University of Alberta

Swine Manure Treatment

By

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This manuscript is dedicated to my family, teachers and friends who have always encouraged and supported me in my academic and life pursuits.

"Contemplate and reflect upon knowledge, and you will become a benefactor to others"
(Shri Guru Granth Sahib, Page 356)

ABSTRACT

Swine liquid manure, supplied by the Swine Research & Technology Center of the University of Alberta, Edmonton, Canada, was treated by physical/chemical methods. The treatment chain involved coagulation, flocculation and settling in a sludge blanket clarifier, and lastly, the filtration through patented Martin filters. Alum was used as a coagulant. The effectiveness of the treatment was determined by the reduction in total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total phosphorus (TP) and total Kjeldahl nitrogen (TKN) etc. In the laboratory, jar tests were performed for the coagulation/flocculation and settlement, and the filtration through polycarbonate membrane filters. The treatment was effective in removing the TSS and TP. In the laboratory, a low-pressure collimated beam of Ultraviolet (UV) irradiations was tested as a microbial inactivator using the laboratory-treated samples of swine manure. Total coliform (TC) and fecal coliform (FC) indicators were used for microbial analysis.

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ACRONYMS

BOD_5	5-day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CFU	Colony Forming Units
Counts/mL	Number of particles measured by Particle Counter per milliliter of sample
FC	Fecal Coliforms
gpm	Gallons per minute
kPa	Kilopascal
mg/L	Milligram per liter
mL	Milliliter
mm	Millimeter
µm	Micrometer (10^{-6})
mJ/cm^2	Millijoule per square centimeter
$mW\text{-}s/cm^2$	Milliwatt second per square centimeter
min	Minute
m^3/s	Cubic meter per second
N	Nitrogen
nm	Nanometer (10^{-9})
P	Phosphorus
psi	Pound per square inch
s	Second
TP	Total Phosphorus
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
TC	Total Coliforms
WWTP	Waste Water Treatment Plant

1.0 INTRODUCTION

1.1 Problem statement

The swine industry is an increasingly important agricultural sector. Rapid industrial expansion and human population growth has been accompanied by a shift from family farming to industrial scale animal production in confined facilities. This unprecedented growth in confined animal production has substantially benefited the farming community of every nation. Land application of liquid manure originating from animal production units has been used as a BMP (Best Management Practice) for reclaiming its fertilizer value. This technique has only focused on nutrient management. Problems associated with swine manure stem from odours caused by gases produced by decomposing manure in swine production facilities and their manure disposal systems, from nutrients entering water bodies through seepage into ground water, and from runoff due to precipitation and leakage from manure storage facilities. Some research studies have found that excessive rates of nutrient application on land, failure to check sudden leakages from manure storage facilities and runoff from feedlots may create environmental problems such as ground water/ surface water contamination and human health concerns due to the presence of different kinds of zoonotic microorganisms in animal manures.

Research concluded in the past and at present is focused on determining the best possible ways to utilize/reuse the manure in such a way that causes minimum environmental side effects. Manure treatment is one such option and is aimed at finding out an eco-friendly technology that can effectively help in managing the nutrients. There are several benefits of treating the manure before its utilization, such as, separation of

liquid and solid fractions, utilization of larger quantities of treated manure on limited areas, and reuse possibilities of treated effluents in animal barns etc.

Physical/chemical methods have been shown to be potentially effective in removing solids and nutrients from animal manure. This project involves a physical/chemical approach for treating swine liquid manure. The pilot plant is located at the University of Alberta Research Station in Edmonton, Alberta, Canada. The manure was supplied by a 1,500 head (including 300 fully grown sows) of swine at the Swine Research & Technology Center located at the University Research Station. The treatment chain included the primary settlement of fresh swine manure for 24 hours, clarification (coagulation, flocculation and settlement) in a customized sludge blanket clarifier, and then filtration of the clarified supernatant through glass bead media filters (patented Martin filters). Different doses of low-pressure collimated beam of UV irradiation were analyzed for their ability to inactivate microbial populations in the treated manure samples. The treatment chain at the pilot plant was simulated in the laboratory. Jar tests were performed for coagulation and flocculation, followed by filtration through polycarbonate membrane filters of different pore sizes. Samples from the pilot plant, as well as from laboratory treatment, were analyzed and compared.

