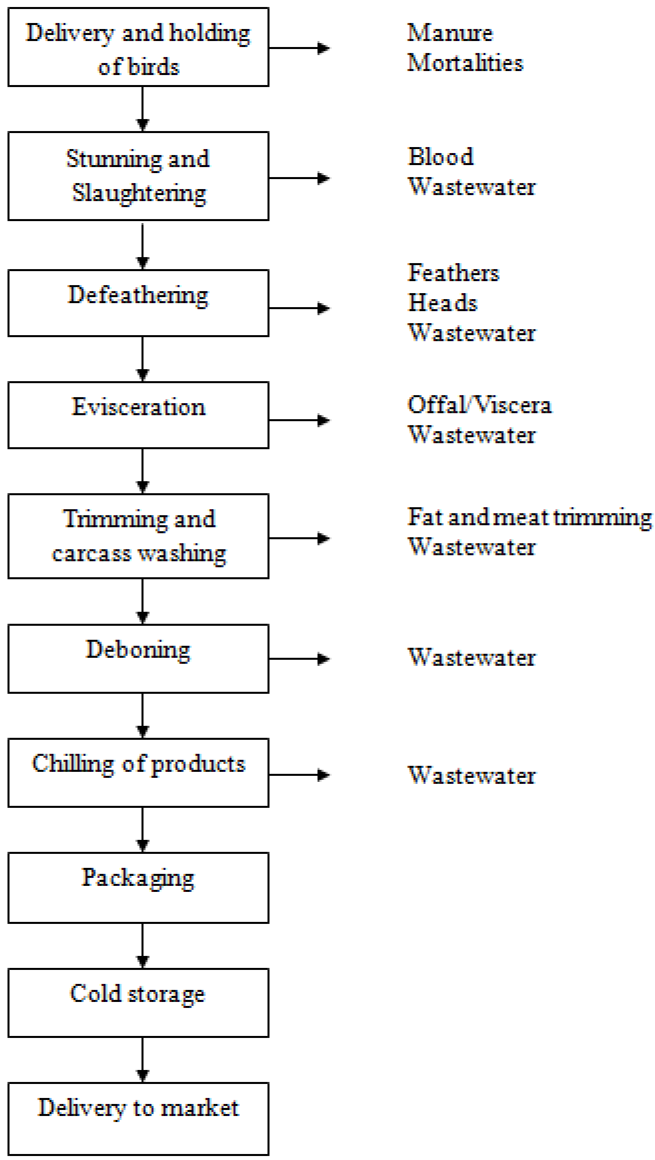

Figure 1-1. General process flow in poultry processing plants (Modified from Arvanitoyannis and Ladas, 2008)

Blood accounts for about 2% of the weight of a live bird (Salminen and Rintala, 2002). After bleeding, birds are scalded by immersing them in hot water to ease feather removal. Feather removal may be performed by rubbing the scalded carcass with rotating rubber fingers and using pressurized water jets. Dried feathers contain 85% to 99% protein. High nitrogen content in feathers and manure may lead to ammonia inhibition in anaerobic digestion. Blood, due to relatively high nitrogen content, may be used to produce ammonia. Ammonia's high buffering capacity may help to increase the VFA production before the pH drops to a level inhibitive of VFA production (Salminen and Rintala, 2002). Subsequent evisceration produces, in percentage of live weight, head (6.9%), feet (4.4%) and viscera (10%). Further processes like deboning produce trimmings and bones in varying amounts, depending on practices and processes and the degree of processing. Poultry slaughterhouses produce also a variety of spoiled meat and condemned materials, and their wastewater treatment yields waste such as screenings, fat from grease traps, settlings, excess activated sludge, and flotation tailings (Salminen and Rintala, 2002). contaminated feather, feet and processing equipment may contain several species of micro-organisms, including pathogens such as *Salmonella sp.*, *Staphylococcus sp.*, and *Clostridium sp* (Salminen and Rintala, 2002).

Wastewater from a processing plant originates from different stages of the process such as washing the birds, bleeding out, skinning, cleaning of animal bodies and cleaning of rooms and equipment. The wastewater contains blood, particles of fat, skin and meat.(Rajeshwari et al., 2000).

Table 1-1: Typical characteristics of by-products for a broiler processing house (Salminen and Rintala, 2002)

	TS (%)`	VS (% of TS)	Kjeldahl-N (% of TS)	Protein (% of TS)	Lipids (% of TS)	Methane potential (m^3/kg VS added)	Methane potential (m^3/kg wet weight)
Carcass	37	NA	NA	NA	NA	NA	0.20-0.25
Litter	52-81	61-65	3.2-5.7	NA	NA	0.14-0.22	0.10-0.15
Manure	20-47	60-76	4.6-6.7	NA	1.5-2.1	0.2-0.3	0.04-0.06
Feather	24.3	96.7	15	91	10-Jan	0.2	0.05
Blood	22	91	7.6	48	2	0.5	0.1
Offal, feet and head	39	95	5.3	32	54	0.7-0.9	0.3
Trimming and bone	22.4	68	68.6	51	22	0.6-0.7	0.15-0.17

1.3. Discharge regulations in the State of Virginia

The national pollutant discharge elimination system (NPDES) program regulates the discharge of pollutants from point sources to waters of the United States. Poultry processing plants are considered point sources and have some limitations in discharging their wastes. A poultry processing plant that discharges into the nation's waters must obtain a permit before discharge. Each processing plant must provide data showing the different types of pollutants present in the facility's effluent. The permit will then set conditions and effluent quality limitations for that specific processing plant (EPA 2010).

An NPDES permit may also include discharge limits based on federal or state water quality criteria or standards that were established to protect designated uses of surface waters, e.g. to support aquatic life. These standards, unlike the technology based standards, generally do not consider technological feasibility or costs. Water quality criteria and standards vary from state to state, depending on the use classification of the receiving body of nation's waters. Most states follow EPA guidelines that propose aquatic life and human health criteria for many of the 126 priority pollutants (EPA 2010).

Nitrogen (N), phosphorus (P) and total solid (TS) limits are the most important regulations for point source discharges such as processing plants. Each point source with significant discharge has a specific permit for N and P discharge load in Virginia. The annual mass load of total N and P and average annual concentration of these are two limits included in each permit. In the state of Virginia, each discharger should install a nutrient removal technology to achieve specific annual average total nitrogen (TN) effluent concentration and annual average total phosphorus (TP) effluent concentration. Concentration limits depend on the treatment system capacity or the equivalent load of nitrogen and phosphorus.

Total N of 1,043 kg/yr and TP of 136 kg/yr discharged by an industrial facility are considered equivalent to the load discharged from sewage treatment works with a design capacity of 151 m^3/d; 2,585 kg/yr of TN or 345 kg/yr of TP discharged by an industrial facility are considered equivalent to the load discharged from sewage treatment works with a design capacity of 378 m^3/d, and 12,927 kg/yr of TN or 1724 kg/yr of TP discharged by an industrial facility are considered equivalent to the load discharged from sewage treatment works with a design capacity of 1893 m^3/d (DEQ, 2010). Based on design capacity, discharge regulations differ from plant to plant. Different biological nutrient removal (BNR) design capacities and their equivalent N and P load are shown in table 1-2.

Table 1-2: BNR design capacities and equivalent N and P loads

Biological nutrient removal design capacity(m^3/d)	Nitrogen equivalent load (kg/yr)	Phosphorus equivalent load (kg/yr)
151	1,043	136
378	2,585	345
1,893	12,927	1,724

An owner or operator of a facility authorized by a Virginia Pollutant Discharge Elimination System, to discharge 151 m^3/d and more, or an equivalent load, should install: a. At a minimum, nutrient removal technology at any facility authorized to discharge up to and including 378 m^3/d, or an equivalent load, directly into tidal and nontidal waters or up to and including 1893 m^3/d, or an equivalent load, to nontidal waters and achieve an annual average TN effluent concentration of 8.0 mg/L and an annual average TP effluent concentration of 1.0 mg/L; and: b. State-of-the-art BNR technology at any facility that discharges 378 m^3/d and more, or an equivalent load, directly into tidal waters or 1893 m^3/d and more, or an equivalent load, directly into nontidal waters and achieve an annual average TN effluent concentration of 3.0 mg/L and an annual average TP effluent concentration of 0.3 mg/L.

Samples for nitrogen and phosphorus analysis should be collected twice a month with more than 7 days between sample collection (DEQ, 2010). Samples should be analyzed using the EPA guideline for testing procedures of pollutants (EPA, 2010).

1.4. Overview on current treatments in poultry processing plants

1.4.1. Treatments for processing byproducts

In this section, different treatment and disposal methods for poultry processing plants byproducts are reviewed. Animal waste is classified either as high-risk material, if it presents serious health risks to humans or animals, or as low-risk material, if it does not (Angelidaki and Ellegaard, 2003). Different processes have been used for treating poultry processing byproducts such as rendering, composting, landfilling, animal feed and anaerobic digestion. A description for each treatment has been provided below.

1.4.1.1. Rendering

Rendering refers to various heating processes to separate fat from meat. Rendering at 133 °C for a minimum of 20 min at 3 bars of pressure or an alternative heat treatment is needed for high-risk materials intended for animal feed or as an intermediate product for the manufacture of organic fertilizer or other derived products. Rendering produces meat-bone meal, which may be used in animal feed or as fertilizer or be further processed via anaerobic digestion or composting. In addition, rendering produces fat, which may be used for animal feed (Salminen and Rintala, 2002).

1.4.1.2. Animal feed

As rich sources of protein and vitamins, slaughterhouse byproducts are preserved with formic acid and used as animal feed. Feathers are not suitable for animal feed because they degrade poorly, but pre-treated feathers are sometimes used in making animal feed. Legislation, however, is becoming more limiting with regards to the use of slaughter byproducts for animal feed to reduce the risk of disease transmission via the feed and the food chain such as transmissible spongiform encephalopathies (TSEs) transferred through blood containing byproducts (Farrugia et al., 2005; Salminen and Rintala, 2002).

1.4.1.3. Composting

Composting, an aerobic biological process to decompose organic material, can be done in either windrows or reactors. Composting is a method to treat poultry slaughterhouse waste, including screenings, flotation tailings, grease trap residues, manure, litter, and sometimes feathers. However, waste with high moisture and low fiber content needs considerable amounts of moisture-sorbing and structural support to compost well. In addition, leaching to water, and land may present a problem, and this may also reduce the nitrogen (fertilizing) content in the compost (Salminen and Rintala, 2002).

1.4.1.4. Incineration

Incineration is one of the safest methods of disposal in case of microbial contamination. Incineration refers to technologies that use thermal destruction. Incineration of waste materials can produce energy through burning low moisture content materials. In incineration, the air emission, process conditions, and the disposal of solid and liquid residues need to be strictly controlled (Salminen and Rintala, 2002). Organic arsenicals used in poultry feed are converted to inorganic arsenicals in incineration of poultry waste, remaining in incinerator ash which can be sold as fertilizer, may be harmful (Nachman et al., 2005). Commercial incineration units are available with oil or gas burners. After-burning devices are usually installed for incineration systems to complete gas combustion and recycle fumes to reduce odors (Blake, 2004).

1.4.1.5. Anaerobic digestion

Anaerobic digestion is a biological process in which microorganisms degrade the organic matter to methane and carbon dioxide under anaerobic conditions. Methane can then be used for energy to replace fossil fuels and thereby to reduce carbon dioxide emissions. Anaerobic digestion reduces pathogens and odor, requires little land space for treatment, and may treat wet and pasty wastes (Salminen and Rintala, 2002). Also releases to air, water, and land from the process can be controlled. Codigestion of organic wastes is proven as an attractive strategy in anaerobic digestion. By codigestion of different agricultural and food processing byproducts, the C/N ratio can be optimized for anaerobic digestion and biogas recovery.

Anaerobic digestion of poultry processing by-products has some challenges. Meat processing wastes are different from other food industry wastes. They are strong wastes containing grease, blood and feces. During anaerobic digestion, protein and lipid degradation may lead to the accumulation of ammonia and long chain fatty acids (LCFAs), which are inhibitors of anaerobic microorganisms. Adsorption of LCFA onto the microbial surface has been suggested as the mechanism of inhibition, affecting transportation of nutrients to the cell (Palatsi et al., 2009). For ammonia inhibition, some mechanisms have been proposed, such as a change in the intracellular pH, increase of maintenance energy requirement, and inhibition of a specific enzyme reaction (Chen et al., 2008). The difficult nature of these wastes could be overcome by codigestion, which could be advantageous due to an improved carbon to nitrogen ratio and dilution of the inhibitory compounds (Chen et al., 2008).

One of the byproducts of poultry processing house is feathers. Feathers in particular are major concern in poultry processing plants since they are produces in significant amounts (5% of poultry body). Composed of over 90% hard to degrade beta-keratin, a fibrous and insoluble protein highly cross-linked with disulphide and other bonds feather may not be the best option for codigestion (Salminen et al., 2003; Vasileva-Tonkova et al., 2009).

