THIS MANUSCRIPT IS DEDICATED TO MY PARENTS AND WIFE WHO HAVE ALWAYS ENCOURAGED AND SUPPORTED ME IN MY ACADEMIC AND LIFE PURSUITS.

"Is it not pleasant to learn with a constant perseverance and application?"
(Confucius, page 1)

A thesis presented on a novel chemical / physical swine manure treatment process, comprising the third year of research of a three-year project.

University of Alberta

LIQUID SWINE MANURE: BENCH AND PILOT-SCALE TREATMENT

By

Tao Jin ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Master of Science in

Environmental Engineering

Department of Civil and Environmental Engineering

Edmonton, Alberta

Fall, 2005

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ABSTRACT

Liquid swine manure, supplied by the Swine Research & Technology Center of the University of Alberta, Edmonton, Canada, was treated by physical/chemical methods, including preliminary settling in an underground tank, coagulation, flocculation, and settling in an up-flow floc blanket clarifier, and lastly, filtration through patented Martin filters. Alum and cationic polymers were used as coagulant and coagulant aid, respectively. Bench and pilot-scale tests were performed for the optimization of treatment processes. In case of performing on-line control, relationships between electric conductivity (EC) and total phosphorus (TP) / total dissolved solids (TDS) were also investigated.

It was found that physical/chemical treatment was effective in removing the TSS (87% removal on average) and TP (90% removal on average), but had limited success in removing organic and nitrogen compounds. Ten hours preliminary settling was recommend before any treatment. EC could be used to predict TDS and TP in swine manure treatment.

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to Dr. Mohamed Gamal El-Din and Dr. Ian Buchanan for their guidance, support, encouragement, positive criticism, and valuable suggestions throughout my research program.

I would like to acknowledge Mr. David Bromley of David Bromley Engineering Ltd., Vancouver, BC and NSERC for providing the necessary funding for this project. Also thanks to Mr. David Bromley and Mr. John Martin for their personal visits to the pilot plant and their help in setting up the system.

Special thanks to Ms. Maria Demeter who guided and helped me tirelessly with the laboratory experiments. I would like to express my gratitude to Mr. Garry Solonynko and Mr. Nick Chernuka for helping me in the pilot plant set-up and troubleshooting.

Finally, I would like to thank the Department of Civil and Environmental Engineering for providing the facilities for this research. Thanks also to the members of the school council for their valuable input. The support of Jay Willies of the Swine Research and Technology Center, University of Alberta, was very much appreciated, as was the occasional assistance of my colleagues Zheng Zhang, Jian Xiao, Hao Yang, Parmjit Singh, and Yishi Zhu.

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GLOSSARY

Mil. Spec. #	Filter Media Size
BOD_5	5-day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
Counts/ml	Number of particles measured by Particle Counter per milliliter of sample
gpm	Gallons per minute
kPa	Kilopascal
mg/L	Milligram per liter
ml	Milliliter
mm	Millimeter
μm	Micrometer (10^{-6})
min	Minute
m^3/s	Cubic meter per second
N	Nitrogen
nm	Nanometer (10^{-9})
P	Phosphorus
s	Second
TS	Total Solids
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
TP	Total Phosphorus
TKN	Total Kjeldahl Nitrogen
EC	Electrical Conductivity
UFFBC	Up-Flow Floc Blanket Clarifier
PMF	Patent Martin Filter
AFOs	Animal Feeding Operations
CAFOs	Concentrated Animal Feeding Operations

1 INTRODUCTION

A customized pilot-scale facility was studied for swine manure treatment. To optimize the process, jar tests, settling tests, column tests, and trial runs were conducted according to chemical dosage, pre-treatment, and sludge-blanket operating conditions, respectively. Alum and cationic polymer were used as coagulant and coagulant aid. A submerged filter was used to improve the clarifier process. Two stage clarifiers were used to achieve maximum treatment effects and improve the final effluent quality in terms of solids and phosphorus removal.

1.1 Statement of problem

Manure is a bio-product that should be considered as an asset. Manure can be used as a fertilizer, converted to make gas and electricity, or compost recycled into re-useable water or an organic fertilizer (U.S. EPA, 2005).

However, with the growth and centralization of livestock industries, manure handling and management has become a mounting priority for Animal Feeding Operations (AFOs). Despite traditional treatment approaches, such as digestion and composting, there are ongoing issues related to nutrient management, air quality, and water quality. A comprehensive approach must be undertaken.

It was found that traditional liquid-based manure practices, such as manure ponds, anaerobic lagoons, and holding tanks, account for more than 80 percent of total methane emissions from animal wastes. On the other hand, solid manure management systems, such as spreading manure on fields, produce insignificant amounts of gas, but can lead to increased nutrient runoff, thus affecting water quality. (U.S. EPA, 2000)

In terms of air quality, both greenhouse gases and ammonia are important issues, especially with respect to human health. Furthermore, any loss of nitrogen

(N) to the atmosphere constitutes a significant loss to the producer, because it necessitates a greater reliance on mineral fertilizer. The decomposition of animal waste in an anaerobic (oxygen free) environment produces methane, a powerful greenhouse gas. Manure storage and treatment systems account for about 9 percent of total U.S. methane emissions, and about 31 percent of methane emissions from the agricultural sector. Over a 100-year time span, methane is 21 times more effective than carbon dioxide at trapping heat in the atmosphere and is responsible for about 10 percent of the warming caused by U.S. greenhouse gas emissions.

In terms of the effects on water, not only the issue of water quality, in that swine manure runoff or leachate may contaminate water, but also the issue of quantity, in that water may become scarce, as many other users are also strongly dependent on this resource for their expansion, is pertinent.

The trend towards more confinement in livestock industries intensified the manure disposal problem. Consequently, water pollution from concentrated animal feeding operations (CAFOs) led to revised regulations in North America. Along with the duty to secure a permit, significant changes address coverage of pollutants, separation of production and land application areas, effluent limitation guidelines, and the differentiation of agricultural storm water discharges from other discharges. The new law ensures that the CAFOs are environmentally sustainable and serves to reduce the environmental impact on the surrounding areas.

In 2003, the Advanced Manure Management Technologies for Ontario (AMMTO) report was released. It showed the results of several years of study and review. The project was viewed as a proactive measure to assist farmers with the adoption of new and innovative technologies to address odour, nutrient, and groundwater issues related to livestock production. It was found that every specific operation has different potential uses for manure, depending on its individual activities. In general, the solid/liquid separation process provides significant removal of nutrients and pathogens. It can also greatly reduce the land requirements for AFOs. Meanwhile, the overall cost remains relatively low. (AMMTO, 2002)

The goal of this project is to develop reliable and economical means to treat swine manure on site, based on the solid/liquid separation process. These technologies need to allow for rural economic development, while also reducing public concern surrounding the land application of manure, potential impacts on surface and groundwater, and the production of odours.

1.2 Purpose of study

The whole project was divided into three stages. The first and second stages were completed in the year 2002 and year 2003, respectively, with their objectives being successfully achieved. The current research, as a portion of the third stage of the project, was carried out to achieve the following objectives:

- Simulating the treatment processes performed at the pilot plant in the laboratory under controlled conditions to find the best pilot plant operation conditions, which includes:
    - Optimizing the functioning of the preliminary settling using settling tests
    - Optimizing the flow rate of the pilot plant through column tests
    - Optimizing the chemical type and chemical dose of the pilot plant with Jar tests
- Optimizing the functioning of the pilot plant by investigating the best operating conditions (flow rates, chemical dose, stages of up-flow floc blanket clarifier, filter media size, and in-line pressures) for the newly designed up-flow floc blanket clarifier and patented Martin filters

- Investigating the relationship between chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5), total dissolved solids (TDS) and electrical conductivity (EC), and total solids (TS) and total phosphorus (TP)
- Evaluating the chemical/physical process in its capability for TSS, TP, TDS, COD, and Total Kjeldahl Nitrogen (TKN) reduction.

2 LITERATURE REVIEW

2.1 Livestock industries and regulations

In the U.S., there are approximately 1.3 million farms with livestock. About 238,000 of these farms are considered to be AFOs, where animals are kept and raised in confinement (U.S. EPA, 2003). The United States Department of Agriculture estimates that AFOs generate about 500 million tons of manure annually, which is three times more raw waste than is generated by humans in the U.S. Among those AFOs, there are an estimated 15,500 CAFOs, which produce 300 million tons of manure annually. It was estimated that hog farming (~82,000 Pig Farms) accounted for 3.4% of all livestock producing operations. These establishments accounted for US $12.4 billion of the total sales (USDA, 2004). The five-year history is shown in Table 2-1. It indicates that the number of farms with 2,000 or less hogs was significantly reduced, while the number of farms with 5,000 or more hogs almost doubled.

Table 2-1 Hogs and pigs in the U.S. (Adapted from USDA, 2004)

Hogs and pigs	1997			2002		
	Farms	Number	Value ($1,000)	Farms	Number	Value ($1,000)
Total hogs and pigs sold	112,377	142,956,569	13,833,370	82,028	184,997,686	12,400,977
Farms with-						
1 to 24	33,226	289,299	34,597	34,032	233,429	20,813
25 to 49	9,969	352,610	37,447	5,545	189,128	14,167
50 to 99	9,759	680,239	71,630	5,019	336,718	24,716
100 to 199	10,377	1,429,795	152,491	4,925	666,814	50,238
200 to 499	15,512	4,873,669	540,718	6,947	2,184,766	173,508
500 to 999	11,857	8,283,620	941,834	6,143	4,324,402	358,854
1,000 to 1,999	9,733	13,221,164	1,527,532	6,148	8,361,901	692,422
2,000 to 4,999.	6,822	20,336,849	2,292,866	6,059	18,504,172	1,521,681
5,000 or more	5,122	93,489,324	8,234,256	7,210	150,196,356	9,544,579
5,000 to 7,499	1,800	10,732,658	1,154,276	2,189	13,089,798	1,056,695
7,500 or more	3,322	82,756,666	7,079,980	5,021	137,106,558	8,487,884

In Canada, the number of hogs rose sharply in 2001 to 13.9 million — a 26.4% jump since the last census. This significant increase in hog production was driven by a strong export demand from the U.S. (Statistics Canada, 2001). The total export of fresh and frozen pork was estimated to be $1.6 billion (Canadian) in the year 2003 (AAFC, 2003). The extended history of the hog sector is shown in Figure 2-1.

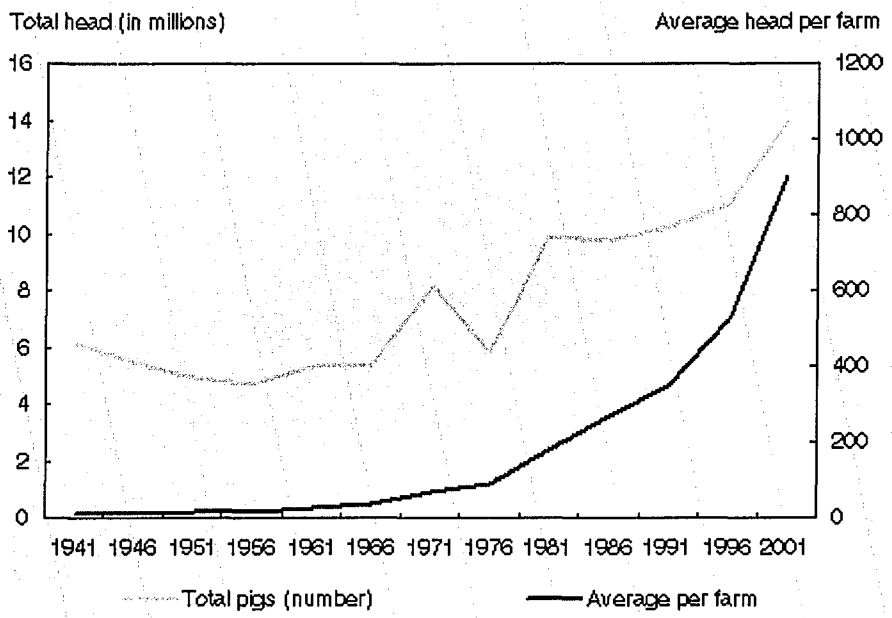

Figure 2-1 More pigs than ever on bigger farms (adapted from statistics Canada, 2001)

As the second largest livestock-producing province, Alberta contributes 14% of Canada's total hog production, as shown in Table 2-2. The total heads increased from 1.8 million to 2.1 million in the last seven years.

Table 2-2 Pigs on farms in Alberta (adapted from AOPA 2002)

('000 Head)	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Breeding Stock	189.2	199.3	183.6	189.5	202.6	219.2	215.5	214.1
All Other Pigs	1,617.10	1,643.60	1,670.40	1,693.00	1,762.20	1,905.90	1,924.30	1,835.90
TOTAL	1,806.30	1,842.90	1,854.00	1,882.50	1,964.80	2,125.10	2,139.80	2,050.00

It is clearly shown that the hog industry has expanded very rapidly within the past few years. Environmental issues related to this growth led to the revision of related regulations. In 2002, US EPA published "National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs); Final Rule", which became effective in April 2003. It requires that the treatment of animal waste represents the degree of effluent reduction attainable by the application of the best practicable control technology currently available (BPT). In Alberta, Canada, province-wide regulations and standards governing new and expanding Confined Feeding Operations (CFOs) were released. The new rules affect all agricultural operations and other users that produce or receive manure as a soil nutrient source or supplement (AOPA, 2002) and put requirements on manure application to allow better utilization of nutrients by crops.

2.2 Manure Management and Main Usage

Because of the various swine facilities and the different kinds of manure produced, there are three management systems for handling swine manure: Solid Manure Handling, Semi-solid Manure Handling, and Liquid Manure Handling (U.S. EPA, 2005). Among these three systems, liquid manure handling is perhaps the easiest and most efficient technique because it requires less time and labour, and handling can be postponed to fit field schedules, soil conditions, and expected rainfall if the storage unit is properly sized.

As we know, manure can be used as a fertilizer, converted to make gas and electricity, and compost recycled into re-useable water or an organic fertilizer. In general, manure is used as fertilizer before or after treatment, due to its high nutrient content. The advantage of organic matter recycling combined with mineral fertilization has been clearly proven through experimentation (Berecz et al., 2004). In the U.S., manure is now used as fertilizer on about 17 percent of the nation's corn crops and 9 percent of soybean crops (Kaplan et al., 2002). In Alberta, according to the census, there were 197 certified organic farms on Census Day, 0.4% of all farms in the province (AOPA, 2002). This information shows there is plenty of room for certified organic farms to grow and to recycle swine manure

2.3 Manure Characteristics and Environmental Concerns

Swine manure is difficult to characterize due to its high concentration, variation, and complexity. Many research efforts have been conducted on a wide range of topics, from representative sampling to physical, chemical, and biological analyses. In general, swine manure contains a mixture of urine, feces, and water spillage, and it may contain undigested dietary remains, endogenous end products, indigenous bacteria, and antimicrobial drug residues added to the diet of the swine. All of these could cause environmental concerns.

Swine manure contains five to 15% total solids, depending upon the quantity of water spilled during drinking. According to the standards of ASAE (2003), typical swine manure is characterized by its high solid content, high 5-day biochemical oxygen demand (BOD_5), high total phosphorus (TP) and nitrogen (N) contents, and high level of microbial population. Table 2-3 lists typical characteristics of fresh swine manure.

Table 2-3 Fresh swine manure production and characteristics (Adapted from ASAE, 2003)

Component	Units	Mean	Standard Deviation
Total manure	kg	84	24
Urine	kg	39	4.8
Density	kg/m3	990	24
Total solids	kg	11	6.3
Volatile solids	kg	8.5	0.66
BOD5	kg	3.1	0.72
COD	kg	8.4	3.7
pH		7.5	0.57
TKN	kg	0.52	0.21
NH3 - N	kg	0.29	0.10
TP	kg	0.18	0.10

Component	Units	Mean	Standard Deviation
Ortho-P	kg	0.2	n/a
Potassium	kg	0.29	0.16
Calcium	kg	0.33	0.18
Magnesium	kg	0.070	0.035
Sulphur	kg	0.076	0.040
Sodium	kg	0.067	0.052
Chloride	kg	0.26	0.052
Iron	kg	16	9.7
Manganese	kg	1.9	0.74
Boron	kg	3.1	0.95
Molybdenum	kg	0.028	0.30
Zinc	kg	5.0	2.5
Copper	kg	1.2	0.84
Cadmium	kg	0.027	0.028
Nickel	kg	**	**
Lead	kg	0.084	0.012
Total coliforms	Colonies	45	33
Fecal coliforms	Colonies	18	22
Fecal streptococcus	Colonies	530	290

[1] Values based on per 1000 kg live animal weight per day,

** Data not found

Many studies were conducted to investigate the correlation of manure characteristics. Higgins et al. (2004) conducted a study with 88, 63, and 39 samples from finisher pig pit, cow pit, and dairy earthen storage basins, respectively. It was found that TP was strongly correlated with solids, while total nitrogen (TN) was also influenced by the manure storage facility, animal growth stage, and season (Higgins et al., 2004). Normally, the design biological treatment requires the determination of the chemical oxygen demand (COD) fractions of the effluent. Research was conducted to quantify the inert soluble (SI) and particulate (XI) COD fractions, as well as the readily (SS) and the slowly (XS) biodegradable COD fractions. For the four piggery wastewaters tested, the SI and the XI fractions were equal to 3 to 4 g-O_2/L and 17 to 28 g-O_2/L, respectively, which resulted in a total inert fraction of 42 to 84% of total COD. The SS and the XS fractions were very variable, ranging from 0 to 5 g-O_2/L and 4 to 25 g-O_2/L, respectively, depending on the farm management practices and the storage conditions prior to biological treatment (Boursier et al., 2005).

Particle size distributions and the associated chemical compositions were evaluated by (Sophonsiri and Morgenroth, 2004). Most of the organic matter in agriculture wastewaters was larger than a molecular weight of 103 amu. The agricultural wastewaters contained mainly soluble organic matter (<103 amu) and larger particles (>10 mm), leaving a gap in the size range of large macromolecules and colloids. The relative protein and carbohydrate concentrations varied for the different size fractions, compared to the measured chemical oxygen demand (COD) in the corresponding size fraction (Sophonsiri and Morgenroth, 2004). In another study, fresh swine manure was sieved into seven different particle size categories, i.e., <0.075 mm, <0.15 mm, <0.25 mm, <0.5 mm, <1.0 mm, <1.4 mm, and <2.0 mm (Zhu et al., 2001b). Total volatile fatty acids (VFAs), BOD_5, TS, TSS, and total volatile solids (TVS) were analyzed. The results showed that total VFAs correlated well with BOD_5 (R^2=0.8297). The levels of TSS only explained 40% of BOD_5 and 46% of VFAs. Data also showed that, for swine manure, it is critical to run separation treatment within the first ten days after the manure is excreted to potentially improve the separation efficiency. After ten days, the degradation of TSS was accelerated due to increased biological activities, which may greatly reduce the separation efficiency (Zhu et al., 2001b).

Pollutants associated with swine manure include nutrients (including ammonia), organic matter, solids, pathogens, and odorous compounds. Pollution may also result from salts and various trace elements (including metals), as well as pesticides, antibiotics, and hormones (U.S. EPA, 2003). There are many pathways through which these pollutants can cause environmental contamination, such as: surface runoff and erosion, overflows from lagoons, spills and other dry-weather discharges, leaching into soil and ground water, and volatilization of compounds and subsequent re-deposition on the landscape.

Many research efforts have indicated that the excessive use of manure may lead to environmental concerns. Based on the U.S. EPA's 2000 inventory data, it was found that water quality concerns tend to be greatest in regions where crops are intensively cultivated and where livestock operations are concentrated (U.S. EPA, 2003). One study pointed out that excessive and over-application of manure causes infertility in croplands and deteriorates the ground water quality, rendering it unsuitable as drinking water (Bromley et al., 2002). One other study reported that a fraction of the nutrients applied for crop production are not present in the plant-available form, and therefore, are potentially carried away with runoff. These nutrients enter surface water channels or seep into the ground water, resulting in the pollution of natural resources (Norwood and Chvosta, 2003). The phosphorus build-up in land caused by excessive swine manure application, and its impact on the N: P requirements of the crops, was also discussed. Phosphorus may be carried away with runoff, which results in the eutrophication of surface and ground waters (Vanotti et al., 2003). Campagnolo et al. (2002) showed that animal waste used as fertilizer for crops might serve as a source of anti-microbial residues for the environment.

For nutrient management purposes, it is important to understand the impact of manure application on soil phosphorus sorption characteristics and what it means with regard to potential environmental problems. Manure application increased sorption capacity significantly in the Nicollet soil series. Phosphorus sorption capacity was unchanged by manure application in the Waukegan soil series. Manure application reduced P sorption capacity in the Port Byron, Sanburn, Verndale, Ves, and Barnes soils. Phosphorus sorption strength decreased in five of the seven soil series after manure application (Laboski and Lamb, 2004). When manure application increased phosphorus sorption capacity to more than 26%, sorption strength was reduced; P was bound less tightly to the soil at low strength sorption sites, such that P was more readily available (Laboski and Lamb, 2004).

Nitrogen (N) and phosphorus (P) are essential nutrients for most of the life forms on Earth. Major inputs and outputs of N and P associated with human activity are fertilization, the use of animal and green manure, addition of municipal/industrial by-products (e.g. biosolids, urban composts), and plant uptake and P removal in harvested crops. Excessively fertilized soils have been shown to have a greater potential for environmentally significant losses of P to surface waters and shallow ground waters (Sharpley et al., 1994; Simard et al., 1995; Sims et al., 2000). It was also found that the N input to our environment has increased tremendously during the last 40 years, as shown in Figure 2-2 (Howarth, 2003). As a side effect, nitrous oxide, an oxidized form of nitrogen, not only contributes to greenhouse warming effects when it is in air, but also leads to increased incidences of cancer, miscarriage, and other health-related problems when it is in water (Howarth, 2003).

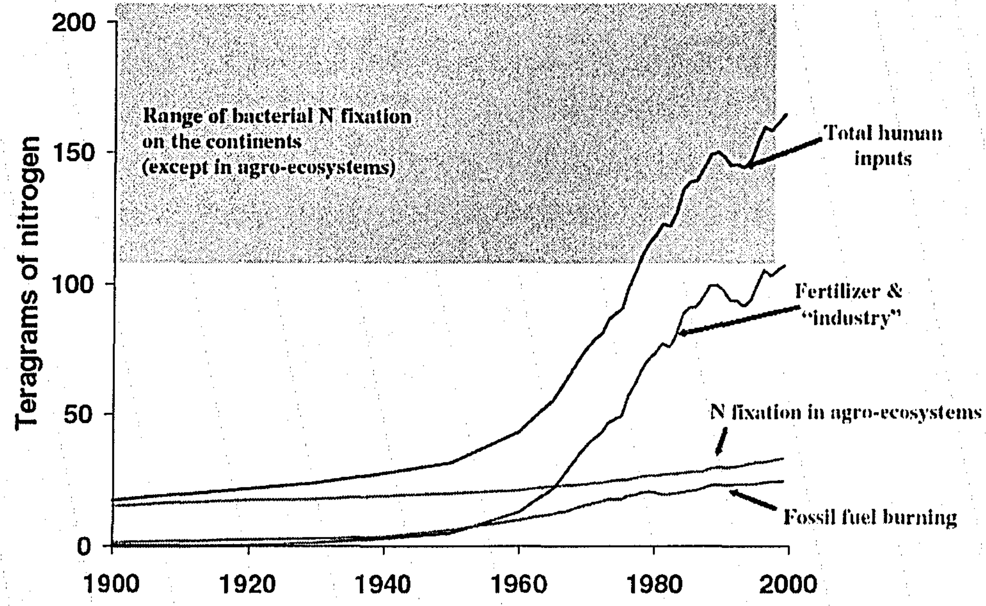

Figure 2-2 The increase in mobilization of nitrogen from human activities (Adapted from Howarth, 2003)

Excessive nitrate levels in drinking water and exposure to waterborne human pathogens and other pollutants in manure can also affect human health. Young (1974) and Cole et al. (1999) discussed several diseases that can be transmitted in water from animal to animal and from animals to humans. Some examples include bacterial infections of *Salmonella*, *Listeria*, *Leptospira*, *Vibrio*, *Brucella*, *Coxiella*, and *Chlamydia*. Other infectious agents such as Mycoplasma, fungi, and protozoa (*Cryptosporidium*) can also be transmitted in water. For example, the deadly waterborne outbreak of *E. Coli* O157:H7 and *Campylobacter* spp. in Walkerton, Ontario, Canada in May - June 2000 was traced back to contamination from livestock farm waste (Juteau et al., 2004).

Gas emissions from swine manure storage systems represent a concern to air quality, due to the potential effects of hydrogen sulphide, ammonia, methane, and volatile organic compounds on environmental quality and human health. In 2001, Zahn et al. developed a classification system based on gas emission characteristics and effluent concentrations of TP and total sulphur. Four swine manure management system classes were identified and it was found that odour intensity and the concentration of VOCs in air emitted from swine manure management systems were strongly correlated (R^2=0.88). The concentration of VOCs in air samples was highest with outdoor swine manure management systems that received a high input of volatile solids (Type 2) (Zahn et al., 2001). Moreover, research has indicated that those gas emissions may affect climate change (U.S. EPA, 2000a). It was also found that substantial amounts of methane and carbon dioxide are produced by animal manure in an open fed-batch system kept at 15 to 20 degrees C, even when stored for a short time (Moller et al., 2004).

2.4 Swine Manure treatment

Traditionally, swine manure treatment options were modified versions of the techniques used for municipal (human sewage) or industrial wastewaters. Those techniques include manure handling, storage, transportation, and application.

However, several factors impeded the adaptation of all municipal wastewater treatment technologies for AFOs. Swine manure is typically concentrated and contains high levels of nutrients. CAFOs also produce higher volumes and strengths of manure than do municipal facilities, due to intensified activity and reduced dilution rates. The decentralized nature of AFOs and CAFOs is another factor that often results in higher treatment cost, which the animal industry cannot afford.

In general, there are two options available – physical/chemical methods and/or biological treatment methods – to be applied in swine manure treatment. Those two types of treatment can be linked together as a combined treatment.

2.4.1 Physical/chemical treatment

Physical/chemical methods include preliminary settling or sedimentation, media and membrane filtration, aeration and stripping, and chemical precipitation or coagulation/flocculation, to remove solids, organic content, and nutrients present in swine manure.

2.4.1.1 Physical separation

In this section, pure physical solid/liquid separation, which includes gravity settling, screening, filtration, membranes, aeration, and stripping, was discussed and reviewed.

2.4.1.1.1 Gravity settling

Gravity settling is the most popularly used method for the treatment of agro-wastewater; however, it is still being investigated for better performance in treating animal manure. Experiments were conducted to determine the effect of solid levels on the natural sedimentation of swine manure. Total solids (TS) levels of 0.5, 1.0, 2.0, 4.0, and 6.0% were evaluated. Natural sedimentation was impeded at higher than 2.0% and also at lower than 1.0% TS concentrations. Unaided natural sedimentation at this TS concentration removed 66% and 42% of the SS and phosphorus, respectively (Ndegwa et al., 2001). Martinez et al. (1995) also reported somewhat similar results. It was found that the TS concentration of the swine manure was a significant factor in gravitational sedimentation: very thin or very concentrated slurries did not separate effectively. Meyer et al. (2004) evaluated the effectiveness of a settling basin with a large dewatering surface area (weeping wall separation system) for the treatment of dairy manure wastewater on a field scale. The results demonstrated the system's capacity for high solids removal. The percentages of TS removed were 63.41%, 59.65%, 63.07%, and 49.39% for each of the sampling periods. The differences were consistent with animal husbandry practices. However, there was no difference in the concentration of soluble nutrients from selected influent and effluent samples (Meyer et al., 2004). Zhu et al. (2004a) found that preliminary settling time had an effect on TSS removal only within the first 24 hours for swine manure treatment. TSS removal efficiency reached 75% after 24 hours of preliminary settling.

It was found that the relative protein and carbohydrate concentrations varied for the different size fractions with respect to the measured chemical oxygen demand (COD) in the corresponding size fraction. Thus, the design of the solid–liquid separation process at a treatment plant could be used to purposefully modify the overall chemical composition of the organic matter before further biological treatment (Sophonsiri and Morgenroth, 2004).

Trias et al. (2004) studied the optimization of cation balance in the sedimentation phase of swine manure treatment. Their results indicated that the addition of cations produced no statistically significant improvement in the sedimentation process.

2.4.1.1.2 Screening

Screening is generally the first unit operation encountered in a wastewater treatment plant. A screen is normally a device with openings, generally of uniform size, which is used to retain solids from waste water.

The use of screens in swine manure treatment was investigated by Zhu et al. (2001b). The results showed that most of the odorous compounds (measured by VFA and BOD levels) were contained in manure solid particles less than 0.075 mm in size. These cannot be removed by commercial mechanical separators with screen sizes ranging from 0.5 to 3.0 mm. With an average separation efficiency of 25% for most commercially available mechanical separators, the removal efficiencies for BOD_5 and VFAs were as low as 10% and 12%, respectively. Data also showed that for swine manure, it is critical to run separation treatment within the first ten days after the manure is excreted to potentially improve the separation efficiency. After ten days, the degradation of TSS was accelerated due to increased biological activities, which may greatly reduce the separation efficiency (Zhu et al., 2001b).

2.4.1.1.3 Filtration and membranes

Filtration and membranes are purely physical techniques used in the treatment of agricultural wastes. They are used to achieve supplemental removal of suspended solids (including particulate BOD) from the wastewater effluents of biological and chemical treatment processes, in order to reduce the mass discharge of solids. These methods are also used as pre-treatment steps for membrane filtration. Single- and two-stage filtration is also used to remove chemically precipitated phosphorus (Metcalf & Eddy, 2003).

The application of granular media filtration was assessed in wastewater reclamation and reuse and the results indicated that considerable improvements in effluent quality could be attained through tertiary sand filtration (Hamoda et al., 2004). The tertiary treatment of biologically treated swine manure using a vibratory shear enhanced RO membrane (VSEP RO) was investigated (Lee et al., 2004b). Direct application of the RO membrane to the biologically treated effluent, without any pretreatment, has proven to successfully reduce high-suspended solids. When the operation pressure was 1.3MPa, the combination of VESP UF followed by RO filtration processes produced an average recovery rate (70%) in the three-week pilot test, while CIP (clean-in-place) was conducted every two weeks (Lee et al., 2004b). Another study was conducted to investigate low-rate and high-rate media filtration. Seven parameters were: effective size of the media (0.4 or 2.0 mm), depth of the media (50 or 300 cm), water head (50 or 300 cm), filtration rate (5 or 30 m/h), uniformity coefficient (1.3 or 1.5), raw water turbidity (1 or 5 NTU), and type of filtering media (sand or anthracite). It was found that four of the parameters (flow rate, filter depth, media size, and pressure) had the most significant impacts on the filter (Tchio et al., 2003). The global cost analysis showed that a well designed and properly operated high-rate filtration process is more cost-effective than low-rate filtration.

2.4.1.1.4 Aeration and striping

Aeration was traditionally used to remove volatile organic compounds (VOCs). It was also used to strip out ammonia nitrogen from animal manure. Recently, the usage of aeration in phosphorus removal and struvite recovery was investigated by several researchers. The mechanism behind the removal of soluble P in aeration is pH-dependent. Passing an aerating gas mixture through the slurry purges CO_2 out of solution and causes pH to rise. Two low level aeration schemes (intermittent vs. continuous) were investigated on a laboratory scale, in conjunction with swine manure pH adjustment using sodium hydroxide (1.0 M), for manure phosphorus (P) removal. According to the data, an 80% reduction in soluble P was observed when the manure pH was increased to 8. Both intermittent and continuous aeration treatments could raise manure pH above 8 with an airflow rate of 1 L/minute in a period of 15 days. A drastic increase in pH (about 1 unit) was observed for both aeration schemes within the first day of the test, resulting in a 76% reduction in soluble P concentration in the liquid. It appeared that there was no difference, in terms of P removal, between the two aeration programs, thus suggesting that intermittent aeration is preferable as it saves energy while still achieving the same level of P removal (Luo et al., 2001;

Zhu et al., 2001a). Two other studies conducted by Suzuki et al. (2004; 2001) concluded that through aeration, 95% pure struvite can be removed from swine waste and a 65% dissolved phosphorus removal efficiency can be achieved.