1.2 Objectives

This project was divided into four phases. The first phase was completed in the year 2003, with its objectives being successfully achieved. The current project, the second phase of the full project, was carried out to achieve the following objectives:

- Optimizing the functioning of the pilot plant by investigating the best operating conditions (optimum flow rates, alum dose and in-line pressures) for customized sludge blanket clarifier and patented Martin filters;
- Simulating the treatment processes performed at the pilot plant in the laboratory under controlled conditions; and comparing the results obtained from both levels to check for their relative effectiveness and consistency;
- Testing the feasibility of UV irradiations for the microbial reduction of treated swine manure effluents.

2.0 LITERATURE REVIEW

2.1 Pig farming in North America

According to Ag Censes-1997, conducted by the EPA (Environmental Protection Agency) in the United States, pig farming accounted for 4.6% of all livestock producing establishments. These establishments accounted for 14% (US $14 billion) of the total sales achieved from all firms dealing with livestock production. There was a significant increase in sales, from 11 to 14%, between the years 1992 and 1997. In Canada, the total export of fresh and frozen pork was estimated to be $1.6 billion (Canadian) in the year 2003 (AAFC, 2003). Growth in the industry is expected to continue in the future.

2.2 Operations of animal production and manure management

Animal feeding and transport (loading and unloading) are the main activities involved in the livestock production operation. Animal feed generally includes grain, hay, vitamin and mineral supplements, silage and antibiotics. The quality of the manure produced in animal operations depends primarily on the characteristics of the feed provided to the animals (Loehr, 1977; Powers and Flatow, 2002).

According to the EPA (2001), 70 to 85 lbs (31 to 38 kg) of manure is produced daily per 1,000 lbs (450 kg) of swine weight. Estimates of the liquid manure produced by swine facilities may vary significantly. Hog manure typically contains about 85 to 90% water and 10 to 15% solids when it is excreted. In liquid manure handling systems, the manure may be diluted with flushing water. By the time the manure reaches the collection pit or tank, it contains about 95 percent water and 5 percent solids (ASAE, 1999). According to Barker *et al.*, (1994), the mean manure production for a finishing pig

is 5.05 kg/day; with a mean manure density of 1 kg/L. Anastasiou (2003) reported that the actual amount of manure produced on hog farms is often miscalculated as the amount of total water wasted during drinking and cleaning the animal houses is ignored.

Animal housing and animal manure management are other key factors that determine the quantity and quality of the manure produced on farms (EPA, 2003). At present, most swine raising facilities are indoor establishments. The main advantages of this type of facility are the area saved per head and modified and controlled environment for animals. This arrangement is the only option left for countries with harsh cold weather. Optimum use of water in cleaning and flushing operations, odour control and keeping the manure dry are the key areas in animal manure management. Manure management objectives can be achieved by improving manure collection methods, reducing the quantity of water usage in cleaning and recycling the manure produced from the barns.

2.3 Manure characteristics and public health concerns

Swine manure contains the urine and feces of pigs, water spillage, undigested remains of feed items, antimicrobial drug residues added to their diet. Swine manure can be 80 to 95% liquid (or 5 to 15% solid) depending upon the quantity of water spilled during drinking. According to AAFRD (1997), typical swine manure is characterized by its high solid content, Biochemical Oxygen Demand (5,000 or higher), high phosphorus (upto 450 mg/L in fresh untreated manure) and nitrogen (Total Kjeldahl Nitrogen, 2500 mg/L) contents, and high level of microbial population (Fecal Coliforms, 10^6 CFU/mL). Table 1.1 lists typical characteristics of fresh swine manure.