Blood is another challenging byproduct in case of treatment and disposal. Anaerobic treatment of poultry blood is sensitive and prone to failure due to high levels of total ammonia resulting from the degradation of the nitrogen- rich protein components of blood. Also a pasteurization unit (with minimum requirements of 70 ° C, 60 min, particle size <12 mm) is required as a mandatory treatment (Cuetos et al., 2009).

1.4.2. Poultry Processing Wastewater Treatment

There are three steps for wastewater treatment: (i) primary treatment: separation of floating and settleable solids using screening, catch basin, dissolved air flotation (DAF) and flow equalization, (ii) secondary treatment: removal of organic matter using lagoons, activated sludge systems, extended aeration, oxidation ditches and sequencing batch reactors, and (iii) tertiary treatment: removal of N or P using biological and chemical processes (Masse and Masse, 2000).

1.4.2.1. Primary treatments: Solid reduction

Dissolved air floatation (DAF) is often used for primary treatment in poultry processing plants. In DAF, air bubbles are injected at the bottom of the flotation tank, light solids and other material such as fat and grease are transported to the surface by bubbles and scum is continuously skimmed off from the surface. In this process, either the entire or a fraction of the influent or effluent is saturated with air and then introduced into a flotation tank. Chemicals such as polymers and flocculants are often added prior to the DAF process for better performance. Various coagulant and flocculant combinations are used for the removal of organic matter and suspended particles from industrial effluents. In addition to the traditional coagulants, alum, iron salts, and lime (Metcalf and Eddy Inc., 2003), polyaluminum chloride (PAC) and organic polymers have been widely used. The cationic polymers are used as primary coagulants since they enhance the coagulation of negatively charged particles. Anionic and non-ionic polymers are referred to as either coagulant aids or flocculants used together with primary coagulants, e.g. metal salts in the flocculation stage to improve the subsequent separation unit efficiency and to reduce the coagulant dosages (de Nardi et al., 2008). Blood coagulants (e.g. aluminum sulphate and ferric chloride) and/or flocculants (e.g. polymers) are added to wastewater to increase protein clumping and precipitation as well as fat flotation (Mittal, 2006). In addition to the chemical-DAF systems, the electro-coagulation process has also proved to be an effective method for removing solids from poultry slaughterhouse wastewater (Kobya et al., 2006). Electro-coagulation reactor may be made up of an electrolytic cell with one anode and one cathode. Electro-coagulation is the electrochemical production of destabilization agents (such as Al, Fe) that brings about neutralization of electric charge for removing pollutant. The particles bond together like small magnets to form a mass when they are charged (Emamjomeh and Sivakumar, 2009).

Grit chambers, screens, settling tanks and DAF systems remain widely used, prior to the biological processes, for removing suspended solids and oil and grease. Instability of DAF system has been reported due to the changes of quality and quantity in wastewater characteristic (Del Nery et al., 2007).

1.4.2.2. COD reduction

1.4.2.2.1. Anaerobic treatments

Current anaerobic treatment processes used for processing wastewater include lagoons, anaerobic contact, up flow anaerobic sludge blanket, anaerobic sequencing batch reactor and anaerobic filter processes. Methane and carbon dioxide are produced through anaerobic treatment.

Anaerobic systems are efficient for removing a high-degree of both soluble and insoluble BOD. Lagoons are considered as low-rate treatment and they are popular due to their low capital cost (Johns, 1995). Lagoons are usually 3 to 5 meters deep and have hydraulic retention times of

5 to 10 days. Covering lagoons will result in prevention of heat loss and also protect the lagoon from snow in cold weather season (Johns, 1995).

Up flow anaerobic sludge blanket (UASB), anaerobic contact reactor (ACR), sequencing batch reactor (SBR) and anaerobic fixed film reactors (AFFR) are considered as high-rate processes. They are most common in Asia and Europe to accelerate treatment and reduce the land requirement.

In UASB reactors, the influent enters at the bottom of the digester, flows upward through a compact layer of bacteria (the sludge blanket) and exits at the top of the reactor. The tendency of granules to float out is a limitation at high load rates for UASB (Rajeshwari et al., 2000). Reactor operation requires close supervision. Average COD removal is 80% to 85% and the reactor is efficient when organic loading rate is between 2.7-10.8 kg COD/m^3d. The TS content of wastewater is also a limiting factor for UASB systems (Mittal, 2006).

An ACR consists of a stirred tank reactor followed by a sludge separator. Sludge is recycled to the system to maintain a long SRT at a relatively short HRT. In an ASBR system, feeding, reaction, settling and decanting occur in the same tank with intermittent mixing during the reaction phase. AFFRs are rectangular or cylindrical reactors using packing to retain bacteria. For poultry wastewater treatment, COD reduction efficiencies ranging from 85% to 90% were reported for 8 kg COD/m^3d at mesophilic condition (del Pozo et al., 2000).

1.4.2.2.2. Aerobic treatment

Aerobic treatments involve biodegradation of organic matter in the presence of oxygen. Aerobic systems require daily drainage of excess sludge and a separate treatment for sludge disposal. Aerobic treatments are very effective for reducing pathogens and odor. These systems require large space, maintenance, management and energy for providing oxygen to the system. Aerobic treatments include aerobic lagoon, activated sludge processes-conventional, extended aeration, complete mixed, oxidation ditches, sequencing batch reactor (SBR), and trickling filters and rotating biological contactors (RBC) (Mittal, 2006).

Facultative lagoons are large shallow basins that use algae in combination with other microorganism to treat wastewater. Oxygen is supplied by wind and BOD reduction is up to 95%. But the solid concentration is not low enough in effluent because of poor settling (Mittal, 2006).

Activated sludge processes are commonly used in the United States. Process includes conventional, complete mixed, extended aeration, oxidation and sequencing batch reactor. The sludge is maintained by continuously recycling a fraction of settled solid to aeration basin. The remaining sludge should be stabilized using a separate aerobic or anaerobic treatment (Mittal, 2006).

RBC uses an attached microbial film to absorb and degrade organic matter. Attached growth of microorganism on rotating discs makes the oxygen transfer more efficient compared to suspended growth systems. These bioreactors have been widely used for both domestic and industrial wastewaters with typically smaller installations (Grady et al., 1999).

1.4.2.3. Phosphorus and Nitrogen removal

When considering the residual organic matter and nutrients, the addition of a post-treatment unit is necessary so that the wastewater treatment system effluent quality will meet the requirements of the environmental regulation for protection of the receiving watercourses. There are some challenges in simultaneous N and P removal: The complete nitrification of ammonia nitrogen components produces a high level of nitrate, which has proved to be a challenge to the development of a stable and reliable Bio-P removal process. P removal requires an anaerobic condition and high level of nitrate makes it difficult to develop anaerobic condition (Lemaire et al., 2009). Another challenge in nutrient removal is maintaining the appropriate ratio of chemical oxygen demand to total kjeldahl nitrogen (COD/TKN) and COD/ ΔP for nutrient removal. the former should be more than 7 and latter should be more than 34 for high efficiency reduction (Grady et al., 1999).

One of the problems of simultaneous removal is the inhibitory role of nitrate in Phosphorus removal process. A^2 / O, VIP and UCT are some processes used for phosphorus and nitrogen removal simultaneously (Grady et al., 1999). A^2 / O consists of an anaerobic, an anoxic and an aerobic reactor in order with a recycle stream from aerobic reactor to anoxic reactor and a return activated sludge stream (RAS) from settling tank to anaerobic reactor. The University of Cape Town process (UCT) consists of the same three stages with an additional stream from anoxic stage to the influent going through anaerobic stage. There are three recycle streams in UCT process, one from second aerobic tank to first anoxic tank. VIP stands for Virginia Initiative Plant. It consists of two anaerobic, two anoxic and two aerobic tanks., another recycle stream from second anoxic tank to influent to first anaerobic tang and a RAS from settling tank to first anoxic tank. The UCT and VIP are two processes that eliminate the nitrate recycle to the anaerobic zone. In the UCT process, this is accomplished by routing RAS to the anoxic zone and including a recycle stream from the anoxic stage to the anaerobic stage. In the VIP process, every stage has two separate tanks and RAS is recycled to the anoxic zone and there is also a recycle from the anoxic to the aerobic zone. Basically high nitrogen removal is not possible with these processes. The Five-Stage Bardenpho process is another process which can provide high nitrogen removal but large reactor volumes are required. Also experience indicates that it's phosphorus removal capability may be only moderate to poor which can be a result of the long SRTs that are used (Grady et al., 1999).

Sequencing batch reactors have worked successfully in simultaneous P and N removal (Lemaire et al., 2009; Thayalakumaran, 2003; Wang et al., 2009). Lemaire et al (2009) have reported complete nitrification using SBRs but denitrification was not efficient enough without adding external VFA. To improve the denitrification, extra VFA was suggested to be added during the feeding time. The reason is that when the concentration of COD decreases, nitrate will increase and a competition between polyphosphate accumulating organisms (PAOs) and denitrifiers for COD will decrease the phosphorus removal. Also over-supply of carbon sources would increase aeration costs and sludge production in the SBR system (Lemaire et al., 2009). Two-sludge SBR systemv has been studied in literature. These processes promote denitrifying polyphosphate accumulating organisms (DNPAOs) which is a solution to the problem of COD limitation. DNPAOs are capable of anoxic P uptake (Kuba et al., 1996; Li et al., 2006; Peng et al., 2004; Wang et al., 2009). The anaerobic-anoxic, nitrification (A2-N) SBR process, which couples an Anaerobic-Anoxic SBR with a nitrification SBR, is one of the two sludge systems configuration

Phosphorus can be removed through chemical precipitation by adding different chemicals such as lime $Ca(OH)_2$ and Al^{3+} and Fe^{3+} salts (Tchobanoglous et al., 2003). The salt compounds release metal cations (Ca,Al and Fe). The released cations and their hydroxides effectively serve as coagulants for phosphorus removal. Chemical precipitation in wastewater treatment plants is broadly commercialized (De-Bashan and Bashan, 2004).

Phosphorus removal through struvite crystallization (PRS) has been proposed for phosphorous removal. Further use of nutrient removed as fertilizer is possible. Precipitation of Struvite as a slow release fertilizer has been studied for high strength ammonium poultry manure (Yetimezsoy and Sapci-Zengin, 2009).

An alternative nitrogen removal processes is anaerobic ammonium oxidation (Anammox) process. This process consists of the oxidation of ammonia to nitrogen gas using nitrite as electron donor and as a result it doesn't need organic matter. The SHARON (single reactor system for high activity ammonium removal over nitrite) and OLAND (oxygen limited autotraphic nitrification-denitrification) processes have been proposed (Karakashev et al., 2008; Mosquera-Corral, 2005). High N removal has been reported with these processes. There are two concerns about the anammox: first is that a separate process must be designed for Phosphorus removal. Second, controlling this process is complicated and it might not be a good option for industrial scale nutrient removal. Partial oxidation followed by OLAND has been studied for pig manure and 96% nitrogen removal has been reported (Karakashev et al., 2008). The advantage of this combination is less sludge production and also it does not require an additional carbon source. Since a COD concentration of more than 0.3 g/L will inhibit the OLAND process, partial oxidation before N removal process can solve the inhibition problem. This autotrophic process consumes 63% less oxygen and 100% less biodegradable organic carbon compared to the widely used wastewater treatment heterotrophic nitrification–denitrification (Karakashev et al., 2008).

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2. Objective

The objective of this research is to design an alternative wastewater treatment system for turkey processing plants to recover energy and reduce N and P to allowable discharge levels. The specific objectives were:

1. Determine the quantity and quality of biogas produced from the turkey processing wastewater (TPW) and COD reduction efficiency.
2. Design a waste treatment system and validate proof of concept for simultaneous P and N removal to attain effluent concentrations of 0.1 mg/L and 4 mg/L, for P and N, respectively.

3. Anaerobic digestion and biogas recovery

3.1. Introduction

Anaerobic digestion is degradation of organic compounds to CH_4 and CO_2 through the action of numerous microorganisms in the absence of oxygen (Atuanya and Aigbirior, 2002). Compared to aerobic treatment of wastewater, anaerobic treatment has some advantages including lower cost and less sludge production which make it an attractive alternative for conventional aerobic wastewater treatments such as activated sludge processes and oxidation ditches (Tchobanoglous et al., 2003).

Anaerobic reactors used in wastewater treatment have been mentioned in chapter one. Upflow attached growth anaerobic reactors have the capability to be used for high COD loading in relatively small volume reactors. The main limitations of attached growth systems are the cost of packing materials and maintenance and operational problems caused by solid accumulation and possible packing plugging (Tchobanoglous et al., 2003). The process is not suitable for wastewater with relatively high suspended solid concentration. Successful wastewater treatment process with AFFR has been reported in literature for wastewater TS content up to 2.7% (Rao et al., 2005).