2.4.1.2 Chemical solid/liquid separation

Chemical precipitation is a common primary wastewater treatment, and may include three steps: (1) chemical-aided coagulation, (2) mixing and resulting particle aggregation (flocculation), and (3) sedimentation of the flocculation product (flocs) due to gravity or centrifugation (Hammer and Hammer Jr., 2001). Normally, the addition of chemicals can alter the physical state of dissolved and suspended solids and facilitate their removal by sedimentation.

In the past, chemical solid/liquid separation was often used to enhance the degree of TSS removal. However, the coagulation process is not restricted to the removal of TSS. It also reacts with some dissolved species (e.g. natural organic matter (NOM), inorganic, and hydrophobic synthetic organic compounds (SOCs)) and makes them insoluble (U.S. EPA, 2000b; Karthikeyan et al., 2002). It was also found that humus significantly inhibited particle destabilization and impaired the aggregation of microflocs (Fettig and Ratnaweera, 1993).

The chemical precipitation of phosphorus is brought about by the addition of the salts of multivalent metal ions that form precipitates of sparingly soluble phosphates. The most commonly used multivalent metal ions are Ca^{2+}, Al^{3+}, and Fe^{3+} (Metcalf & Eddy, 2003). The basic reactions involved in the precipitation of phosphate are described in the following equations:

$$10Ca^{2+} + 6PO_4^{3-} + 2OH^- \leftrightarrow Ca_{10}(PO_4)_6(OH)_2$$

$$Al^{3+} + H_nPO_4^{3-n} \leftrightarrow AlPO_4 + nH^+$$

$$Fe^{3+} + H_nPO_4^{3-n} \leftrightarrow FePO_4 + nH^+$$

However, these reactions must be considered in accordance with many competing reactions and their associated equilibrium constants, and the effects of alkalinity, pH, trace elements, and ligands found in wastewater (Metcalf & Eddy, 2003).

Several studies were conducted to investigate the coagulants used in swine manure treatment - two flocculants (ferric chloride and aluminium sulphate) commonly used in the municipal wastewater treatment industry. Ndegwa et al. (2001) evaluated their enhancement of natural sedimentation and the concomitant removal of phosphorus from swine manure. Each flocculant was evaluated at five levels: 0 (control), 500, 1,000, 1,500, and 2,000 mg/L on swine manure with an adjusted TS level of 1.0%. At dosage levels of 1,500 mg/L (5.4 mM Fe^{3+}), ferric chloride removed 76% suspended solids (SS) and 86% phosphorus, while aluminium sulphate at the same dosage level removed 96% SS and 78% phosphorus. Chemical flocculation can, therefore, be an effective method of removing solids and phosphorus from swine manure (Ndegwa et al., 2001). Zhu et al. (2004a) also investigated those flocculants and found that in both TSS and TP reduction, alum was more effective than ferric chloride. During one-step dosing of alum at a concentration of 1,600 mg/L, the ratios of TSS and TP masses removed to alum mass applied were about 0.38 and 0.16, respectively.

Limestone is another chemical that can be used in physical phosphorus precipitation. A study using lime dust to remove TP and TS from fresh swine manure was conducted recently (Barrington et al., 2004). In this experiment, 3 L of lime dust was added to 1.30 m^3 of manure and mixed with the manure using a rectangular container and a paddle mixer operated by a motor. After mixing, the precipitated manure was allowed to settle for 12 days. The sludge depth was measured every day. After 12 days, the supernatant liquid and sludge were analyzed for density, TS, TP, and pH. The sludge and supernatant masses were calculated by multiplying the density by the depth and cross-sectional area of the mixer. The data indicated 96 and 90% removals of TP and TS (as high as 7.4% at the beginning), respectively (Barrington et al., 2004).

Polymers were widely used as coagulant aids. Eight different polyacrylamides (PAM) were studied for use in removing solids and phosphorous from liquid dairy manure. The results confirmed that all the PAMs and alum tested increased solids removal and TP reduction significantly (Timby et al., 2004). It was found that the cationic PAMs exhibited larger and more consistent increases in solids and TP removal, while the combination of alum and PAM resulted in higher removal of solids and TP (Timby et al., 2004). The ability of a PAM flocculant-aided solids separation treatment to increase swine manure separation efficiency through gravity settling (sedimentation) was evaluated before and after the addition of a proprietary polymeric flocculant. Results indicated that polymer amendments at a concentration of 62.5 to 750 mg/L improved solids separation efficiency and significantly reduced pollution indicator concentrations in raw (untreated) swine manure. Additionally, lower doses of PAM were equally, and in some cases more, efficient than higher doses (Walker and Kelley, 2003).

Struvite crystallization has been broadly investigated in recent years and a tendency has developed to use it in the recovery of phosphorus from animal manure. The reaction equation is:

$$NH_4^+ + Mg^{2+} + PO_4^{3-} \leftrightarrow NH_4MgPO_4 \downarrow$$

Heinzmann (2004) reviewed several processes currently applied for phosphorus recovery, but indicated that there was no one fully developed technique. Laboratory and field experiments were conducted using magnesium chloride ($MgCl_2$) to force the precipitation of struvite and reduce the concentration of soluble phosphorus in swine waste. The experiment achieved 76% removal efficiency at a 1.6:1 magnesium to phosphorus molar ratio and the soluble phosphorus removal efficiency increased to 91% then the pH was adjusted to 9.0

(Burns et al., 2001). A fluidized-bed magnesium ammonium phosphate (MAP) reactor was proposed for use with seed crystals to help promote further MAP crystallization on the seed surfaces (Ishikawa et al., 2004). Suzuki et al. (2004) proposed a reactor capable of dual function, crystallization through aeration, and separation of formed struvite by settling, for the removal and recovery of phosphorous from swine wastewater. Factors affecting struvite generation were investigated. Seco et al. (2004) investigated struvite crystallization using a stirred reactor. At HRT=10.6 hours, 60-80% P-removal was reliably achieved, with struvite being precipitated in the form of easily dried crystals or pellets. Removal efficiency was increased with a higher pH value and Mg/P ratio, these ranging from 8.5-8.9 and 0.8-1.1, respectively (Seco et al., 2004).

Several studies were conducted with regard to auto nucleation and seeding in struvite generation. One research effort investigating the nucleation and growth of struvite by using synthetic wastewater suggested a surface diffusion controlled mechanism (Kofina and Koutsoukos, 2004). One experimental plant using silica sand as seed material demonstrated an inexpensive method of removing and recovering P from anaerobic supernatants (Battistoni et al., 2004). However, another study conducted by Burns et al. (2003) indicated that seeding the reaction did not significantly enhance the struvite recovery process. It was confirmed that reactor seeding was not a factor of any particular importance since, once the struvite crystallization reactions were underway, the reactor appeared to be “self-seeding” (Adnan et al., 2004).

The relationship between major ions and induction time in struvite crystallization was investigated. The results indicated that the presence of more than 50mM of sodium ions retarded induction time significantly. Calcium ions at 0.25mM did not cause a marked change in the induction time, while carbonate ions had a slight effect. Sulphate ions increased the induction time (Kabdasli et al., 2004). Another investigation of laboratory and pilot batches was carried out on a continuously operated scale. Results indicated that struvite precipitation is a function of pH when using ferric chloride and cationically charged polyacrylamide coagulant pre-treated swine effluent (Laridi et al., 2004). It was also found that, by increasing the concentration of Ca in solution, the size of the struvite crystals was reduced (Corre et al., 2004).

2.4.2 Biological treatment

Biological methods employ biological or natural processes, such as aerobic and anaerobic digestion, lagoons and Sequential Batch Reactors (SBRs), algae and plant-based systems, constructed wetlands, and other biological treatments, to transform dissolved and particulate biodegradable constituents into acceptable end products and to remove nutrients such as nitrogen and phosphorus (Metcalf & Eddy, 2003).

2.4.2.1 Anaerobic treatment

Anaerobic digestion has been widely used in swine manure treatment. A major advantage of the anaerobic treatment process is that, compared with aerobic processes, energy consumption is low and there is little excess sludge production. One other advantage is that its by-product, biogas, can be used as an alternative energy source.

Experiments in a lab-scale SBR were conducted to demonstrate the feasibility of using an internal carbon source (non-digested pig manure) for biological nitrogen and phosphorus removal in digested piggery wastewater. The internal C-source used for denitrification had similar effects to acetate. 99.8% of nitrogen and 97.8% of phosphate were removed in the SBR, from an initial content in the feed of 900 mg/L ammonia and 90 mg/l phosphate (Obaja et al., 2005).

The effect of influent substrate concentration on the performance of down-flow anaerobic fixed bed reactors (AFBR) treating swine manure was studied at hydraulic retention times (HRTs) in the range of one to six days at tropical temperatures (24.2 to 30.5 °C). Six down-flow anaerobic fixed bed reactors of 6-L total volume (5-L effective volume) operated in parallel at influent strengths of 2, 4, 6, 8, 10, and 12 g total COD (TCOD)/L. The highest substrate removal efficiencies were obtained in the reactors that operated at influent strengths in the range of 4 to 8 g TCOD/L at HRTs of one and two days. At higher influent strengths, the efficiency of the process deteriorated. The removal rates of TCOD, soluble chemical oxygen demand (SCOD), biological oxygen demand (BOD), and total suspended solids (TSS) increased with the influent strength up to 8 g TCOD/L, and then decreased further for higher influent substrate concentrations. In addition, the concentration of microorganisms within the reactors increased with the influent strength. The results obtained demonstrated that the substrate removal rate was correlated with the effluent substrate concentration through a second-order kinetic model for multicomponent substrate degradation. The values of the kinetic constants obtained increased with the influent strength and were found to be 0.59, 0.83, 0.88, 1.09, 1.17, and 1.26 g TCOD/g volatile suspended solids (VSS) per day for influent strengths of 2, 4, 6, 8, 10, and 12 g TCOD/L, respectively, for a probability level of 95% (P=0.05) (Sánchez et al., 2005). Another investigation indicated that, in the anaerobic digestion process, using a mixture (9.7% w/v total solids (TS) and 7.6% w/v volatile solids (VS) on average) of pig manure, fish oil waste, and bentonite waste from the edible oil filtration process resulted in the constant production and quality of biogas at 183.7 ml (average) of biogas per gram of volatile solids available in the reactor per day. The best biogas composition was 73.6% v/v CH_4 and 26.4% v/v CO_2 (Francese et al., 2000).

A pilot-scale cylindrical rotating fermentor with a 3.41m^3 capacity was studied. Recovered swine manure solids were combined with milled sorghum and fermented. The fermented product was mixed with a nutritious swine supplement and fed directly to the pigs. For a 4000-head hog farm, it was estimated that about 64.4% of recovered solids can be recycled with an approximately 16.5% saving of grain sorghum consumption in fattening pigs (Iniguez-Covarrubias et al., 1994).

A methane fermentation system for treating swine wastes was developed in a field test plant (0.5m^3/d). The system was composed of a screw-press dehydrator, a methanogenic digester, a sludge separator, an oxidation ditch (OD) and composting equipment. It was found that TS and COD removal by screw-press press pre-treatment could reach efficiencies of 38% and 22%, respectively. The digestion gas (biogas) production rate was 25 m^3/m^3-slurry (NTP) and the methane content of the biogas was 67%. A 65% COD removal with the methane fermentation treatment of the slurry operating at 35 ^{o}C was observed. Mass balance from the study showed that 1 m^3 of a mixture of swine excrement and urine (TS 9%) was biologically converted to 25 m^3/m^3-slurry (NTP) of biogas, 100 kg of compost, and 0.80 m^3 of treated water (Kataoke et al., 2002).

While composting has been applied to treat agricultural waste for a long time, many researchers continue to study the composting of mixtures of agriculture wastes and/or other wastes. A composting trial was conducted to evaluate the effect of C/N on the composting process of pig manure, with a view to reducing the amount of sawdust normally used as a co-composting material. Co-composting pig manure with sawdust at a low initial C/N would require a composting period of longer than 63 days, and the high salinity resulting from the large amount of pig manure could potentially inhibit plant growth (Huang et al., 2004). Composting materials, such as olive press cake, olive tree leaves (OTL) and branches, vine branches (VB), pressed grape skins (PGS), pig manure (PM), sewage sludge, and the organic fraction of municipal solid waste (OFMSW), were evaluated for their behaviour during composting, their compatibility in mixtures, and the quality of the end product (Manios, 2004). It was found that all materials were composted successfully, especially when mixed. When any of the produced compost was used in a ratio of 30% by volume (v/v), it increased plant growth, whereas in larger volumes, it presented phytotoxic behaviour, inhibiting both root and shoot development.

2.4.2.2 Aerobic treatment

Aerobic treatment has also been widely investigated in swine manure treatment for nutrients, pathogen, and solids removal. Compared to anaerobic treatment, it produces an odourless, biologically stable end-product, which is more beneficial for land application than anaerobic sludge in terms of basic fertilizer value, and its effluent contains little soluble biodegradable organics.

Beline et al. (2004) summarized the treatment results of four types of biological aerobic units in France: (1) intermittent aeration without any separation, (2) intermittent aeration followed by sedimentation of the aerated slurry, (3) mechanical separation of raw slurry followed by intermittent aeration of the liquid fraction and sedimentation of the aerated slurry, and (4) mechanical separation of raw slurry followed by intermittent aeration of the liquid fraction and mechanical separation of the aerated slurry. It was found that between 60% and 70% of the nitrogen was removed in gaseous form. Phosphorus and heavy metals were concentrated in the sludge (60% to 90%). The clarified supernatant obtained through the separation of the treated slurry could be used for irrigation with a reduced environmental risk. Concerning the biological reactor, the variation of the volumetric load, owing to the variation of raw slurry characteristics, was identified as the main parameter influencing treatment efficiency (Beline et al., 2004).

The use of 59-L Aerobic Thermophilic Sequencing Batch Reactors (AT-SBR) was reported upon with regards to the treatment of pig manure. An HRT of six days was chosen and the process yielded a 98% removal of BOD_5 (Juteau et al., 2004). It was also confirmed that AT-SBR is an efficient method for the reduction of pathogens. Mohaibes and Heinonen-Tanski (2004) reviewed aerobic treatments, with a specific focus on the thermophilic aerobic treatments, for farm slurry and food wastes and concentrates. From their review, the most suitable physical-microbiological treatments are aerobic thermophilic treatments, which could be used to assist decontaminations on farms. Such technologies are already used in routine slurry treatment on many farms (Mohaibes and Heinonen-Tanski, 2004).

The limitations on the removal of orthophosphates (Ortho-P) from piggery slurry during aeration treatments were examined and the results indicated that a depletion of calcium ions (and/or other similarly acting metal ions) and accumulated insoluble P are most probably the two main factors limiting further removal of soluble ortho-P during aeration treatments (Ndegwa, 2004). The performance of the intermittently aerated dynamic-flow system (IADS) in the removal of nutrients (N & P) from swine wastewater was evaluated (Hur et al., 2004). It was found that the removal efficiencies of TP decreased from 80-87% to less that 30% with a reduction in the volume fraction of the anaerobic reactor VFAR from 13% to 0%. When the MLVSS was greater than 5000 mg/L, the removal efficiencies of TN and TP were not correlated with VFAR at a predetermined SRT. The results showed that IADS has a greater buffer capacity and is very adaptable, allowing it to resist the shock resulting from the loading of high concentrations of N. Furthermore, IADS offers significant advantages over other biological nutrients removal processes (Hur et al., 2004).

Thermophilic oxic process (TOP) was applied to swine waste treatment by Lee et al. (2000). When food oil was added to swine waste and the BOD load was 3 kg/m^3•day *at an aeration rate of* 100L/m^3•min, 86% of carbon was converted to CO_2 and 98% of water was evaporated in one cycle. In general, about 90% of the total added swine waste (40kg) and virgin food oil (2kg) was removed as gases, 8% was accumulated in the reactor, and 2% was drained in 60 days (Lee et al., 2000).

2.4.2.3 Plant-based system

One solution to reducing the environmental problems that result from animal waste nitrogen is the fixation of nitrogen as biomass and the utilization of the resulting product as fertilizer in plant-based systems. This can help avoid the environmental problems associated with the disposal of large volumes of animal waste. Research was conducted to select superior duckweed (*Lemnaceae*) genotypes for the utilization of nutrients in animal wastes. A two-step protocol was used to select promising duckweed geographic isolates to be grown on swine lagoon effluent (Bergmann et al., 2000). Forty-one geographic isolates from the worldwide germplasm collection, noted to be fast-growing genotypes during routine collection maintenance, were used in an in vitro screening test. In vitro screening was accomplished by growing geographic isolates on a synthetic medium that approximated swine lagoon effluent in terms of nutrient profile, total ionic strength, pH, and buffering capacity. Large differences among geographic isolates were observed for wet weight gain during the 11-day growing period; percent dry weight and percent protein in dry biomass were also found to differ. Total protein production per culture jar differed 28-fold between the most disparate of the 41 geographic isolates and was the variable used for the selection of superior geographic isolates. The challenge posed to eight of the 41 geographic isolates, to grow on full-strength swine lagoon effluent in the greenhouse, led to the selection of the three most promising genotypes to be grown on lagoon effluent (Bergmann et al., 2000).

A study was done to fix the nitrogen of swine waste as biomass. An isolated alga, chlorella sp., and bacteria naturally living in liquid manure were grown in batch cultures (diluted swine manure) and continuous cultures (undiluted liquid manure) to achieve reduction of NH_4^+ and total organic carbon (TOC) contents. An 80% TOC reduction was achieved with batch cultivation, and NH_4^+ was totally removed during continuous cultivation. It was not possible to establish a steady population of algae and bacteria in continuous cultivation (Baumgarten et al., 1999).

Autochthonous species for swine manure treatment were investigated by Jimenez-Perez et al. (2004). Two nanoplanktonic algal species isolated from different sources of pig manure were studied in laboratory experiments which focused on their growth rates and capacities for phosphorus (P) and nitrogen (N) uptake. The results were markedly higher than the rates described in experiments that used commercial species. This is likely due to the fact that the former species are better adapted to high nutrient concentrations (Jimenez-Perez et al., 2004).

2.4.2.4 Bio-filtration

Bio-filtration and infiltration are physical-biological combined treatment processes, which are recent technologies with various advantages (small specific dimensions, easy integration into the site environment, modularity, no secondary clarifier). Biological aerated filtration is a recent and intensive process which has been greatly developed over the last few years. It is a technology based on biological processes with certain advantages, in particular the absence of secondary clarifiers, the modular nature, and the wide variety of treatment applications.

The monitoring of a dozen medium-capacity plants (7,500 to 150,000 person equivalents), which were designed to treat organic pollution, was carried out by Canler and Perret (1994). The results obtained show that at applied loads of less than 7 kg of COD, the effluent is of satisfactory quality (< 90 mg/L of COD), and that the process has a high removal efficiency for suspended solids. Numerous other aspects have been studied and the data collected confirm the potential of this process, which, nevertheless, requires a careful and regular system operation procedure (Canler and Perret, 1994).

One research effort studied a nitrification and post-denitrification lab-scale plant with a down flow aerobic submerged filter for the removal of organic matter and nitrification, followed by an anoxic upflow biofilter for denitrification. Concerning the organic matter removal efficiency, the aerobic reactor accepted a maximum COD volumetric loading of 16.0kg COD/m^3 per day with a 75% COD removal (Galvez et al., 2003). Another study found that, by using a double-layer submerged biological aerated filter, effluent concentrations of under 20 mg $TBOD_5$/L and 25 mg suspended solids (SS)/L were achieved, according to 4.87 $TBOD_5/m^3$/day and 3.0 SS/m^3/day, respectively (Osorio and Hontoria, 2002).

The problems associated with a submerged biofilter have also been investigated. Construction of very large units raised questions relating to possible flow heterogeneity within the filter bed. Seguret and Racault (1998) indicated that the heterogeneity observed within the filter bed would have no significant effect on water quality.

The influence of packing media on nitrogen removal was investigated in a subsurface infiltration system. The results indicated that it is very important to use a suitable packing soil which can present favourable oxidation-reduction conditions for simultaneous nitrification and denitrification (Zhang et al. 2004a). The effects of substrate solubility or availability on the removal of volatile organic compounds (VOCs) in trickle-bed biofilters was investigated by applying butanol, ether, toluene, and hexane, which have Henry's constants ranging from 0.0005 to 53. The results demonstrated that, in a gas-phase aerobic biofilter, nitrate can serve both as a growth-controlling nutrient and as an electron acceptor in a biofilm for the respiration of VOCs with low Henry's constants (Zhu et al., 2004b).

The performances of two submerged filter systems, a hive filters-in-series system and a single combined filter system, in treating a strongly nitrogenous wastewater (nitrogen concentration of 480 mg/L) were evaluated. Both systems were equally effective in removing up to 90% of nitrogen and 98% of COD from the wastewater for loading rates of up to 5 kg $COD/m^3{\bullet}d$ and 0.5 kg $N/\ m^3{\bullet}d$. The second system, in which anaerobic, anoxic, and aerobic zones were incorporated in a single filter, offers a greater flexibility in treatment in that, by repositioning the locations of the aeration point and the effluent recycling inlet, the system can easily be altered to treat wastewaters with different COD and nitrogen concentrations (Chui et al., 2001).

2.4.3 Combined Treatment

It has been well discussed that every treatment method has its strengths and limitations. To satisfy the different effluent criteria and application conditions, aside from using physical/chemical, anaerobic, and aerobic treatments, further studies were conducted to investigate combinations of these treatment methods.

The modified Ludzack Ettinger (MLE) process, coupled with a membrane bioreactor (MBR), was investigated by field study for swine waste treatment (Chung et al., 2004). It was found that the efficiency of denitrification was highest when an external carbon source was added to maintain a C/N ratio of 6.0. Nitrogen compounds, especially NO_x-N, were removed to a considerable degree. By adding a powdered activated carbon, the removal efficiencies of COD (Cr) and COD (Mn), and the membrane flux, were dramatically increased (Chung et al., 2004).

Laboratory experiments were conducted to investigate two-stage aerobic thermophilic and anaerobic mesophilic treatments of swine waste. The two-stage system included a one-day sludge retention time (SRT) aerobic thermophilic reactor operating at 62 °C and with 1.0 mg dissolved oxygen/l, followed by a 5, 9, and 14-day SRT anaerobic mesophilic digester operating at 37 °C. A single stage anaerobic mesophilic digester operating at 6, 10, and 15-day SRTs and 37 °C was used as the control. The two-stage system operating at 6, 10, and 15-day system SRTs reduced VS by 46, 54, and 61%, respectively, and performed significantly better than the control at each SRT. Supernatant COD reduction by the two-stage system (56 to 67%) was significantly better than that obtained in the control (44 to 60%). It was also found that the two-stage system performed better in relation to fecal coliform density reduction, methane yield ratio, methane to H_2S ratio, and sludge dewater-ability (Pagilla et al., 2000).

A prototype of a swine waste treatment system for a 20 to 25 sows operation was investigated for its potential for odour control, by-product utilization, and treated wastewater reuse. The high solid portion of the swine waste ranging from 4% to 8% TS was treated and stabilized by the anaerobic process with an HRT (hydraulic retention time) of 32 days. The diluted liquid portion of the raw and anaerobically digested swine wastewater was effectively treated by the aeration and sedimentation units with HRTs of three and four days, respectively. The overall removal efficiencies of 89 to 95% for TCOD, 82.3–88.5% for TKN, and 81.2% for TP were achieved. More than 830 pigs (or approximately 80 sows) are required to achieve the break-even point for the application of the swine waste treatment system. Thus, a profit could be made with the application of this treatment system to more than 830 pigs, if the comprehensive utilization of methane gas and stabilized sludge could be realized (Yang and Gan, 1998).

Another new nitrogen removal process (up-flow sludge blanket and aerobic filter, USB-AF) was proposed and its treatment of real sewage was assessed. The results showed that the T-N removal efficiency was 70% at a recycle ratio of 300% (Jun et al., 2004). The efficiency of the removal of high-concentration organic matter and nutrients from slurry-type swine waste was investigated using a combined up-flow anaerobic sludge blanket reactor to carry out the dissolved air flotation/aerobic submerged biofilm/anoxic/aerobic process (Kim et al., 2004a). It was found that the overall process gave a removal rate of COD of more than 99%. In the aerobic submerged biofilm, over 95% of the ammonium nitrogen (NH_4^+-N) was removed at a volumetric loading rate of 0.08 to 0.16 kg NH_4^+-N/m^3/day. The specific denitrification rate was 0.257g NO_3-N/g MLVSS/day and the removal efficiency of total nitrogen was 86.7%. Phosphorus was removed by flocculation in the dissolved air flotation process, and 0.16 g of PO_4-P was removed by 1 g of ferric ion (Kim et al., 2004a). The performance of a bench-scale integrated swine wastewater treatment system was evaluated on the basis of energy recovery, fertilizer production, and water reclamation (Zhang et al., 2004). The system consisted of one anaerobic sequencing batch reactor (ASBR), one or two aerobic sequencing batch reactors (SBR1 and SBR2), one sludge-settling tank, one sand filter, and one reverse osmosis (RO) unit. The results indicated that various operational cost and maintenance issues associated with the individual processes, and with the overall system, need to be addressed when the treatment system is scaled up and evaluated for farm applications (Zhang et al., 2004).

Subsurface flow constructed wetlands (SSFCW) were studied on a pilot scale for the treatment of pre-treated swine effluent under heavy loads (Lee et al., 2004a). Three hydraulic retention times were studied, with 8.5, 4.3, and 14.7 days in phases I, II, and III, respectively. The average reduction efficiencies for SS, COD, TP, and TN were 96 to 99%, 77 to 84%, 47 to 59%, and 10 to 24%, respectively. The results indicated that the SSFCW effluent was appropriate for further treatment in land applications, and for nutrient assimilation (Lee et al., 2004a).

A reed bed system was investigated in two studies. The fate of ammonium-nitrogen (NH_4^+-N) was investigated by using a lab-scale downflow reed bed system to treat artificial landfill leachate. The results indicated that, in general, a greater rate of effluent recirculation around downflow reed beds gives higher NH_4^+-N removal (Connolly et al., 2004). The purification capacity of a laboratory scale tidal flow reed bed system was evaluated with a heavy load of strong agricultural wastewater. The results suggested that the multi-stage reed bed system could be employed to treat strong wastewater under high loading, and would be especially useful for the mass removal of solids, organic matter, and ammoniacal-nitrogen (Zhao et al., 2004).

Loewenthal (2004) proposed 'three phases mixed weak acid/base chemistry kinetic modeling of multiple mineral precipitation problems' for aerated swine wastewater and anaerobically digested swine wastewater. With a batch aeration test of swine wastewater, the pH was raised from 7.2 to 8.5 in five hours. pH became stable after two hours; the phosphate concentration decreased from 170 to 20 mg/L, and was largely reduced during the first two hours. With anaerobically digested swine wastewater, the pH was raised from 6.85 to 8.0 in 3 hours, and the phosphate was reduced from 180 to 100mg/l. Most changes occurred within the first hour (Loewenthal et al., 2004).

A two-pond system was studied to treat dairy farm wastewater for nutrient removal. The field experiment for the system was performed over a period of seven months. The results showed that the two-pond system was not effective in the removal of nutrients. However, subsequent adsorption by bark or zeolite was effective in removing N, P, and K from the effluent. These materials can be placed in the second pond, and the porous materials treated with effluent can be used as nutrient sources to be spread onto the farm as mulching material to conserve soil moisture, and as bedding material for vermicomposting (Bolan et al., 2004).

Control and optimization are important issues in a waste treatment plant. An integrated strategy of real time control was applied with C/N ratio adjustment for practical swine wastewater treatment by using a laboratory-scale sequencing batch reactor (SBR) (Chen et al., 2004). The results showed that the average removal efficiencies of total organic carbon and nitrogen were over 94% and 95%, respectively. Another new integrated real-time control system of sequencing batch reactors was proposed with fluctuating influent loads for swine wastewater treatment. The average removal efficiencies achieved for TOC and nitrogen were over 94% and 96%, respectively (Kim et al., 2004b).

2.4.4 Trends and Needs in Swine Manure Treatment

From the literature review, it can be concluded that swine manure is difficult to treat due to its high concentration, variation, and complexity. Many research efforts have been conducted on a wide range of topics, including manure characteristics, management, public concerns, and treatment. In general, due to the intensification of the hog industry and the growing concern of swine manure related public health topics and eutrophication issues, new and stringent regulations have been issued and new treatment systems have been developed.

Existing swine waste pit storage and lagoon swine manure treatment technologies may be inadequate to store or treat waste prior to land application in such a manner as to satisfactorily address these concerns. Many studies have been conducted to investigate and develop various approaches in swine manure treatment, which include physical/chemical and biological treatments, and their combinations.

An efficient technique for separating solids out of swine manure is a desired option because it is inexpensive and effective in TSS and TP reduction, which would also reduce environmental health concerns and generate a value-added bio-resource. Anaerobic digestion has been widely used in swine manure treatment since it greatly reduces sludge and generates bio-gas. Aerobic treatment has also been widely investigated in regards to swine manure treatment for nutrients, pathogen, and solids removal because it produces an odourless, biologically stable end-product and an effluent with low organic concentration. Because of their strong flexibility, combined treatments, such as bio-filtration and infiltration, were intensively investigated for adaptation to newly approved regulations and various treatment conditions.

Chung et al. (2004) indicated that: "In the area with limited crop land and grass land, the most feasible method to handle slurry type swine wastewater would be that the solids portion from the solids/liquid separation process is treated by composting and then the liquid portion is treated by a series of wastewater treatment processes, ..., to satisfy the different effluent criteria."

2.4.5 Conclusion and recommendations of previous studies

Two stages of research were completed in this project prior to the current one. The first stage was carried out in the years 2002-2003, mainly in the laboratory, to investigate chemical precipitation and filtration (Zhu, 2003). The second stage took place in the years 2003-2004 (Singh, 2004).

It was found that: (1) swine manure characteristics vary from sample to sample; (2) 24 hours of preliminary settling gives a very good TSS and TP removal efficiency and is recommended for any further treatment; (3) Alum is the most cost-effective coagulant and performs the best for swine manure chemical/physical treatment processes in terms of reducing TSS and TP. TP removal efficiency is primarily dependent on alum dose at a 95% confidence level; (4) Physical/chemical treatment is not very effective in reducing TDS, TKN, and BOD_5 in liquid swine manure; (5) Particle count analysis indicated that most of the particles present in untreated and treated swine manure samples are less than $8\mu m$ in size; (6) Ultraviolet (UV) disinfection is an effective alternative to conventional disinfection techniques.

Previous study recommends that the following concerns be addressed: (1) the patented Martin filters did not work properly because of filter screen clogging due to high solids levels in the primary settled swine wastewater. Therefore, the filter design needs to be modified in order to achieve better filtration performance; (2) a comprehensive study aimed at investigating the effect of filter run time on head loss development and break through curve is necessary to understand filter performance, and thus to achieve the best effluent quality; (3) air stripping can be applied during the production of future pilot plant effluent to reach higher TKN removal efficiencies; (4) composting of the clarified sludge from the pilot plant should be investigated; (7) the treatment system needs an additional step to manage the nitrogen present in the swine manure, and the option of combining the physical/chemical and biological methods may further improve the results; (8) fine glass bead media (> Mil-spec 13) may be used in Martin filters to facilitate the removal of those particles less than $5\mu m$ in size. This can improve UV absorbance, and hence, result in more effective UV inactivation.

3 METHODOLOGY

3.1 System Overview

This project was conducted at the University of Alberta farm in the city of Edmonton, Alberta, Canada. The system was composed of two parts: physical/chemical treatment and biological treatment.

During physical/chemical treatment, a Preliminary Settling Tank (PST), an Up-Flow Floc Blanket Clarifier (UFFBC), and a Patented Martin Filter (PMF) were used with a view to removing TSS and TP. To avoid odour emission and foam generation, the UFFBC and PMF were designed as a pressured system. A submerged filter was installed in the UFFBC to enhance the treatment. A struvite reactor was also investigated as an alternative method to the UFFBC.