Table 1.1 Fresh swine manure production and characteristics[1] (Adapted from ASAE, 2003)

Component	Units	Mean	Standard Deviation
Total manure	kg	84	24
Urine	kg	39	4.8
Density	kg/m^3	990	24
Total solids	kg	11	6.3
Volatile solids	"	8.5	0.66
BOD_5	"	3.1	0.72
COD	"	8.4	3.7
pH		7.5	0.57
TKN	kg	0.52	0.21
NH_3 - N	"	0.29	0.10
TP	"	0.18	0.10
Ortho-P	"	0.2	n/a
Total coliforms	colonies	45	33
Fecal coliforms	"	18	22
Fecal streptococcus	"	530	290

[1] Values based on per 1000 kg live animal weight per day, n/a – not available

Environmental water quality problems resulting from swine manure arise mainly because of excess manure generation relative to land available for application, and inadequate manure storage and handling facilities. In Alberta (Canada), animal manure is generally stored in earthen storage facilities for six to nine months for the winter season, followed by its application on the farms in summer. In the year 2002, Alberta's Agricultural Operation Practices Act (AOPA) was enacted to regulate and to improve standards for better environmental management in livestock industry. The new law ensures that the confined feeding operations (CFOs) are environmentally sustainable and to reduce the environmental impacts on the surrounding areas. Under land limiting areas, the risk of pollution from land application practices is higher, but areas (e.g. Alberta)

where abundance of land is available for application the risks are comparatively less provided all the regulatory standards are met properly.

Swine manure has several components that can pollute water. These include oxygen demanding materials (organic matter), plant nutrients, and infectious agents. Colour and odour are potential pollutants of secondary importance. Plant nutrients (primarily nitrogen and phosphorus) may have a significant impact on the acceptable water quality. Bromley *et al.*, (2002) strongly emphasized nutrient management practices as being important for any CFO (Confined Feeding Operation). They pointed out that excessive and over-application of manure cause infertility of croplands and deteriorates the ground water quality, rendering it unsuitable as drinking water. Norwood and Chvosta (2003) reported that a fraction of nutrients applied for crop production is not present in the plant-available form and is potentially carried away with runoff. These nutrients enter surface water channels or seep into the ground water, resulting in the pollution of natural resources. Riddell and Rodvang (1992) and Sri Ranjan *et al.*, (2001) reported the leaching of nitrates below the root zone of plants due to the excessive application of cattle feedlot manure. Vanotti and Hunt (2003) discussed the phosphorus (P) buildup in lands caused by excessive swine manure application and its impact on the N: P requirements of the crops. Phosphorus may be carried away with runoff which results in the eutrophication of surface and ground waters.

Anthropogenic factors can markedly influence P concentrations in the solution and solid phases of soils. Major inputs and outputs of the 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. P management consists largely of making decisions about the need to add fertilizers and by-products to soils at rates and manners that will sustain economically optimum plant production and minimize the likelihood of P losses to water. Fertilization is an essential part of soil management because, as plants absorb P from the soil solution, or soluble P is lost in runoff or leaching, labile P dissolves or desorbs from the solid phase to solution. If soils are left unfertilized, or are under-fertilized, labile P concentrations will progressively decrease, through crop removal or P loss, to the point where soil can no longer adequately meet plant P needs. New additions of P are then necessary to ensure that sufficient labile P is available to meet the needs of plants. The greater the concentration of labile P, the longer the soil will be able to maintain plant growth at desired levels. However, consistent over-fertilization, to the point where labile P increases to concentrations well beyond those needed for optimum plant growth, should be avoided. 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)

Another potential water pollution hazard resulting from animal production is the transmission of disease through water-borne organisms. 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, Leptospiea, Vibrio, Brucella, Coxieplla*, and *Chlamydia*. Other infectious agents such as *Mycoplasma*, fungi, and protozoa (*Cryptosporidium)* can also be transmitted in water.

2.4 Animal manure treatment

Animal manure is being increasingly recognized as a valuable resource, and consequently, the use of reclaimed water is expanding worldwide (Tanji, 1997). Traditionally, the municipal wastewater treatment industry has been a source of technologies adapted to treat animal manure to improve handling, storage, transportation, and application. The difficulty in adapting all municipal wastewater treatment technologies lies in the fact that municipal manure is dilute and low in nutrients, whereas animal manure is concentrated and contains high levels of nutrients. Another factor is the cost involved in adopting advanced technology, which the animal industry can not afford.

As discussed in the literature, the wastewater (municipal or industrial) can be treated using two different types of treatment methods – physical/chemical methods, biological treatment methods and/or a combination of both. Physical/chemical methods include preliminary settling or sedimentation, media and membrane filtration, disinfection, and chemical precipitation or coagulation/flocculation, whereas biological methods employ biological or natural processes, such as aerobic and anaerobic digestion, lagoons and SBRs (Sequential Batch Reactors), to remove solids, organic content and nutrients present in the manure.