Upflow anaerobic sludge blanket (UASB) reactors has been used as an alternative for conventional treatment processes of poultry wastewater (Atuanya and Aigbirior, 2002; Chavez et al., 2005; Del Nery et al., 2007). The granular sludge UASB reactor is a good choice for an anaerobic treatment systems with the only limitations being the tendency of granules to float out and shearing of granules at high loading rates (Rajeshwari et al., 2000). Atuanya et al. (2002)

studied a UASB reactor of 3.50 L capacity to treat poultry wastewater and assess its methane production. The maximum chemical oxygen demand (COD) removed was found to be 78% when the organic loading rate (OLR) was 2.9 kg COD/ m^3 day at hydraulic retention times (HRT) of 13.2 h. The average biogas yield was 0.26 m^3 Methane/ kg COD with an average methane content of 57% at average temperature of 30 °C. In a study by Chavez et al. (2005), poultry slaughter wastewater treatability was investigated by adding three different types of inoculums. A 95% removal of BOD_5 from poultry slaughter wastewater was obtained with organic loading rates up to 31 kg BOD_5/m^3d in temperature range of 25 to 39 and HRT of 3.5 to 4.5 h. the average BOD_5/COD was 0.75. Del Nery et al (2007) studied a full scale UASB reactor along with DAF process treating poultry wastewater have reported the TCOD removal of 67% for anaerobic digestion of poultry slaughterhouse wastewater with organic loading rate of 1.6 kg/m^3day and total solids of 2457 mg/L by UASB reactor. Not only is UASB a good choice for low organic load treatment but also efficient COD reduction has been reported for high organic loads up to OLR of 30 kg/m^3d (Torkian et al., 2003). Adding an acidification tank prior to UASB reactor can add advantage of production of useful biogas at short HRT (Hwang et al., 2006) since the optimal pH for acidification is lower than optimal pH for methanogenesis, having two separate tanks with different pH can give the chance of a more efficient methane production . The UASB reactor has lower energy consumption for heating and mixing comparing to completely mixed reactor (Grady et al., 1999). One of the disadvantages of UASB in digestion is the limitation in feed TS which cannot work with high TS wastes and as a result it might not be a good choice for wastes with high solid content. Also the volume of reactor is high compared to other high rate processes. A gas separator is needed for UASB reactor which in the case of using CSTR is not needed (Grady et al., 1999).

A complete mixed reactor on the other hand can work with wide range of TS content and it is more suitable for digesting high solid wastes (more than 6 g/L of total suspended solids) (Tchobanoglous et al., 2003). Also it needs less operating skills though it can be a good choice for smaller processing facilities. The CSTR has been used for treating the wastes with higher total solids instead of attached growth reactors. With the total solids content as high as 7.8% and Ammonia Nitrogen content of 3800 mg/L, TS and VS removal has been reported as 76% and 64% respectively and specific methane yield has been reported 0.52-0.55 m^3/ kgVS for loading up to 0.8 kgVS/m^3 d metric ton (Salminen and Rintala, 2002). In another study by Rosenwinkel and Meyer (1999), a CSTR has been used for slaughter house wastewater in mesophilic condition and resulted in methane yield of 0.233-0.32 m^3/kg TS.

In this study, a complete mixed reactor has been chosen over an attached growth system and a UASB reactor to have the potential to be used for codigestion with other turkey processing by-products as a future study. The objective was to determine the quantity and quality of biogas produced from the turkey processing wastewater (TPW) and COD reduction.

3.2. Materials and method

3.2.1. Turkey processing wastewater

Figure 3-1 illustrates materials flow in the turkey processing plant where the material for this study was obtained and the current treatment for turkey processing wastewater. Turkey processing wastewater which was the substrate used in this study for anaerobic digestion in this research is the stream which mixture of wash water and returned sludge that have been marked in figure 3-1.

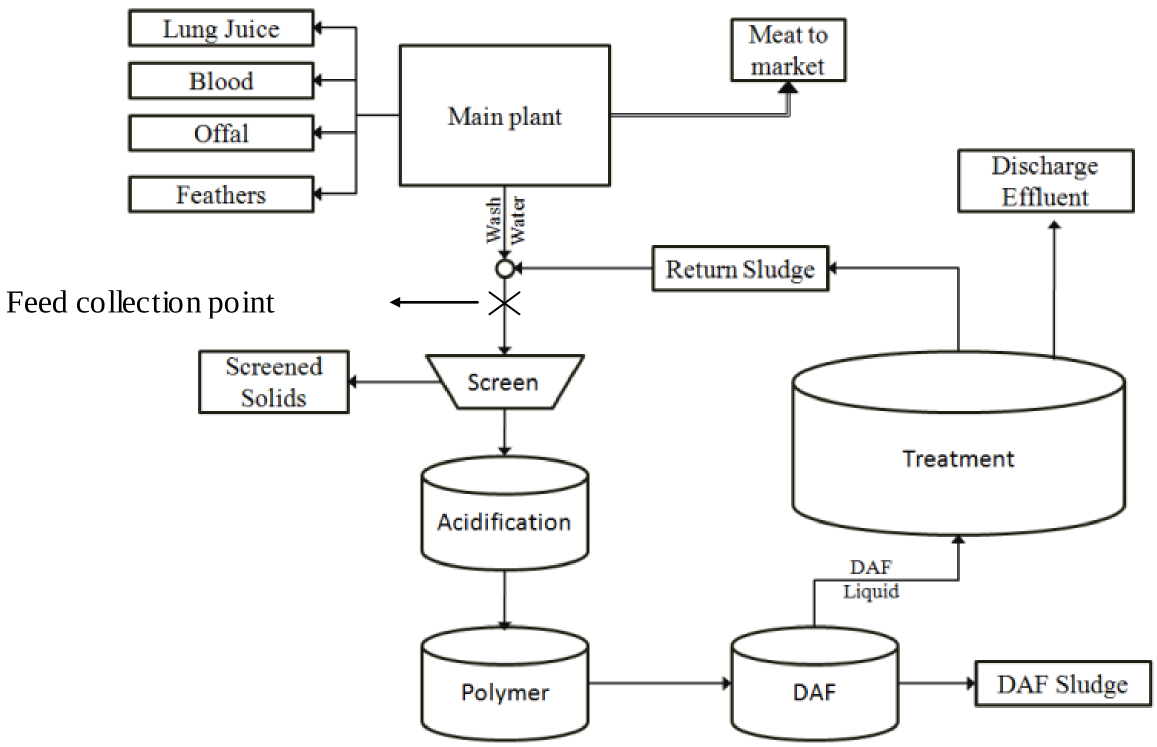

Figure 3-1: Material flow in turkey processing plant

The wash wastewater was collected from a turkey processing plant in Rockingham County, Virginia. Turkey processing wastewater (TPW) was collected before passing through a rotary screen separator, which is the first step in the plant's waste treatment system. TPW is generally a mixture of water used for cleaning at various locations such as deboning area and slaughtering section and includes blood, fat and skin residuals and other pollutants. The wastewater was collected in December 2009 and in May 2010 in 20 L buckets and brought to Virginia Tech where they were stored in a freezer at -20ºC. When needed, the buckets were taken out and transferred into a 4 ºC cooler in Bioresidual Management Laboratory. The feed was blended when it was necessary to reduce large particles in wastewater.

3.2.2. Reactor design

A complete mix anaerobic digester had a total volume of 15 L and a working volume of 12 L. The digester was made from a schedule 40 PVC pipe capped off with 0.95 cm thick PVC plates. A total of two pumps (Masterflex, Model 7553-70 and 77200-62, Cole Parmer Instrument Co., Chicago, IL.) were used to feed and discharge the reactor contents. The digester was heated by an electric oil heater (Model ARTMO-250T4, Chromalox, La Vergne, TN). The reactor was insulated by fiberglass material (Model SP24, Thermwell Products Co., Mahwah, NJ). The digester temperature was controlled by a temperature controller (Model 11-463-47A, Fisher Scientific, Waltham, MA) and the set point on 37 $\pm$ 1°C. Discharge, feed and mixing in the digester were controlled by a Chrontrol XT top timer with AC outlet (ChronTrol Corporation, San Diego, CA).

3.2.3. Digester start up and feeding

The digester was started up at an HRT of 20 d with 60% anaerobic digester effluent obtained from wastewater treatment plant, Christiansburg, VA., and 40% flushed manure obtained from the sedimentation tank of dairy farm manure treatment system at Virginia Tech, Blacksburg, VA. Details of the farm are described by Debusk et al. (2008). After 10 days, the content of the feed was changed to 50% TPW and 50% flushed manure and each week the TPW ratio was increased 10% to eventually reach the %100 TPW after 45 days. On day 52 after start up, the HRT was changed to 15 days. 75 days after the start up, the system was assumed to reach steady-state. The reactor was fed 4 times a day and the effluent was discharged from the reactors 2 times a day. The effluent of digester was transferred to the nutrient removal system which was second phase of experiment for nutrient removal.

3.2.4. Sample collection and analysis

The quantity of biogas produced was measured by a wet-tip gas meter (Rebel wet-tip gas meter company, Nashville, TN) and daily recorded. Feed and effluent samples were collected every week and analyzed for total solids (TS), volatile solids (VS), total nitrogen (TN) total phosphorus (TP), total ammonia nitrogen (TAN) and pH. The TS and VS were determined using standard methods for wastewater treatment (APHA, 1995). The pH of the feed and AD effluent stream were monitored using an Orion 5 Star pH/ISE/dissolved oxygen/conductivity, meter (Thermo Fisher Scientific, Fort Collins, CO, U.S.A.).

Once every two weeks 1 L of biogas was collected in 1 L Tedlar bags and analyzed for composition (CH_4 and CO_2) using a gas chromatograph (Model 8610C, SRI Instruments, Torrance, CA) equipped with FID detector; a HAYESEP D column and nitrogen as a carrier gas. The feed and effluent samples were collected every two weeks and analyzed for total COD (tCOD) and soluble COD (sCOD) using method HACH 8000 which is a USEPA approved reactor digestion method (HACH, Loveland, CO). Total Nitrogen (TN) and Total Phosphorus (TP) and NO_3/NO_2 was measured weekly using simultaneous digestion method (USGS Method I-4650-03, 2003) for AD feed, AD effluent.TAN was measured weekly for AD effluent using an ammonia probe (Orion, Thermo Fisher, Fisher Scientific, Columbus, Ohio) as outlined in method 4500-NH_3 (APHA, 1995).

3.2.5. Energy balance

An energy balance analysis of a mesophilic digester for a turkey processing facility with wastewater production rate of 2160 m^3/day was conducted using the experimental results. Biogas produced in the digester can be used to produce electrical power at 35% efficiency through a combined heat and power engine (CHP) which can be used to run the equipment. CHPs are very common in biogas plants which in parallel to generation of electricity. They develop a high percentage of heat (Deublein and Ateinhauser, 2008). Waste heat from the CHP is then used to heat the digester at 55% efficiency using water as the heating medium and 10% of the heat is unrecoverable (Zupancic and Ros, 2003).

In order for biogas production to be part of an alternative treatment system for TPW, the net energy of the system should be positive, which means that the energy produced from biogas and recovered energy should be more than the energy that is consumed by the system.

Net energy (E_{net}) is estimated as shown in the following equation 3.1 (Ogejo and Li, 2010).

$$E_{net} = E_p - E_C \tag{3.1}$$

Where E_{net} is the net energy produced per day added, kJ/day, E_p is energy produced from biogas, kJ/ day, and E_c is energy consumed by the process including the energy required to raise the feed temperature, heat loss through the walls and energy consumed through mixing and pumping. E_p is the product of volume of methane and lower heating value of methane (LHV= 35800 kJ/m^3). E_c is the energy consumed by the process. The energy requirement of digester can be divided to two parts: first, the heat requirement to maintain the mesophilic temperature and second the energy required for mixing and pumps. The heat requirement includes 3 parts. First the heat consumed to raise the temperature of the feed to 37 °C (E_f). Second to keep the temperature at 37 °C to compensate the heat loss through the digester wall (E_w) and at the end the heat loss between the heat source and digester which is neglected in calculations. E_f is summed to come from three sources: i) external source (H_E). ii) Regenerative heat exchanger (H_R). iii) Heat loss from CHP engine (H_W) and has been shown in equation 3.2. Basically the heat exchanger takes the heat from digester effluent (37 °C) and uses it to preheat the feed. Regenerative heat exchanger is assumed to use the digester effluent with 70% efficiency (Ogejo and Li, 2010). E_w is calculated as shown in equation 3.3. k_{cout} is heat transfer coefficient through the walls from inside the digester to outside air. A is the surface of the digester. T_D, T_{in} and T_{amb} are digester temperature, feed temperature and ambient temperature respectively. Based on the capacity of the digester a cylindrical digester has been assumed to have to height of 30 m and radius of 17.5 m.

$$Ef = Q \times Cp \times \rho \times (T_D - Tin) - (H_W + H_R + H_E) \tag{3.2}$$

$$Ew = k_{cout} \times A \times (T_D - T_{amb}) \tag{3.3}$$

Q is the feed flow rate, Cp is the specific heat of the feed and ρ is the density of the feed. A simple energy balance has been conducted on a pilot scale digester with wastewater flow rate of 2160 m^3/day and HRT of 13.3 days. Heat capacity of wastewater has been calculated based on Carbohydrate, protein, lipids and total solid content of wastewater (Lubken et al., 2007) and it value 4.172 (KJ/Kg·K). Calculations should be conducted for cold and warm season with temperatures of 7 °C and 24 °C (Ogejo and Li, 2010).