For biological treatment, soil columns were used to simulate the nutrient and organic processing area (NOPA) and land application (LA) processes.

The system overview is shown in Figure 3-1.

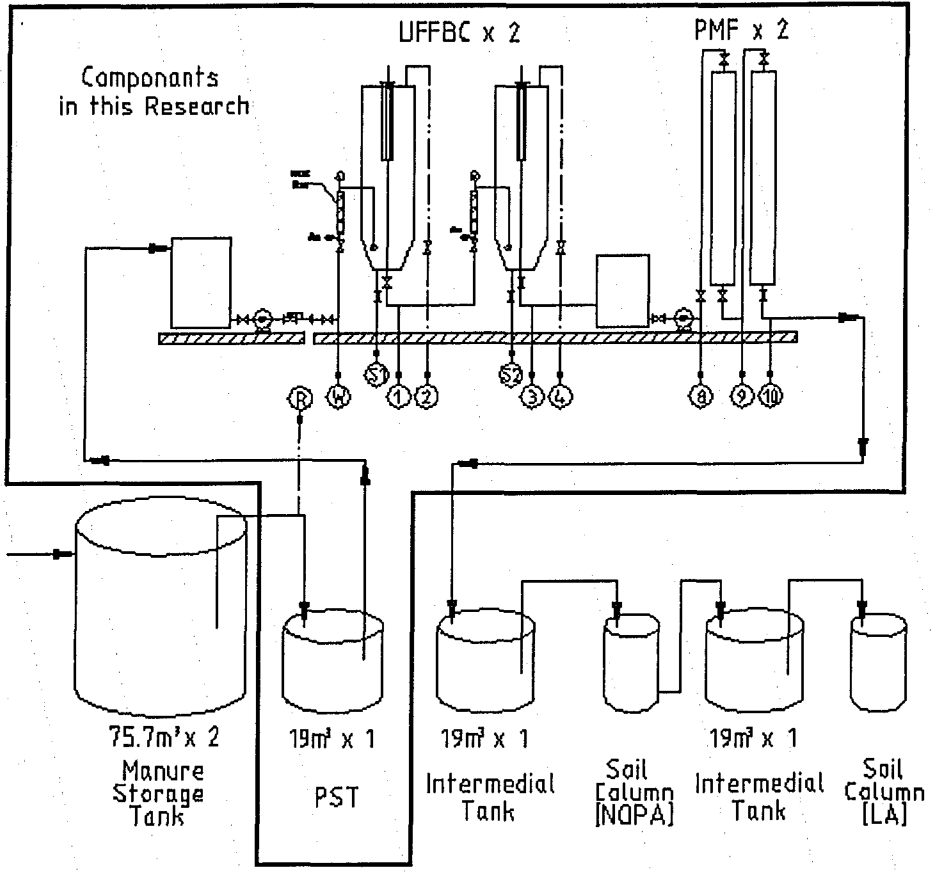

Figure 3-1 System Overview

In order to focus on the main process, implemented systems such as the compressed air system and the backwash system are not shown in the above drawing. Sample points are indicated in the drawing by circled letters or numbers.

In this research, PST, UFFBC, and PMF were investigated with regards to settling time, chemical selection, chemical dosage, floc blanket overflow rate, and filter performance. The other sections of this project were conducted in other studies.

There were 11 sample points in the overall treatment system and every sample point was assigned a letter or number:

- R: Raw swine manure, samples were taken directly from the manure storage tanks
- W: Swine Manure, samples were taken from the supernatant of PST after preliminary settling, or the pilot plant Inlet Tank after complete mixing
- 1: Samples taken from UFFBC stage one before the submerged filter
- 2: Samples taken from UFFBC stage one after the submerged filter
- 3: Samples taken from UFFBC stage two before the submerged filter
- 4: Samples taken from UFFBC stage two after the submerged filter
- 8: Samples taken from the intermediate tank after the boost bump, before the PMF
- 9: Samples taken immediately after PMF stage one
- 10: Samples taken immediately after PMF stage two
- S1: Sludge taken from UFFBC stage one
- S2: Sludge taken from UFFBC stage two

3.2 Selection of Material

The Raw Swine Manure (Sample point: R) was obtained from the University of Alberta Swine Research Facility located in the city of Edmonton, Alberta, Canada. The facility houses approximately 1,500 pigs (300 fully grown and 1,200 growing pigs and piglets). According to information obtained from the supervisor (operations), the average water consumption per pig per day is approximately 7 L. This means that approximately 75.7 m^3 water is consumed per week. This gives us a rough estimate of the amount of liquid manure produced weekly in the facility.

The facility has two indoor storage tanks with a total storage capacity of approximately 75.7m^3. The raw swine manure was taken directly from this storage tank and pumped to the PST.

The settled swine manure (Sample point: S) was taken from the PST supernatant, and was then carried by a trailer to the Inlet tank of the pilot plant. A submerged pump was used inside the Inlet tank to mix the liquid manure.

3.3 Experiment set-up

3.3.1 Sample collection and storage

All samples from this research were collected using 250 ml plastic bottles. All bottles were acid washed and autoclaved before use. The collected samples were then put into a refrigerator @ 4°C. Samples were removed from the refrigerator one hour before analysis and allowed to reach room temperature.

3.3.2 Experiment Location

Experiments were performed in two places:

1) University Farm, University of Alberta: pilot plant facilities were located here. All pilot scale experiments regarding UFFBC, PMF, and PST were performed here.

2) Laboratories located in the Environmental Engineering Building, University of Alberta: Lab facilities were located here. All lab scale experiments regarding the barrel settling, Jar, and Column tests, as well as sample analyses were performed here.

3.4 Pilot plant design and operation

The swine manure used in this research was collected by according to the following process. A submerged type suction pump was used to pump the manure from the lift station pit. The liquid manure was then pumped to one of the three preliminary settling tanks (Steel built circular tanks 3.0 m in diameter and 3.0 m deep, with a volumetric capacity of 19 m^3) located nearly 25 m away from the lift station. The raw manure was normally left in the tank for a minimum period of 12 hours. The settled manure (supernatant) was then pumped from the settling tank to a trailer. A pick up truck was used to pull the trailer to the pilot plant. The settled manure was then pumped from the trailer to the inlet tank of the pilot plant. Flexible hoses (5 cm diameter) were used in these transmissions. Separate hoses were used for fresh raw manure and settled manure to avoid mixing different manures and changing the manure characteristics.

The pilot plant was operated manually. The overall system is shown in Figure 3-2.

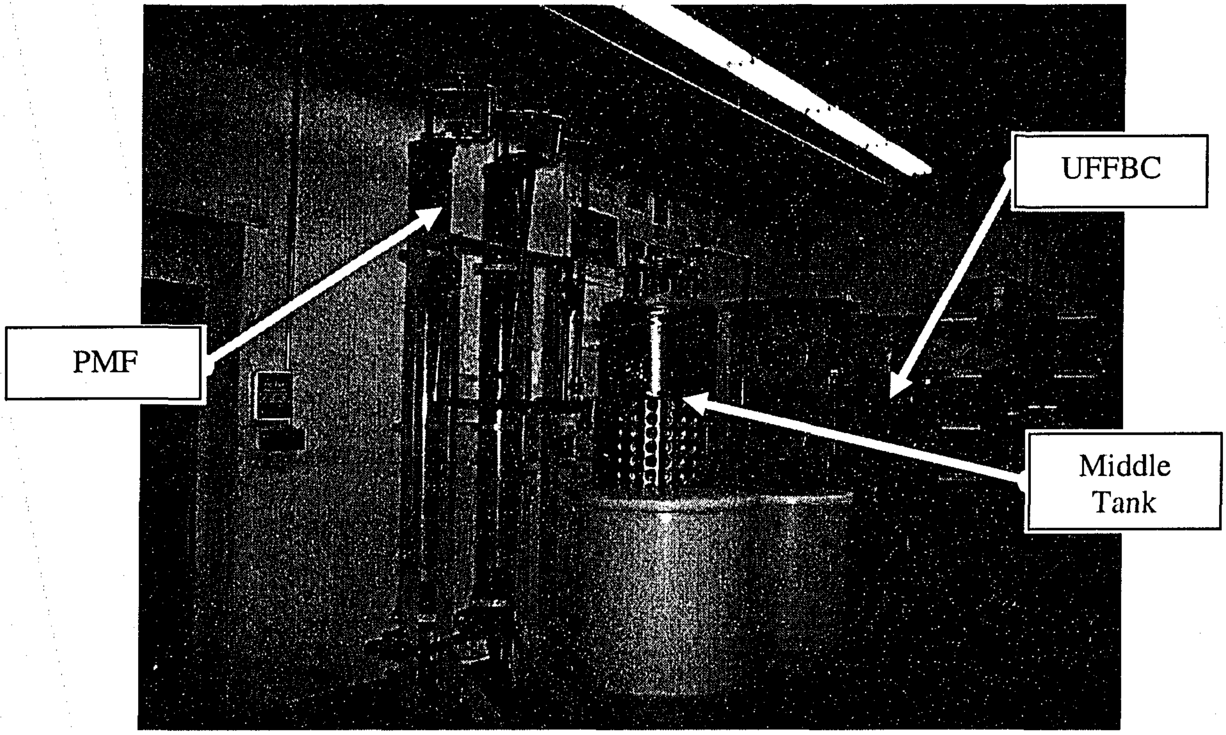

Figure 3-2 Overall Pilot Plant System (Inlet Tank not shown)

3.4.1 UFFBC set up and operation

The inlet tank received the preliminary settled manure (supernatant) from the trailer. A submerged pump (1.2kw) was used in this tank to ensure that the manure was completely mixed. A peristaltic pump (Figure 3-4) was used to feed the manure to the UFFBC (Figure 3-3). The flow rate was controlled by a digital control block (Figure 3-5). Because this was a pressured system, automatic air vent valves and pressure release valves were installed to maintain normal operating conditions.

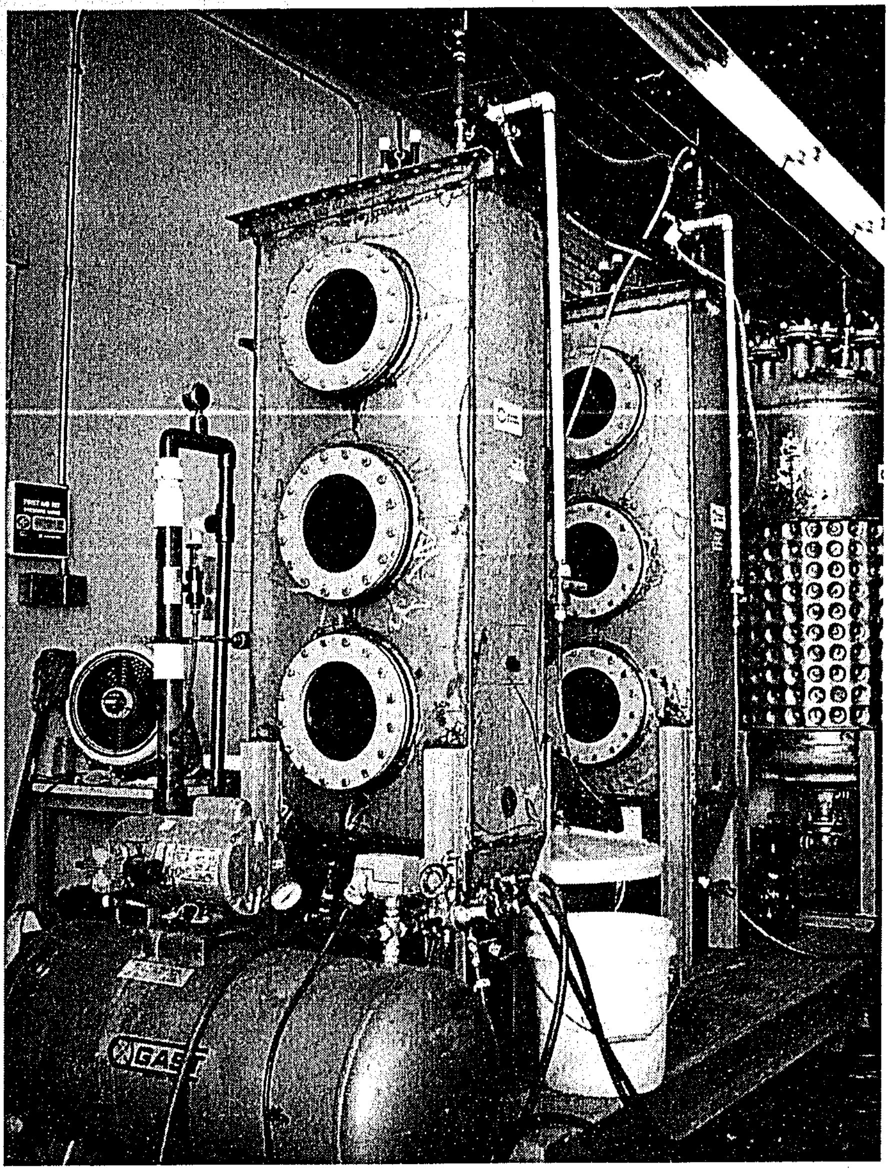

Figure 3-3 Up flow floc blank clarifier (UFFBC)

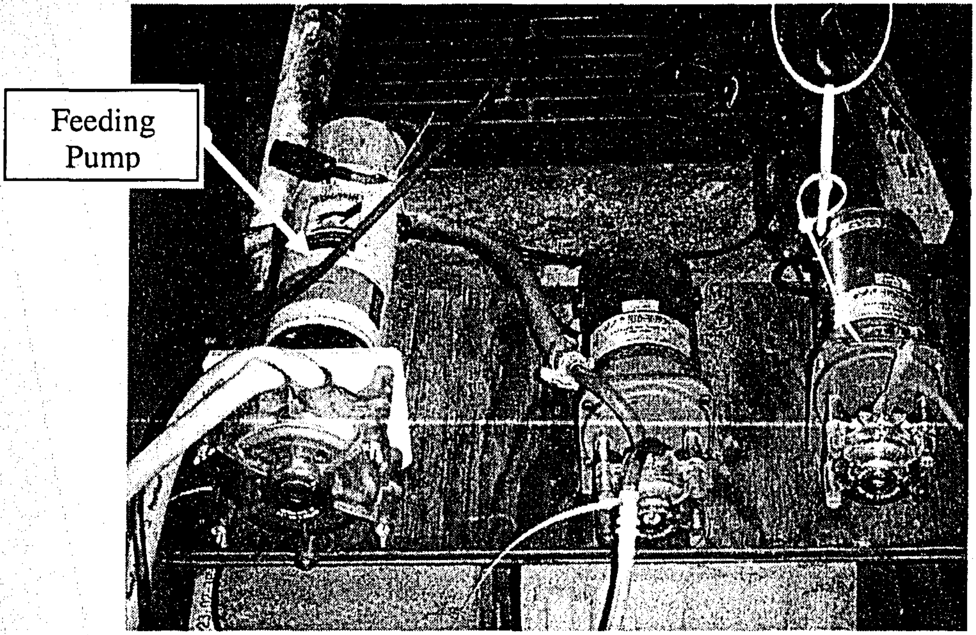

Figure 3-4 Peristaltic pump used as UFFBC feed pump

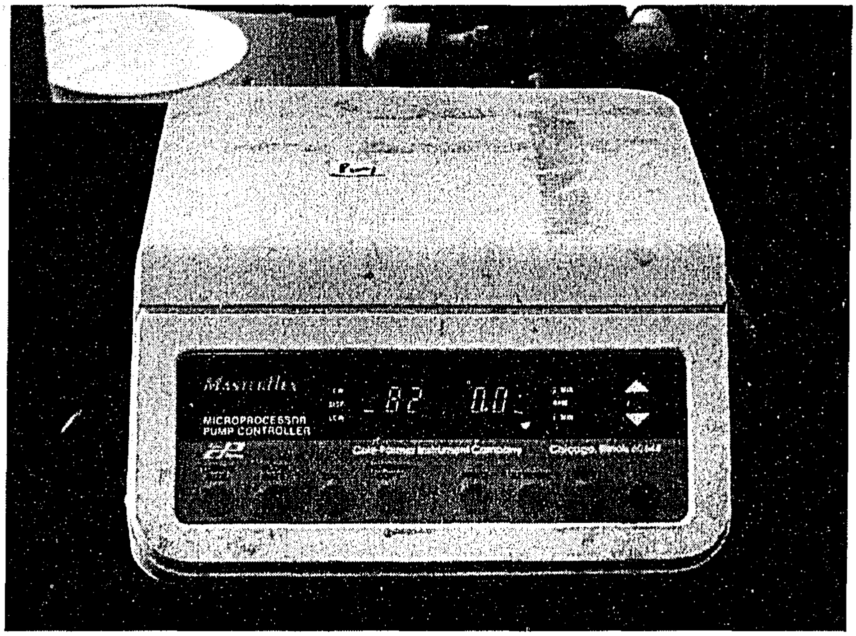

Figure 3-5 Digital controller of peristaltic pump

The first stage of the UFFBC contained two chemical feed pumps (C – 1500N, Figure 3-6): one for alum feeding and the other for polymer feeding. After chemical injection (Figure 3-7), a statistic mixer was used for rapid mixing. To avoid clogging, a larger sized statistic mixer (KOFLO 2-40C-4-6-1SP) was installed. The chemicals reacted with the manure and flocs of different sizes were produced at this stage. The coagulated manure was then moved under pressure to the bottom of the UFFBC.

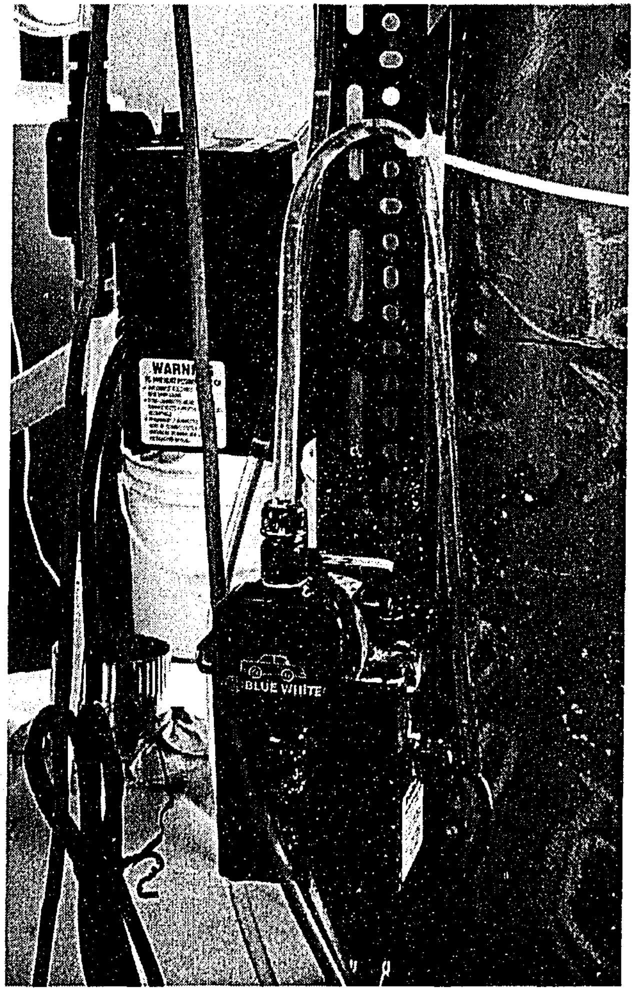

Figure 3-6 Chemical injection pumps

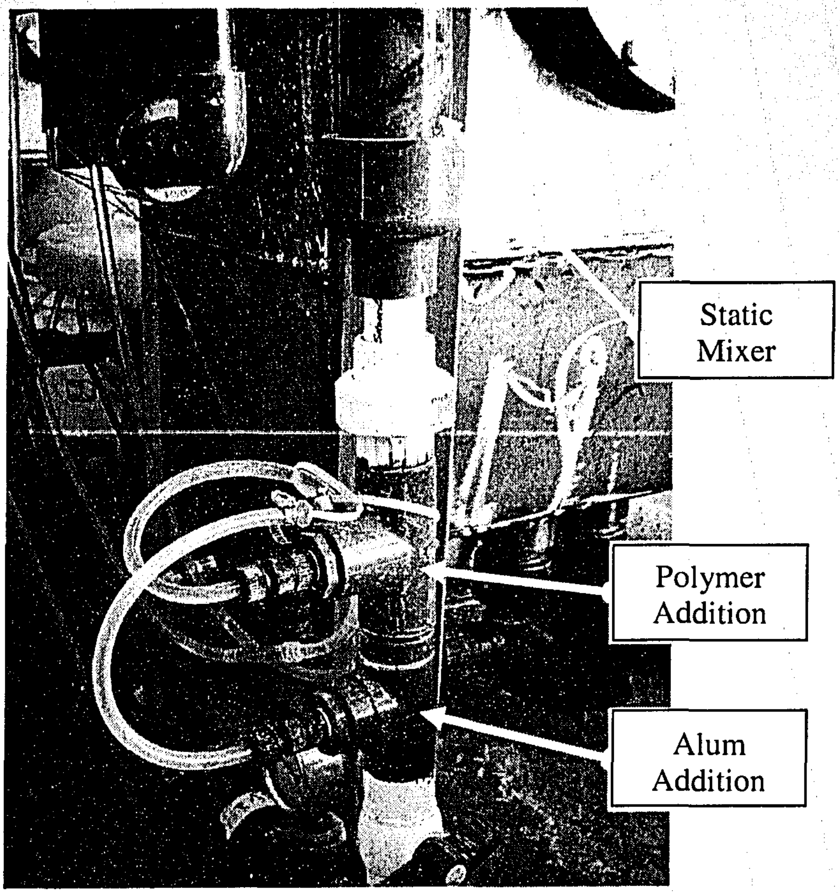

Figure 3-7 Chemical injection connections

Flocculation was achieved in the floc blanket area of the UFFBC. Small flocs were bridged together and reserved by the floc blanket. The supernatant passed through the floc blanket (Figure 3-8) to reach the submerged filter. The filtered supernatant was collected by a separated pipe and transferred to the bottom outlet of this unit.

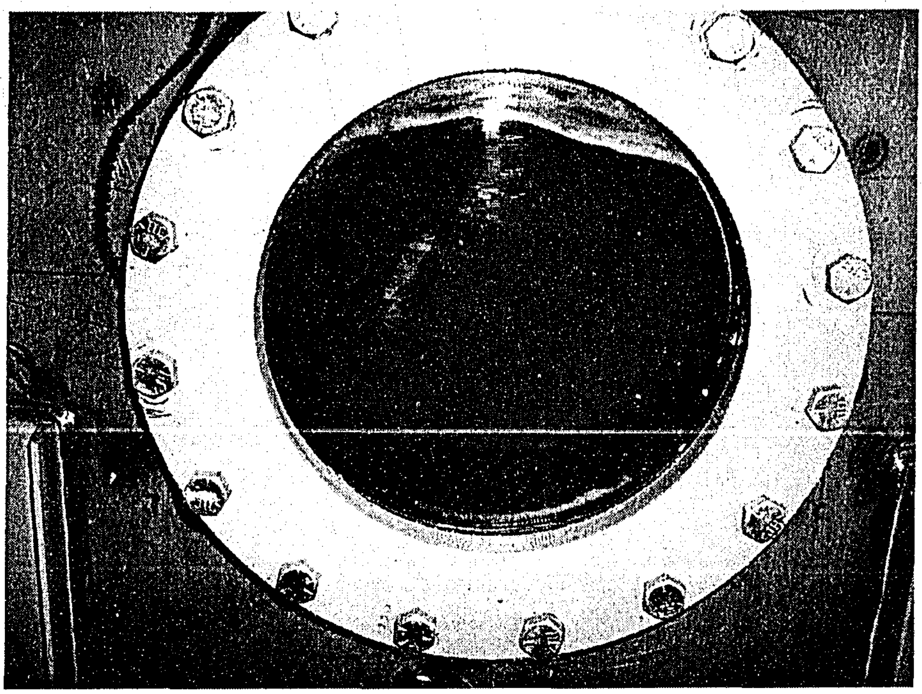

Figure 3-8 Floc Blanket

The second stage was almost the same as the first stage in the UFFBC. The only two differences are that the second stage contained only one chemical feed pump for alum feeding, and a small size static mixer (KOFLO ½-40C-4-12-2) was installed since the second stage influent was much better than that of the first stage.

The normal operating pressure of the UFFBC was 0.1Mpa. The pressure increased if the submerged filter became clogged. To avoid a drop in the pressure of the submerged filter, and to reduce the floc blanket initialization time, a side outlet was provided on the top of UFFBC and connected to the dumping pipe in both stages. It was used as a by-pass line before each run to generate a floc blanket.

The bottom outlet was connected to an intermediate storage tank where the clarified supernatant (manure) was stored and subsequently used as influent for the filtration step.

Before every run, the UFFBC was dumped and the submerged filter was air back-pulsed to reach an initial operation point. Then, the UFFBC was operated for three hours, without storing the clarified supernatant, in order to build up the floc blanket at the bottom of the tank. To enhance the settling process, and hence, floc blanket formation, inclined plate settlers were provided in the tank.

When the floc blanket was fully developed, the plant was run at a pre-set condition for four hours to reach a steady state. The submerged filter needed to be backwashed if the operation pressure was higher than 0.2MPa. Samples were simultaneously collected at each sample point after the UFFBC reached a steady state. The effect of every treatment was assessed through the analysis of these samples.

It was found that the UFFBC was sensitive to variations in the influent flow rate. The best flow rate was determined by a floc blanket model with a column test.

In the trial runs, it was found that pressure loss in the submerged filler greatly depended on the media size. Base on this result, Mil. Spec. # 6 (diameter range: 0.21 to 0.30 mm) glass beads were used in submerged filter #1, while Mil. Spec. # 10 (diameter range: 0.09 to 0.15 mm) glass beads were used in submerged filter #2.

In this project, two-stage treatments of a total alum dose of 1,600 mg/L were used during pilot plant operation. Different dosages were applied to different stages. Also, cationic polymer treatment was investigated based on the results obtained from sections 4.3 and 4.4. Overall, 10 pilot runs were conducted to optimize the UFFBC, with eight runs using preliminary settled swine manure and two runs using diluted preliminary settled swine manure. The chemical dosages and operation schedule are shown in Appendix F.

3.4.2 PMF set up and operation

The patented Martin Filter (PMF) columns were supplied by the John Martin Company of Wichita Falls, Texas. A total of two columns were used in this project and are shown in Figure 3-9. Figure 3-10 shows a dismantled Martin filter, with the concentric pipes shown individually.

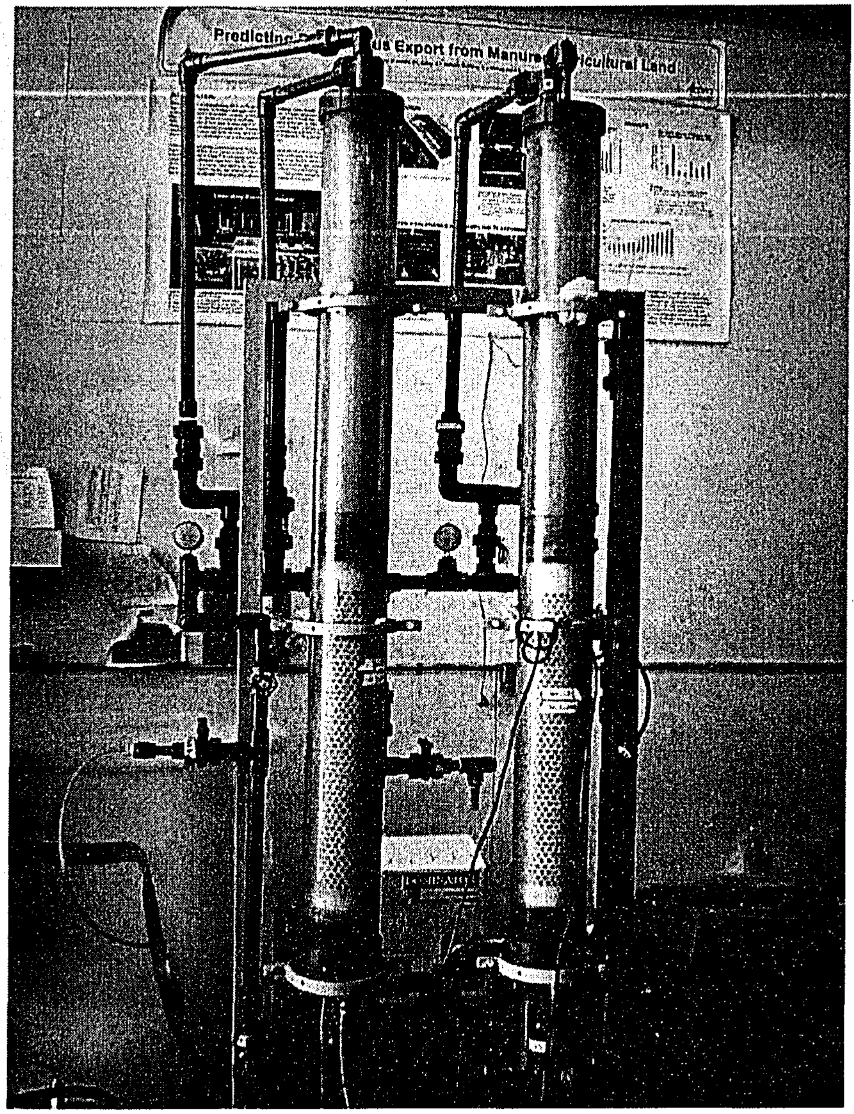

Figure 3-9 Patented Martin Filter (Supplied by the John Martin Company of Wichita Falls, Texas)

The design consisted of two concentric perforated pipes, a porous (glass bead) media filling the space between the pipes, a perforated liner, and a cylindrical case to enclose the unit. The design of these filter columns was modified from the earlier design by the addition of a liner, and consequently, an increase in the diameter of the columns. The Martin filters without liners did not function satisfactorily. It was found that these filters might have developed a blocking layer (mat) between the media and the screen. The liner had perforations to provide a spray of water to the screen in order to remove the mat. Filter operation was totally manual. The filters worked very well; no difficulty was encountered.

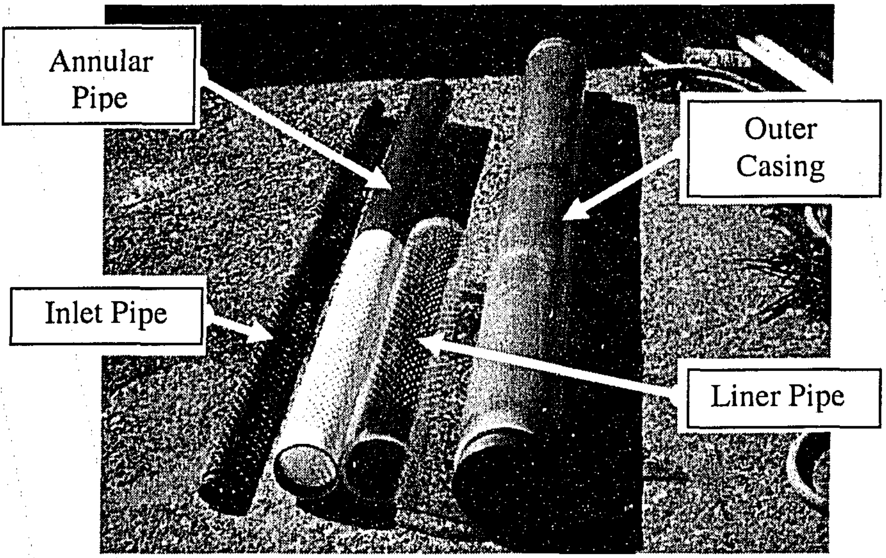

Figure 3-10 Dismantled Martin Filter

Mil. Spec. # 13 (diameter range: 0.04 to 0.09 mm) glass bead media was used in the PMF. During filtration mode (Figure 3-11), the clarified effluent was pumped from the top to the first filter column. There were two main points of entry provided for the influent, namely, the central and annular inlets. The annular space surrounding the innermost pipe was filled with glass bead media. The liquid manure was filtered there and was then moved downwards by the pressure provided by the pump. The effluent exiting the first filter entered the second filter from the top via a pipeline joining the two columns. The flow rates were set at 8L/min.