2.4.1 Physical/chemical treatment

Animal manure is a resource and can be reclaimed for the subsequent utilization of either the treated manure or the separated organic and/or inorganic fractions. Animal manures, being very concentrated and highly rich in nutrients, can be a potential source of surface and ground water contamination. In order to meet provincial or federal

guidelines, these manures are applied at specific application rates and new techniques (e.g. direct manure injection into soil) are being adopted for their application so that potential risks (seepage, runoff and odours) can be minimized. Under land limited areas (e.g. North Carolina in the United States), physical and chemical processes can be applied to agricultural manures for either disposal or reuse purposes.

2.4.1.1 Solids/ liquid separation: problems and methods

Hundreds of millions of tons of swine manure are generated annually worldwide as a by-product of international pork production (Rhymer *et al.*, 1995). In the late 20th century, a shift has occurred in the pork industry from the more traditional, limited-confinement production techniques, to swine confinement facility production in order to meet the rapidly increasing public demand for pork meat. This has led to a rapid increase in the swine production business, and hence, the amount of manure generated in the animal facilities. Solid/liquid separation can assist in nutrient management (Zhang and Westerman, 1997). Hatfield and Stewart (1998) indicated that manure generation might increase the capacity of the local or regional environment to properly assimilate the manure through agricultural land application and/or discharge to natural water systems.

In Canada, swine manure management consists primarily of manure retention in concrete and earthen storage facilities for six to nine months, followed by its application on the fields during summer time. In United States, storage practices include deep pits, anaerobic and aerobic lagoons, aboveground and belowground slurry storage (tanks or pits) and dry storage (EPA, 2001). Increased swine production and the encroachment of residential human populations onto formerly rural areas has resulted in public opposition

to lagoon treatment due to the environmental degradation potential and the aesthetic issues raised (e.g., accidental releases and off-odours). The failure of lagoon systems to adequately store or treat swine manure prior to discharge has led to environmental concerns in major pork-producing states in the United States. Excessive land application of swine manure may also result in off-odours, runoff into surface water systems or degradation of soil-groundwater systems (Ritter and Chirnside, 1990; Burkholder *et al.*, 1997; Haywood, 1997; Bromley *et al.*, 2002). These problems are more persistent in United States than in Canada, as the latter uses its vast land source for manure application. Solid/ liquid separation can be used successfully as an alternative (to conventional land application) for reuse purposes and better management of manures.

2.4.1.2 Physical treatment processes

For the best management of animal manures, it is, at times, desirable to separate the solid and liquid components. This can be accomplished by physical methods for the following purposes:

- To separate liquid and solid fractions for better management
- To use the liquids for flushing and drinking in the animal barns
- To reduce the volume of manure to be hauled

2.4.1.2.1 Natural and mechanical separation

Separation of solids is a physical treatment process whereby a portion of the larger solids and fibers are removed from the manure and can be reused (EPA, 2003). In order to treat swine manure more efficiently and economically, application of modified traditional treatment technologies to swine manure slurry may be feasible. Solids

separation 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, 2001).

Natural settling, preliminary settling or gravitational settling is a naturally-occurring solid-liquid separation process that employs gravitational force to separate the most settable solids in the animal manure. In CFO (Confined Feeding Operation), gravitational settling occurs in a settling basin designed in such a way as to lower the runoff from the animal feedlots so that the manure can settle properly under gravity. Schmidtke (1981) emphasized the importance of natural settling and stressed the need for more detailed investigation into this process.

Fischer *et al.*, (1975) concluded that the settling characteristics of hog manure are highly variable, but that most type II settling occurs within the first 100 minutes. Moore *et al.*, (1975) reported about 70% solids removal in 1000 minutes (approximately 16 hours) in swine manure containing 1% total solids. In their study, solids removal efficiency was found to decrease with the decrease in total solids (TS) concentration in the unsettled swine manure. Lott *et al.*, (1994) examined solids in manure from feedlots and differentiated two components – large particles that settled within 10 minutes and small particles that required extremely long settling times. The rapidly settling portion varied from 45 to 75% of the total solids (TS).