3.3. Results and discussion

3.3.1. Feed characteristics

The characteristics of TPW are presented in table 3-1. The average TS for the feed was 1.89 mg/L and the VS was 86% of TS. sCOD concentration in TPW was 12% of tCOD. Total nitrogen (TN) and total phosphorus in TPW were 262.2 $\pm$ 34.7 mg/L and 10.1 $\pm$ 3.0 mg/L respectively which gives COD/TN ratio of 9.1. The pH is in a range that is preferable for anaerobic digestion and pH adjustment was not required. The optimal range for aceticlastic methanogens is 6.8 to 7.4 (Grady et al., 1999).

3.3.2. Solid reduction

Table 3-1 shows the characteristic of feed and AD effluent. Average TS and VS in AD effluent were 1.24 $\pm$ 0.05 g/L and 0.84 $\pm$ 0.04 g/L, respectively. Average TS and VS removals in digester were 33% and 45%, respectively. Total COD and sCOD removal in anaerobic digester were 56% and 51%, respectively, over a 3-month period. Average tCOD, TS and VS removal of the system has been shown in figure 3-2.

Table 3-1: Mean characteristics of the feed and anaerobic digester effluent.

	Feed	AD Effluent	Percentage removal (%)
TS (g/L)	1.81 ± 0.13	1.21 ± 0.05	33
VS (g/L)	1.49± 0.13	0.82± 0.04	45
TSS (g/L)	1.39 ± 0.18	1.35 ± 0.20	
VSS (g/L)	0.71 ± 0.12	0.51 ± 0.05	
tCOD (mg/L)	2320 ± 144	1013 ± 149	56
sCOD (mg/L)	296 ± 41	146 ± 19	51
TN (mg/L)	262.2 ± 34.7	256.5 ± 29.7	
TAN (mg/L)		86.74±18.37	
TP (mg/L)	10.1 ± 3.0	12.7 ± 6.6	
pH	6.95 ± 0.15	6.23 ± 0.05	

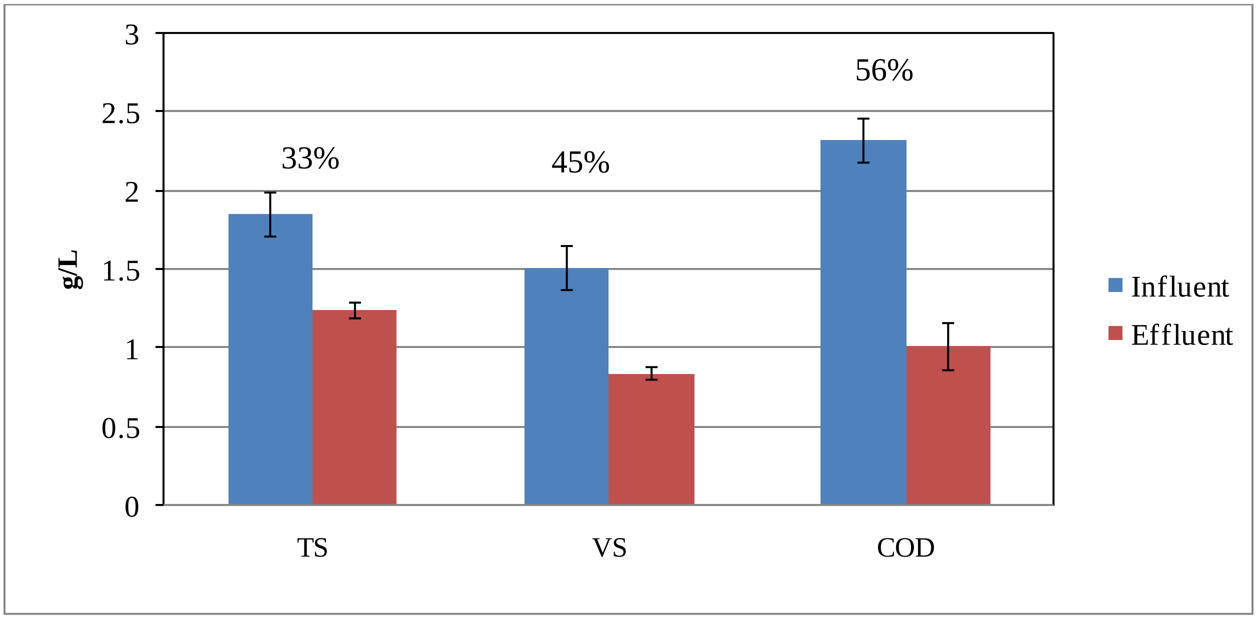

Figure 3-2: Average tCOD, TS and VS of anaerobic digester

Feed and AD total solid and volatile solid changes versus time are shown in figure 3-3. Day 1 in this gragh corresponds to 75 d after digester start up. Feed characteristics fluctuated and it was considerably different from bucket to bucket. But AD effluent characteristics were more consistent. At some data points in graph TS and VS in digester effluent in higher than TS and VS in feed. Solid removal cannot be judged based on single data points. For some single data points (TS in effluent and influent in the same day) negative removal is observed for TS and VS since the measurements in the same day for AD effluent and feed is not associated with each other. Average TS and VS in feed and AD effluent are the base for solids removal calculations.

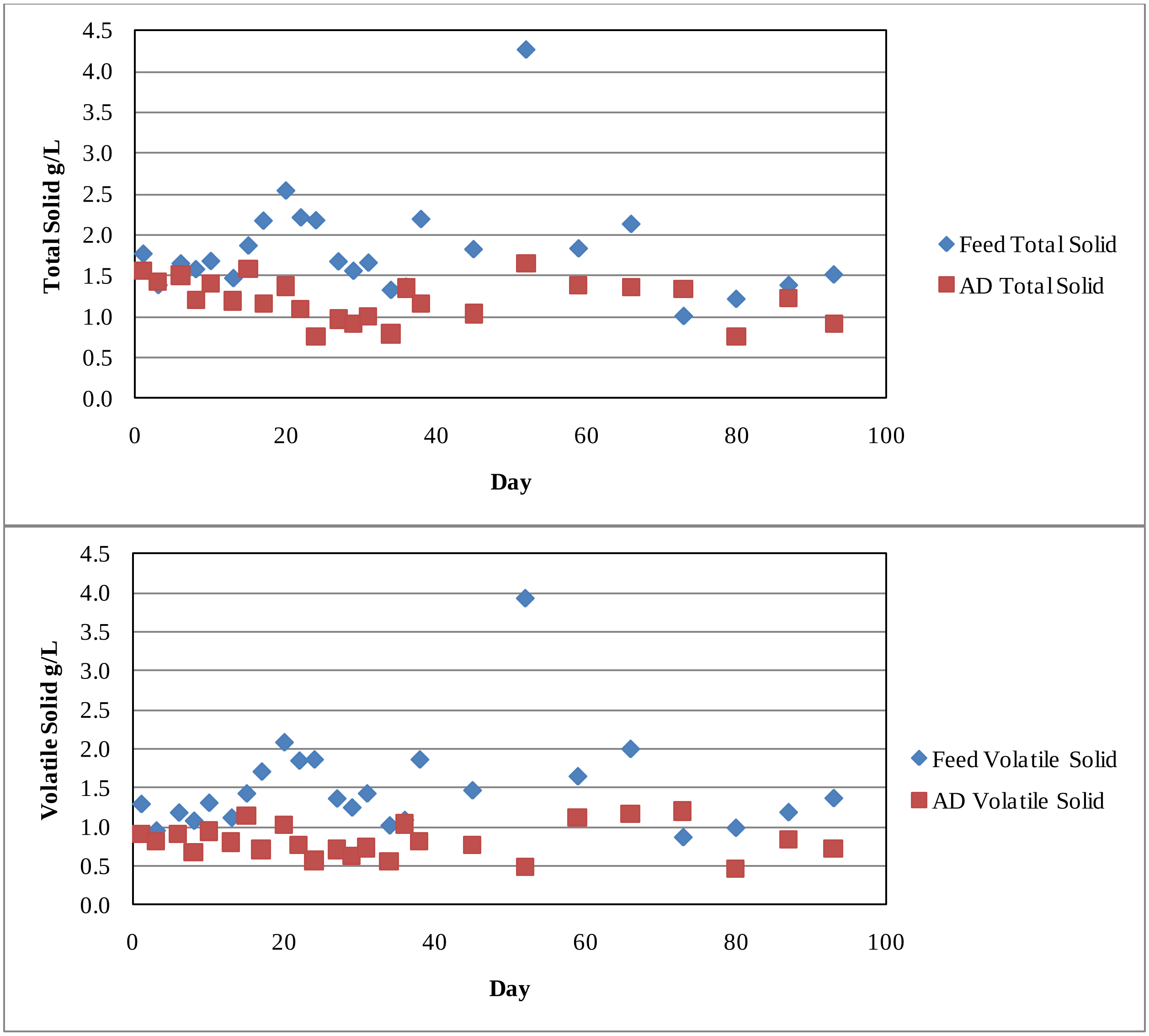

Figure 3-3: Total solid and volatile solid of feed and anaerobic digester effluent versus time.

Higher solid removals with systems such as UASB, anaerobic fixed film reactor (AFFRand static granular bed reactor (SGBR) have been reported in the literature (Debik and Coskun, 2009; Del Nery et al., 2001; del Pozo et al., 2000). Del Pozo et al. (2000) reported COD removal of 87% for poultry processing wastewater using an anaerobic fixed film reactor (AFFR) under mesophilic conditions. The COD range in wastewater is reported to be 2560-5080 mg/L and the HRT is 6-15 h. Del Nery et al. (2001) studied the start up and operation of a pilot scale UASB reactor treating poultry slaughterhouse wastewater. The average COD of the influent was 2695 mg/L. the startup of the reactor took 144 days and the COD reduction during this time was higher than 80%. Debik and Coskun (2009) have used a Static Granular Bed Reactor (SGBR) for poultry processing wastewater treatment with COD range of 4200-9100 mg/L under ambient temperature (22 °C). They obtained the COD removal higher than 94%.The advantage of these systems to complete mixed reactor is maintaining a higher SRT. Increasing the HRT in mixed reactor may improve the solid removal. In general, reactors such as AFFR and suspended granular sludge reactors such as UASB may have been a better choice for anaerobic digestion of TPW since higher solid removal has been reported in previous studies and also reactor volume would decrease by using UASB since the reactor can operate with lower HRT and higher loading rate. The reason for using completely mixed reactor for this study was to have the potential to be used for codigestion with other byproducts of the turkey processing plant such as lung juice and offal that has been shown in figure 3-2.

Total and volatile solids of AD effluent were measured for mixed liquor without being settled. Adding a settling tank after anaerobic digester and recycling the sludge back to the digester for pilot plant scale may be helpful to achieve higher solid removal and a potential higher biogas yield due to SRT increase.

3.3.3. Biogas recovery

The average biogas production was 1,278 ± 113 mL/d and average biogas yield was 778.39 ± 89.27 mLl/gVS$_{added}$. Biogas yield which is the volume of biogas produced per mass unit of VS ranged from 628 to 3904 ml/ g VS$_{added}$. The quality of biogas ranged from 57% to 80% with average value of 71% ±7. The main composition of biogas was methane (CH_4) and carbon dioxide (CO_2). The biogas yields are reported as volume per unit mass of VS added to digester per day which is the most used method of measuring biogas yield (Angelidaki and Ellegaard, 2003). Also biogas production has been shown as volume per day to demonstrate the trend of biogas production during the time period of experiment. Figure 3-4 shows the biogas yield and biogas production during a 56-day period. No explanation was found for high biogas production at the end of the period since the feed and AD characteristics didn't go through any change and the temperature was controlled.