During backwashing mode (Figure 3-12), tap water stored in another storage tank was pumped to the filter columns by an axial flow pump. All the valves that were open during the filtration mode were closed during backwashing. The backwash water entered the columns from the bottom, exited the unit from the top, and then proceeded to the drainage line. Backwashing time and frequency were selected so as to yield better results by taking into account the filter run times and the head loss. During the running of the pilot plant, in-line pressures were continuously monitored to avoid any troubleshooting.

A total of two PMF columns were used in this project. Two scenarios were involved in filter runs - with or without the addition of chemicals before filtration, respectively. The PMF schedule is shown in Appendix G.

Scenario I involves the running of a set of two filters without the addition of any chemicals before filtration. Filters were run at a flat flow rate of 8 L/s. To get representative results, effluent from the UFFBC was stored in the middle tank before it was pumped into the PMF. For the middle tank size, the filter operation interval was set at 30 minutes.

Since there was still a high concentration of particles < 3 µm, Scenario II was designed to analyze the effect of chemical addition before filtration in the removal of fine particles. Scenario II (A) involves the running of a set of two filters with 100mg/L alum. Scenario II (B) involves the running of a set of two filters with 20mg/L polymer.

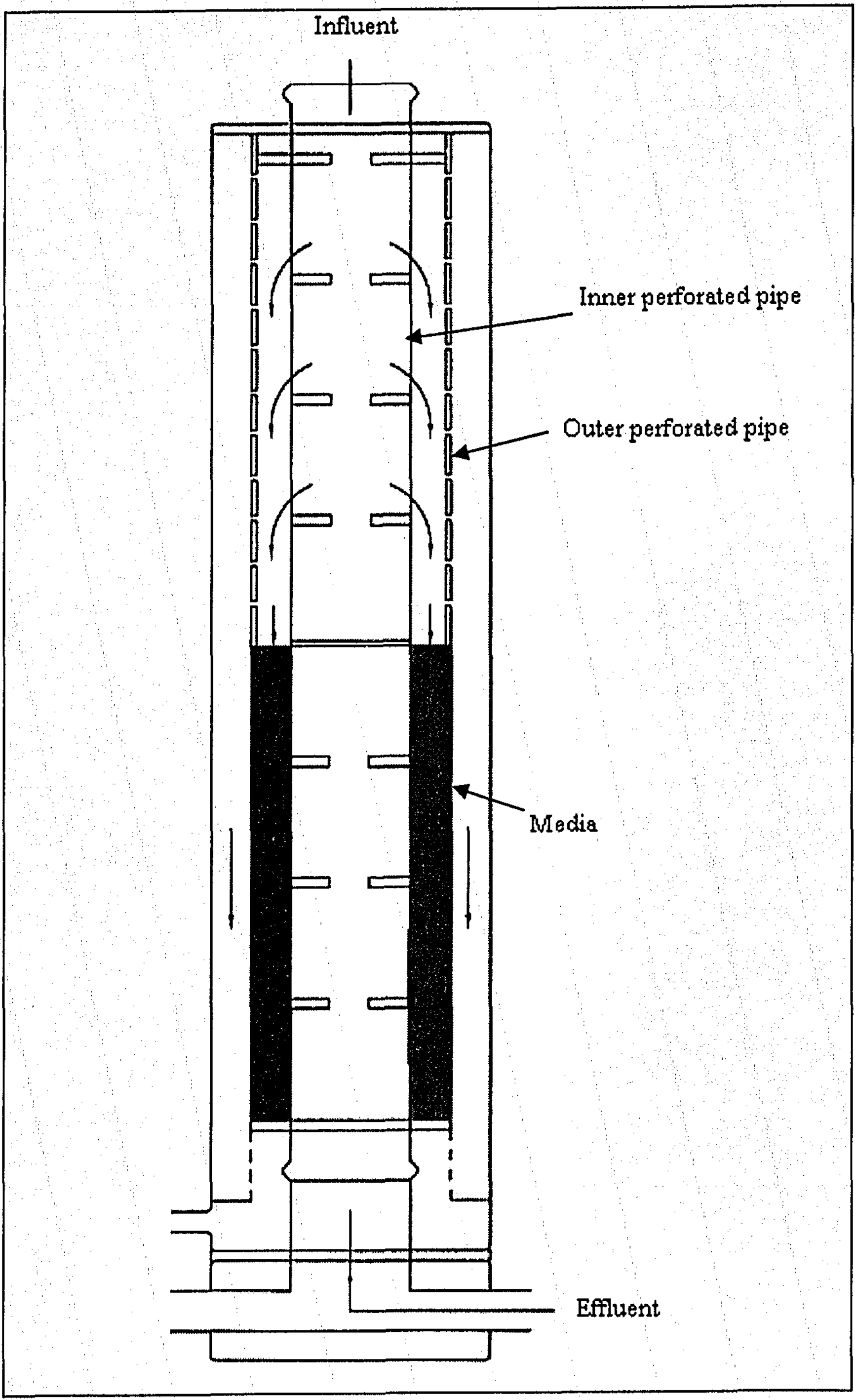

Figure 3-11 Martin filter during filtration mode (Adapted from Baxter *et al.*, 2001)

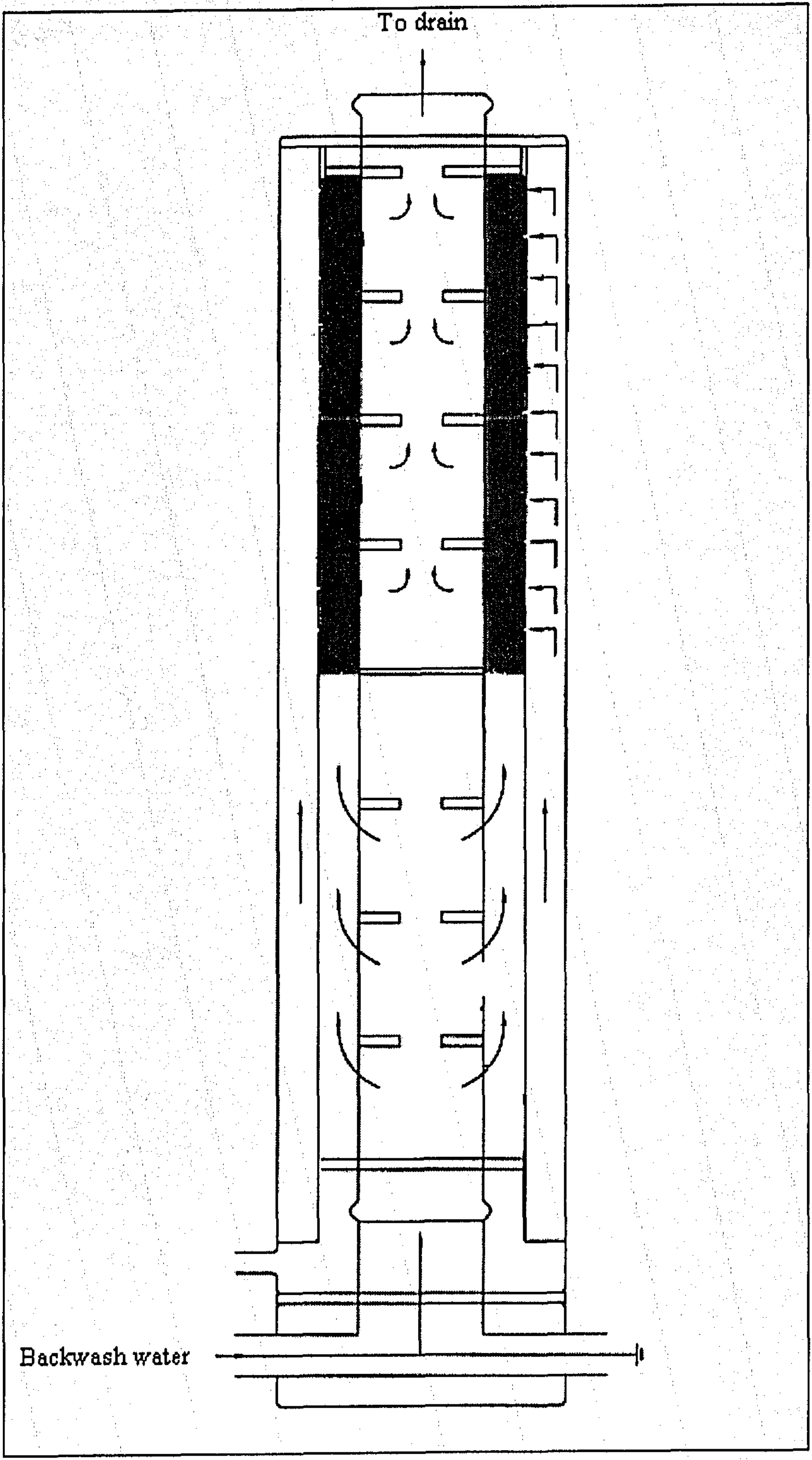

Figure 3-12 Martin filter during backwash mode (Adapted from Baxter et al., 2001)

3.5 Experimental design

3.5.1 Preliminary settling

In previous research completed for this project, it was found that 24 hours was sufficient for preliminary settling (Singh et al., 2004; Zhu, 2003). In this research, a further experiment was conducted to investigate the possibility of reducing settling time to less than 24 hours. To determine the treatment effects of preliminary settling, two tests, in laboratory and in-situ, were conducted.

The laboratory test was conducted by taking samples from a 300 L barrel (Figure 3-13) every two hours. The barrel had two sample points at two different heights, which represented top supernatant and middle supernatant, respectively.

The in-situ test was conducted in the PST (Figure 3-14). After the raw swine manure was transferred to the PST, samples were taken by glass pipe from the top and middle layers every two hours.

Those samples from the above two experiments were then analyzed immediately with respect to TSS and TP contents.

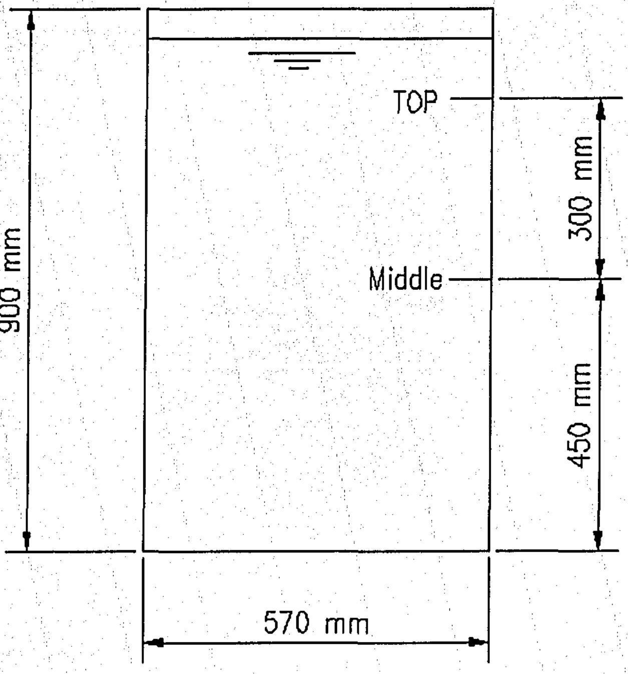

Figure 3-13 Barrel for preliminary settling test

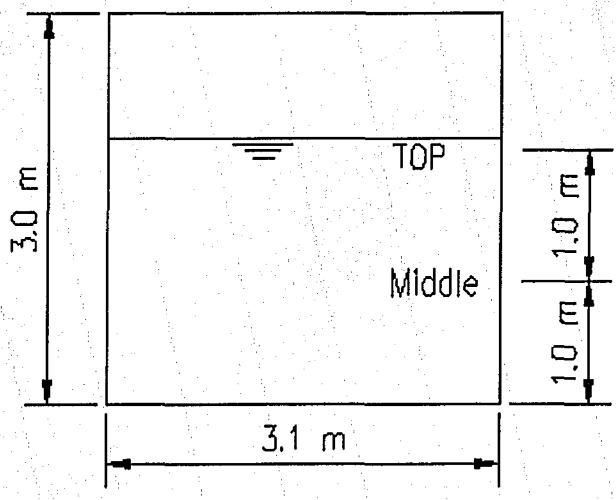

Figure 3-14 Underground tank for preliminary settling test

3.5.2 Floc Blanket

The floc blanket clarification process has been widely used in wastewater treatment. However, the overflow rate of every floc blanket clarifier is quite different from that of others due to many factors. In 1997, Head et al. (1997) proposed a model to predict the performance of the floc blanket clarification process. In this model, a column test was conducted to determine the settling parameters. The optimum overflow rate was then calculated from this model and applied to the UFFBC.

This model was based on Gould's theory of the operation of floc blanket clarifiers. After a change in the up-flow rate, or the settling velocity of the blanket, the surface of the blanket will rise or fall at a rate equal to the difference in velocities between the up-flow and the hindered settling rate. This change in position of the blanket surface can be expressed as (Head et al., 1997):

$$\frac{dH}{dt} = U - V_s$$

Where H is the height of the blanket above the bottom of the tank

U is the instantaneous upflow velocity in the tank

V_s is the instantaneous hindered settling velocity of the blanket.

To simulate hindered settling, a modified version of the Barnea-Mizrahi equation was used (Gregory, 1979):

$$V_s = V_{\max}\left[1 - s(C - C_{\min})\right]^n$$

Where $C_{\min}$ defines the cut-off point on the hindered settling curve, below which the settling velocity of the suspension remains constant

V_{max} is the settling velocity at and below C_{min}

C is the sludge volume (SVI) index defined as the 30 minute settled volume

S is a shape factor (no unit)

n is an exponent factor (no unit)

In this research, the UFFBC was operated at steady state. Therefore, dH/dt=0, which means U=Vs. A column test was then conducted to calculate V_s from the above model.

The column settling apparatus consists of columns that are 100 mm in diameter and 2400 mm tall (Figure 3-15). The columns are backlit with a strong light source to permit easy discrimination of the interface. Before settling, coagulant and coagulant aid were added to the columns and aeration was applied to simulate rapid mixing and slow mixing processes. Sludge height was then measured every 10 minutes, the results of which measurements were used to compute sludge settling speed in order to calibrate the floc blanket model.

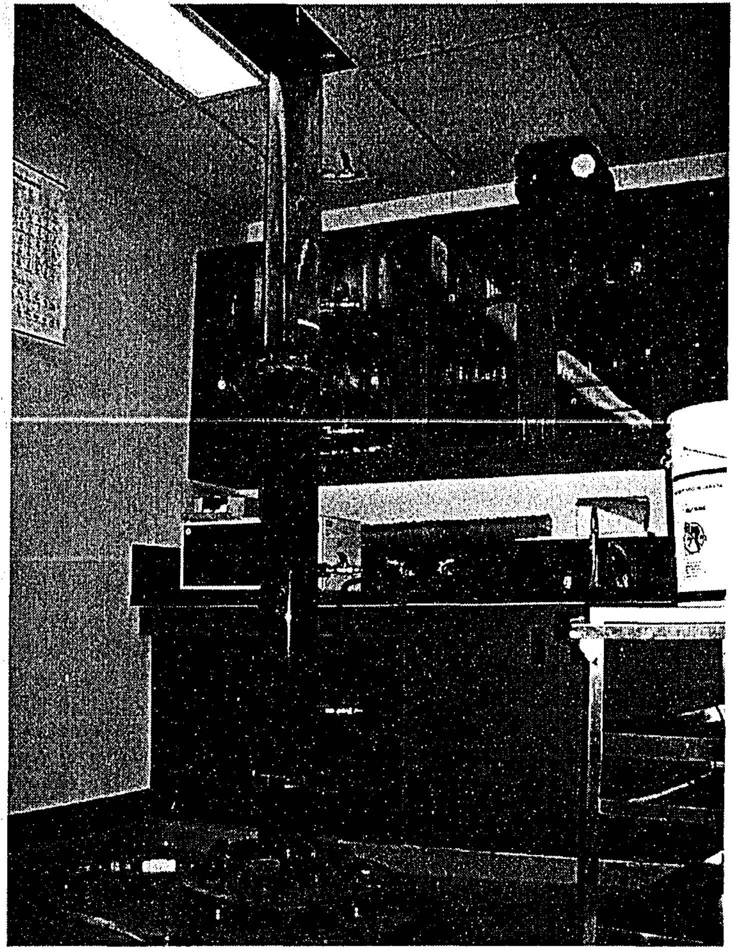

Figure 3-15 Column test

3.5.3 Chemical Pump addition calibration

Three chemical pumps were used in this experiment and all of them were calibrated before the running of the pilot plant. A volumetric cylinder was applied to measure the chemical consumption within 20 minutes. The adjust node of the chemical pump was turned to a different position within the full range to obtain the flow response curve. The final results are shown in Appendix B.

3.5.4 Jar test

3.5.4.1 General

The jar test was used to help optimize the pilot plant operation. Two groups of Jar tests, described in sections 3.5.4.2 and 3.5.4.3, respectively, were conducted as part of this research to determine: (1) Which is the best polymer for application in swine manure treatment; (2) What is the best combination between a polymer and alum.

The 24-hour settled supernatant was used as a sample in all the jar tests performed. Alum doses of 1600 mg/L were used in all experiments as a contrast treatment to the polymer treatment. To determine the effectiveness of the jar test, blank control (without any chemical addition) was involved in all of the tests performed. The rapid and slow mixing speeds and times were 150 rpm and 30 s, and 20 rpm and two min, respectively. After rapid and slow mixing, the samples were allowed to settle in the jars for approximately one hour. The Gt values for slow and rapid mixing were 1,650 and 10,000, respectively. Transfer pipettes (wide open) were used to collect the samples from each jar.

3.5.4.2 Chemical selection

Both alum and ferric chloride are popular coagulants for treating swine wastewater (Gao et al., 1993; Hanna et al., 1985; Powers et al., 1995; Sievers, 1989; Sievers et al., 1994). A study was conducted to compare these two coagulants (Zhu, 2003). It was found that, based on economics and TSS and TP removal efficiency, alum was better than ferric chloride. As a result, alum was selected as the coagulant for treating liquid swine manure in this research.

There are three types of polymers: cat-ionic polymer, an-ionic polymer, and non-ionic polymer. Many studies have indicated that, in swine manure treatment, cationic polymer addition may enhance the process. In this research, eight cationic polymers were analyzed in jar tests. An alum dose of 1600mg/L was used as a control for these tests.

In the jar test (A) of the group-1 polymers, there were eight different polymers and a total of 26 jar tests were conducted at different dosages. Following the suggestion of the chemical manufacturer, polymers P 2465, P 439, P 2478, and P 2495 were used as coagulant aids with 1000 mg/L alum, while PCT 4 was used as coagulant alone. Dosages are shown in Table 3-1.

Table 3-1 Polymer dosages (mg/L) in group-1 polymer jar test (A)

	P 2465	P 439	P2478	P 2495	PCT 4
Dose A	2	2	2	2	25
Dose B	10	10	10	10	50
Dose C	20	20	20	20	100
Dose D	40	40	40	40	200
Dose E	100	100	100	100	400

In the jar test (B) of the group-2 polymers, there were eight different polymers and a total of 15 jar tests were conducted at different dosages. Following the suggestion of the chemical manufacturer, CTTL (polymer alone) was used as a coagulant aid with 500mg/L alum, while CT 49 (Aluminium hydroxychloride with polymer), PAC (Poly aluminium silicate chloride with polymer), and PAC+ (Poly aluminium chloride with polymer) were used as coagulants alone. Their dosages are shown in Table 3-2.

Table 3-2 Polymer dosages (mg/L) in group-2 polymer jar test (B)

	CTTL	CT49	PAC	PAC+
Dose A	2	20	100	100
Dose B	10	50	500	200
Dose C	20	100	1000	500
Dose D	50			1000

Both the group-1 and group-2 jar tests were conducted according to section 3.5.4.1, and the jar sequences were determined by the random function of Microsoft Excel.

3.5.4.3 Polymer and alum combination

Base on the results from the past two years of this project, it was concluded that alum alone, at a dose of 1600 mg/L, would give the best performance/economical results (Singh, 2004; Zhu, 2003). However, two-stage treatment at the same dosage gave an even better result. The objective of this experiment is to determine the best dosage for each stage and how to combine the alum and polymer dosages.

Two jar tests were then conducted to determine the optimum alum and polymer combination dose. Jar test (C) was designed as a factorial experiment to find the optimum range of alum and polymer dosages. The factorial design was a 3^2 full factorial design with a total of nine runs. As a result, three levels (high, center, and low) and two factors (alum dose and polymer dose with their interaction) constituted the full factorial design matrix experiment for this project. This factorial matrix is shown in Table 3-3.

Table 3-3 Factorial design of jar test (C)

Run #	Chemical Dose		Factorial Code Unit		
	Alum	Polymer	Alum	Polymer	Interaction
5	350	10	-1	-1	1
4	350	20	-1	0	0
10	350	40	-1	1	-1
1	550	10	0	-1	0
9	550	20	0	0	0
2	550	40	0	1	0
3	750	10	1	-1	-1
6	750	20	1	0	0
12	750	40	1	1	1

To further investigate the optimum polymer dose, jar test (D) was conducted based on the results from jar test (C). Since jar test (C) only tested polymer dosages at 10 mg/L intervals, it was necessary to examine polymer dosages at smaller range. In jar test (D), the alum dose was fixed at 550 mg/L. Polymer dosages were selected to be 2 mg/L, 8 mg/L, 8 mg/L, and 10 mg/L. A total of six jar tests were conducted, as well as a control. The dosage chart is shown in Table 3-4.

Table 3-4 Chemical dosages for jar test (D) (mg/L)

Run #	Alum	Polymer
3	0	0
2	550	0
6	550	2
1	550	4
4	550	8
5	550	10

Both jar test (C) and jar test (D) were conducted according to section 3.5.4.1 and the jar sequences were determined by the random function of Microsoft Excel.

3.6 Analytical Methods

In this project, all parameter analyses were based on Standard Methods (APHA, 1995). Storage guidelines in Standard Methods (APHA, 1995) were also followed.

3.6.1 Total Solids (TS)

3.6.1.1 General discussion

An important physical characteristic of wastewater is its TS content, which is composed of floating matter, settle-able matter, colloidal matter, and matter in solution (Metcalf & Eddy, 2003). Total solids is analysed by measuring the material residue left in the vessel after evaporation of a sample and its subsequent drying in an oven at a defined temperature (103 to 105 °C) (APHA, 1995). Total solids are composed of total suspended solids (TSS) and total dissolved solids (TDS).

3.6.1.2 Sample container, Sample preservation:

Resistant-glass or plastic battles (The material in suspension does not adhere to container walls)

Analyze as soon as possible, keep at 4 °C, preferably less than 24 hours, must be less than seven days

3.6.1.3 Apparatus

Gooch crucible (two for each sample)

Wide-bore pipet

Oven, for operation at 108 °C

Desiccator, for moisture control, provided with a colour indicator or instrumental indicator

Analytical balance, Mettler AE 163

3.6.1.4 Procedures (refer to Standard Method (APHA, 1995), 2540 (B))

3.6.2 Total Dissolved Solids (TDS)

3.6.2.1 General discussion

The dissolved solids consist of what remains after the filtered sample has been evaporated. A known volume of filtrate obtained after filtering a well-mixed sample through the glass fibre filter is evaporated in a pre-weighed dish and dried to a constant weight at 180 ± 2°C (APHA, 1995). The evaporation of the filtered sample leaves a salt residue, which causes the weight of the evaporating dish to increase and thus gives us the measure of total dissolved solids (TDS). Dissolved solids content can also be measured with specific-conductance measurements (Sawyer et al., 1994). Most of the dissolved solids content in waters and treated wastewaters is present in the form of ionized substances and hence can be measured by determining the specific conductance or conductivity of the water. Other than that, wastewater contains a high fraction of colloidal solids that typically range in size 0.01 to 1 μm. This portion of the particles also contributes to the TDS value.

3.6.2.2 Sample container and Sample preservation:

Use resistant-glass or plastic battles (The material in suspension does not adhere to container walls). The sample should be analyzed as soon as possible. Keep the sample at 4°C for, preferably, less than 24 hours, and no more than seven days.

3.6.2.3 Apparatus

Evaporating dishes, 40 ml capacity

Gooch crucibles, 20 ml capacity

Glass fibber filters, specially cut A/E glass filter with 1.0 μm pore size and 33.8 mm diameter

Analytical balance, Mettler AE 163

Drying oven, for operation at 108 º C

Desiccator, for moisture control, provided with a colour indicator or instrumental indicator

Vacuum Filtration assembly, vacuum suction pump, volumetric flasks, and holding unit for Gooch crucibles

3.6.2.4 Procedure (refer to Standard Method (APHA, 1995), 2540 (C))

3.6.3 Total Suspended Solids (TSS)

3.6.3.1 General Discussion

According to (Sawyer et al., 1994) the measurement of TSS is considered as important as biochemical oxygen demand (BOD) because it is one of the main parameters used to assess the strength of wastewaters and to determine the efficiency of treatment plants. It is also a significant parameter for controlling biological and physical wastewater treatment processes and assessing the compliance of these processes with regulatory wastewater effluent limits. In the case of surface and ground waters, TSS is usually determined as turbidity, which represents very fine and colloidal suspended matter.

In preliminary experiments, it was found that the standard deviation for TSS was more than 200mg/L if measured directly, while the standard deviations for TS and TDS were less than 100mg/L. Therefore, TSS was computed from the TS and TDS parameters in this research.

3.6.3.2 Calculation:

$$TSS\,(mg\,/\,L) \;=\; TS\,(mg\,/\,L) - TDS\,(mg\,/\,L)$$

Where:

TS = Total Solids in the sample

TDS = Total Dissolved Solids in the sample

3.6.4 Total Phosphorus (TP)

3.6.4.1 General Discussion

Phosphorus is essential to the growth of algae and other biological organisms, as well as to plants. Because of noxious algal blooms that occur in surface waters, there is presently major interest in controlling the amount of phosphorus compounds that enter surface waters through manure application and natural runoff. Phosphorus occurring as orthophosphate can be measured quantitatively by gravimetric, volumetric, or colorimetric methods. In order to determine the amount of total phosphorus in a sample, the polyphosphates and organic phosphate have to be converted to orthophosphate. The sample must undergo acid hydrolysis and oxidative digestion by boiling at a low pH in the presence of potassium per sulphates.

In this project, the Ascorbic Acid Colorimetric Method (APHA, 1995) was used to determine the total phosphorus concentration levels in the raw and treated swine manure samples.

3.6.4.2 Apparatus

*Wide mouth bo*ttles, 125 ml capacity

Autoclave @ 121°C

Spectrophotometer @ 880 um

Pasteur pipets

Volumetric pipets

3.6.4.3 Procedure (refer to Standard Method (APHA, 1995), 4500-P (E))

3.6.5 Total Kjeldahl Nitrogen (TKN)

3.6.5.1 General Discussion

Nitrogen is essential to the growth of microorganisms, plants, and animals, because it is an essential building block in the synthesis of protein. Nitrogen data will be required to evaluate the nutrient content of waste water. The Kjeldahl method is a means of determining the nitrogen content of organic and inorganic substances. It may be broken down into three main steps: digestion, distillation, and titration. The amount of nitrogen in a sample can be calculated from the quantified amount of ammonia ions in the receiving solution. A concentrated acid solution is used for the decomposition of nitrogen in organic samples. This is accomplished by boiling a homogeneous sample in concentrated sulphuric acid. The end result is an ammonium sulphate solution. A basic example of a general equation for the digestion of an organic sample is shown below:

$$Organic\ N + H_2SO_4 \xrightarrow{Heat+Catalyst} CO_2 + H_2O + NH_4HSO_4$$

Potassium sulphate is added to raise the boiling point of the mixture, thus speeding the decomposition. The amounts of sulphuric acid and potassium sulphate used must be controlled, depending on the amount of organic material present in the sample, to insure that a proper digestion temperature range of 370 - 400°C is maintained. Too low a temperature may lead to long digestion times and/or incomplete digestion, while too high a ratio of potassium sulphate to sulphuric acid may raise the temperature above 400°C, thus resulting in pyrolytic loss of nitrogen and low results. A metal catalyst ($CuSO_4$) is also added to accelerate the digestion. Mercury has been the most common catalyst used, but copper and selenium are being used more now, for safety and environmental reasons.

The ammonia can be distilled into a boric acid solution containing methyl red indicator, and then the ammonia content can be determined by direct titration with a standard acid (0.005N HCl). The main chemical reaction is:

$$\mathrm{NH_3 + H_3Bo_3 \rightarrow NH_4^+ + H_2Bo_3^-}$$

In the titration process, to quantify the amount of ammonia in the receiving solution, the main chemical reactions are:

$$NH_4^+ + HCl \rightarrow NH_4Cl + H^+$$

$$H_2BO_3^- + H^+ \rightarrow H_3Bo_3$$

3.6.5.2 Apparatus

Tecator Kjeldahl 2020 digestion

1026 distillation apparatus

Mettler-Toledo automatic titrator

Digestion tubes, 250 ml capacity, duplicate

Beakers, 250 ml capacity

Volumetric flasks and pipets

Boiling rod

3.6.5.3 Chemicals (good for a period of time up to six months)

4% boric acid (40g H_3BO_3/ 1L) with methyl red indicator,

Concentrated sulphuric acid,

40% NaOH (400g NaOH/ 1L),

Kjeltabs ($CuSO_4$, K_2 SO_4) S/3.5--- two pieces,

0.005N hydrochloric acid (0.413 ml concentrated HCl /1L)

0.005N Na_2CO_3 (0.1325 g /500 ml H_2O, dried @103°C for one hour) used to standardize 0.005N HCl (one week)

NH_4Cl 50mg N/L (0.1910g NH_4Cl /1L water, dried @105°C for four hours) as a standard solution. (one to three months)

3.6.5.4 Procedure (refer to Standard Method (APHA, 1995), 4500-NH_3 (C))

3.6.6 5-day Biochemical Oxygen Demand (BOD_5)

3.6.6.1 General Discussion

Determining 5-day biochemical oxygen demand (BOD_5) involves measuring the dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter. The test is useful for determining the amount of oxygen required to biologically stabilize the organic matter and for evaluating the size and efficiency of manure treatment plants. The BOD_5 test is performed more often than the longer BOD tests (such as BOD_7 and BOD_{20}) because it takes less time for completion and it avoids the nitrification process that normally occurs after five to seven days.

3.6.6.2 Sample volume and storage:

250 ml of sample should be analyzed immediately. If not, it should be store at 4°C for less than 24 hours.

3.6.6.3 Apparatus

BOD incubation bottles, 300 ml, 6 bottles/sample + 6

Magnetic stirrer, to mix the sample during titration

Incubator, 20°C

DO meter: YSI incorporated model 50B

3.6.6.4 Required Solutions

BOD Buffer: prepared one day before the BOD test, needs to be saturated with [DO]. DI water + 1 ml/L of each following:

- *a.* Phosphate buffer: 8.5g KH_2PO_4, 21.75g K_2HPO_4, 33.4g $Na_2HPO_47H_2O$ and 1.7g NH_4Cl to 1L. Or, 42.5g KH_2PO_4 or 54.3g K_2HPO_4 to 700ml, adjust pH=7.2 with 30% NaOH, and dilute to 1L.
- *b.* Magnesium Sulphate: 22.5g $MaSO_47H_2O$ to 1L
- *c.* Calcium Chloride: 27.5g $CaCl_2$ to 1L
- *d.* Ferric Chloride: 0.25g $FeCl_36H_2O$ to 1L
- *e.* Glucose-glutamic acid standard: Prepared just before the BOD test, 150 mg glucose + 150 mg glutamic acid were diluted to a 1L volume
- *f.* Acid and alkali solution: 1N & 5N, for neutralization of caustic or acidic waste samples
- *g.* Seed: made out of swine waste for 20 days

3.6.6.5 Procedure (refer to Standard Method (APHA, 1995), 5210 (B))

3.6.7 Chemical Oxygen Demand (COD)

3.6.7.1 General Discussion

The COD test is used as a measure of the oxygen equivalent of the organic matter content of a sample susceptible to oxidation by a strong chemical oxidant. It is also used to measure the strength of domestic and industrial manures (APHA, 1995; Sawyer *et al.*, 1994). There are two methods commonly used to determine the COD of a sample: the open reflux method and the close reflux method. In this project the close reflux method was used.