Jett *et al.*, (1975) studied the settling characteristics of swine manure with solids concentrations of 0.5, 1, 2 and 3%. Settling curves were developed using the settling

column technique. They found that maximum solids removal (50 to 60%) occurred during the first 10 minutes of settling. Increasing the settling time (20 minutes to 1 hour) resulted in a further 10 to 15% reduction in solids. However, the results were produced only at the bench scale in the laboratory. Gao *et al.*, (1993), in their laboratory scale studies, achieved 14 to 70% suspended solids removal in raw swine manure containing 1 to 7% total solids (low to high strength), with a detention time of 5 hours.

Pieters *et al.*, (1999) found that natural settlement is a more economical and efficient separation technique for swine manure slurries with dry matter content below 5%. Sedimentation has proved effective for treating highly diluted manure or feedlot runoff consisting of less then 3% TS (Total Solids). The separation efficiency (% removal of TS) of settling basins has been reported as high as 64% for a concrete swine feedlot, and 39 to 75% for an earthen beef feedlot (Mukhtar *et al.*, 1999). Ndegwa *et al.*, (2001) reported 66 and 42% removal of suspended solids (SS) and phosphorus, respectively, in unaided natural sedimentation of swine manure containing 1% total solids and 4 hours detention time.

Zhu *et al.*, (2003) reported 60 to 75% suspended solids removal from liquid swine manure containing 5 to 6% total solids (TS) after 24 hours of preliminary settling in a circular settling tank of approximately 5,000 gallons (19 m^3) capacity. The effect of settling time on suspended solids removal was analyzed for 4 days in the settling tank. They found that suspended solids removal was at its maximum, and almost complete, after 24 hours settling and remained approximately constant thereafter.

Mechanical separators of animal manure include screens (inclined screens, rotating screens, vibrating screens), belt and screw presses, and centrifuges. Such equipment has long been used in both municipal and industrial wastewater operations, but has not been commonly used for livestock manures. The liquid portion from the settling basin and/or mechanical separator is normally sent to storage or treatment, or used to irrigate cropland. The collected solids may be used for soil amendment, or compost.

Centrifuges and hydrocyclones use centrifugal force to increase the settling velocity of suspended particles and thus separate solids from liquid. Vertical and horizontal centrifuges have been used in food processing and industrial manure management operations. Livestock producers have used them to separate manure solids (Ford and Fleming, 2002).

Mechanical screening of animal manures for solids separation was extensively researched from 1970 to 1990, with a primary focus on maximizing solids separation efficiency (Glerum *et al.*, 1971; Graves and Clayton, 1972; Shutt *et al.*, 1975; Shirley and Butchbaker, 1975; Rorick *et al.*, 1980; Hegg *et* al., 1981; Prince and Hill, 1985; Koegel *et al.*, 1990). Glerum *et al.*, (1971) evaluated the performance of a centrisieve using swine manure. The separator was a conic drum 560 mm in diameter and lined with a filter cloth. It also had screen openings of 0.031 mm in size. Using this centrifuge separator, between 30 and 40% of the dry matter could be removed, and a separated material with a dry matter content of 14 to 19% was achieved. More recently, Hill and Baier (2000) and others have included the determination of chemical properties such as pH, chemical oxygen demand (COD), N, P and carbon (C) in their studies.

Performance data for mechanical separators vary widely, not only because of different testing and reporting procedures, but also because the characteristics of the manure used are sometimes different. Zhang and Westerman, (1997) concluded, from a review of previous research results on the mechanical separation of animal manures, that fine particles in the manure decompose faster than coarse particles, and most of the reduced carbon compounds, protein, and nutrient elements are contained in fine particles. Because these compounds are the precursors for odour generation and the carriers of organic nitrogen and phosphorus, they recommended that solid-liquid separation processes be designed to remove both coarse material and particles smaller than 0.25 mm to significantly reduce both odour generation and nutrient contents. This conclusion was further confirmed by studies conducted by Hunt and Vanotti (1999), indicating a reduction in odour emissions from lagoons if major portions of the solid and organic contents in the liquid manure were removed before reaching the lagoons.