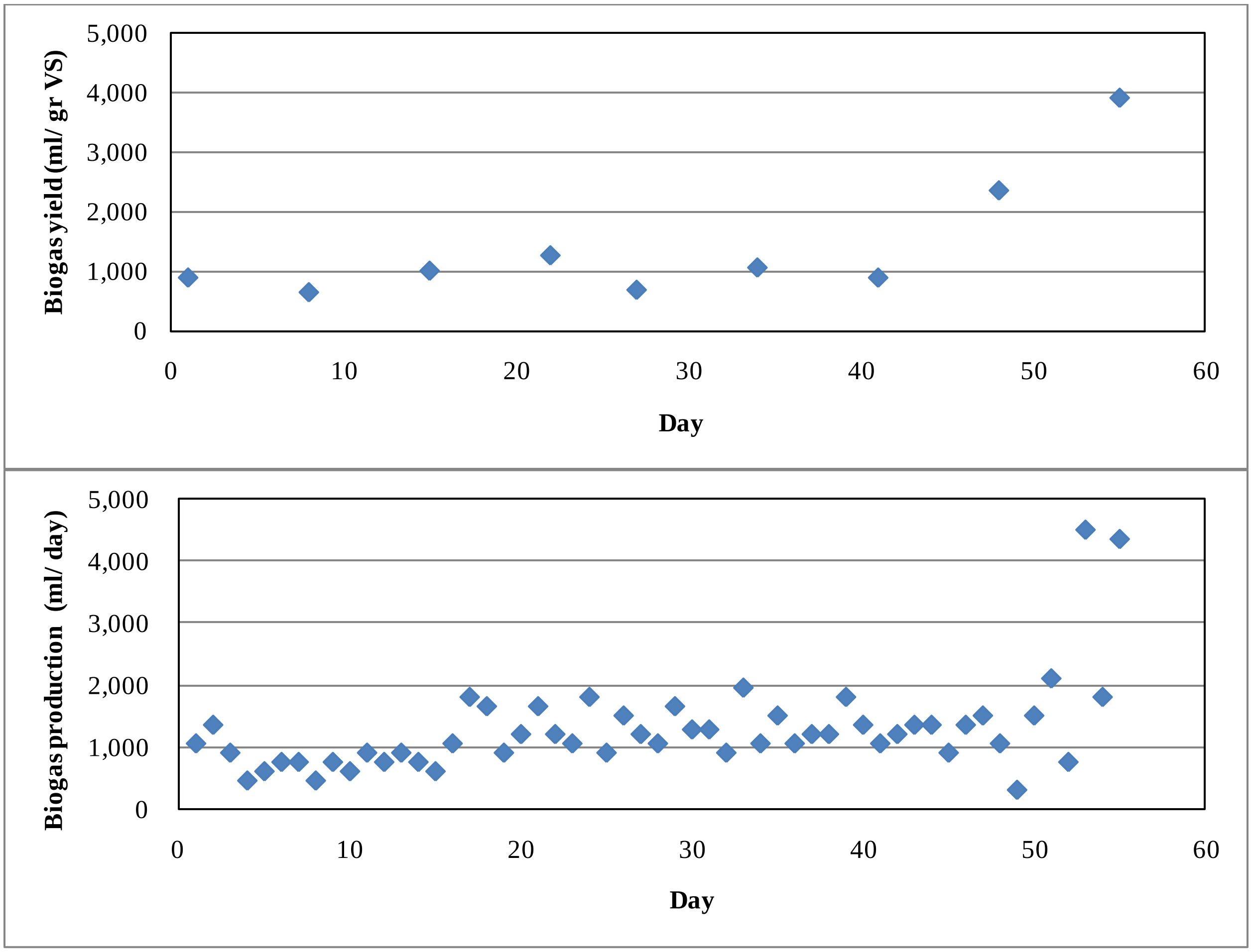

Figure 3-4: Biogas yield and biogas production in anaerobic digester using turkey processing wastewater as feed

The biogas yield results can be compared to using other poultry processing byproducts digestion presented in table 1-1 (Salminen and Rintala, 2002) in the same reactor configuration, semi-continuous and complete-mixed with longer HRT. In a study by Salminen and Rintala (2002) they used poultry wastes as feed containing minced and mixed fractions of bone and trimmings (42.1% wt.), blood (15.8% wt.), offal (31.6% wt.), and feather (autoclaved at 120 C for 5 min, 10.5% wt.) which was diluted to reach TS of 4.7 to 9.4% in a semi-continuous stirred reactor with HRT of 50-100 days. They obtained biomethane yield of 0.52-0.55 $m^3/kg\ VS_{added}$. It can be concluded that wastewater digestion gives a high yield compared to mixtures of other byproducts with a higher solid content and loading rate. Although a longer HRT may have resulted in higher yield of biogas, in a full scale wastewater treatment plant, choosing the higher HRT would lead to higher digester volume to maintain the treatment of the same wastewater load. Increase in the volume of digester increases the heating requirement as well to maintain digester temperature.

The pH of the digester ranged from 5.95 to 6.45. The optimal pH range for methane production has been reported 6.5 to 8.5 (Speece, 1996). Low pH of AD effluent for some samples taken during the experiment may indicate presence of high volatile fatty acid (VFA) in digester and incomplete methanogenesis. A separate acidification tank may be used to improve the biogas production since they maintain two different environments for acidification and methane production. Also increasing the HRT may improve the methanogenesis which will also increase the reactor size.

Average TAN in anaerobic digester was 87$\pm$ 7 mg/L which is below the inhibitory level. Inhibition has been reported to start at a total TAN level of 1,500–14,000 mg/L. However, an TAN tolerance of up to 3,000 to 4,000 mg/L for an adapted process has also been reported (Chen et al., 2008; Nielsen and Angelidaki, 2008). Anaerobic digestion degrades protein and this result in the production and accumulation of ammonia while degrading organic matter (Grady et al., 1999). Ammonia is known as one of the methane production inhibitors. The fraction of unionized ammonia increases with temperature, which is reported more toxic than the ionized one because of its capability to penetrate through the cell membrane (Sung and Liu, 2003).

Theoretically 393 mL of methane is produced for every gram of COD at 36 °C (Grady et al., 1999). Average methane yield based on COD removed was 675 mL/gCOD which is much higher than what we theoretically expected. A possible explanation for it can be that more COD and biogas samples might have been needed to give a more accurate methane yield calculation. It may also be caused by the lost COD in the feed tank at the sampling time and sample keeping time period.

3.3.4. Energy balance

The sample calculations have been done for summer condition. The summary of energy balance calculations is shown in table 3-2.

Heat required for feed (reactor):

E_f has been calculated with the assumption of using a regenerative heat exchanger with 70% efficiency which uses the digester effluent to heat the substrate.

$$\mathrm{Ef} = 2163.09\frac{\mathrm{m3}}{\mathrm{day}} \times 1000\frac{\mathrm{kg}}{\mathrm{m3}} \times \frac{4.172\mathrm{KJ}}{\mathrm{kg.K}} \times (37-24) \times (1-0.7) = 3.515\ \times 10^{7}\mathrm{KJ/day}$$

Heat loss rate through digester walls:

From the study by Zupancic et al. (2003) the digester wall consists of the layers of water insulation, inside mortar, concrete, heat insulation and aluminum plates. k_{cout} has been calculated to be 0.265 W/m^{2}K.

Area of digester wall= 3298 m^2

$$Ew = 0.265\ \frac{W}{m^2 K} \times 3298\ m^2 \times (37 - 24) \times \frac{1KJ}{1000J}$$

$$\times\ 86400 \frac{s}{day} = 9.818 \times 10^5\ \frac{KJ}{day}$$

As it is shown in calculations, the energy needed for heating feed is the major part of heat requirement. The percentage of heat losses through the walls decreases with capacity of wastewater treatment process. Zupancic and Ros (2003) have studied heat requirement for WWTP thermophilic digester with size range from 1,360,000 to 68,000,000 TOD/d and HRT range of 1 to 10 days. They concluded that in the thermophilic digester the heat loss through the walls is about 2 to 8.5% of heat requirement (Zupancic and Ros, 2003). In the calculations presented above the heat loss through the walls is estimated to be 2.7% of the heat requirement at summer condition.

Energy content of biogas:

The energy production of the system was calculated, assuming that the biogas is being provided to a 50 kW CHP engine at 35% and 55% efficiency of electricity and heat recovery (Ogejo and Li, 2010). Energy production is calculated using the lower heating value (Grady et al., 1999; Lubken et al., 2007). The CHP engine is assumed to work continuously for 24 h/d.

$$\mathrm{Ep} = 0.779 \frac{\mathrm{m^3\ Biogas}}{\mathrm{kg\ VS}} \times 1.51 \frac{\mathrm{kg\ VS}}{\mathrm{m^3\ TPW}} \times 2160. \frac{\mathrm{m^3 TPW}}{\mathrm{day}} \times 0.71\ \mathrm{m^3} \frac{\mathrm{methane}}{\mathrm{m^3\ biogas}} \times 35700 \frac{\mathrm{KJ}}{\mathrm{m^3}}$$

$$\times (0.55 + 0.35) = 5.796 \times 10^7\ \frac{\mathrm{KJ}}{\mathrm{m^3}}$$

The net energy can be calculated as shown below.

$$\mathrm{Enet} = \mathrm{Ep} - \mathrm{Ec} = 5.796 \times 10^7\ \frac{\mathrm{KJ}}{\mathrm{day}} - 3.515\ \times 10^7 \frac{\mathrm{KJ}}{\mathrm{day}} - 9.818 \times 10^5 \frac{\mathrm{KJ}}{\mathrm{day}}$$

$$= 2.183 \times 10^7 \frac{\mathrm{KJ}}{\mathrm{day}}$$

Table 3-2: Calculations summary for a pilot scale digester

	Ep (KJ/day)	Ef (KJ/day)	Ew (KJ/day)	Enet (W)
Summer condition	5.796E+07	3.515E+07	9.818E+05	2.53E+05
Winter condition	5.796E+07	8.110E+07	2.266E+06	-2.94E+05

Due to lower temperature in winter conditions, heat loss will be more than summer condition and the net energy will be lower. Based on the assumed condition for this experiment and biogas yield the net energy for winter is negative. The heat produced from the biogas through a CHP engine does not satisfy the energy requirement in winter condition. Calculating a temperature at which the net energy is zero can be helpful to find the seasons that heat recovery would be efficient. The net energy at 16 °C was calculated to be zero which means at a temperature lower than 16 °C, the net energy will be negative.

By using efficient isolating material heat loss can be minimized in pilot scale digester and the overall net energy will be less negative.

3.4. Conclusion

Anaerobic digestion in a complete mixed reactor was studied as an alternative primary treatment for turkey processing wastewater for biogas recovery with a hydraulic retention time of 13.3 d at temperature of 36 °C. The average biogas production was 1,278 $\pm$ 113 mL/d and biogas yield was 778 $\pm$ 89 ml/ g VS_{added}. The biogas yield range was 628 to 3904 ml/ g VS_{added}. The quality of biogas ranged from 56.83% to 80.10% of methane with average value of 71%. Average biogas yield based on COD removed was 951 mL/ g COD. Average TS and VS in the AD effluent was 1.24 $\pm$ 0.05 g/L and 0.84 $\pm$ 0.04 g/L respectively. Average TS and VS removals in digester were 33% and 45% respectively. Total COD and sCOD removal in anaerobic digester were 48% and 46%, respectively. The energy balance conducted on a pilot scale digester using experimental results showed that at summer conditions the net energy production of 2.53E+05 W was estimated for a turkey processing facility with wastewater production rate of 2160 m^3/day. In winter conditions the net energy was -2.94E+05 W. thickening the feed in winter conditions can be an option to decrease the heat requirement for feed and improve the energy recovery.

Even if other kind of reactors such as UASB had shown higher solid removals in previous studies, using a complete mixed reactor for biogas recovery of turkey processing wastewater has the potential of codigestion with some other turkey processing byproducts and the capacity of receiving a higher solid content. Codigestion of some by-products with wastewater can be studied as an alternative to their current treatment which may have some costs for plants.

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4. Simultaneous Nitrogen and Phosphorus Removal from Turkey Processing Wastewater

4.1. Introduction

Agro-industrial wastewaters treated by anaerobic digestion still contain large amounts of phosphorus (P) and nitrogen (N). These nutrients are directly responsible for eutrophication in water resources worldwide. Removing nitrogen and phosphorus is usually obligatory. Some conventional wastewater treatment for point sources were presented in chapter one. In all cases, phosphorus is removed by converting the phosphorus ions into a solid fraction either biologically or chemically. The solid fraction can be removed as an insoluble salt precipitate, a microbial mass in an activated sludge, or a plant biomass in constructed wetlands (De-Bashan and Bashan, 2004). Some phosphorus removal including chemical and biological processes have been described in chapter one.

Nitrogen removal is obtained biologically and it is maintained through two sequential steps of nitrification and denitrification (Tchobanoglous et al., 2003). Nitrification is an aerobic process in which ammonia (NH_3) is transformed to nitrate (NO_3-) in the presence of autotrophic bacteria through the reaction below:

$$O_2 + NH_3^- \rightarrow H_2O + NO_2^-, NO_3^-$$

In denitrification, NO_3- is transformed to nitrogen gas (N_2) through the reaction below:

$$\text{Carbon source} + NO_3^- \rightarrow CO_2 + N_2$$

Denitrification occurs in anoxic condition (lacking oxygen) where heterotrophic bacteria use NO_3- as their terminal electron acceptor in the absence of dissolved oxygen. Alternating aerobic and anoxic zones are typically used to promote nitrification and denitrification to convert NH_3 to N_2 (Grady et al., 1999). Nitrification can be obtained in both suspended growth and attached growth systems. For suspended growth, a more common approach is to have biological oxygen demand (BOD) removal and nitrification simultaneously. In attached growth systems, most of the BOD must be removed before nitrifying organisms can be established since the heterotrophic bacteria have higher biomass yield so it can dominate the surface of fixed film system over nitrifiers (Tchobanoglous et al., 2003).