3.6.7.2 Apparatus

Digester, HACH COD reactor

Spectrophometer, Pharmacia Biotech Novaspec II

COD vials, 10 ml

3.6.7.3 Procedure (refer to Standard Method (APHA, 1995), 5220 (D))

3.6.8 Particle Counting (PC)

3.6.8.1 General discussion

Particle counting is recognized as a more sensitive and accurate measurement of water quality than turbidity. The advantage is that a particle count analyzer can simultaneously count the number of particles in a sample and distribute (classify) them according to their size ranges. This data can help researchers to understand and evaluate the treatment processes already in use and to determine the need for future modifications.

3.6.8.2 Apparatus

Particle Counter, HIAC ROYCO 8000 by Pacific Scientific Instrument

3.6.8.3 Procedure

a. *Sample preparation:* The samples were diluted adequately. Normally, a dilution factor of 100 was selected for the raw manure samples, while the other samples were diluted by a factor of 50 with DI water. All the samples were run in duplicate to ensure quality and consistency.
b. *Particle Counting:* The operator's manual for the models 8000A/8000S was followed. Particle classifications were selected from the 2, 3, 5, 7, 10, 12, 15, and 20 μm size ranges. The counter consisted of a laser sensor that identified the particles in a known volume of sample. The sensor was connected to an electronic counter that performed the counting and sizing of the particles. The apparatus was programmed to pass 10 ml of diluted sample thrice through the sensor and to display the results on the screen of the electronic counter after taking the average of the three observations.

3.6.9 pH and Temperature

3.6.9.1 General discussion

Measurement of pH is one of the most important and frequently used tests in water chemistry. Practically every phase of wastewater treatment is pH dependent. At a given temperature, the intensity of the acidic or basic character of a solution is indicated by the pH or hydrogen ion activity. PH, as defined by Sorenson, is –log[H+]; it is the "intensity" factor of acidity.

The basic principle of electrometric pH measurement is determination of the activity of the hydrogen ions by potentiometric measurement using a standard hydrogen electrode and a reference electrode.

3.6.9.2 Procedure (refer to Standard Method (APHA, 1995), 4500-H^+)

3.6.10 Electrical Conductivity (EC)

3.6.10.1 General discussion

Electrical conductivity (EC) is a measure of the ability of an aqueous solution to carry an electric current. This ability depends on the presence of ions, on their total concentration, mobility, and valence, and on the solution temperature at the time of measurement. The solutions of most inorganic compounds are relatively good conductors. EC can be used to estimate the TDS in a sample by multiplying conductivity (in micromhos per centimetre) by an empirical factor.

YSI Model 34 Conductance-resistance meter

Cell YSI 3417, K=1.0/cm

The meter is calibrated to read directly in submultiples of mhos/cm when used with any conductivity cell that has a cell constant K of 1.0/cm.

3.6.10.2 Calibration

Increased temperature provides increased activity or ionic movement that enables more electricity to be carried through a solution from one electrode to another. In order to better correlate electrical conductivity to ion concentration, the effect of temperature on a solution's ability to conduct electricity should be considered (McPherson, 1997).

$$G_t = G_{tcal}(1 + \alpha(t - t_{cal}))$$

Where G_t is the EC value at measurement temperature t, G_{tcal} is the EC value at calibrated temperature t_{cal}, and α is a temperature compensating factor.

3.6.11 Scanning Electron Microscope (SEM)

Scanning Electron Microscope (SEM) analysis was performed on the sludge samples generated by the pilot runs. The Scanning Electron Microscope Lab is located in Room 2-17C in the Earth Sciences Building. This facility utilizes a JEOL 6301F (Field Emission Scanning Electron Microscope) to provide high-resolution digital images at magnifications ranging from 20x to 250,000x. Qualitative elemental analysis is performed by an attached PGT Analyzer and cryogenic capabilities are available. The FESEM is used by the entire University community, as well as by industry and various government agencies. Image output is in the form of high-quality laser prints, photographic prints, or digital images stored on CD-ROMs.

The SEM machine is generally composed of an electron gun which provides a beam of electrons with energies forming an electric potential of 1 to 50 keV. The electron beam produced by the electron gun is accelerated after passing through a series of condensing lenses that intensify the beam into a small-diameter probe. The condensed beam is then scanned over the specimen. In order to obtain the final image, a set of deflecting coils is placed between the condensing lenses to produce a rectangular pattern over the sample. The signals transmitted from the deflecting coils are conveyed to the cathode ray tube (CRT) of the SEM through a scan generator. The scan generator acts to synchronize the signals incident on the sample and the signals transmitted to the CRT, thus producing an image of the specimen (Hayat, 1974).

4 RESULTS AND DISCUSSION

4.1 Swine Manure Characterization

4.1.1 General Results

Swine manure characteristics vary significantly depending upon many factors, such as animal and feed type, water consumption, on-site operations, seasonal conditions, and manure management practices (ASAE, 2003; Powers et al., 1995; Ra et al., 1998). Table 4-1 summarizes the raw and preliminary settled swine manure characteristics observed in this research. It should be noted that swine manure characteristics vary substantially from sample to sample.

Table 4-1 Swine manure characteristics* (in mg/L)

Parameter	Number of Samples	Raw Manure				Primary (24 hours) Settled Manure			
		Mean	Standard Deviation	Min	Max	Mean	Standard Deviation	Min	Max
TSS	5	4692	1216	3220	6193	1756	793	610	2570
TDS	5	6989	916	6204	8500	6080	844	5100	7100
TKN	5	2694	326	2137	2936	2639	360	2044	2945
BOD	5	8506	1439	6850	10575	5821	1335	4185	7665
COD	5	21925	3133	17940	26095	16440	2590	13809	19789
TP	5	232	20	213	257	197	25	174	227
PH	5	8.26	0.14	8.03	8.37	8.21	0.19	7.89	8.38

*Based on samples taken during pilot plant operation.

Some of the parameters, such as BOD_5 and TDS, are complicated and time consuming to analyze. On the other hand, analyses of COD and conductivity, which have natural relationships to BOD_5 and TDS, respectively, are relatively easy to conduct (Metcalf & Eddy, 2003). For the samples of swine manure, these relationships were evaluated based on the data obtained from this research.

4.1.2 Electrical Conductivity (EC) Temperature Compensation

Conductivity measurements are temperature dependent. The degree to which temperature affects conductivity varies from solution to solution and can be calculated using the following formula:

$$G_t = G_{tcal}\{1 + \alpha(t - t_{cal})\}$$

Where:

G_t=conductivity at any temperature t in °C

G_{tcal}=conductivity at calibration temperature t_{cal} in °C

α = temperature coefficient of solution at t_{cal} in °C

Table 4-2 Temperature coefficient of swine manure

Sample	Temp	Conductivity (mhos)	Alpha
1	16.0	16.13	0.0154
	20.6	17.36	
2	15.4	15.33	0.0155
	20.6	16.67	
3	15.9	15.54	0.0174
	20.6	16.92	
4	15.5	13.58	0.0165
	20.5	14.80	
5	15.3	14.03	0.0177
	20.7	15.51	
Average			0.0165
Std Dev.			0.0010
Std Dev. %			6.36%

Normally, samples' conductivity was measured within a temperature range of 15 to 21 °C. Table 4-2 shows the results of the temperature coefficient of swine manure at t_{cal} in about 20 °C. This coefficient was used for temperature compensation in measuring the conductivity of the swine manure samples in this research.

4.1.3 Relationship between TDS and EC

Conductivity is the ability of a material to conduct electric current. Since the charge on ions in solution facilitates the conductance of electrical current, the conductivity of a solution is proportional to its ion concentration, that is, TDS. However, ionic interaction can change the linear relationship between conductivity and concentration to a non-linear relationship in some highly concentrated solutions. In this research, the TDS and EC measurements of the samples were pooled into two group and the analysis results are shown in Figure 4-2 and Figure 4-2. It was found that TDS was directly proportional to conductivity. However, the regression function is similar but different for those two groups. The 90% prediction areas covered most of the same area in those two figures.

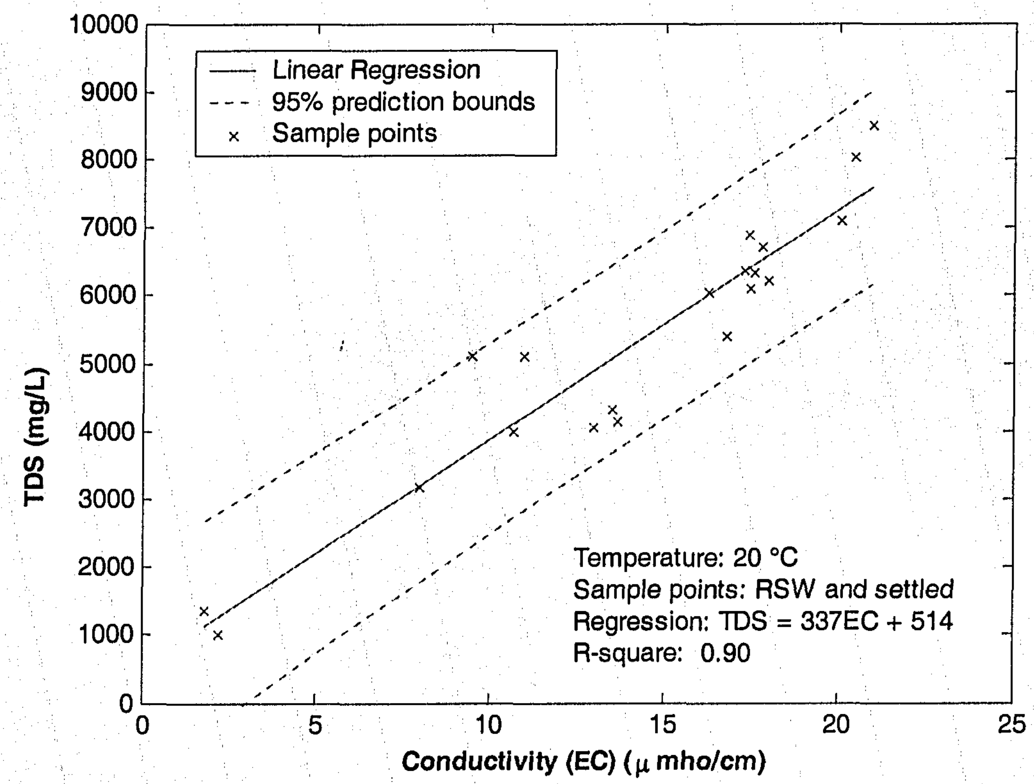

Figure 4-1 Relationship between TDS and EC (A)

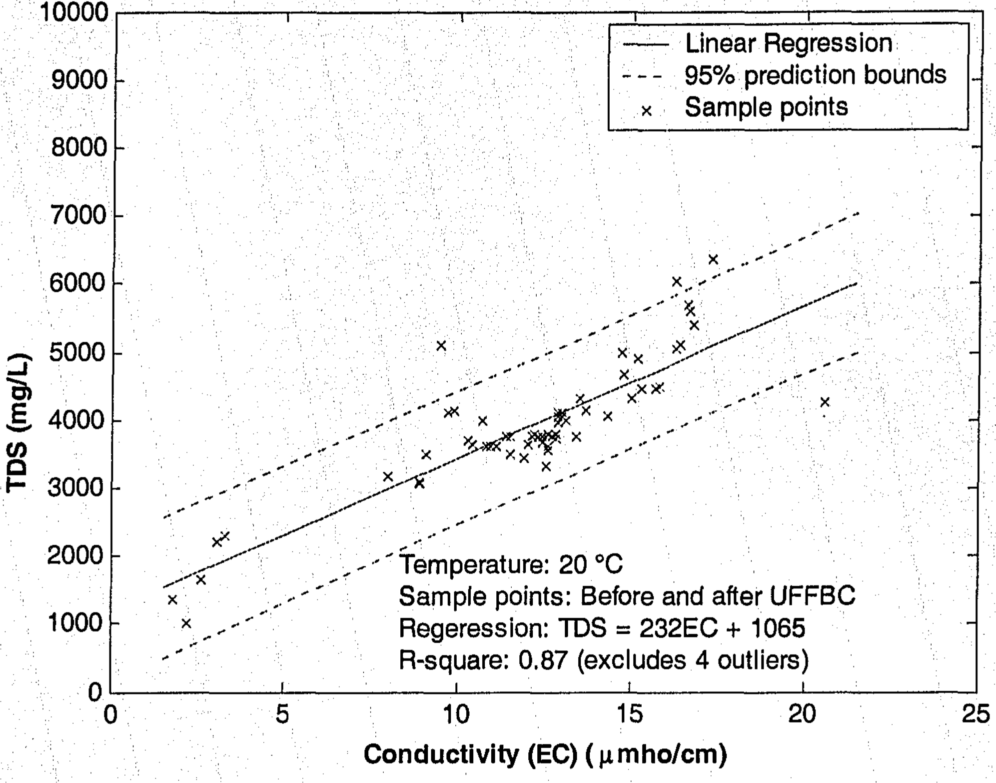

Figure 4-2 Relationship between TDS and EC (B)

4.1.4 Relationship between COD and BOD_5

Both BOD_5 and COD analyses look at carbonaceous constituents. For a given wastewater sample, their relationship is relatively constant and the BOD_5 measurement of a solution is proportional to its COD measurement (Metcalf & Eddy, 2003). In this research, COD and BOD_5 measurements of all the raw and settled swine manure are plotted in Figure 4-3. It was found that they are strongly correlated, with an R^2 equal to 0.88.

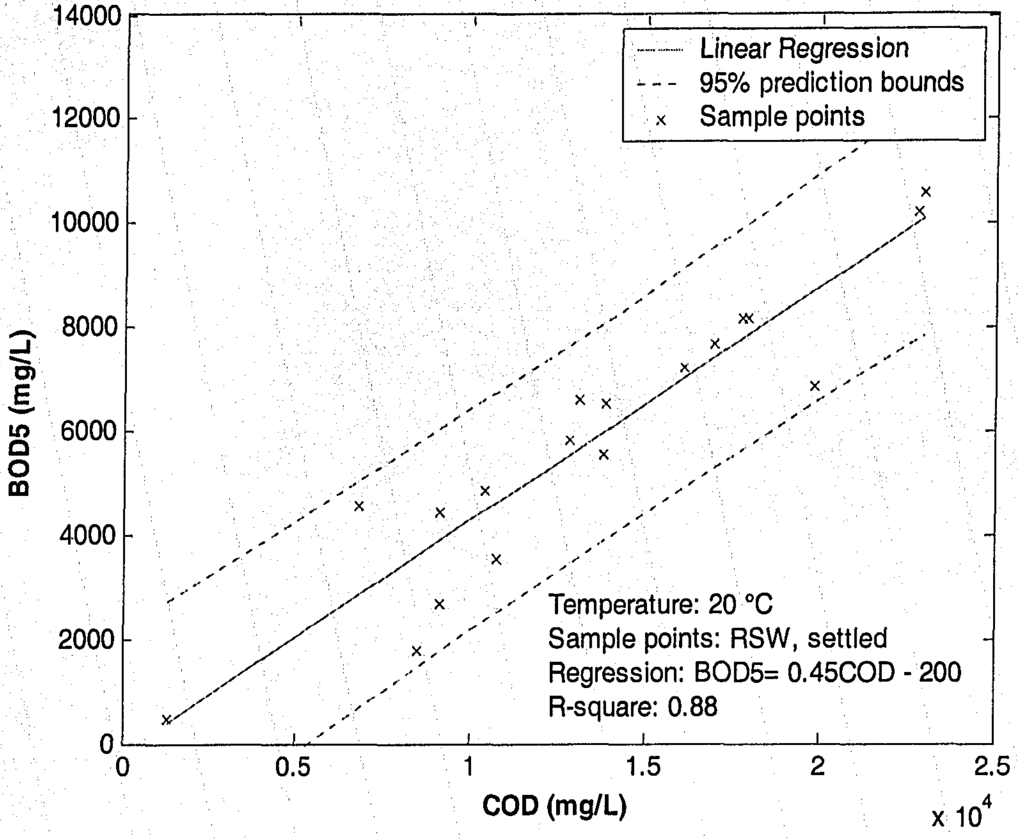

Figure 4-3 Relationship between BOD_5 and COD

4.1.5 Relationship between solids and TP

As a chemical component, phosphorus can be contained in swine manure as ortho-phosphate, poly-phosphate, and organic phosphorus, which can be dissolved or un-dissolved. Higgins et al. (2004) indicated that there is a strong relationship between phosphorus and solids. The relationship between TP and solids was investigated in this research. TS, TDS, and TSS measurements of all raw and settled swine manure are plotted in accordance with TP in Figure 4-4, Figure 4-5, and Figure 4-6. It has been suggested that TP has a stronger correlation with TS and TDS than with TSS. This could be explained by the fact that phosphorus is mainly associated with very fine particles in swine manure. The research conducted by Singh (2004) indicated that the majority of phosphorus

(>80%) is associated with particles of size less than 10μm, which account for 70 to 80% of the total particles in swine manure samples.

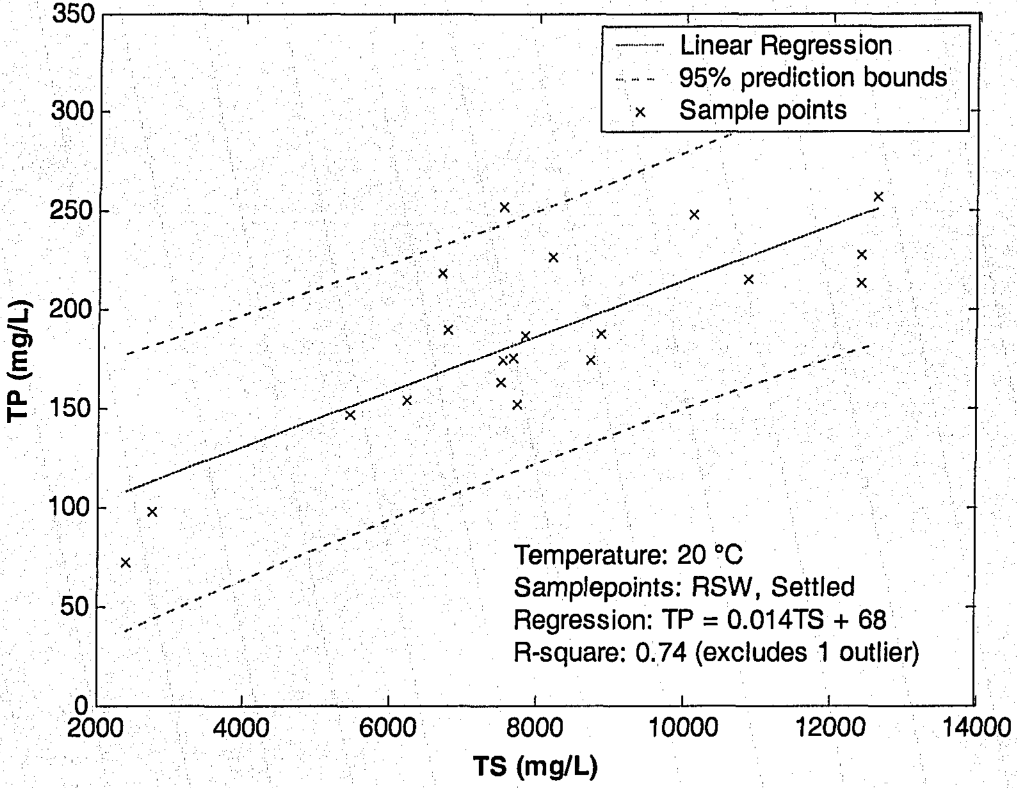

Figure 4-4 Relationship between TP and TS

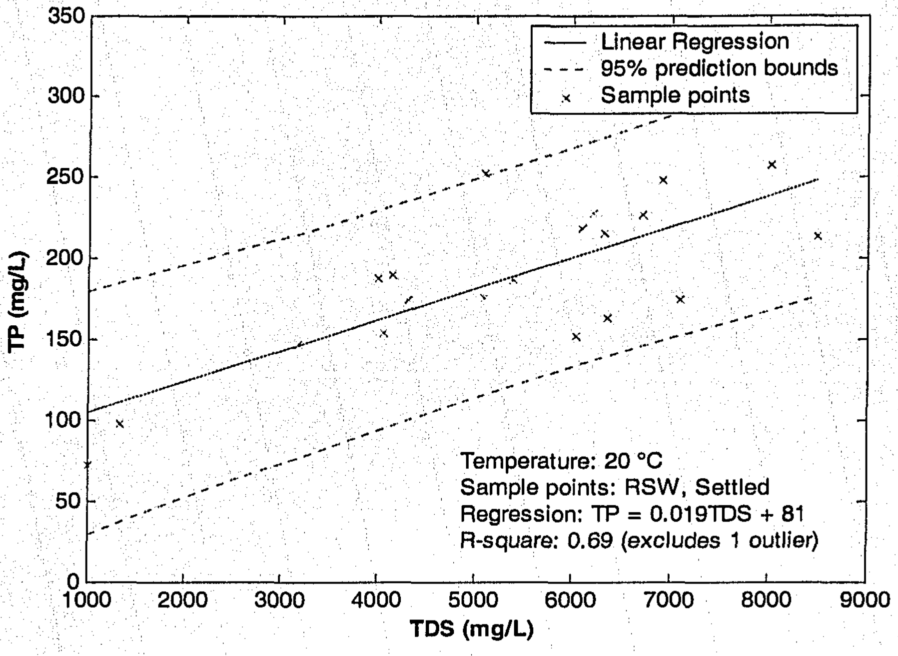

Figure 4-5 Relationship between TP and TDS

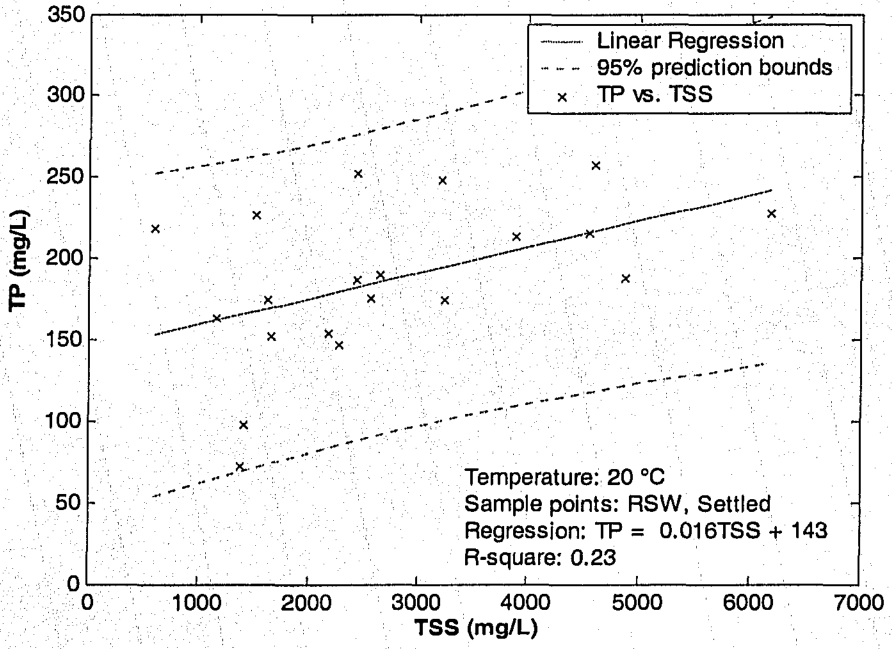

Figure 4-6 Relationship between TP and TSS

4.1.6 Relationship between TP and EC

Since relationships exist between EC and TDS, and TDS and TP, further analysis of the relationship between TP and EC was undertaken. The results are shown in Figure 4-7.

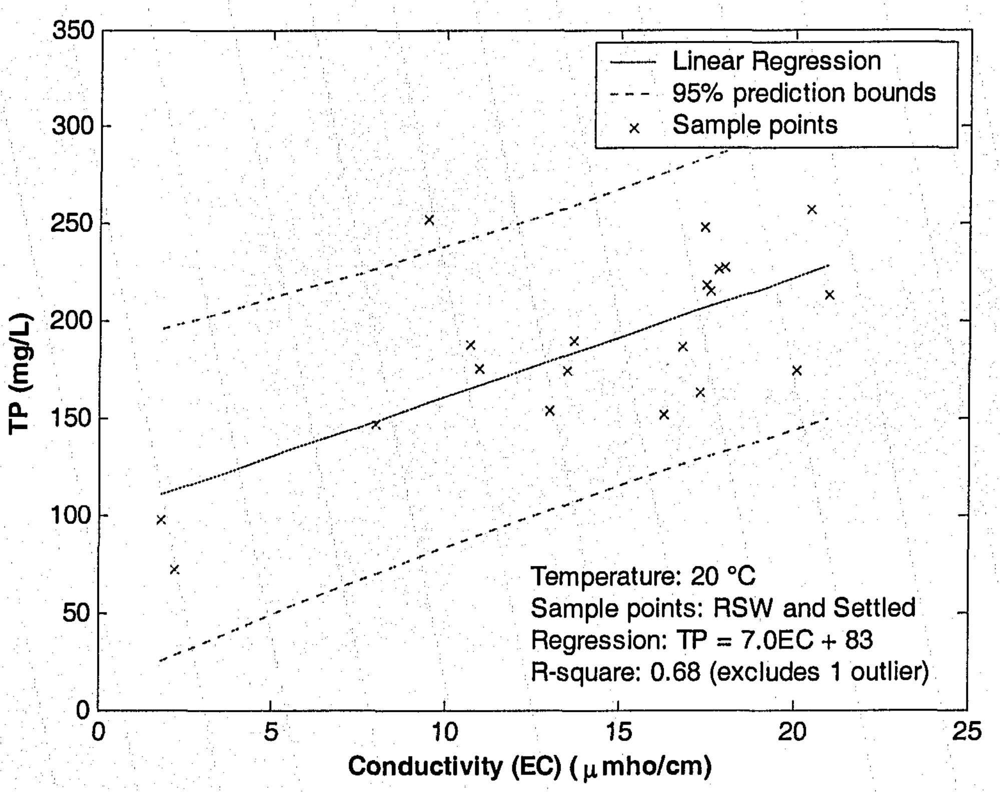

Figure 4-7 Relationship between TP and EC

4.2 Preliminary Settling

Preliminary settling has been described as an effective and economic liquid manure treatment process by many researchers (Gao et al., 1993; Jett et al., 1975; Ndegwa et al., 2001; Singh, 2004; Zhu et al., 2004a; Zhu, 2003). Most of the previous work on preliminary settling has been conducted at the bench scale level and on wastewater containing 1 to 7% total solids (TS). It has also been concluded that medium strength wastewaters (1 to 3% TS) settle thoroughly in less time than high and low strength manures. In addition, it has been found that the major portion of type II settling occurs during the initial hours.

Previous studies in this project showed that 24 hours settling can give 53% to 75% TSS and 22% TP reductions. No significant TSS and TP reductions were observed after 24 hours. In this research, settling times of less than 24 hours were investigated. This could have a significant impact on further research and design.

Two settling jar tests were conducted during the summer. Winter operation should not change the settling results significantly, since the settling tank is underground and the temperature remains relatively constant. The first settling test was conducted on 22nd July, with a 200 L barrel. There were two openings on the barrel at heights of about 45 cm and 60 cm from the bottom. The fresh swine wastewater was pumped from the holding tank into the barrel, and then the barrel was taken to the test site, where the sample was stirred and counting of the settling time commenced. Samples were taken after three hours, four hours, and then every two hours for a total of 12 hours. The samples were analyzed for solids and the results are shown in Figure 4-8.

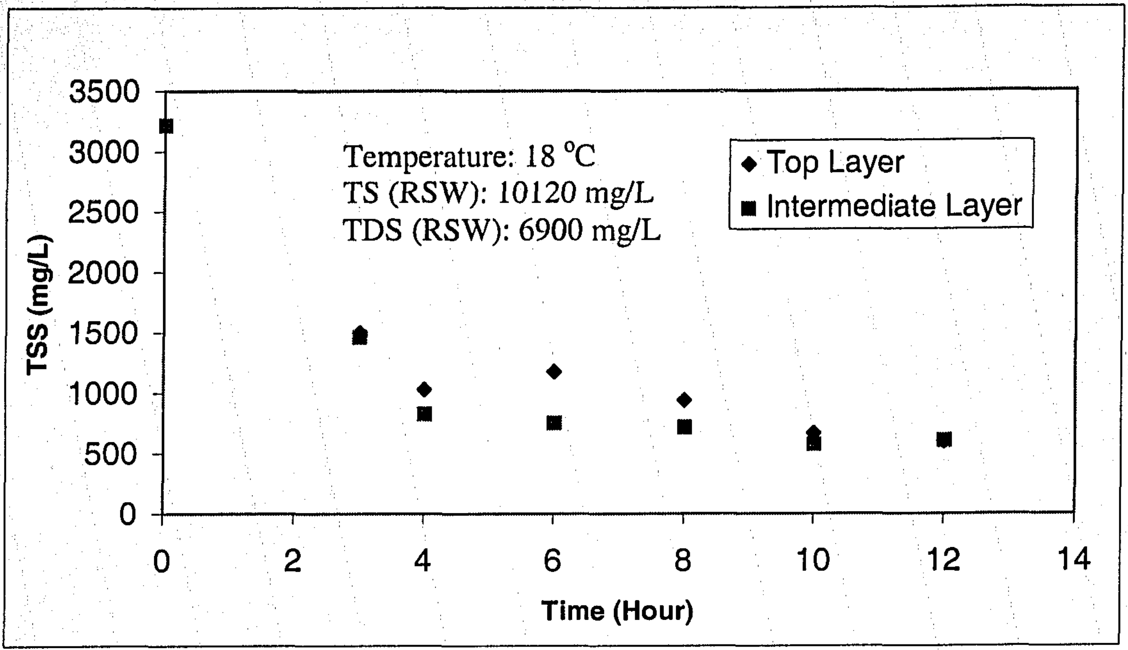

Figure 4-8 Barrel settling test results

From Figure 4-8, it is clearly shown that TSS reduced to about 600 mg/L after ten hours of settling for both the top and middle samples, and then remained almost constant.

The second settling test was conducted on 11th Aug using the underground preliminary settling/storage tank. Samples were collected by glass sucker from the top and middle layers of the swine manure after two hours, three hours, and then every two hours for a total of 11 hours. The samples were analyzed for solids and TP. The results are shown in Figure 4-9 and Figure 4-10.