Another study conducted by Holmberg *et al.*, (1983) on swine manures reported a TS (Total Solids) recovery in the range of 11 to 23% using a vibrating wet sieve shaker and a screen with number 8 mesh (2.45 mm). He also observed TKN removal in the range of 7.9 to 8.9% and P removal of 3 to 23%. However, Powers *et al.*, (1995) concluded that P reduction during screening experiments was a variable phenomenon.

2.4.1.2.2 Drying, freezing and incineration

Drying is used primarily for volume reduction and concentration of solids. The design and use of drying beds for the dewatering of sludge are affected by climatic conditions (Eckenfelder, 2000). Drying systems must be covered to protect them from rainfall, and

supplemental heat or forced air is needed to encourage rapid evaporation. Tchobanoglous and Burton (1991) have mentioned five mechanical processes for drying sludge: (1) flash dryers, (2) spray dryers, (3) rotary dryers, (4) multiple-hearth dryers, and (5) multiple-effect evaporation. Freezing has been demonstrated to improve dewatering in manure, facilitating settling and filtering.

Incineration is an extension of drying. Manure is converted to an ash requiring application or disposal. Self-sustaining incineration requires a manure of approximately 30% solids (Tchobanoglous and Burton, 1991). Wetter manure with lower solids content requires supplemental fuel to continue incineration.

2.4.1.2.3 Media Filtration

Filtration is a solid-liquid separation process in which the liquid passes through a porous medium or other porous material to remove as many fine suspended solids as possible (Reynolds and Richards, 1996). Gravity, vacuum, or pressure can be used to move the liquids through the media. Filtration is now used extensively for screening fine suspended solids and particulate BOD from the wastewater effluents of biological and chemical treatment processes. Practically, filtration through columns consists of two steps: filtration mode and backwashing mode. In the former step, fine suspended solids and BOD associated with particulates are trapped across porous media, while the latter step involves the use of pressurized water to wash away the particulate matter attached and clogged in the media. The efficiency of the filtration process is a function of: (1) the concentration and characteristics of the solids and suspension, (2) the concentration of the filter medium and other filtration aids, and (3) the method of filter operation.

The application of filtration processes for water treatment and the advanced municipal treatment of wastewater has been widely researched. Hamoda *et al.*, (2004) demonstrated the use of granular media filtration in the reclamation and reuse of municipal and industrial wastewaters. Wastewater filtration prior to disinfection can potentially help in reducing the enteric microorganisms, and therefore, can be a cost-effective treatment technique (Ausland *et al.*, 2002). However, others have demonstrated only a limited reduction of microorganisms through media filtration (Hill and Sobsey, 1998). Dohmann *et al.*, (1996) analyzed the operational problems encountered in the filtration treatment plants. They came up with a set of possible solutions to the operational problems encountered with sand and biofilters, which, according to their findings, can ensure the trouble free and reliable running of plants for longer times.

Szögi *et al.*, (1997) used a marl gravel media filter enclosed in a tank to treat swine manure after anaerobic treatment in a lagoon. The treatment achieved a 54% reduction in chemical oxygen demand (COD) and a 50% removal of total suspended solids (TSS) in one cycle, with no further reduction in COD and an approximately 7% reduction in TSS per addition of filtration cycle. Phosphorus removal ranged between 37 and 52%.

In a laboratory scale study, Samkutty and Gough (2002) investigated the effectiveness of various filtration agents in the primary treatment of dairy processing wastewater. The filtration agents used were: zeolite, crushed coral, charcoal, sand and crushed coral, and glass beads. Chemical oxygen demand (COD), total solids (TS) and total suspended solids (TSS) were analyzed before and after filtration. Sand plus crushed coral and glass bead media yielded the most effective results, followed by charcoal and crushed coral.

Zeolite was found to be least effective. The study indicated a potential for using filtration processes as effective tool in manure treatment and reuse.

2.4.1.3 Chemical treatment processes

Chemical treatment of municipal and industrial manures by precipitation, coagulation and flocculation is a widely accepted and well published treatment method. Treatment of animal manures through the addition of chemicals has been practiced for the last few decades. Several chemicals known as coagulants are used for treatment. Common coagulants include inorganic chemicals (alum, ferric salts, polyaluminum chloride (PAC)) and organic substances (polyamines, polyquaternary amines, and epi-polyamines) commonly known as polymers. (Reynolds and Richards, 1996; Tchobanoglous and Burton, 1991).