Enhanced biological phosphorus removal (EBPR) refers to bacterial uptake of P exceeding the amount needed for cell components. In EBPR, the process is enhanced by increasing the storage capacity of phosphorus as poly-phosphate by the microbial biomass (De-Bashan and Bashan, 2004). Phosphorus removal can be attained through an anaerobic/aerobic sequence. Polyphosphate accumulating organisms (PAOs) are heterotrophs which uptake and store P in greater quantities than needed for cell components. In EBPR, the anaerobic environment is required for fermentation of COD to volatile fatty acids (VFAs) and release of phosphate (PO_4). Phosphorus accumulating organisms transport VFA, mainly acetate, into their cells accumulating Poly-3-Hydroxybutyrate (PHB). PHB is the most abundant form of PHA accumulated when acetate is the dominant organic substrate. Phosphorus accumulating organisms store PHB using energy from the hydrolysis of intracellular polyphosphate, releasing inorganic PO_4 to wastewater. The PHB content in PAOs increases as the polyphosphate content decreases. In the aerobic stage, PHB molecules provide energy from oxidation and carbon for new cell growth with polyphosphate storage capacity to form polyphosphate bonds in cell storage so that larger amount of orthophosphate than the amount originally released during the anaerobic process is uptaken, and this enhanced uptake includes the phosphorus arriving with the new wastewater. This leaves the wastewater phosphate-poor, and in case of complete EBPR success, phosphate-free (De-Bashan and Bashan, 2004; Tchobanoglous et al., 2003).

Alternatively, denitrifying phosphate accumulating organisms (DNPAOs) are capable to accumulate phosphate along with denitrification thus there will be no competition over carbon source. For these bacteria, nitrate is used for oxidizing stored PHB and removed as Nitrogen gas (N_2). The main advantage of DNPAOs is the possible saving of carbon source and energy (aeration) and less sludge production (Peng et al., 2004). COD supply usually is a limiting factor for phosphorus release (anoxic stage) and denitrification for wastewaters with low COD (Wang et al., 2009).

To effectively apply DNPAO for simultaneous nitrogen and phosphorus removal, Kuba et al. (1996) studied a two sludge system named Anaerobic-Anoxic/Nitrification (A^2N) process. A^2N process couples an anaerobic/anoxic Sequencing batch reactor with a separate nitrification tank as a two sludge system. Having a separate nitrification tank reduces the need for sludge recirculation as its necessary in most of the conventional Nutrient removal processes and promotes the use of SBRs and also separate optimization on nitrogen and phosphorus removal can be operated by autotrophic nitrification and utilization of oxygen for nitrification only (Kuba et al., 1996; Oehmen et al., 2007; Peng et al., 2004).

Kuba et al. (1996) used a synthetic wastewater as substrate in an A^2N system to study simultaneous P and N removal with acetate was used as the carbon source. They have reported a stable removal of P and N of 15 mg/L (99%) of phosphorus and 105 mg/L (88%) respectively while consuming 400 mgCOD/L. They found the optimal COD/N ratio to be 3.4 which is the relatively low comparing to the COD/ N ratios that have been reported studying the same system (Li et al., 2006; Peng et al., 2004; Wang et al., 2009). Kuba et al. (1996) also concluded that A^2N system 50% less COD comparing to conventional nitrogen and phosphorus removal systems.

Peng et al. (2004) used raw domestic wastewater as substrate with the A^2N process. Phosphorus removal ranged 73.61% to 97.12% for an average effluent TP of 0.5 mg/L. The nitrogen removal efficiency ranged 80.99% to 92.99% with TN in effluent ranging from 3.67 mg/L to 11.47 mg/L and achieving complete nitrification. They found the optimal conditions for phosphorus and nitrogen removal was having the feed COD/TN ratio around 6.5 and an SRT of 14 days. Li et al. (2006) have studied simultaneous P and N removal in a continuous flow A^2N system using municipal wastewater as substrate. They reported complete nitrification and COD, TP and TN removals of 82%, 93% and 76% respectively. They also found the optimal C/N ratio to be in the range 3.8 to 6 (Li et al., 2006). Wang et al. (2009) in a recent study on A^2N-SBR system have reported optimal phosphorus and nitrogen removal of 94% and 91% respectively with influent COD/P and COD/N ratios of 19.9 and 9.9 using a domestic wastewater as substrate (Wang et al., 2009).

The objective of this part of study was to design a waste treatment system and validate proof of concept for simultaneous P and N removal to attain effluent concentrations of 0.1 mg/L and 4 mg/L, for P and N respectively. A^2N-SBR system was chosen for simultaneous N and P removal in this study due to a limitation of the carbon source in the receiving influent and also the choice of optimizing N and P removal separately.

4.2. Materials and Methods

4.2.1. Reactor Setup

A flow diagram of AD and A^2N-SBR in series is presented in figure 4-1. The two-sludge sequencing batch reactor (A^2N-SBR) consists of an anoxic-anaerobic reactor (SBR-A^2) and a nitrification reactor (SBR-N). Two 2-L cylindrical glass reactors were used with a working volume of 1.6 L each were used. SBR-A^2 was mechanically mixed during the anaerobic, anoxic and aerobic period. SBR-N was an attached growth reactor. The media for attached growth was made from a 1.6-cm diameter polypropylene material (Jaeger Products, Houston, Texas) and was contained in the working volume of the reactor. A total of 4 pumps were used for transferring the supernatant from SBR-A^2 to SBR-N and back, recirculation in the SBR-N and discharge from SBR-A^2. The feeding pump is the discharge pump of AD system that transfers the AD effluent to SBR-A^2. Two aerator pump were used for SBR-A^2 and SBR-N aeration through diffusers installed at the bottom of both reactors (Model 400-3910, Barnant company, Barrington, IL) (Model MOA-P122-AA, Benton Harbor, MI). The reactors were operated at room temperature in the laboratory.

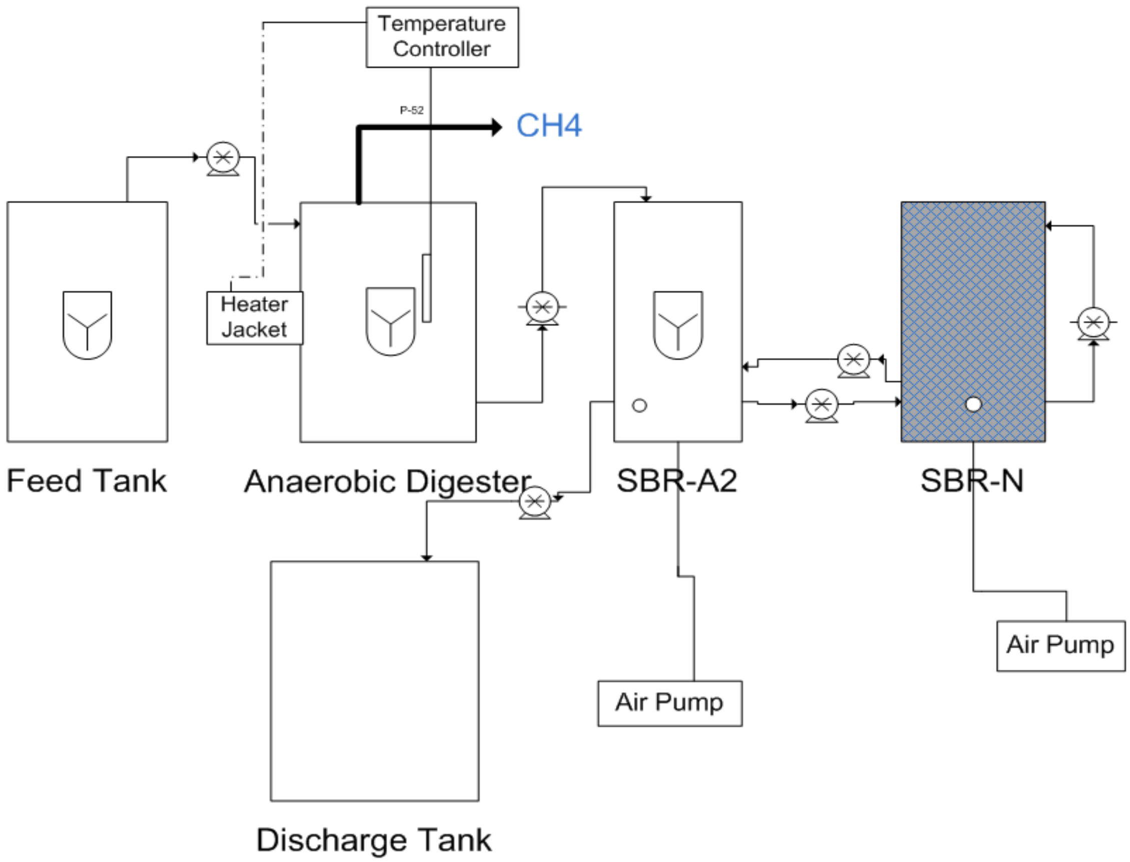


Figure 4-1: Anaerobic Digester and SBR-A^2N flow diagram

4.2.2. Sequencing batch reactors configuration

The process of P and N removal with the two-sludge system consists of anaerobic, nitrification, anoxic and an additional aerobic stage. The anaerobic, anoxic and additional aerobic stages occur in SBR-A^2 reactor and nitrification occurs in SBR-N reactor.

The schedule for the SBR system is presented in table 4-1. The cycle of 12 h was chosen for the system since the cycle duration should have been multiple of 6 h - the time period between digesters feeding and discharging. The nitrification stage requires more time than the anaerobic and anoxic stages. The anaerobic digester HRT was fixed at 13.3 d and the digester discharged 0.9 L of mixed liquor per day. An HRT of 42 h was chosen for the SBR system. Since the SBR system is in series with the anaerobic digester and the same amount of effluent was discharged from SBR, the working volume of SBR-A^2 was 1.6 L.SBR-A^2 was operated at an SRT of 15 days which was maintained by discharging 52 mL of mixed liquor at the end of aerobic stage before settling. 398 mL of supernatant was discharged after settling to keep the overall volume of effluent of 450 ml/cycle.

Table 4-1: The operating procedure for two-sludge SBR system

Reactor	Procedure	Duration (min)	Operation description
SBR-A2	1) Anaerobic phase	90	0.45 L of anaerobic digester effluent was transferred into SBR-^{A2,} mixed with 0.5 L of settled sludge, biological phosphorus release and COD consumption takes place
	2) Settling	25	After settling 0.6 L anaerobic supernatant rich in PO_4 and NH_4^+ was transferred into SBR-N thus giving the volume exchange ratio of around 0.63
SBR-N	3) Nitrification	300	Nitrification was maintained
	4) Settling	5	Settling and transferring to SBR-A^2
SBR-A2	4) Anoxic stage	210	0.9 L supernatant with high nitrate concentration was transferred from SBR-N to SBR-A^2 providing DNPAOs and PAOs with electron acceptors for anoxic phosphorus uptake
	5) Aeration phase	60	Final aeration to complete the phosphorus uptake and strip the residual ammonia. At the end of aeration phase, 52 mL phosphorus-rich mixed liquor is discharged to keep the SRT at 15 days
	6) Settling	30	Settling to keep the remaining sludge in SBR-A^2 reactor
	7) Final discharge		Discharging 398 mL supernatant as final effluent

The SBR-A2 was aerated continuously during the aerobic stage. SBR-N was being aerated intermittently 50 minutes aeration and 10 minutes of no aeration in each hour during nitrification.

4.2.3. Start up

The SBR system was started up 3 months after setting up the anaerobic digester. 1.1 L of waste activated sludge of a running EBPR system was used as seed for SBR-A2 tank. Activated sludge tank effluent obtained from Christiansburg wastewater treatment plant was used to inoculate the SBR-N with nitrifying bacteria. 450 mL of anaerobic digester effluent was transferred to SBR-A^2 2 times a day and the same amount was discharged from SBR-A^2 each cycle. Two SBRs was started up at the same time using AD effluent as SBR-A^2 influent. All through the experiment, in SBR-N the attached growth environment was not visible. Characterization of different streams started on May 5th 2010, 4 weeks after the A2N-SBR set up.