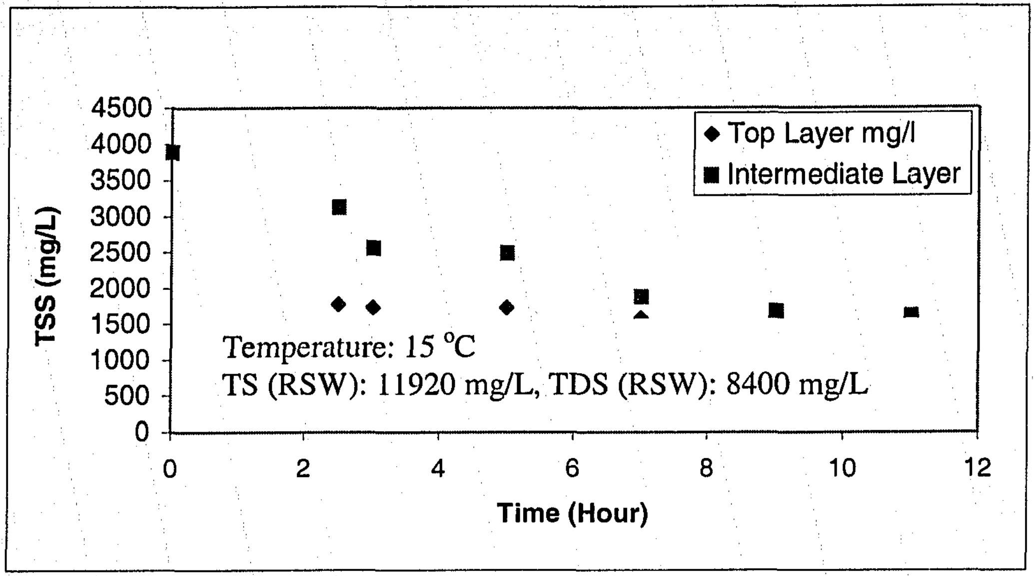

Figure 4-9 Underground Tank (A) settling test results

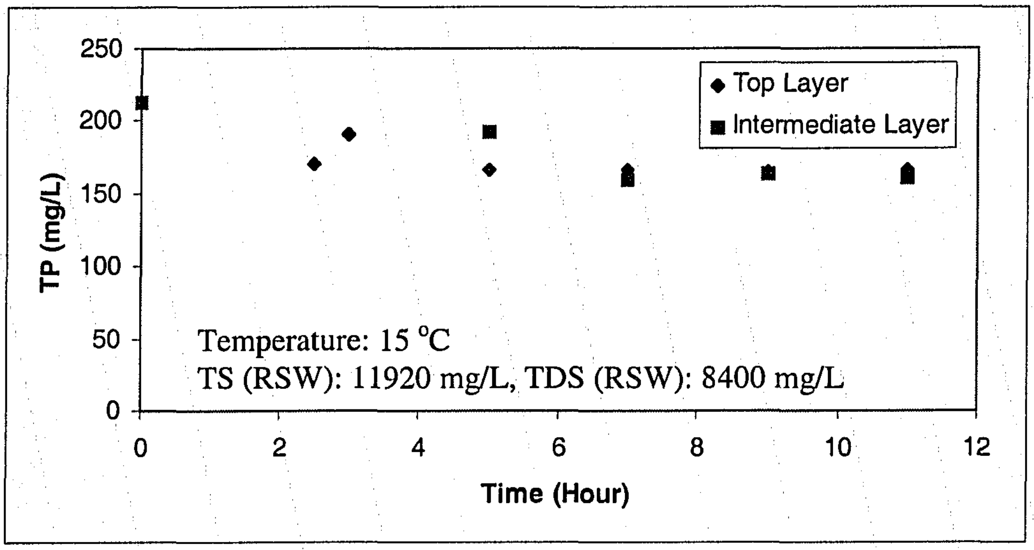

Figure 4-10 Underground Tank (B) settling test results

It was found that, in the underground tank, preliminary settling of raw swine manure reached a constant TSS and TP level (about 1600 mg/L and 160 mg/L, respectively) during the first nine hours, which was similar to the results of the barrel settling test. There are two things one should pay attention to: 1) the TSS removal efficiency of the underground tank is lower than that of the settling barrel; 2) the TP removal efficiency is less than that of TSS.

The first phenomenon indicated that there were factors other than settling time influencing the final settling efficiency. Two of the factors were the size of settling facilities and the initial solids' concentration, which should be considered into the future design of settling treatment process (Metcalf & Eddy, 2003).

The second phenomenon could be explained by the nature of settling, which depends on particle size. Based on the research conducted by Singh (2004), the majority of phosphorus (>80%) is associated with particles of size less than 10μm. These account for 70 to 80% of the total particles in swine manure samples and have lower settling velocities than TSS. Therefore, phosphorus was very hard to be removed by gravity settling.

As was previously discussed in the literature review, preliminary settling has been described as an important and economic animal manure treatment process because it does not involve the use of any chemicals and can remove major portions of solids and some portions of phosphorus from raw swine manure. The results of this study confirmed the effectiveness of preliminary settling as an important pre-treatment process for swine manure.

Settling time depends on the type, strength, volume, temperature, and other characteristics of the manure. In this project, primary settled supernatant samples were always collected from the top 0.5m depth of the tank after at least 10 hours of settling. This was also done to ensure consistency and precision in sample collection.

4.3 Chemical Selection

4.3.1 Coagulant selection

Previous studies conducted as part of this project indicated that alum was a more effective coagulant than ferric chloride in removing TSS and TP from liquid swine manure. The cost of alum is five times less than that of ferric chloride (according to supplier's information). Alum applied at an average dose of 1600 mg/L removed approximately 70% of both TSS and TP, while ferric chloride applied at 2500 mg/L could only remove 45% of TSS and about 60% of TP (Zhu, 2003). Factorial analysis was also carried out to determine the effect of factors such as coagulant dose, slow mix Gt, and rapid mix Gt etc. Coagulant dose was determined to be the single most important factor in removing TSS and TP. The relationship between coagulant dose and TP removal efficiency was characteristically linear. TP removal efficiency increased to over 90% at an alum dose of 3,000mg/L, while it reached only 15% at 100mg/L alum (Zhu, 2003). An alum dose of 1,600mg/L was concluded to be, and is thus recommended as, the most effective and economical dose for the treatment applied in this research.

4.3.2 Polymer selection

Many research efforts have indicated that polymer amendments can improve the solids separation efficiency of swine manure treatment (Timby et al., 2004; Walker and Kelley, 2003). Generally, there are two different types of polymers: cat-ionic and ionic polymer.

In a previous study, an anionic polymer (supplied by Ciba Specialty Chemicals Canada Inc.) combined with alum was also analyzed for its efficiency in removing TSS and TP. It was necessary to combine alum (1,000mg/L) with higher polymer doses (up to 200mg/L) in order to match the results obtained from alum used alone at a rate of 1,600mg/L. Therefore, the anionic polymer was deemed unsuitable for treatment and cationic polymers should be further investigated.

In this research, two groups of a total of nine cationic polymers were analyzed by Jar test. The first group of polymers was produced by one company and the price was 20 times that of alum. The second group of polymers was provided by another company with a price five times that of alum.

4.3.2.1 Group #1 polymers

Removal efficiencies of TSS and TP were used as points of reference for polymer selection. Due to the experimental limitations (the raw swine manure varied from sample to sample), Jar tests were performed with different polymer dosages and without replication. The overall trends of %TSS and %TP removal were used to select polymers. Figure 4-11 indicates that polymers P 439 and P 2478 had better overall TP removal efficiencies than other polymers at each dose.

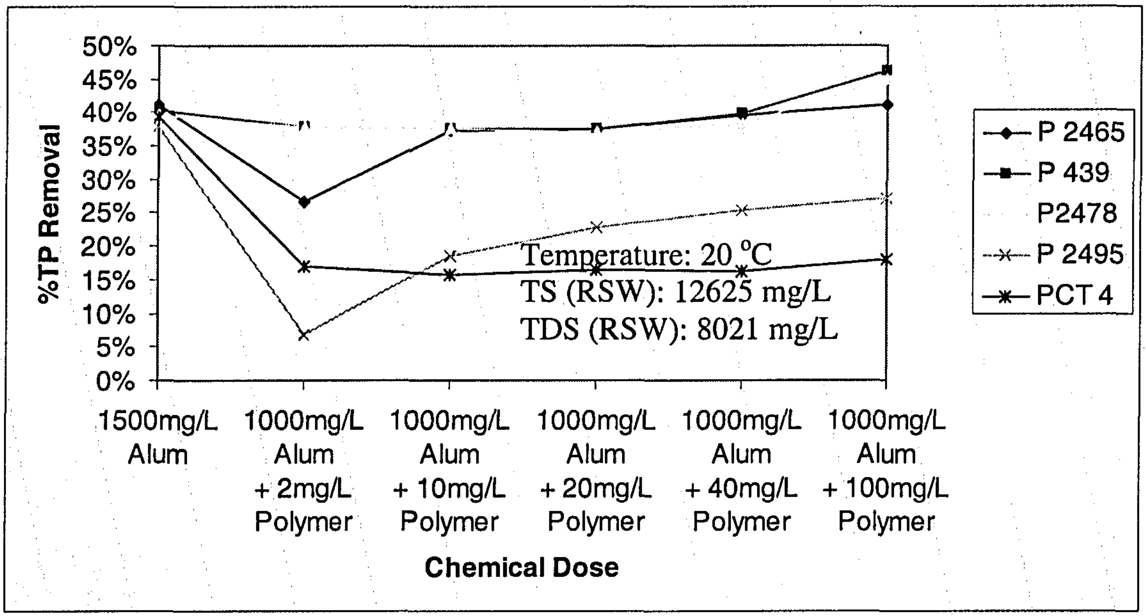

Figure 4-11 TP removal efficiency of group #1 polymers

Due to lab conditions, it was impossible to analyze solids at that time. Pictures were taken to show the visible results. Figure 4-12 shows the TSS removal efficiency at 1000 mg-alum/L + 20 mg-polymer/L. It is clear that all combined treatments gave better TSS removal efficiency than did the control, while polymers P 439, P 2495, and PCT 4 performed better than the others.

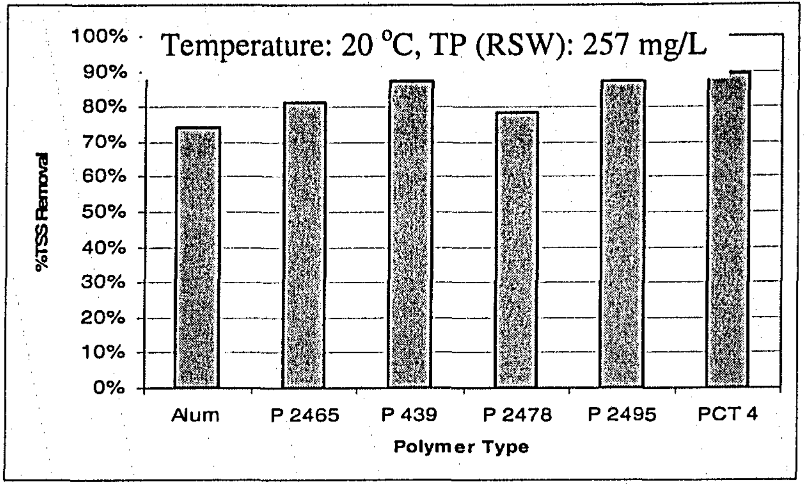

Figure 4-12 TSS removal efficiency of group #1 polymers
(Chemical dose: 1000mg-alum/L + 20 mg-polymer/L)

Combining the results of TP and TSS removal efficiency, polymer P 439 gives above average results in both cases, with TP and TSS removal efficiencies higher than 40% and 80%, respectively.

4.3.2.2 Group # 2 polymers

The Jar test of the group #2 polymers was done in a manner similar to the group #1 polymers, without replication. The overall %TSS and %TP removals were used to select the polymers. The average results of the group #2 polymers are shown in Figure 4-13 and Figure 4-14. It was found that there was only one polymer, CTTL, which had better TSS and TP removal efficiency than the control. The TP and TSS removal efficiencies were 90% and 70%, respectively.

CTTL and P 439 showed similar effects on TSS removal. Their TP removal efficiency was quite different. However, TP removal efficiency is related not only to the chemical, but also to the TDS concentration of the untreated swine manure, as discussed in section 4.7.4. To compare these two polymers, the removal efficiency ratio (a ratio between the percentage removal of the alum alone treatment and the alum-polymer combined treatment) was used. The removal efficiency ratios for P 439 are 1.2 and 1.1 for TP and TSS, respectively, while the ratios for CTTL are 1.3 and 1.1. Therefore, those two polymers have almost the same performance. Because CTTL is much cheaper than P 439, CTTL was selected as the coagulant aid for this research.

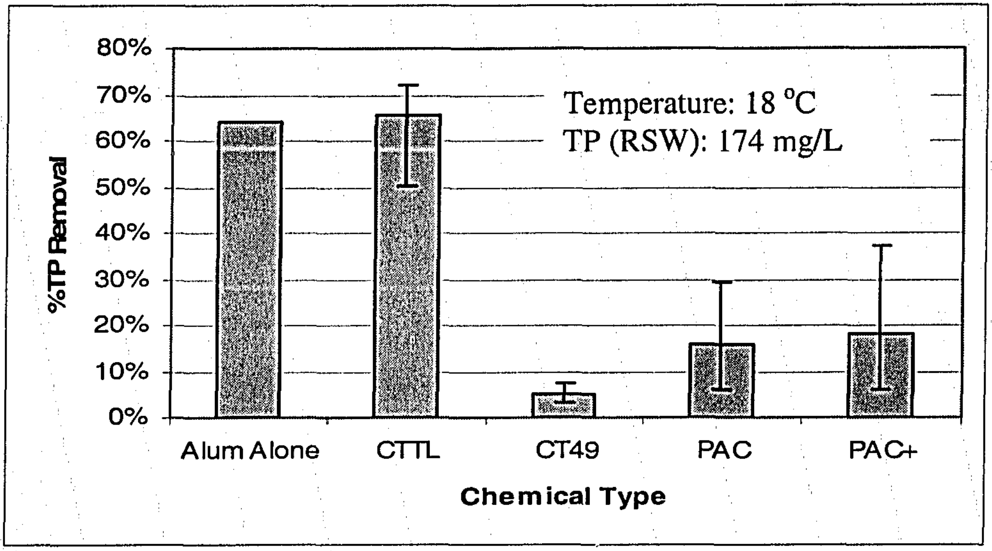

Figure 4-13 TP removal efficiency of group #2 polymers

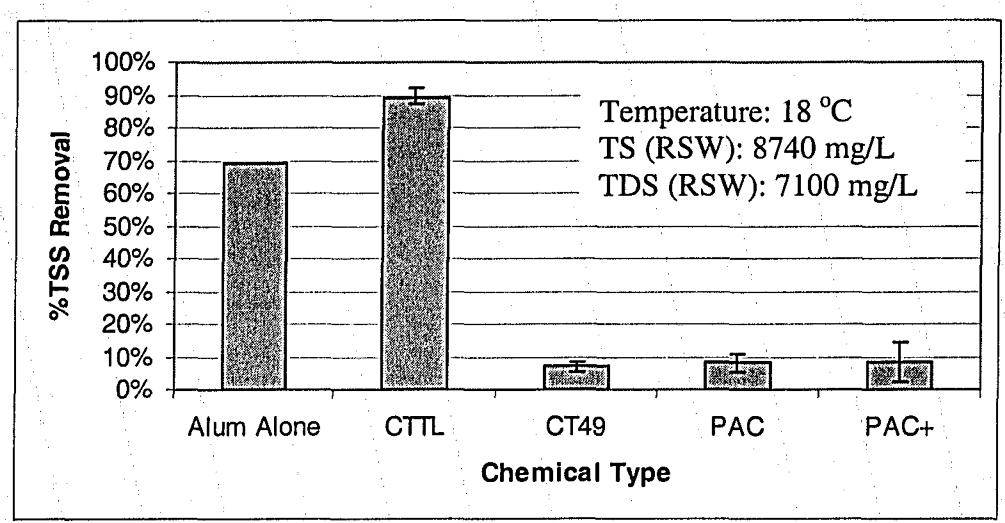

Figure 4-14 TSS removal efficiency of group # 2 polymers

4.4 Chemical Dosage Optimization (factorial design of jar test)

Based on section 4.3, alum and the polymer CTTL were selected as coagulant and coagulant aid for swine manure treatment in this research. Two jar tests were then conducted to determine the optimum alum and polymer combination dose.

Due to experimental limitations (the raw swine manure varied from sample to sample), the first jar test was designed as a factorial experiment without replication (Appendix E) to find the optimum range of alum and polymer dosage. ANOVA statistic analysis was employed to interpret the jar test results, which are shown in Table 4-3 and Table 4-4.

Table 4-3 indicates that neither of the two factors, alum dose and polymer dose, was significant for %TSS removal at a 95% confidence level. But, at an 80% confidence level, both alum dose and polymer dose were significant for %TSS removal. Interaction between the polymer and the alum was not significant at both 95% and 80% confidence levels. This result indicated that both alum and polymer dosages were important in TSS removal at low confidence levels (compared to a 95% confidence level), which could be caused by the small dose range or by some other factor.

Table 4-3 Significant analysis of factors affecting %TSS removal (by ANOVA analysis)

	Coefficients	*t Stat*	*P-value*
Alum	0.077	1.71	0.15
Polymer	0.109	2.40	0.06
Interaction	-0.054	-1.07	0.34

Table 4-4 shows that alum dosage was a very significant factor, as compared to polymer dosage, for %TP removal. It was also found that polymer and alum interaction was not significant at both 95% and 80% confidence levels.

Table 4-4 Significant analysis of factors affecting %TP removal (by ANOVA analysis)

	Coefficients	*t Stat*	*P-value*
Alum	0.035	7.62	0.0006
Polymer	0.004	0.86	0.43
Interaction	0.006	1.16	0.30

Based on the results (shown in Figure 4-15 and Figure 4-16), it was found that treatment using 550 mg-alum/L with 10 mg-polymer/L had the best %TSS removal efficiency, while treatment using 750 mg-alum/L with 20 mg-polymer/L had the best %TP removal efficiency.

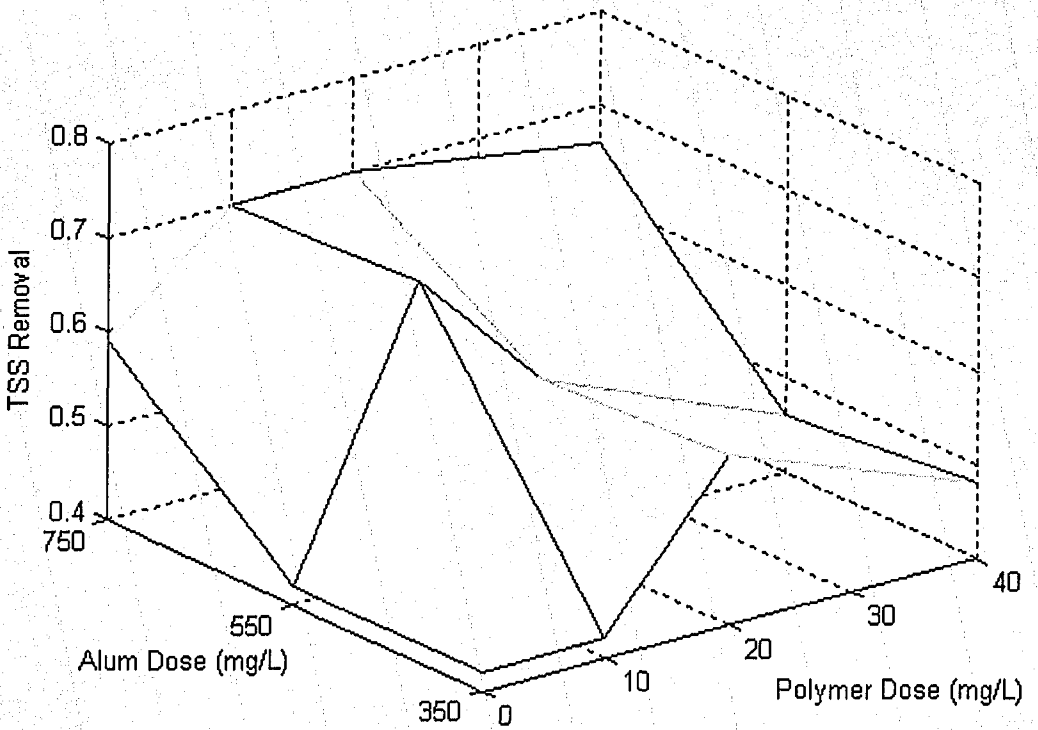

Figure 4-15 TSS removal in factorial jar test

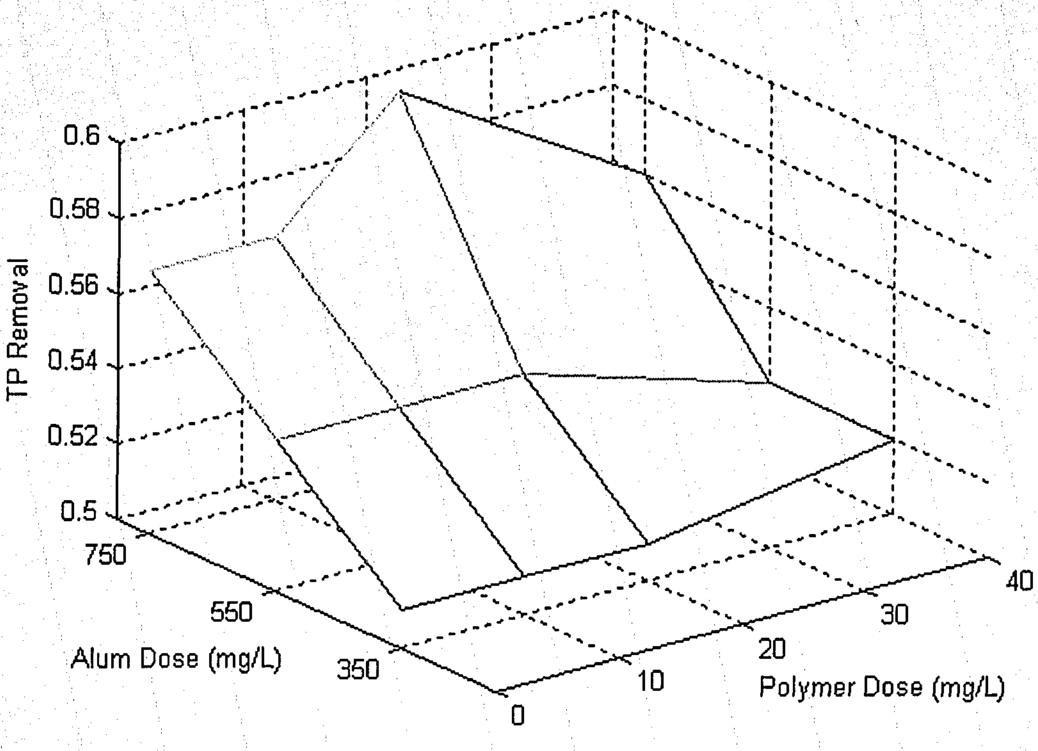

Figure 4-16 TP removal in factorial jar test

The pilot plant was designed as a two stage UFFBC system, while the first stage was designed to remove as much TSS as possible. Therefore, a 550 mg-alum/L with 10 mg-polymer/L chemical addition was selected as the centre point of the combined chemical dose in the second jar test.

In the second jar test, the polymer dosage was further investigated at the 550 mg-alum/L level. Four levels of polymer dosage within a smaller range were tested and the results are shown in Figure 4-17. The results confirmed that polymer dosage has no significant effect on %TP removal, while 10 mg/L polymer gave a significant improvement in %TSS removal at a 95% confidence level.

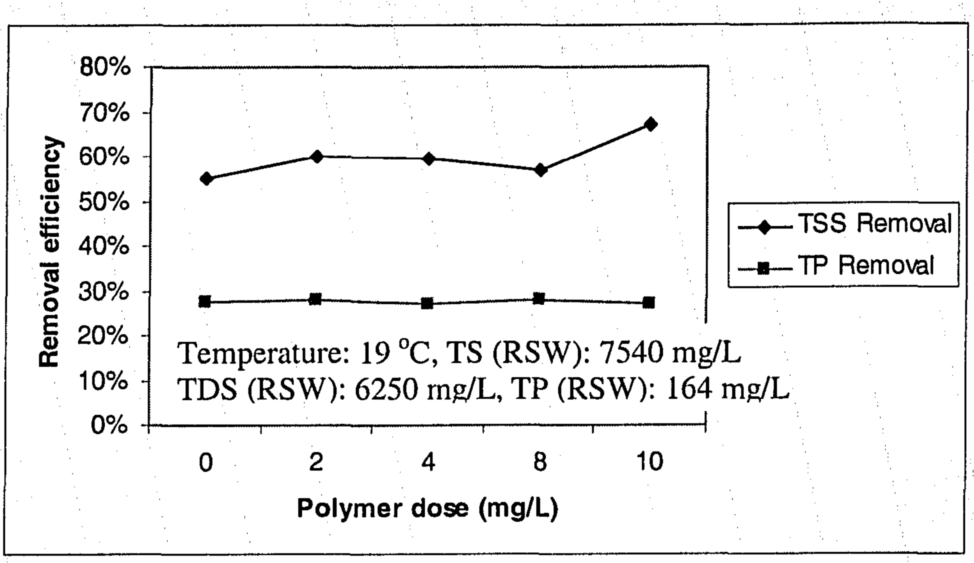

Figure 4-17 Polymer dose optimization

Therefore, 550 mg-alum/L with 10 mg-polymer/L chemical addition was selected as the first stage chemical dose.

4.5 Flow rate of UFFBC

Several trials of the pilot plant were conducted after it was set up. It was found that the UFFBC could not generate steadily at a flow rate of 8 L/min. Therefore, a column test was conducted based on the model described by (Head et al., 1997). This model was based on Gould's theory of the operation of floc blanket clarifiers (Gould, 1974). After a change in the upflow rate, or the settling velocity of the blanket, the surface of the blanket will rise or fall at a rate equal to the difference in velocities between the upflow and the hindered settling rate. This change in position of the blanket surface can be expressed as:

$$\frac{dH}{dt} = U - V_s$$

Where: H is the height of the blanket above the bottom of the tank; U is the instantaneous upflow velocity in the tank; V_s is the instantaneous hindered settling velocity of the blanket.

In the column test, since there is no upflow velocity, V_s=dH/dt. Therefore, V_s and solids concentration (C, defined as 30 minute settling volume) were calculated from sludge heights and time intervals (Appendix D). The results are plotted in Figure 4-18. It was found that hindered settling occurred with V_s less than 0.5m/h.

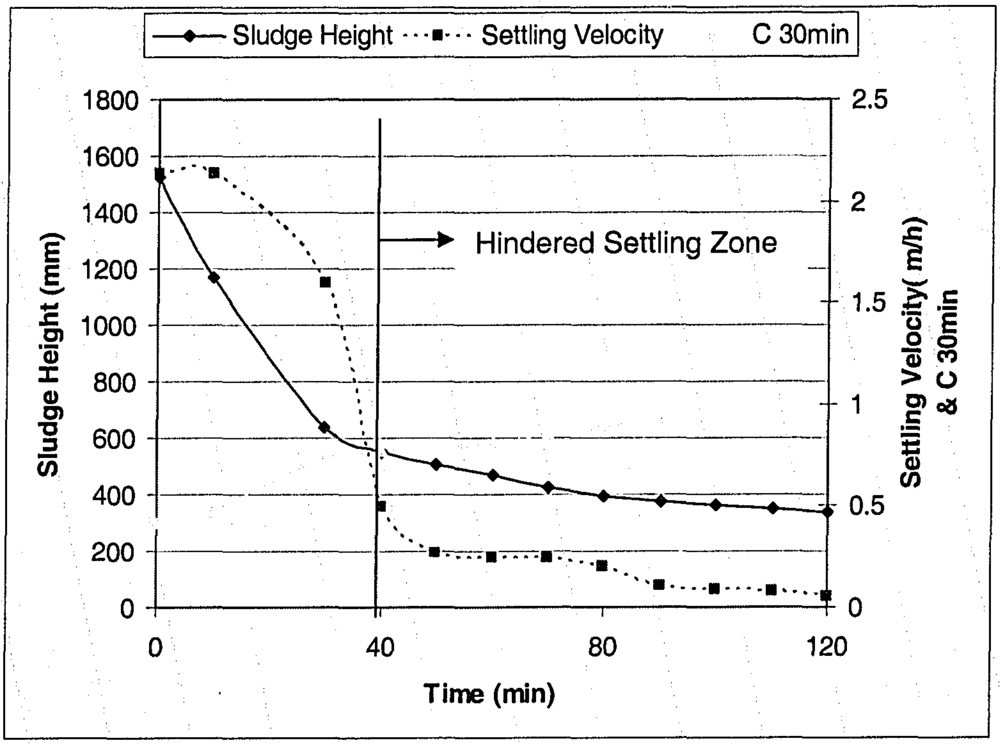

Figure 4-18 Results of Column Test

To simulate hindered settling, a modified version of the Barnea-Mizrahi equation was used (Gregory, 1979):

$$V_s = V_{\max}\left[1 - s(C - C_{\min})\right]^n$$

Where C_{min} defines the cut-off point on the hindered settling curve, below which the settling velocity of the suspension remains constant; V_{max} is the settling velocity at and below C_{min}; C is the sludge volume index (SVI), defined as the 30 minute settled volume; s is a shape factor 1; n is an exponent factor.

Plotting log(V_s) against log(1-s(C-C_{min})) for the data, and optimising C_{min} and S to give the best straight line through the points, gives the calibration constants shown in Figure 4-17. For the site studied, the values found were s=1, n=1.91, V_{max}=3m/h, and C_{min}=10%.

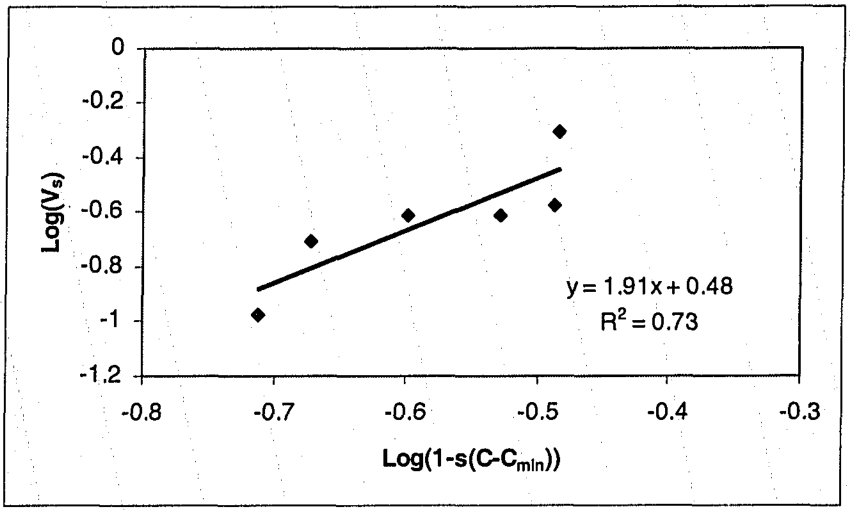

Figure 4-19 Hindered settling model calibration

Based on the above model, it was computed that the V_s settling rate was 0.4-1.1 m/h at solids concentrations between 0.5 and 0.75, which corresponded to flow rates of 0.75-1.5 L/min for the pilot plant of this project.

4.6 General results of the pilot plant

The samples obtained after pilot plant treatment were immediately brought to the laboratory located at the Environmental Engineering Building, University of Alberta, Edmonton, Canada. All tests were conducted in the laboratory following the procedures outlined in Standard Methods, and in the operating manuals for the respective instruments.

There are three chemical injector pumps (model C-1500N, BLUE-WHITE industries) in the UFFBC system. The C-1500N flow rate can be adjusted within a range of 5% -100% of maximum output (20:1 turndown ratio) by means of a mechanical, cam type mechanism. Because the pump's output is reduced by increasing the pressure of the system being injected into, the amount of suction lift, and the viscosity of the fluid being injected, all three pumps were calibrated individually before use. The calibrated results are shown in Appendix B.

The custom designed UFFBC ran successfully. An average of about 87% TSS and 90% TP (base on influent swine manure) were removed during the clarification step. The average overall mg TSS removed to mg alum applied ratio was 1.2, which was higher than the results indicated by Zhu (2003). The chemical cost of this system was $\$3.3/m^3$ RSW. The power consumption ($< \$0.1/m^3$) was negligible compared to the chemical cost.

Clarification in the customized floc blanket clarifier was the key operation in the pilot plant treatment chain. In order to improve performance here, the flow rate was optimized based on the column test (section 4.5).

Compressed air pulse was used to backwash the submerged filter. This approach worked very well and the system pressure loss returned to less than 1 PSI after every backwash.

During operation, it was observed that small chunks of scum had accumulated on the top of the UFFBC and caused an increase in head loss of the submerged filter when the media size was MIL. SPEC. #10. Thereafter, coarse glass bead (MIL. SPEC. #6) was applied to UFFBC #1 and better results were obtained. The total pressure loss was less than 69 kPa for the two-stage UFFBC at steady state. Automatic pressure relief valves were also installed to prevent high pressure damage to the submerged filters.

Another problem associated with the chemical treatment of animal manure is gas production. When alum reacts with the constituents of manure, it produces hydrogen sulphide (H_2S) and ammonia (NH_3) gases. Automatic gas vent valves (combined with vacuum breakers) were installed on the top of the UFFBC. This stragegy worked very well in all UFFBC operating conditions (floc blanket initialization, steady state operation, dumping, and backwashing). As a safety mechanism, gas monitors were always activated by the operators to check instantaneous changes in the gas levels in the unit.