A common approach followed in this method is to produce an insoluble, settable precipitate through chemical reactions occurring between wastewater constituents and the coagulant added. Coagulants destabilize the colloidal particles in a suspension by physical and chemical processes, resulting in the joining of minute particles which can be more easily settled from the solution. The process of coagulation can be enhanced by mixing the coagulant rapidly, followed by slow or gentle mixing to form bigger flocs (flocculation) and, finally, leaving the sample to settle. The settling characteristics of the flocculated manure depend upon the characteristics of the raw manure, the type of coagulant used and the degree of flocculation (Reynolds and Richards, 1996). The settled manure can be subsequently separated and reused.

The basic reactions involved in the precipitation of phosphate with aluminum and ferric based coagulants are described in equations [1] and [2]

$$Al^{+3} + H_nPO_4^{n-3} \leftrightarrow AlPO_4 \downarrow + n\,H^+ \qquad [1]$$

$$Fe^{+3} + H_nPO_4^{n-3} \leftrightarrow FePO_4 \downarrow + n\,H^+ \qquad [2]$$

The main objectives of the chemical treatment of animal manures are to reduce the solids and organic contents and nutrient (N and P) levels (Tchobanoglous and Burton, 1991). Chemical coagulation (with chemical coagulants and polymers), flocculation, sedimentation and other physical processes, such as media and membrane filtrations, can reduce the solids and nutrient levels significantly and, to some extent, the organic matter concentration, which requires biological treatment to maintain within the allowable discharge limits (Tchobanoglous and Burton, 1991; Reynolds and Richards, 1996).

2.4.1.3.1 Case studies

Solids and nutrient removal from animal manure by chemical treatment has been researched by many authors. Miner *et al.*, (1981) treated swine manure from an anaerobic lagoon and found that alum and/or polymer reduced biological oxygen demand (BOD) and suspended solids, but did not change the N and P content. Hanna *et al.*, (1985) tested nine coagulants (aluminum sulfate, ferrous sulfate, calcium hydroxide, ferric chloride, magnesium chloride, chitosan, lignosulfate, and an organic polymer) on 1% total solids flushed swine manure. They found that after treatment with these chemicals, there was an 8 to 13% reduction in volatile solids concentration, except in the cases of magnesium chloride and lignosulfate, which removed only 2% of volatile solids. However, in another study, ferric chloride reduced volatile solids 60-70% in swine and

cattle manure, with a further reduction achieved by the addition of polymers (Sievers *et al.*, 1994). Sievers (1989) conducted a series of jar tests (bench scale) to optimize the coagulation process through best operating conditions such as rapid-mixing, velocity gradient (G) and detention time (t). Two coagulants, ferric chloride and chitosan (ferric iron salt) were used to determine their ability to remove suspended material (turbidity) from diluted beef cattle, poultry and swine manure slurries. Sievers found that chitosan, in the case of poultry manure, outperformed ferric chloride, but the results were comparatively similar for the other two samples.

Shreve *et al.*, (1994) amended poultry manure with alum and ferrous sulfate, applied the manure to fescue (a species of grass) plots, and applied simulated rainfall sufficient to cause runoff. The alum amendment reduced runoff P concentrations, relative to untreated manure, by 87%, and ferrous sulfate produced 77% reductions. The response of runoff P to the amendments was attributed to the precipitation of P into relatively insoluble forms that were less susceptible to transport in runoff. In a related study, Moore *et al.*, (1995) found that amending poultry manure with alum and ferrous sulfate also reduced ammonia volatilization, with alum producing a 99% reduction relative to unamended manure. This work clearly established the potential of chemical amendments to reduce the environmental impacts of poultry production.

Bushee *et al.*, (2000) investigated the use of alum, ferric sulfate and aluminum chloride with swine manure to reduce environmental concerns. The amendments were added to containers containing swine manure and allowed to incubate for a six day period, during which gas emissions were monitored. Afterward, the manure was applied

to fescue plots at the UK Maine Chance Agricultural Experiment Station. All amendments reduced ortho-P, total P and total Kjeldahl N. The amendments were particularly effective with regard to ortho-P reduction, reducing runoff ortho-P concentrations from 6 mg/L (no amendment) to approximately 1 mg/L. The amendments did not generally have a significant effect on the emission of the monitored gases (carbon dioxide, methane, ammonia and hydrogen sulfide). The alum-amended swine manure, however, did lead to significantly less ammonia production in the initial stages of the six-day incubation period.