4.2.4. Sampling and analysis

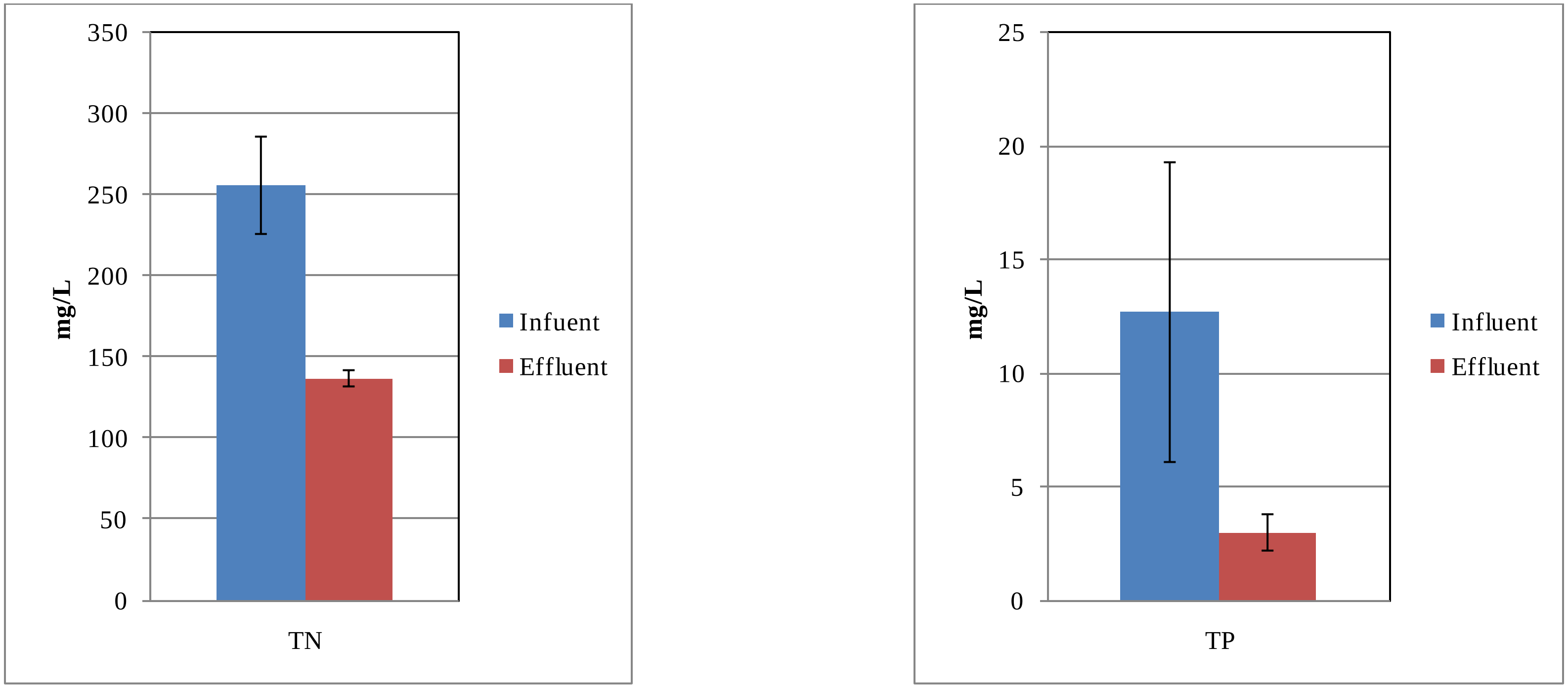
Samples were collected once a week from the AD effluent (SBR feed), SBR-A2 supernatant at the end of anaerobic stage, SBR-N supernatant at the end of nitrification stage and SBR-A2 effluent. SBR-A2 effluent was analyzed for TS, VS, total phosphorus (TP), total nitrogen (TN) total COD (tCOD) and soluble COD (sCOD). Anaerobic stage supernatant in SBR-A^2 was analyzed for TAN. Also the pH of the anaerobic stage was monitored using an

Orion 5 Star pH/ISE/dissolved oxygen/conductivity meter (Thermo Fisher Scientific, Fort Collins, CO). Nitrified supernatant discharged from SBR-N reactor was analyzed for sCOD, TAN and Nitrate/Nitrite. TS, VS analysis were conducted using standard methods for wastewater analysis (APHA, 1995). tCOD and sCOD were analyzed using method HACH 8000, USEPA approved reactor digestion method (HACH, Loveland, CO).Total Nitrogen (TN) and Total Phosphorus (TP) and N-$NO_x$was measured using simultaneous digestion method (USGS Method I-4650-03, 2003) For AD feed, AD effluent and SBR effluent. TAN was measured using probe (Orion, Thermo Fisher, Fisher Scientific, Columbus, Ohio) as outlined in method 4500-NH3 (APHA, 1995).

4.3. Results and discussion

4.3.1. Results

A^2N-SBR different stream characteristics are shown in table 4-2. TP and TN in turkey processing wastewater and anaerobic digester effluent were highly fluctuating. Despite the fluctuation of TN in the influent, the TN in the effluent had low variation. TP in the effluent ranged from 0.7 to 6.1 mg/L. Average TN and TP concentration in system influent and effluent is shown in figure 4-2.TP and TN variation in A^2N-SBR is shown in figure 4-3. The mean total nitrogen and total phosphorus concentrations in effluent were 137 $\pm$ 5 mg/L and 3.2 $\pm$ 0.7 mg/L with 47% and 75% removal respectively. tCOD and sCOD concentrations fed to the A^2N-SBR system were 980. $\pm$ 202 and 398 $\pm$ 43. Total COD and sCOD concentrations in effluent were 158$\pm$ 29 and 82 $\pm$ 15 with 84% and 57% tCOD and sCOD removal. COD/TN, COD/TP and TN/TP in the influent were 3.8, 77.2 and 20.2 respectively. Overall TS, VS, COD, TN, TP reductions in the whole system which consists of anaerobic digester and A^2N-SBR were 68%, 78%, 93%, , 48% and 68%, respectively.



4-2: Average TN and TP in SBR system influent and effluent.

Table 4-2: Characterization of A^2N-SBR different streams

	Influent	End of Anaerobic stage	End of nitrification	Effluent mixed liquor	Effluent
TN (mg/L	256 ± 29				137 ± 5
TAN (mg/L)	89 ± 7	48 ± 7	7.1 ± 2.0		
NOx- (mg N/L)			30 ± 5		
TP (mg/L)	13 ± 7			54 ± 2.5	3.2 ± 0.7
COD (mg/L)	980 ± 201				158 ± 29
sCOD (mg/L)	398 ± 43		114 ± 15		82 ± 15
TS (g/L)	1.21 ± 0.11				0.58 ± 0.14
VS (g/L)	0.84 ± 0.12				0.34 ± 0.12

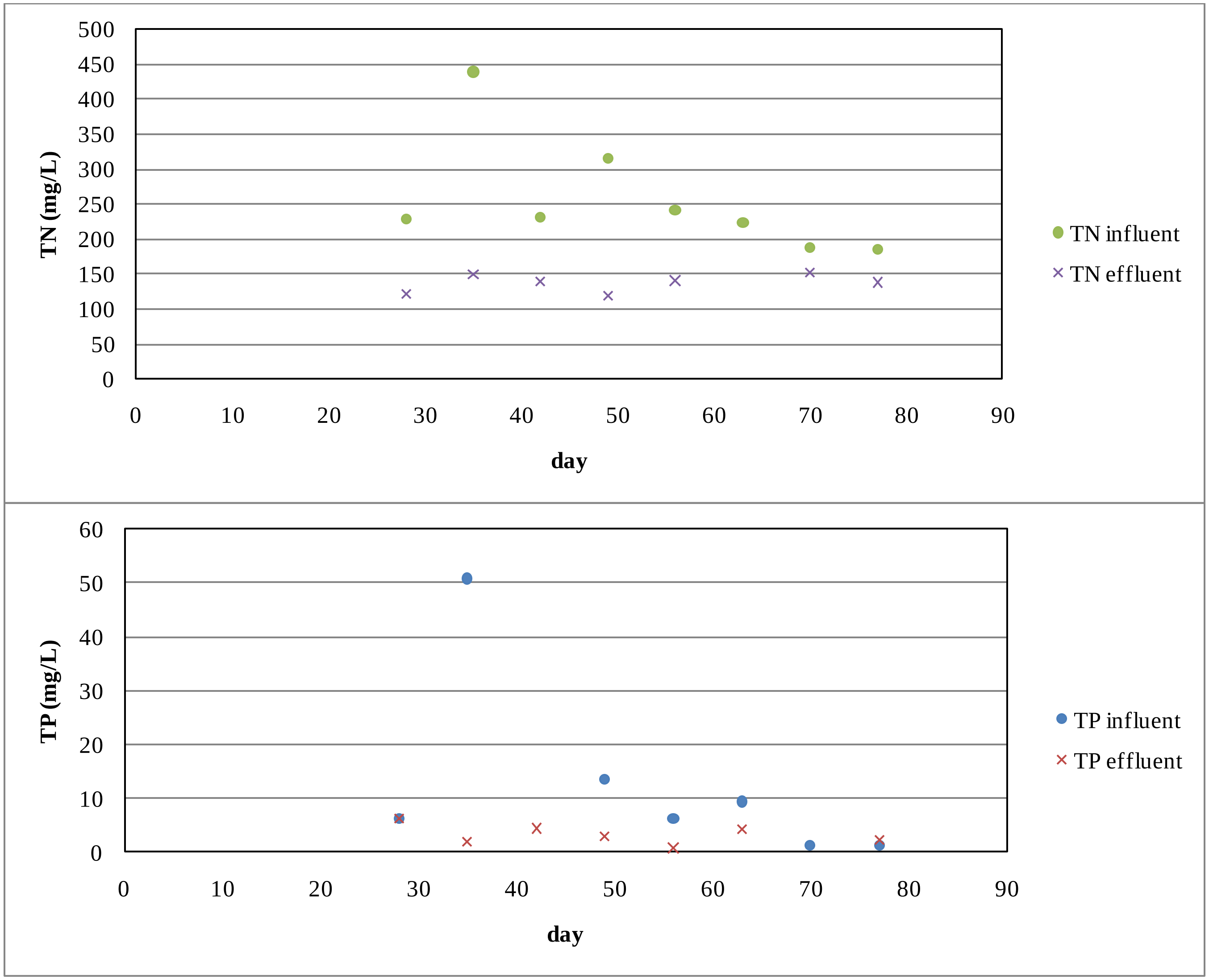


Figure 4-3: TN and TP in A^2N-SBR influent and effluent versus time.

4.3.2. Nitrogen removal

Total nitrogen and ammonia nitrogen in A^2N-SBR influent were 256 $\pm$ 29 and 89 $\pm$ 7 mg/L. The low ammonia nitrogen to total nitrogen ratio is the high concentration of organic nitrogen since AD's unsettled effluent was being used as A^2N-SBR influent and it had anaerobic sludge in it. So a part of high organic nitrogen concentration can be associated with the nitrogen content of anaerobes. Ammonia nitrogen at the end of anaerobic stage was 48 $\pm$ 7 mg/L which is 54% of the ammonia nitrogen in influent. No ammonia removal is expected during the anaerobic stage and the reason for this difference in ammonia concentrations is that influent is being mixed with the sludge with low ammonia nitrogen concentration in the reactor which is 52% of the SBR-A^2 working volume.

The mean TAN concentration after nitrification was 7.1 $\pm$ 2.0 mg/L. Nitrate was measured after the nitrification stage and had a mean value of 30 $\pm$ 5. Average nitrification was 62% and 23% of the TAN entering the nitrification was either consumed for nitrifiers growth or was lost through air stripping. Low nitrification was expected since the attached growth environment in SBR-N was not established. Biofilm growth is reported in attached growth reactor being established through continuous aerobic condition and synthetic wastewater with characteristics close to our system's influent after a month (Zhang et al., 2006). In the A^2N-SBR system during each 12-h cycle, SBR-N was staying idle for 7 h which may interfere with biofilm growth on media. Another important factor for nitrification is sufficient alkalinity which was not measured in this study. For each gram of ammonia nitrogen converted to nitrate, 7.14 g of alkalinity as $CaCO_3$ is required (Tchobanoglous et al., 2003). Adding alkalinity to the nitrification stage may have improved the nitrification.

After settling and transferring the supernatant from SBR-N to SBR-A^2, nitrate in waste water was used for phosphorus removal as electron acceptor to oxidize PHB stored in DNPAOs. Since the volume exchange ratio was 0.63, 37% of SBR-A^2 content remains without nitrification and contains ammonia. After returning the nitrified supernatant to SBR-A^2 the concentration of ammonia will decrease due to dilution with nitrified supernatant. The ammonia remaining in wastewater may be utilized for PAOs and DNPAOs growth (Peng et al., 2004). As nitrate is used as an electron acceptor for phosphate accumulation, a carbon source is required as an electron donor. Soluble COD was measured after nitrification which is the carbon source available for the anoxic stage.