4.6.1 Removal efficiency of TSS and TP

The UFFBC was designed with a focus on reducing TSS and TP to meet stipulated regulations. In the previous study in this project, it was found that alum applied at an average dose of 1600 mg/L removed approximately 70% of both TSS and TP (Zhu et al., 2004a).

The results of this experiment are shown in Figure 4-20. It was found that an average of about 87% TSS and 90% TP reductions (based on UFFBC influent) were achieved during the clarification step. The average effluent TSS and TP values were 260 mg/L and 18 mg/L, respectively. This result is better than that obtained in the previous study conducted by Zhu et al. (2004a), due to three factors: (1) polymer amendment; (2) two-stage treatment; (3) embedded submerged filter. These factors are discussed in section 4.7. It was also found that the TSS removal to alum ratio (ΔTSS/alum) fluctuated significantly, while the percentage TSS removal to alum ratio (%TSS/alum) remained fairly constant at 0.05.

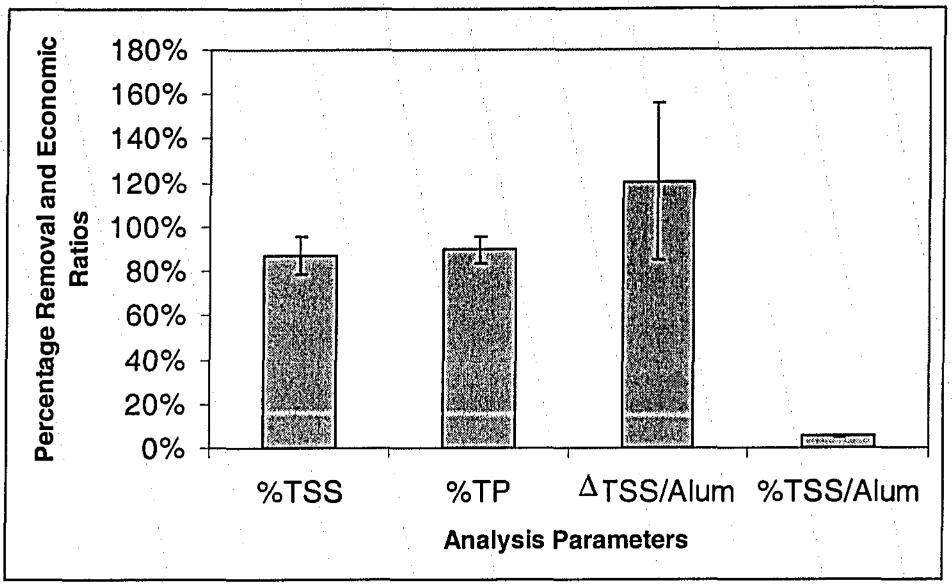

Figure 4-20 Overall %TSS and %TP removal of UFFBC with preliminary settled swine manure

4.6.2 Removal efficiency of TDS

Total dissolved solids (TDS) comprise inorganic salts, small amounts of organic matter dissolved in water, and very fine particles smaller then 1μm. Many of these may not be considered contaminants (Sawyer et al., 1994). Normally, manure separation (by physical and chemical methods) is effective in reducing TSS, but has very little effect on TDS concentration. Some researchers have concluded that chemical treatment with aluminium and iron salts may increase the inorganic salt concentration in the treated samples, and thereby lead to an increase in TDS concentration. On the other hand, coagulants can make some dissolved species, such as natural organic matter (NOM), inorganic species, such as phosphate, and hydrophobic synthetic organic compounds (SOCs), insoluble and the metal hydroxide particles produced by the addition of metal salt coagulants (such as alum) can adsorb other dissolved species (U.S. EPA, 2000b). In our experiments, the results indicated a 10% to 30% decrease in TDS concentration after treatment.

4.6.3 Removal efficiency of COD

Since the treatment was totally physical-chemical in type, it was not very effective in removing organic matter and dissolved matter. This can be achieved through biological treatment, as is well reported in the literature. The total COD removal efficiencies achieved through pilot plant treatment were approximately 40%, except one run which resulted in 67% COD removal. This result agreed with the research indicating that the levels of TSS explained 40% of BOD_5 (proportional to COD) (Zhu et al., 2001b).

4.6.4 Removal efficiency of TKN

Several studies have indicated the ineffectiveness of alum in nitrogen removal in municipal and animal wastewaters (Gilmour et al., 2004; Zhu, 2003). This is due to the fact that the major portion of nitrogen is in ammonia-N form, which cannot be effectively removed by solid/liquid separation processes. In this project, although nitrogen removal was achieved by following nutrient and organic process area (NOPA), %TKN removal was also analyzed in the UFFBC process. It was found that an overall 20% TKN reduction was achieved.

4.6.5 Removal efficiency of particles

Particle counting was performed with a laser sensor based particle counter (HIAC ROYCO 8000 by Pacific Scientific Instrument). This particle counter counts the number of particles in a known volume of sample passed through the sensor per specific run, and classifies them according to their respective size ranges. Particle counting is a very useful test and helps to determine the media size of the filter that can most effectively remove the desired size range of particles.

The untreated and treated swine manure samples obtained after UFFBC treatment were analyzed for particle size distribution and particle counts. The results are depicted in Figure 4-21 and Figure 4-22. The majority of particles (up to 90%) fall within the particle size range of ≤ 7 μm, while the treated sample contains an almost negligible percentage of large particles (up to 99% of particles fall within the range of ≤ 7 μm).

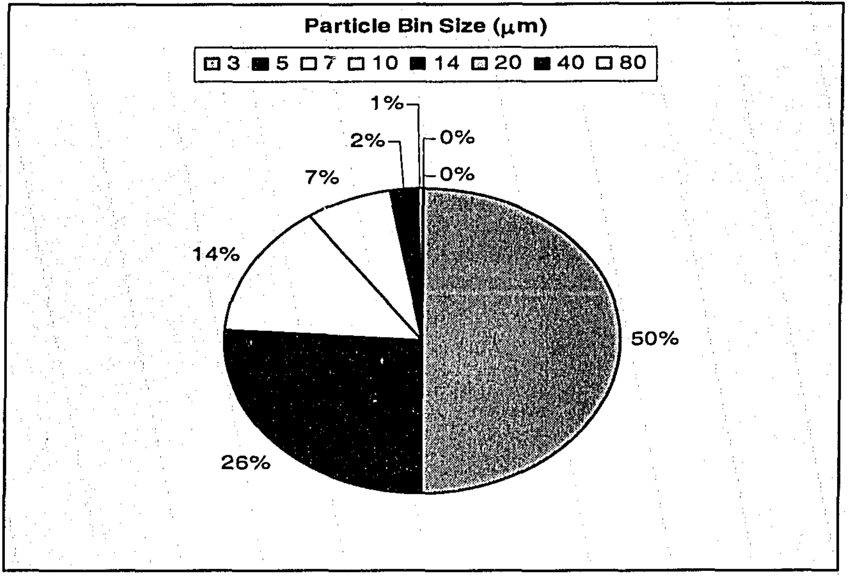

Figure 4-21 Particle size distribution of untreated swine manure

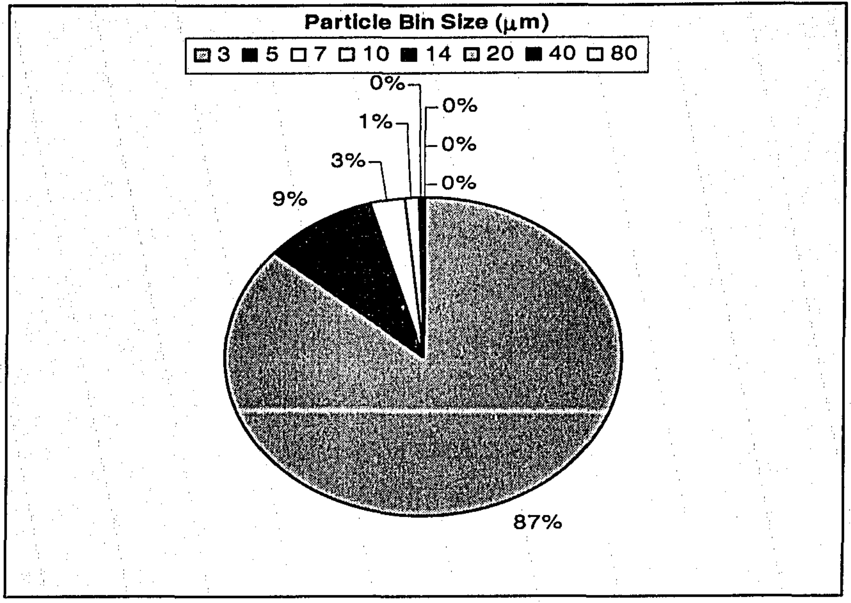

Figure 4-22 Particle size distribution of UFFBC treated swine manure

Particle removal efficiency is plotted in Figure 4-23. It indicates that particles larger than 3 μm were removed at over 99% efficiency (2 log removal) and had very small variance. Meanwhile, particles small than 3 μm were also reduced at an average of 96%, but variation was much higher here than for the larger particles, indicating that this portion of particles was mainly affected by the factors of different pilot runs.

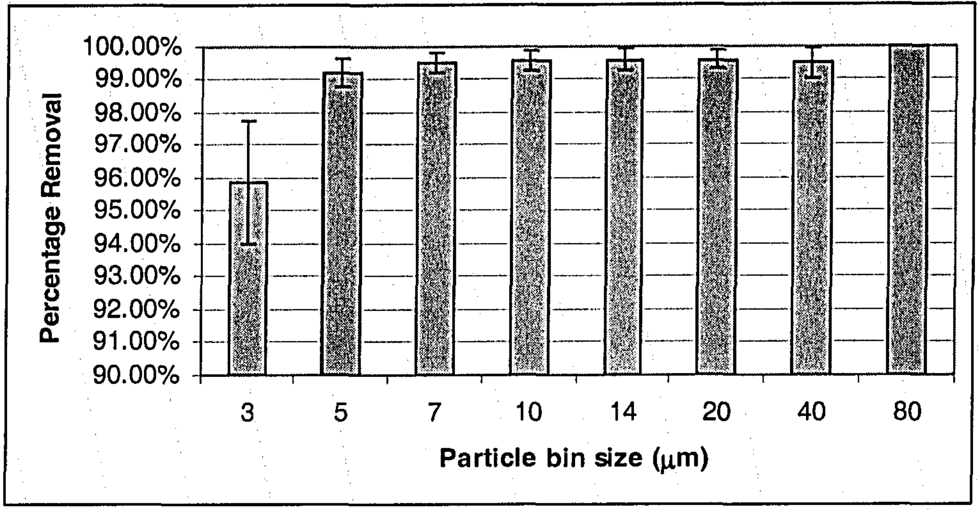

Figure 4-23 Particle remove efficiency of UFFBC

4.6.6 Sludge Analysis

Sludge was dried and analyzed by SEM. The results are shown in Figure 4-24. It was found that there was no significant difference between the two UFFBC stages . The flocs were composted by numerous very fine rod shaped particles, which are shown in Figure 4-25. It is clearly displayed that the diameter and length of these particles are 0.5 μm and 1 μm, respectively. This confirmed the results obtained through particle counting analysis.

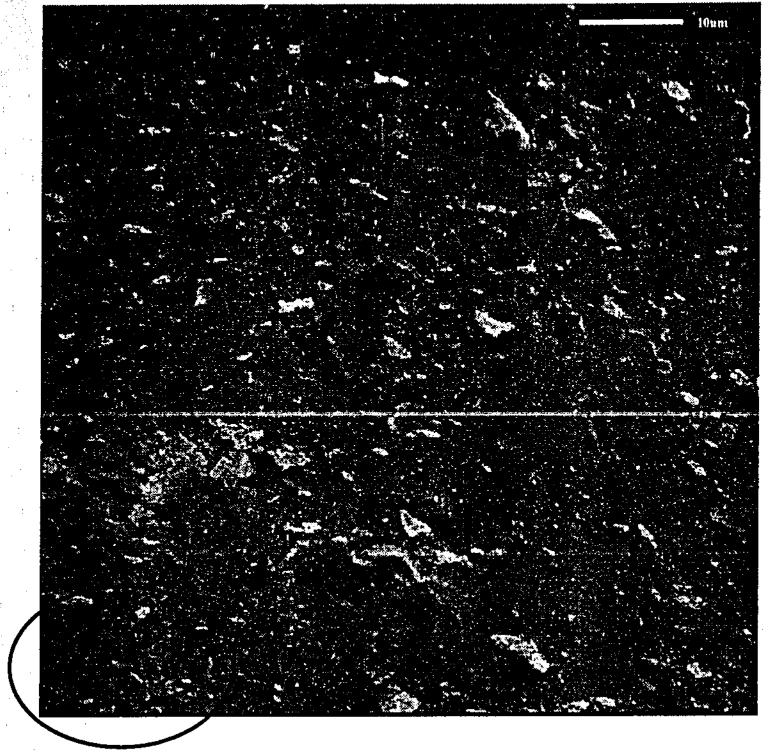

Figure 4-24 SEM picture (A) of UFFBC sludge

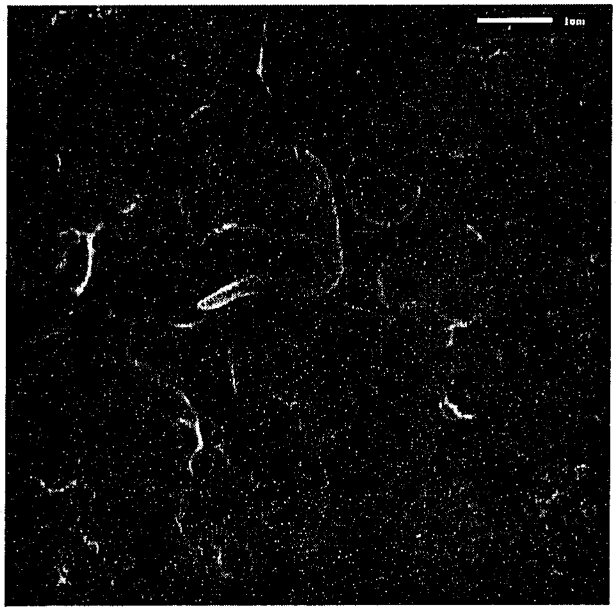

Figure 4-25 SEM picture (B) of UFFBC sludge

The elements composting the sludge were also analyzed by X-ray analysis in the SEM, Figure 4-26. It was found that the main portion of the sludge was composed of aluminium, phosphorus, potassium, and calcium. These results agree with the chemicals used in, and the results achieved through, PC analysis.

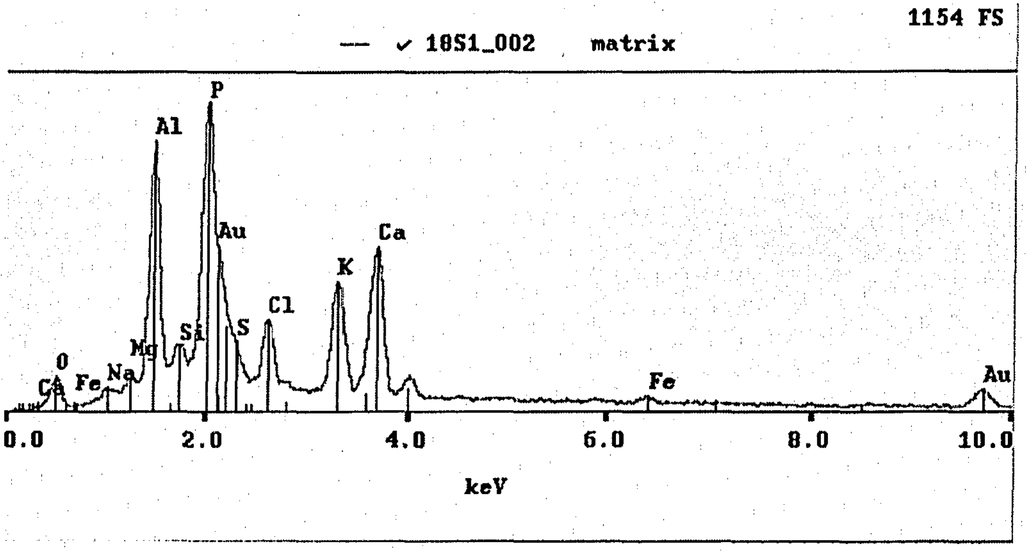

Figure 4-26 Element analysis by SEM (X-ray)

4.7 Factors affecting treatment

The UFFBC effluent quality could be affected by several factors, such as dilution of swine manure, stages of UFFBC, polymer amendment, TDS of influent, and pH of effluent. The effects of those factors are evaluated in this section.

4.7.1 Dilution of swine manure

To confirm the dilution effect on swine manure treatment, two pilot runs were conducted on ½ diluted swine manure with influent TSS less than 2000 mg/L. The results are shown in Figure 4-27 and Figure 4-28. There was no significant difference for %TSS and particle removal. However, dilution led to high %TP removal and low ΔTSS to alum ratio. This could be explained by the dilution itself. Since the chemical dose was the same for both the diluted and undiluted runs, the diluted runs had a relatively higher alum to TSS ratio.

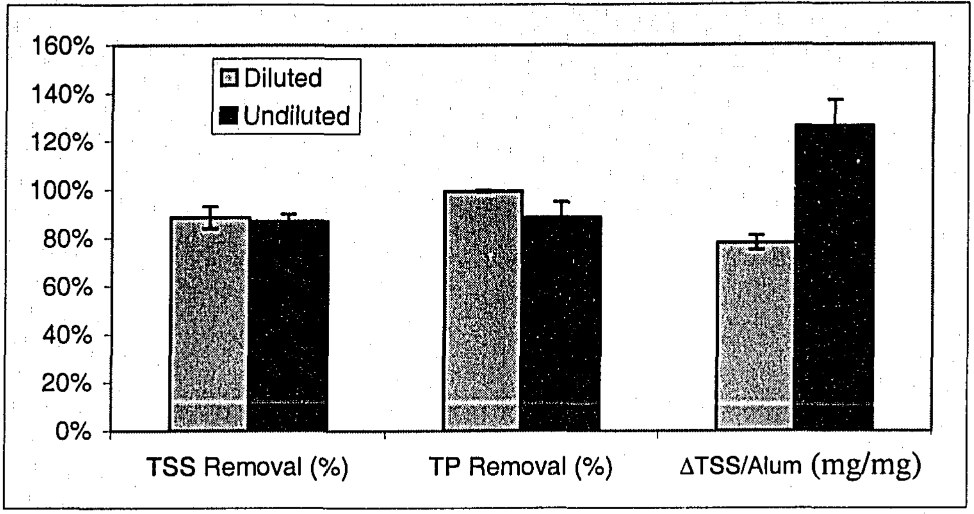

Figure 4-27 TSS and TP analysis of dilution effect

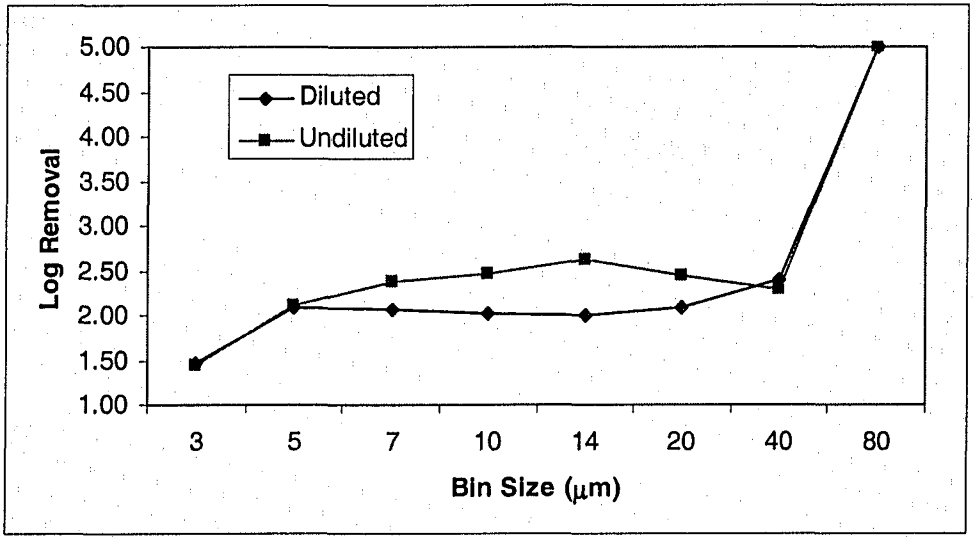

Figure 4-28 Particle counting analysis of dilution effect

4.7.2 Submerged filter

One significant difference between this pilot plant and those employed in previous studies was that the customer designed UFFBC had a submerged filter inside to enhance the treatment. The results are shown in Table 4-5 and Figure 4-29. There was no significant difference in %TSS removal before and after submerged filter #1 at a 95% confidence level but existing significant difference at the 80% confidence level. However, the submerged filter had a significant effect on %TSS removal in UFFBC #2 and %TP removal in UFFBC #1 and UFFBC #2 at a 95% confidence interval. Because submerged filter #1 had a larger media size (MIL. SPEC. # 6) than submerged filter #2 (MIL. SPEC. #10), the former resulted in a relatively bigger P-value.

Table 4-5 Statistic analysis of submerged filter on TSS and TP removal efficiency

	Submerged Filter #1				Submerged Filter #2			
	Runs	Before	After	P-value	Runs	Before	After	P-value
TSS	8	64%	67%	0.17	6	84%	90%	0.02
TP	8	49%	52%	0.01	6	89%	92%	0.00

* P-value was computed by ANOVA analysis.

Particle counting results (Figure 4-29) indicated the same trends in submerged filter effects.

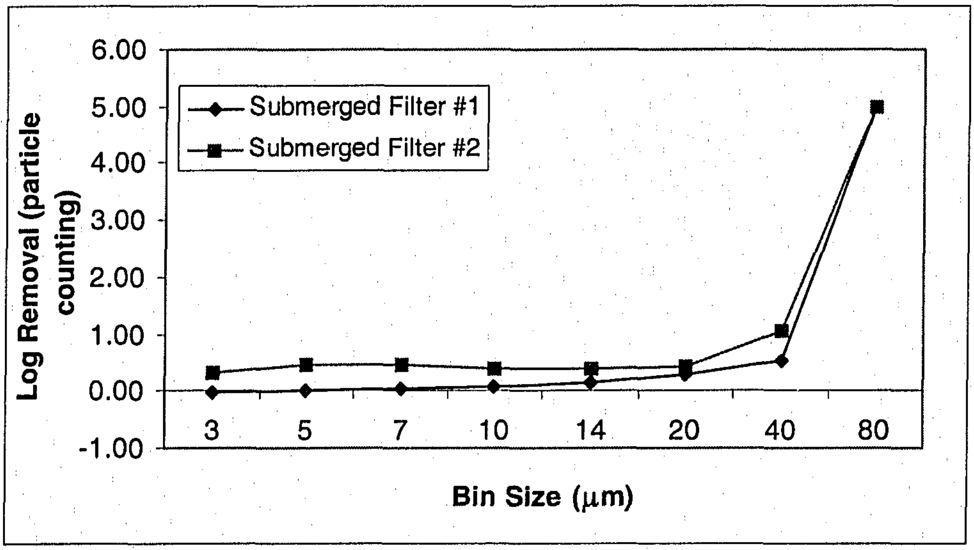

Figure 4-29 log removal of particles by submerged filter

4.7.3 Two stage process

To confirm the effect of TSS on swine manure treatment, one-stage and two-stage pilot runs were conducted. The results are shown in Figure 4-30 and Figure

4-31. There was no significant difference in %TSS, %TP, and particle removal at 95% and 80% confidence levels. Two-stage treatment had a higher ΔTSS to alum ratio with large variation. According to the statistical analysis, there was no difference between the one-stage and two-stage treatments in terms of the ΔTSS to alum ratio at 95% and 80% confidence levels.

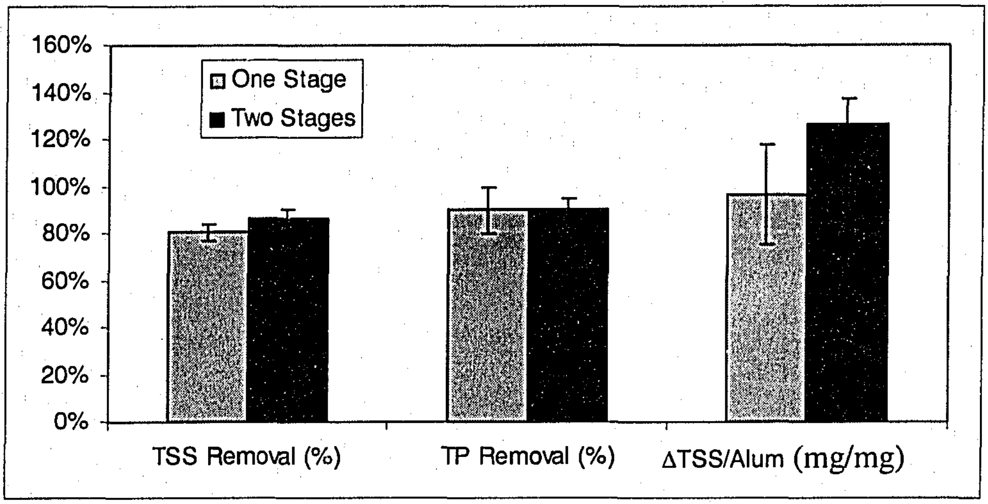

Figure 4-30 %TSS and %TP analysis of stage effect

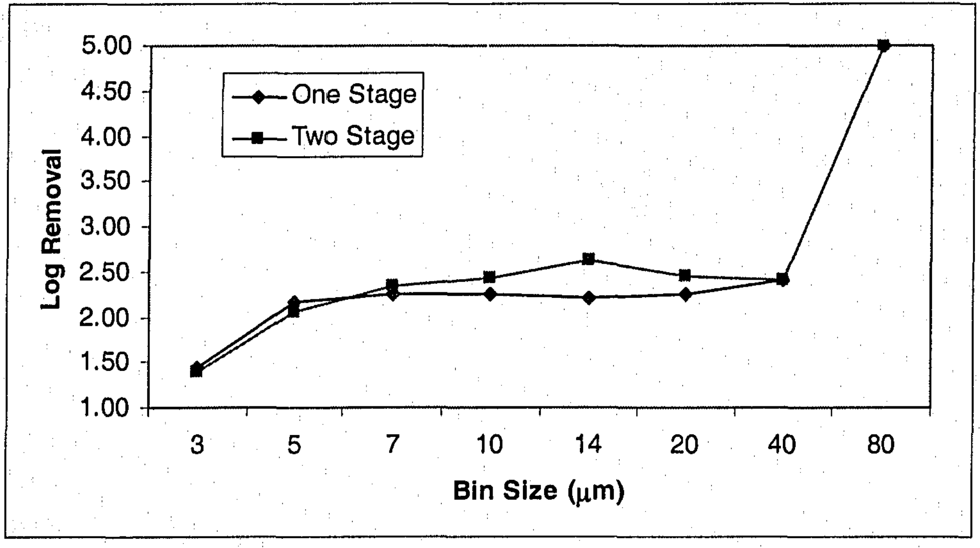

Figure 4-31 Particle counting analysis of stage effect

4.7.4 Polymer amendment

To confirm the effect of the polymer on swine manure treatment, the UFFBC was operated under both conditions (with and without polymer addition). The results are shown in Figure 4-32 and Figure 4-33. There was no significant difference in %TP removal. However, the polymer amendment treatment gave a higher %TSS, ΔTSS to alum ratio, and particle removal efficiency at an 80% confidence level.

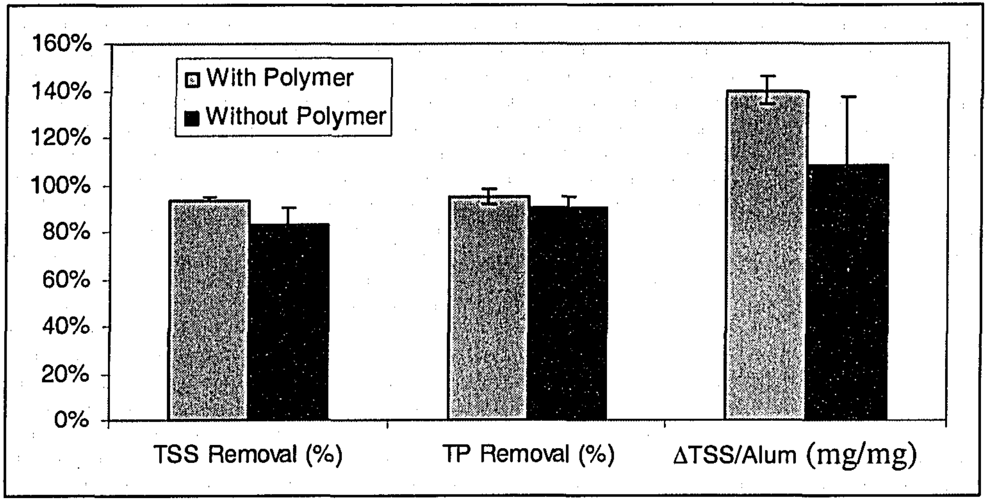

Figure 4-32 %TSS and %TP analysis of polymer effects

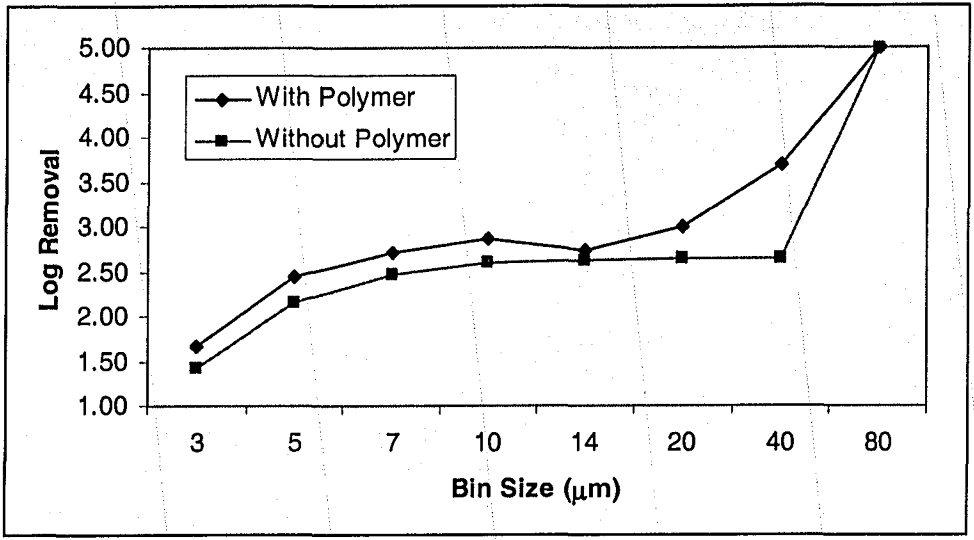

Figure 4-33 Particle counting analysis of polymer effects

4.7.5 TSS of influent

Much research has indicated that the influent TSS might have significant effects on the chemical/physical treatment process. The effect of TSS was also investigated in this research and it was found that the ΔTSS/alum ratio was strongly correlated to influent TSS. The results are shown in Figure 4-34.

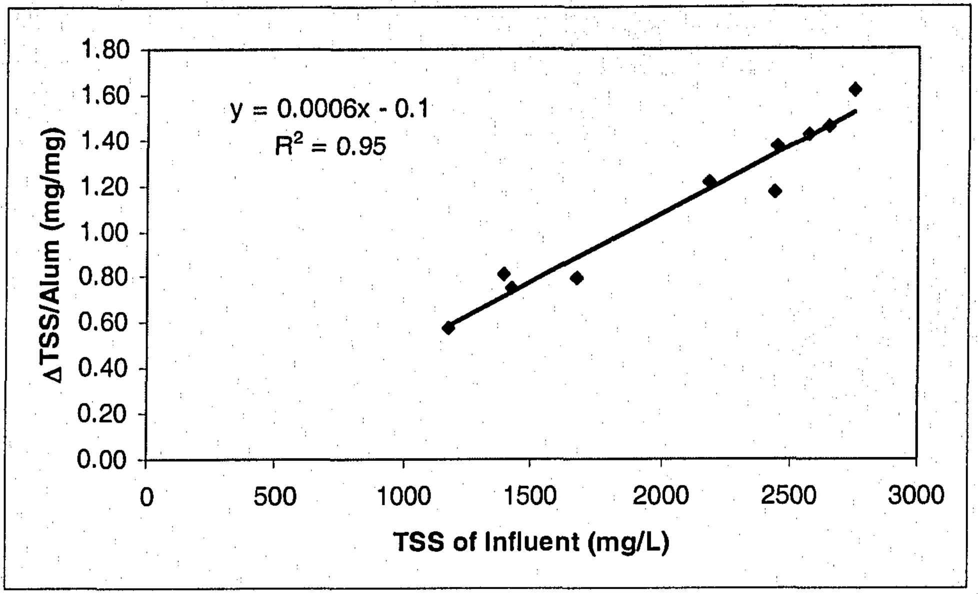

Figure 4-34 Correlation between influent TSS and ΔTSS/alum ratio

4.7.6 TDS of influent

The influent TDS might affect the chemical/physical treatment process, since various TDS components have different effects on the coagulation/flocculation process. Fettig and Ratnaweera (1993) indicated that some TDS compounds, such as humus, significantly inhibited particle destabilization and impaired the aggregation of microflocs. The solubility of Al(III)-phosphate also depends on the effluent pH, which is related to influent alkalinity (Metcalf & Eddy, 2003). The effect of TDS was also investigated in this research and it was found that the influent TSS is related to the %TDS removal and the absolute TP value of the effluent. The results are shown in Figure 4-35 and Figure 4-36. Further research is necessary to convert those patterns to a mathematical model.

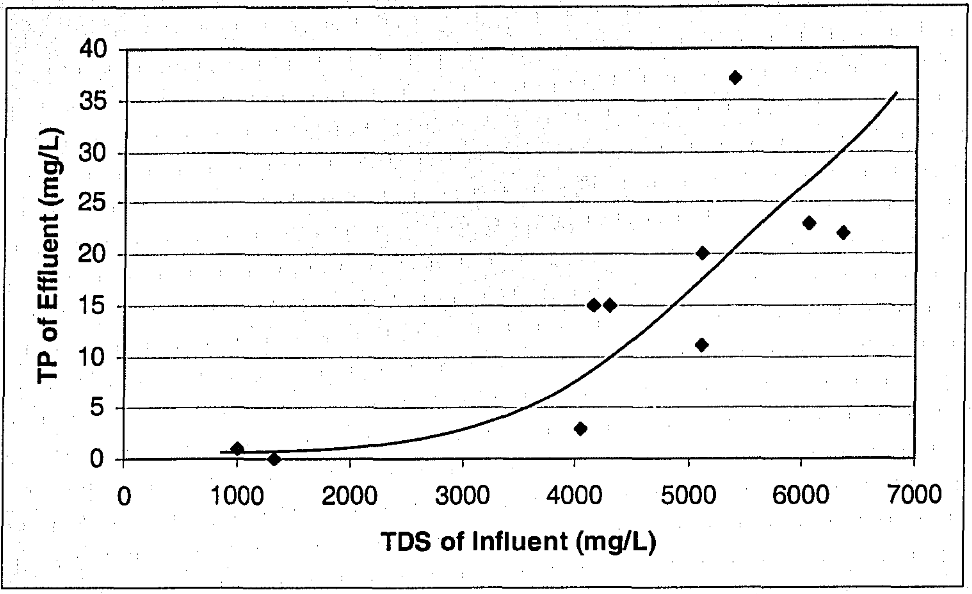

Figure 4-35 Relationship between influent TDS and effluent TP

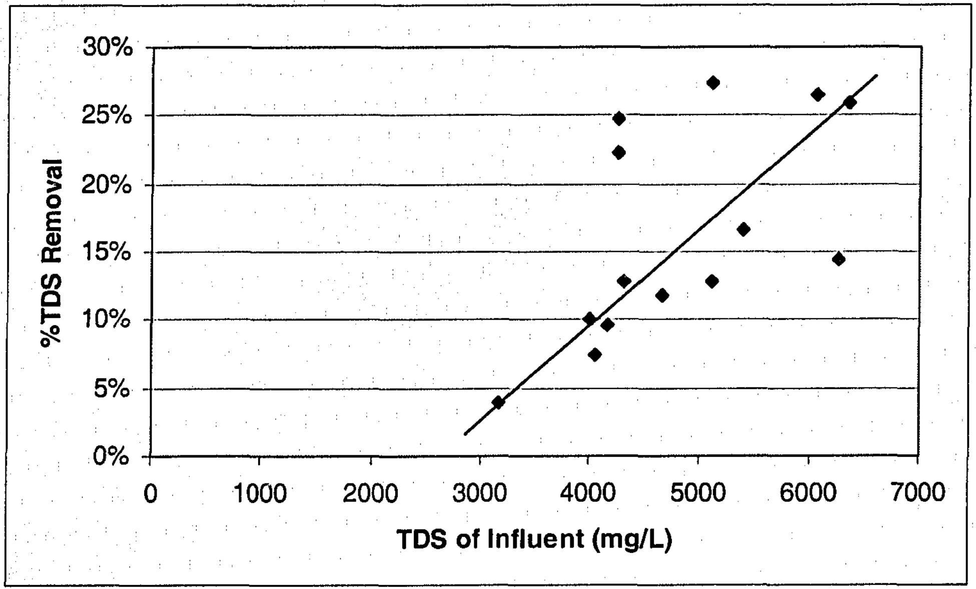

Figure 4-36 Relationship between influent TDS and %TDS removal

4.7.7 pH of effluent

The total concentration of soluble phosphate in equilibrium with insoluble $AlPO_4$ is a function of pH (Metcalf & Eddy, 2003). The lowest soluble point occurs at pH 6. The results of this experiment are shown in Figure 4-37 and confirm this relationship.

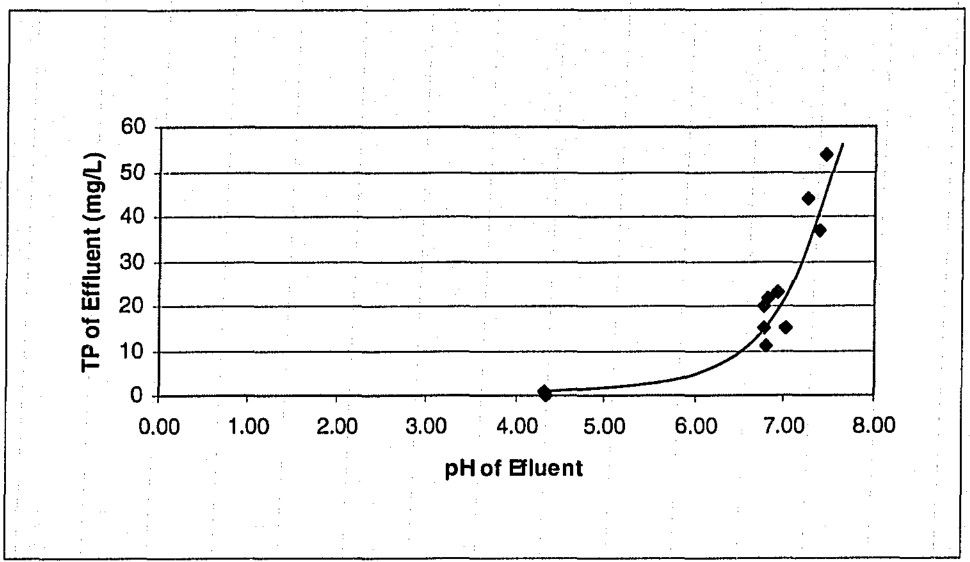

Figure 4-37 pH effects on effluent TP

4.8 Filter treatment

A total of two filter columns were used in this project. Both filters used the same glass bead media size, that is Mil. SPEC. #13. Two filter run scenarios were conducted: with and without chemical addition before filtration.

Scenario I involves the running of a set of two filters without the addition of any chemical before filtration. Filters were run at a flat flow rate of 8 L/s at 30 minute intervals. At the start of filtration, the pressure head increased rapidly to a working pressure, then it remained constant for the remainder of the runs. The filters ran smoothly without any clogging problems. Typical filter performance curves are shown in Figure 4-38. These curves represent the variations in the pressure head during the filtration process.

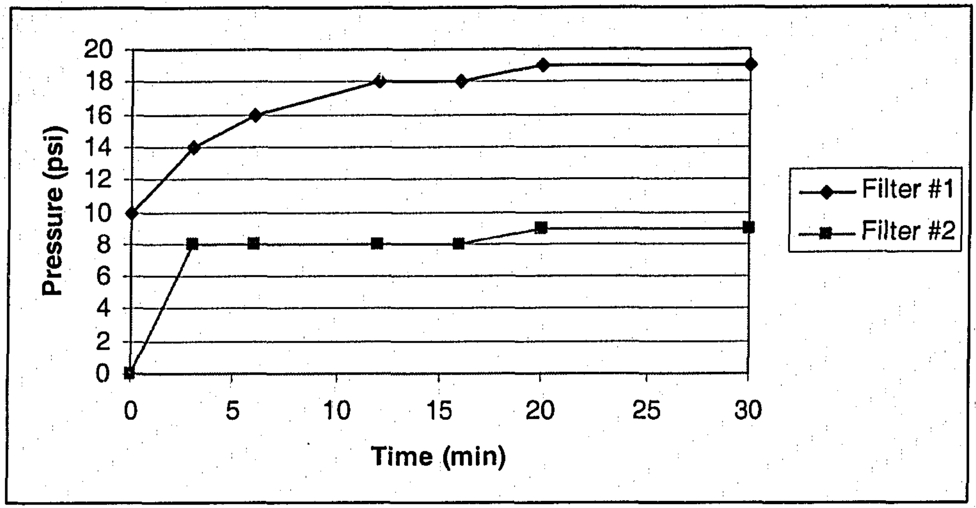

Figure 4-38 Pressure curve of filter run (Scenario I)

It was also found that filtration could further remove 44% of TSS and 18% of TDS from the UFFBC treated swine manure (Figure 4-42). The particle counting analysis is shown in Figure 4-39, which indicates that the filter with Mil. SPEC. #13 media had a very good removal efficiency for particles within the size ranges of 3 μm to 10 μm, and larger than 40 μm. The removal efficiency for particles ranging in size from 10 μm to 20 μm had comparably high variance. The reason for this is unclear and should be investigated further.

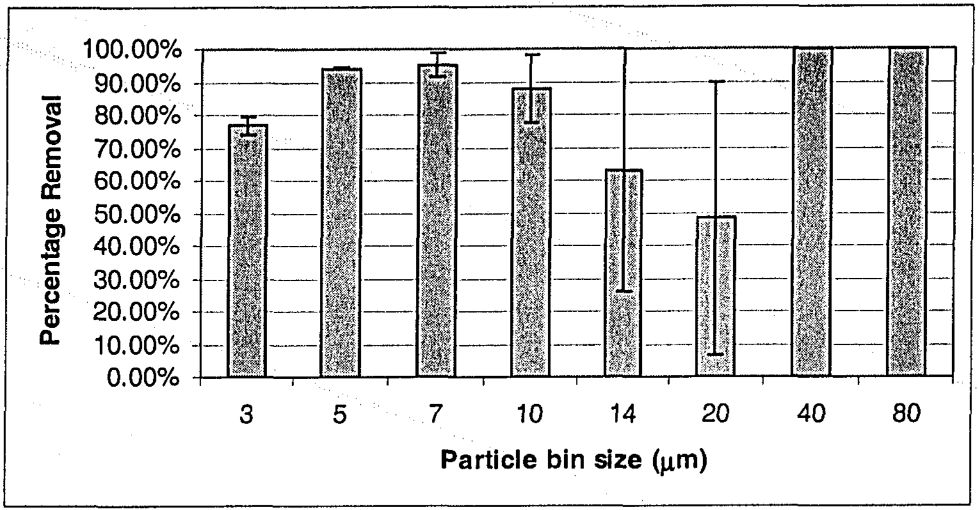

Figure 4-39 Particle counting analysis of filter run (scenario I)

Since there were still high concentrations of particles < 3 μm, more scenarios were conducted to analyze the effect of chemical addition before filtration in the removal of fine particles. Scenario II (A) involves the running of a set of two filters with 100mg/L alum. Scenario II (B) involves the running of a set of two filters with 20mg/L polymer. Those two conditions gave very similar results. The operation performance is shown in Figure 4-40. The figure indicates that the pressure loss in the first filter kept rising during the whole operation, due to coagulant addition.

The particle counting analysis is shown in Figure 4-41, which indicates that the filter with Mil. Spec. 11 media had a steady removal efficiency for particles larger than 5 μm.

The results also indicate that 44% of TSS and 16% of TDS were removed in this case (Figure 4-42). By statistical analysis, there is no significant difference between the results obtained from scenario I and scenario II at an 80% confidence interval. Therefore, there is no significant advantage to adding coagulant before filtration.

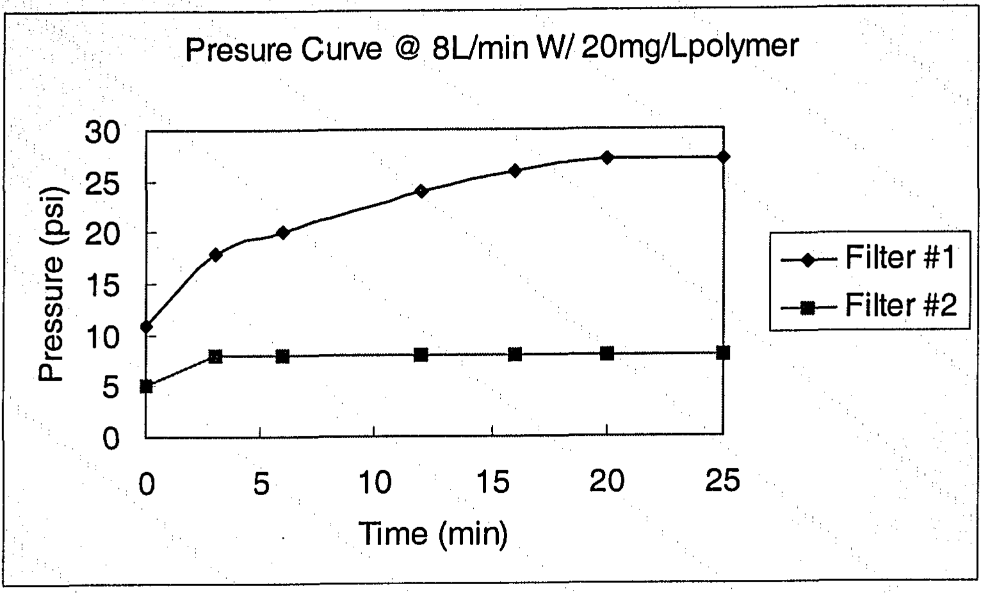

Figure 4-40 Pressure curve of filter running (scenario II)

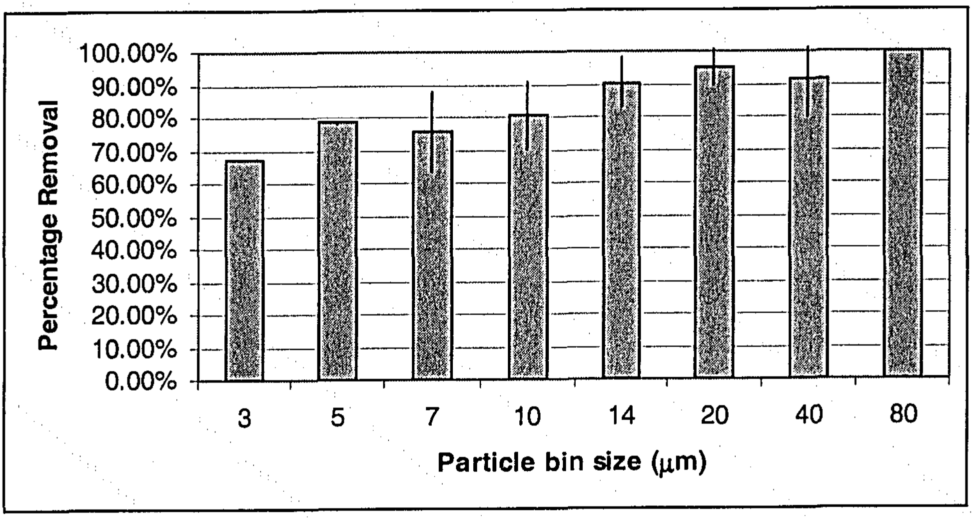

Figure 4-41 Particle counting analysis of filter run (scenario II)

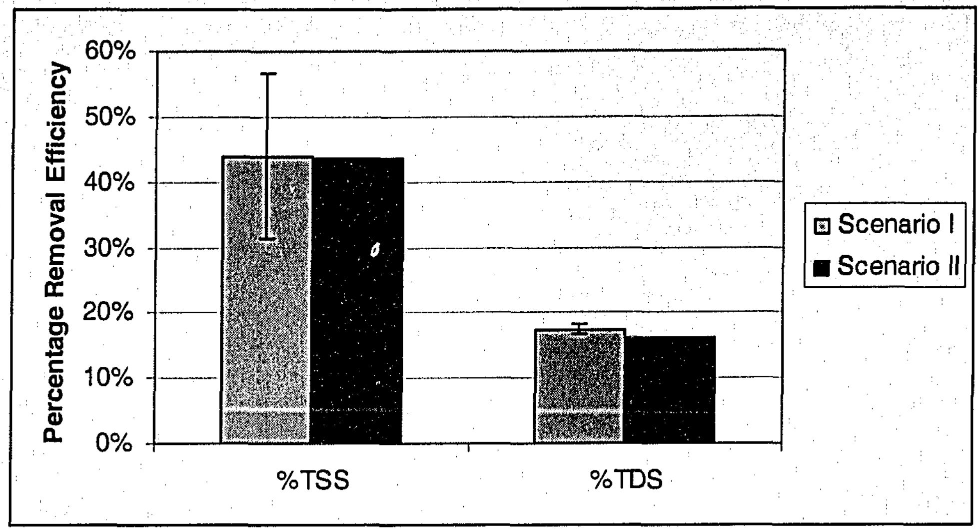

Figure 4-42 TSS and TDS removal efficiency of filters

5 CONCLUSIONS AND RECOMMENDATIONS

In this project, physical/chemical treatment was investigated to treat liquid swine manure supplied by the Swine Research and Technology Center located at the University of Alberta, Edmonton Research Station. A series of laboratory test experiments and customer designed pilot plant operations were carried out and the results obtained from both settings were analyzed and evaluated. Conclusions and recommendations from previous studies in this project were used in setting up the experiment conducted in this research. The following conclusions are drawn from this study:

- Swine manure characteristics vary significantly from sample to sample. Even though the raw swine manure came from the same source, the mean values obtained in this research were different from those obtained in the previous studies in this project.

- The inner relationships between COD and BOD5, TS/TDS and TP, and TDS and EC were confirmed by this research. COD, TS, and EC can be used as a simplified approach to characterizing swine manure.

- Preliminary settling was found to be very effective for swine manure. A period of natural settling longer than ten hours is recommended prior to any further treatment.

- The customer designed UFFBC performed very well. The clarifier foaming and filter clogging problems encountered in the previous studies of this project were solved successfully in this research.

- UFFBC is very effective in removing TSS and TP, with average removal efficiencies of 87% and 90%, respectively. The newly designed UFFBC (with submerged filter inside) performs better than the pilot scale equipment used in the previous studies of this project.

- PMF can further reduce TSS in UFFBC treated swine manure with an efficiency of 44%.
- The overall removal efficiencies for this system are 93% and 90% for %TSS and %TP removal, respectively.
- Physical/chemical treatment has limited performance in reducing TDS, TKN, and COD, with average removal efficiencies of 17%, 22%, and 38%, respectively.
- Two cationic polymers were found to enhance the coagulation/flocculation process in swine manure treatment. However, chemical addition before filtration provides no significant advantage during the filtration process.
- Submerged filters had a significant effect on UFFBC performance based on %TSS, %TP, and particle removal.
- Two-stage UFFBC treatment was compared with one-stage UFFBC treatment and no significant difference was found.
- Influent quality (such as TDS, TSS, and alkalinity) was found to have significant effects on effluent quality. However, the UFFBC system performed robustly and the minimum %TSS and %TP removals achieved were 76% and 80%, respectively.
- Particle counting analysis was applied in this research. It indicated that 99% of particles larger than 3 μm were removed (2 log removal) with very small variance. Meanwhile, particles smaller than 3 μm,

which constitute the largest portion in the swine manure, were reduced by an average of 96%; however, the variation here was much higher than with the larger particles.

- SEM analysis was applied in this research. It was confirmed that swine manure contains a very large portion of fine rod type particles which are less than 1μm (match the size and shape of the coliform). This implied a significant reduction in the number of microorganisms with this treatment. It was also confirmed that the major components of sludge are aluminium and phosphorus.

The following recommendations need to be considered for further investigation:

- Physical/chemical treatment showed its limitations in COD, TKN, and TDS removal. Further research should be considered for biological treatment of the effluent of this research.
- The head loss of the second filter of this pilot plant is very low (less than 69 kPa) during operation. Smaller media size should be applied to achieve higher suspended solids reduction during the filtration process.
- Since two-stage UFFBC treatment shows no significant improvement over one-stage UFFBC, the one-stage system should be considered as the recommenced approach in order to save capital cost.
- Further research should be conducted to investigate the mechanism of TDS effects on the coagulation/flocculation process in swine manure treatment.
- Further research is needed on the composting of UFFBC sludge.

- The removal efficiency of very fine particles varies from one run to another, and should be further investigated.

- Preliminary settling should be further investigated in winter conditions.

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APPENDIX - A

Alum Concentration Calibration

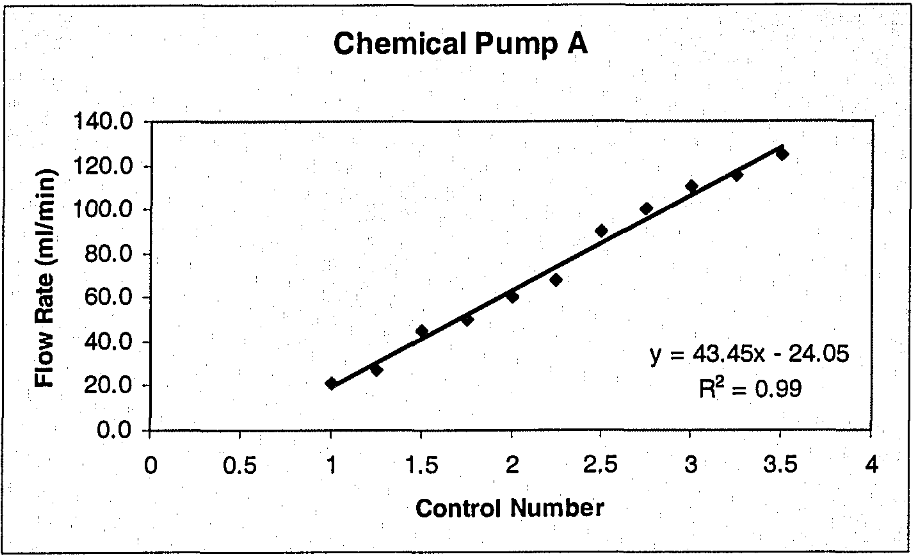
Dated: Aug 21, 2004

Sample ID	Aluminum (mg/L)	Dilution	Aluminum g/100ml	Alum (%)
Blank	0	1	0	0
A	4835	0.1	4.84	30.7
B	489	0.01	4.89	31.0
C	242	0.005	4.84	30.7
Average				30.8
Standard Deviation				0.17

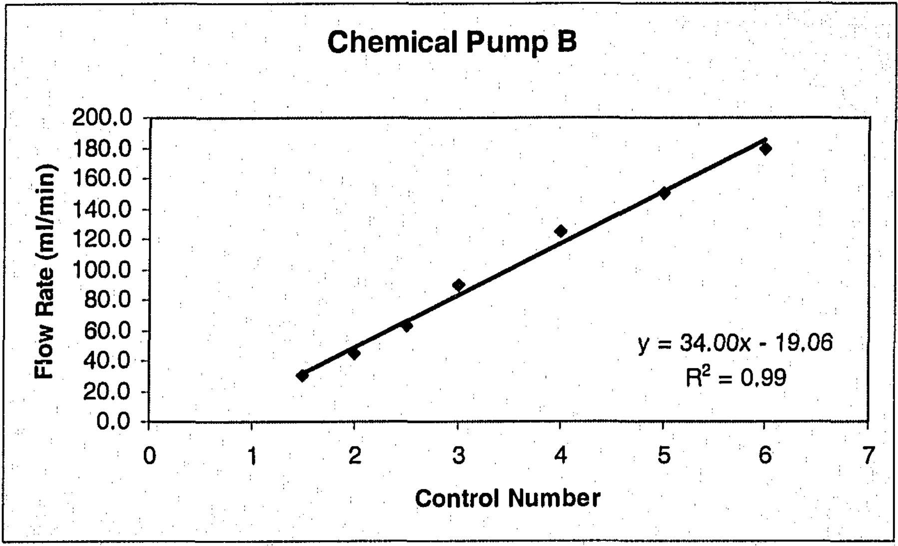
APPENDIX - B

Chemical Pump Calibration

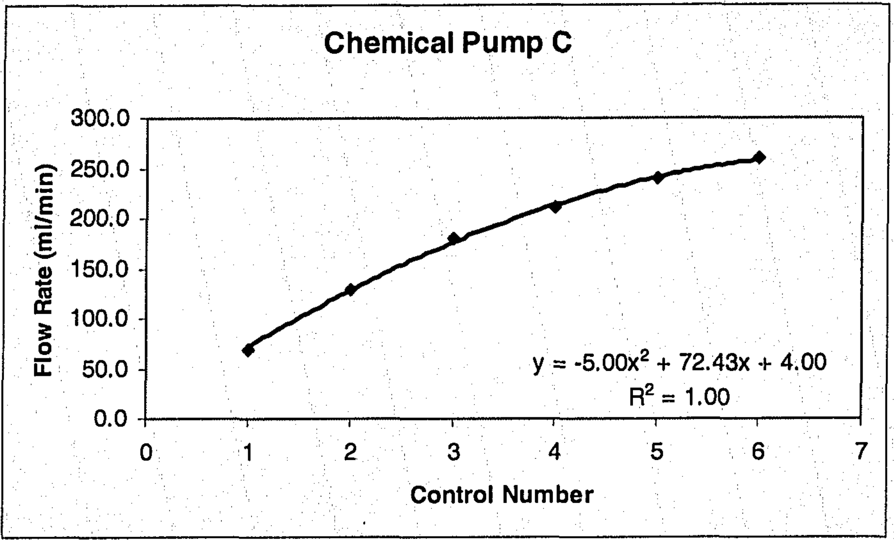
Dated: Aug 17, 2004
Pump ID: A



Dated: Aug 17, 2004
Pump ID: B



Dated: Aug 17, 2004
Pump ID: C



APPENDIX - C

Media Size Conversion Table

U. S. STANDARD SCREEN SIZE	MIL. SPEC. (G-9954A)	MIL. SPEC. (S-13165B)	SAE (J-1173)	BEAD SIZE RANGE (DIA., INCHES)
Dec-14	No. 1			.0661-.0555
14-20	No. 2			.0555-.0331
20-30	No. 3	331	GB-70	.0331-.0234
20-80				.0331-.0070
25-35		280		.0283-.0197
25-45				.0283-.0171
30-40	No. 4	232	GB-50	.0234-.0165
35-45		197		.0197-.0171
35-60				.0197-.0098
40-50	No. 5	165	GB-35	.0165-.0117
40-60				.0165-.0098
40-70				.0165-.0083
45-60		138		.0171-.0098
50-70	No. 6	117	GB-25	.0117-.0083
50-80				.0117-.0070
60-80	No. 7	98	GB-20	.0098-.0070
60-100				.0098-.0059
60-120				.0098-.0049
70-100	No. 8	83	GB-18	.0083-.0059
70-140				.0083-.0041
80-120	No. 9	70	GB-15	.0070-.0049
100-140				.0059-.0041
100-170	No. 10			.0059-.0035
100-200				.0059-.0029
120-170				.0049-.0035
120-200	No. 11			.0049-.0029
140-200				.0041-.0029
140-230	No. 12			.0041-.0025
140-270				.0041-.0021
170-230				.0035-.0025
170-325	No. 13			.0035-.0017
170 and Finer				.0035 and Finer
200-270				.0029-.0021
200-325				.0029-.0017
230-325		24		.0025-.0017
270-400				.0021-.0015
270 and Finer				.0021 and Finer
325 and Finer				.0017 and Finer
400 and Finer				.0015 and Finer

APPENDIX - D

Column Test

Dated: Aug 25, 2004

Time (min)	Sludge Height (mm)	dH (mm)	ΣdH (mm)	dt (min)	dH/dt (mm/min)	Vs (m/h)	C
0	1524	0	0	0	35.56	2.13	0.42
10	1168	356	356	10	35.56	2.13	0.47
30	635	533	889	20	26.67	1.60	0.74
40	552	83	972	10	8.26	0.50	0.77
50	508	44	1016	10	4.45	0.27	0.78
60	467	41	1057	10	4.06	0.24	0.80
70	427	41	1097	10	4.06	0.24	0.85
80	394	33	1130	10	3.30	0.20	0.89
90	376	18	1148	10	1.78	0.11	0.91
100	362	14	1162	10	1.40	0.09	
110	349	13	1175	10	1.27	0.08	
120	340	9	1184	10	0.89	0.05	

Vs (m/h) = dH/dt (mm/min) x 60 (min/h) / 1000 (1000mm/m)

C = H (initial) / H (after 30 min)

APPENDIX - E

Jar test operation schedule

Jar test ID	Date	Objective
A	Jul 16, 2004	Polymer selection of group #1
B	Jul 27, 2004	Polymer selection of group #2
C	Aug 24, 2004	Alum/Polymer dose optimization
D	Oct 14, 2004	Alum/Polymer dose optimization

Jar test C - factorial design with central point

Run #	Alum Dose (mg/L)	Polymer Dose (mg/L)	Coded Units		
			Alum	Polymer	Interaction
5	350	10	-1	-1	1
4	350	20	-1	0	0
10	350	40	-1	1	-1
1	550	10	0	-1	0
9	550	20	0	0	0
2	550	40	0	1	1
3	750	10	1	-1	-1
6	750	20	1	0	0
12	750	40	1	1	1

APPENDIX - F

UFFBC operation schedule

Pilot Run ID	Date	Chemical dose
1	Sep 21, 2004	Stage 1: 1600 mg-alum/L Stage 2: None
2	Sep 28, 2004	Stage 1: 1600 mg-alum/L Stage 2: None
3	Oct 1, 2004	Stage 1: 550 mg-alum/L + 10 mg-polymer/L Stage 2: 1050 mg-alum/L
4	Oct 12, 2004	Stage 1: 750 mg-alum/L Stage 2: 850 mg-alum/L
5	Oct 19, 2004	Stage 1: 550 mg-alum/L Stage 2: 1050 mg-alum/L
6	Nov 4, 2004	Stage 1: 1600 mg-alum/L Stage 2: None
7	Nov 25, 2004	Stage 1: 550 mg-alum/L Stage 2: 1050 mg-alum/L
8	Dec 1, 2004	Stage 1: 550 mg-alum/L + 10 mg-polymer/L Stage 2: 1050 mg-alum/L
9	Dec 9, 2004	Stage 1: 1050 mg-alum/L Stage 2: 550 mg-alum/L
10	Dec 13, 2004	Stage 1: 550 mg-alum/L + 10 mg-polymer/L Stage 2: 1050 mg-alum/L

APPENDIX - G

Filter operation schedule

Pilot Run ID	Date	Scenario
1	Dec 15, 2004	I, without chemical addition
2	Dec 17, 2004	I, without chemical addition
3	Dec 18, 2004	II A, 100mg-alum/L
4	Dec 20, 2004	II B, 20mg-polymer/L