The overall nitrogen removal was 47% in A^2N-SBR. The low efficiency of nitrogen removal may have several reasons. One of the issues is the low volume exchange rate in to the SBR reactors. Increasing the volume exchange ratio may improve the nitrification and decrease the ammonia concentration in anoxic stage. Ammonia may be oxidized in the final aerobic stage still remains as nitrate/nitrite in wastewater.

The optimal COD/TN ratio for nitrogen removal has been reported in literature studying A^2N systems. Kuba et al. (1996), Peng et al. (2004), Li et al. (2006) and Wang et al. (2009) have reported the optimal COD/TN ratio of 3.4, 6.5, 4 to 5 and 9.9 for nitrogen removal. Kuba et al. (1996) has used synthetic wastewater and acetate as carbon source and obtained lower ratio compared to other literature using municipal wastewater. In this study, COD/TN ratio in turkey processing wastewater is 3.8 which is low comparing to optimal ratios reported. Still it is unlikely the reason for nitrogen removal since extra carbon will improve the nitrate removal in anoxic stage and it does not improve the nitrification. During the experiment, the average nitrate concentration was 29.9 $\pm$ 5.0. Theoretically for each gram of nitrate to be converted to nitrogen gas during phosphate accumulation, 2.86 gram of biodegradable soluble COD (bsCOD) is needed (Tchobanoglous et al., 2003). The average sCOD available to anoxic stage was 114 $\pm$ 15 mg/L.

From the results, it can be implied that the amount of organic nitrogen is high in A^2N-SBR influent. To improve the nitrogen removal, there are some changes that could be made to the system. Adding a settling tank after anaerobic digester and prior to SBR-A^2 reduces the amount of methanogenic sludge in SBR-A^2 influent. Also settling conditions after last aerobic stage before discharging effluent can be improved to have less sludge in the final effluent.

4.3.3. Phosphorus removal

Total phosphorus in A^2N-SBR was highly fluctuating as shown in figure 4-2. The average TP in influent was 12.7 $\pm$ 6.6. Ortho-P is the form of phosphorus compounds that can be removed by PAOs and DNPAOs. In anaerobic phosphate release occurs along with fermentation of carbon source. COD removal (84%) was higher than sCOD removal (57%) in the whole system. Even if the influent is anaerobic digesters effluent and the amount of short chain carbon source is relatively high, still some fermentation takes place in anaerobic stage of A^2N-SBR process and short chain carbons such as acetate are used by PAOs to accumulate PHB.

The phosphorus removal was 75% during the experiment. Although the TN/TP is 20.2 in the influent and it is relatively high, due to incomplete nitrification, nitrate concentration introduced to anoxic stage is low for phosphorus removal. As a result there might not be sufficient nitrate as electron acceptor to remove the phosphate. When nitrate is taken up during the anoxic stage and there is not sufficient nitrate for phosphate uptake, “second phosphorus” release may happen in the absence of electron acceptors (Wang et al., 2009). Another concern in A^2N-SBR system was low quality of settling for final discharge. Adding a settling tank prior to discharge may improve the effluent quality.

One way to optimize the process condition and anaerobic, anoxic and aerobic stages duration is to online monitoring the pH, oxidation reduction potential (ORP) and dissolved oxygen (DO). By monitoring these 3 factors, endpoint of each stage can be found and sequencing batch reactors duration of each stage can be set based on them. In a study by Wang et al. (2009) these three variables have been monitored for a stable condition of A^2N-SBR system and endpoints of phosphate release, nitrification and denitrification has been determined successfully.

In their study, in A^2-SBR at the very beginning of anaerobic stage an immediate and sharp increase in pH was observed which is due to the VFAs uptake by PAOs/DNPAOs. After the sharp increase, pH decreased continuously due to the release of PO_4^{3+} ion. Comparing pH trend and PO_4^{3+}-P trend shows that the decrease rate of pH had a close correlation with the P-release rate (Wang et al., 2009). When P-release rate becomes very low, pH remains on a constant value. The point when pH remains constant can be determined as anaerobic stage endpoint (Wang et al., 2009).

In the N-SBR during nitrification process, pH increases sharply during the initial 30 min of aeration reaction which shows the oxidation of remaining biodegradable carbon source. When nitrification starts in N-SBR, pH drops initially and then increased (Wang et al., 2009; Zeng et al., 2008). In N-SBR, DO profile reaches a plateau at the end of nitrification stage, which attributed to complete ammonia conversion to NO_3^-, confirmed by the NH_3-N and NO_3-N profiles(Wang et al., 2009).

During the anoxic stage, a sharp increase of pH is observed as a result of anoxic phosphorus uptake and denitrification. The ORP profile was observed to decline at the beginning and then approach a plateau where the NO_2-N/NO_3-N concentrations both reached the relatively consistent values (Wang et al., 2009). In A2-SBR, during the last aeration stage, the end of nitrification is also identified based on the bending-points of DO and pH profiles when the oxidation of NH_4 –N finished.

4.4. Summary and conclusion

A^2N-SBR has been studied for simultaneous N and P removal from turkey processing wastewater to meet the discharge limits of 4 mg/L for N and 0.1 mg/L for P. During the experiment the limits for N and P were not reached and the attached growth nitrification tank needed more time to develop to biofilm on media. The mean total nitrogen and total phosphorus concentrations in effluent were 137.0 $\pm$ 4.7 mg N/L and 3.2 $\pm$ 0.7 mg P/L with 47% and 75% removal, respectively. tCOD and sCOD concentrations in effluent were 157.8 $\pm$ 28.9 and 81.7 $\pm$ 14.6 with 84% and 57% tCOD and sCOD removal. COD/TN, COD/TP and TN/TP in the influent were 3.8, 77.2 and 20.2, respectively. Overall TS, VS, COD, TN, TP reductions in the whole system which consists of anaerobic digester and A2N-SBR were 68%, 77%, 93%, , 48% and 68%. Even if the objective for P and N concentration was not met, removal of P and N through SBR-A^2N system is considerable and can be improved.

Nitrogen and phosphorus removal through A^2N-SBR may be improved by optimizing the nitrification process. Also improving the settling before discharge will improve the effluent quality. To optimize the process condition and anaerobic, anoxic and aerobic stages duration, online monitoring of the pH, oxidation reduction potential (ORP) and dissolved oxygen (DO) is helpful. By monitoring these 3 factors, endpoint of each stage can be found and sequencing batch reactors schedule can be set based on them.

4.5. References

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5. Appendices

5.1. Appendix A: Daily biogas production, temperature and pH data

Day	Temp (°C)	pH		Biogas production			
		Feed	AD	Cumulative biogas production (L)	Daily biogas peoduction (mL/d)	Average VS load (g VS/d)	Biogas yield (mL/g VS)
1	36.9	7.50	6.38	47.400	450		
2	39.9			47.850	450		
3	36.3			48.300	450	0.943	454
4				48.750	450		
5	36.4			49.050	300		
6	36.3			49.650	600		
7	37.2			50.100	450		
8	37.8	7.24	6.45	50.550	450		
9	37.5			51.150	600		
10	37.0			51.600	450	0.877	611
11	39.3			52.350	750		
12				52.800	450		
13	36.0			53.400	600		
14	37.2			54.000	600		
15	38.0	7.03	6.23	54.600	600		
16	39.1			55.350	750		
17	37.5			55.650	300	1.040	556
18				56.250	600		
19	37.1			56.850	600		
20	36.5			58.950	2,100		
21	36.5			59.700	750		
22	36.5			60.750	1,050		
23	36.5			62.250	1,500		
24	37.6			63.300	1,050	1.419	876
25	37.0			64.650	1,350		

Day	Temp (°C)	pH		Biogas production			
		Feed	AD	Cumulative biogas production (L)	Daily biogas production (mL/d)	Average VS load (g VS/d)	Biogas yield (mL/g VS)
26	38.9			65.550	900		
27	37.5			66.000	450		
28	36.9			66.600	600		
29	38.9	7.22	5.95	67.350	750		
30	38.4			68.100	750		
31	37.1			68.550	450	0.989	628
32	38.0			69.300	750		
33	37.2			69.900	600		
34	37.3			70.800	900		
35	35.9			71.550	750		
36	37.3	7.37	6.12	72.450	900		
37				73.200	750		
38	36.8			73.800	600	0.973	991
39	38.8			74.850	1,050		
40	37.7			76.650	1,800		
41	38.4			78.300	1,650		
42	36.4			79.200	900		
43	36.6			80.400	1,200		
44	36.9			82.050	1,650		
45	36.0			83.250	1,200	1.080	1,250
46	36.0			84.300	1,050		
47	38.0			86.100	1,800		
48	36.0			87.000	900		
49	36.4			88.500	1,500		
50	36.8	5.92	6.13	89.700	1,200	1.890	669
51	37.3			90.750	1,050		
52	37.5			92.400	1,650		
53				93.675	1,275		
54	37.9			94.950	1,275		
55	37.0			95.850	900		
56	37.6			97.800	1,950		

Day	Temp (°C)	pH		Biogas production		Average VS load (g VS/d)	Biogas yield (mL/g VS)
		Feed	AD	Cumulative biogas production (L)	Daily biogas production (mL/d)		
57	37.7	7.11	6.12	98.850	1,050	1.210	1,045
58	38.1			100.350	1,500		
59	36.2			101.400	1,050		
60	36.4			102.600	1,200		
61	36.1			103.800	1,200		
62	36.0			105.600	1,800		
63	36.0			106.950	1,350		
64	36.0	6.39	6.37	108.000	1,050	1.470	875
65	37.9			109.200	1,200		
66	36.0			110.550	1,350		
67	37.8			111.900	1,350		
68	37.5			112.800	900		
69				114.150	1,350		
70	36.2			115.650	1,500		
71	36.2	6.87	6.27	116.700	1,050	0.640	2,344
72				117.000	300		
73	37.7			118.500	1,500		
74				120.600	2,100		
75				121.350	750		
76				125.850	4,500		
77				127.650	1,800		
78	36.8	6.85	6.24	132.000	4,350	0.730	3,904

5.2. Appendix B: Solid data

Week	Feed		AD effluent		SBR effluent	
	TS (g/L)	VS (g/L)	TS (g/L)	VS (g/L)	TS (g/L)	VS (g/L)
1	1.76	1.29	1.56	0.91		
	1.38	0.95	1.44	0.82		
2	1.65	1.19	1.51	0.91		
	1.58	1.08	1.21	0.66		
	1.68	1.31	1.41	0.95		
3	1.47	1.12	1.20	0.80		
	1.86	1.43	1.59	1.14		
	2.17	1.71	1.16	0.71		
4	2.54	2.09	1.38	1.03		
	2.21	1.85	1.09	0.76		
	2.17	1.86	0.76	0.57		
5	1.67	1.37	0.97	0.71		
	1.56	1.25	0.92	0.63		
	1.66	1.43	1.00	0.73		
6	1.32	1.02	0.79	0.55		
	1.36	1.09	1.35	1.04		
	2.19	1.87	1.15	0.81		
7	1.82	1.47	1.04	0.76		
8	4.27	3.93	1.66	0.48	0.47	0.17
9	1.83	1.65	1.39	1.12	1.12	0.78
10	2.13	2.00	1.37	1.17	0.48	0.36
11	1.00	0.87	1.34	1.20	0.42	0.14
12	1.21	0.99	0.76	0.46	0.41	0.23

5.3. Appendix C: Nitrogen and Phosphorus data

Week	TP (mg/L)			TN (mg/L)			NOx (mg-N/L)	TAN (mg-N/L)		
	Feed	AD effluent	SBR effluent	Feed	AD effluent	SBR Effluent	SBR-N to SBR-A^2	AD effluent	SBR-A^2 to SBR-N	SBR-N to SBR-A^2
1	23.0	6.3	6.1	461.3	229.3	121.4	15.26	98.02	29.49	6.74
2	2.0	50.8	2.0	185.9	439.3	148.9	23.18	94.75	69.29	5.31
3	15.0			284.6	230.6	138.6	14.76	90.06	53.10	6.17
4	13.0	13.4	3.0	274.8	314.7	119.1	29.42	50.69	24.00	0.49
5	18.4	6.3	0.7	317.9	242.3	140.7	22.76	100.35	59.36	9.06
6	6.8	9.4	4.1	235.9	223.4	151.9	50.63	102.03	65.16	17.91
7	2.6	1.3		165.1	187.5		51.20	86.57	60.15	11.04
8	0.2	1.2	2.2	171.7	185.1	138.3	32.05		22.79	0.31

5.4. Appendix D: COD and sCOD data

Week	TCOD (mg/L)			SCOD (mg/L)			
	Feed	AD effluent	SBR effluent	Feed	AD effluent	SBR-N to SBR-A[2]	SBR effluent
1	2800	1473	75		186	126	
2	2306			312	150	110	
3	2896	1343	158	586	206	86	
4				390	305	199	
5	2674	1050	116	262	161	58	53
6	2478			375	227	98	
7	1802	473	206	349	150	89	101
8		561	234	510	144		91