In another case study, Gao *et al.*, (1993) investigated the optimum dosage and effectiveness of five different chemical treatments (using $Ca(OH)_2$, $Al_2(SO_4)_2$, $FeCl_3$, synthetic polymers chitosan and PERCOL 728) on low, medium and high strength wastewaters. The effectiveness of the treatments was measured primarily in terms of suspended solids and total solids removal, and chemical and biochemical oxygen demand reduction. It was found that the addition of polymers increased solids removal efficiency by 20%, but was ineffective in removing phosphates. Lime and alum were found to be effective in removing phosphorus from all tested wastewaters. The polymer chitosan was found to be ineffective in removing solids and, therefore, is not recommended for wastewater treatment.

The effect of sedimentation after chemical coagulation was further emphasized by many researchers. Powers *et al.*, (1995) investigated the effect of screening and sedimentation after coagulation on solids and nutrient (N and P) removal. Wet sieving and vibrating type screens were tested. A combination of three chemicals ($Fe_2(SO_4)_3$,

CaO and $CaCO_3$) was tested on dairy manure slurry with 1.5% total solids. CaO and $CaCO_3$ removed 92% of TS, 69% of the N, and 31% of the total potassium (K). CaO was more effective in removing P (93%) than were the other treatments. $Fe_2(SO_4)_3$ was found to be least effective in removing TS and N. The results indicated a potential for more manure solids and nitrogen removal from flushed manure by sedimentation than by screening.

Treatment with polyacrylamide (PAM) polymers prior to mechanical removal or gravity settling has the potential to enhance solid-liquid separation and increase the capture and removal of fine suspended solids. PAM flocculants are high molecular weight, long chain, water soluble polymers capable of destabilizing suspended charged particles by adsorbing them and building bridges between several suspended particles, resulting in flocs that settle out of the liquid. Vanotti and Hunt (1999) found that TSS removal efficiencies greater than 90% were obtained with PAM rates of 26 and 79 mg/L applied to samples containing 1.5 and 4.1 g/L TSS, respectively.

The addition of alum (Aluminum Sulfate) was found to be effective at removing a significant portion of the solids from liquid manure in a settling basin. The basin removed approximately 60% of the solids present in the effluent and, when amended with alum at 0.5% volume, the separation efficiency increased to approximately 70% (Worley and Das, 2000). Zhang and Lei (1998) reported that the use of a metal salt ($FeCl_3$) together with a polymer (Cationic PAM) considerably enhanced the removal of phosphorous from manure and would potentially reduce amount of polymer required, thus lowering the cost of chemicals.

A laboratory experiment conducted by Toth *et al.*, (2001) was based upon reducing the water solubility of phosphorus. Several chemical amendments were investigated to determine their effectiveness on reducing phosphorus solubility in fresh swine manure. The amendments in this study consisted of alum, coal combustion by-products, fluidized bed combustion flyash (FBC), flue gas desulfurization product (FGD), and anthracite refuse flyash (ANT). Preliminary results indicated that alum, FBC, and FGD allowed a significant reduction of water soluble inorganic phosphorus. ANT, however, was found to be ineffective in reducing the solubility of phosphorus. A second extraction trial was performed which resulted in a reduced concentration of water soluble phosphorus and an increase in acid soluble phosphorus.

Polymer treatment has effectively removed solids and organic forms of phosphorous (P) from swine liquid manure, but it has proven ineffective in removing soluble phosphorus (Vanotti *et al.*, 2003; Szögi *et al.*, 2003). The swine liquid effluent emanating from lagoons primarily contains the soluble form of P. In order to solve this problem, Vanotti *et al.*, (2003) investigated another process, both in the laboratory and at field scale, to extract soluble P from swine lagoon effluent. This process included the nitrification of manure in a fluidized bed reactor (Experiment #1) and a sequencing bed reactor (Experiment #2) to remove ammonia and carbonate buffers, followed by lime treatment to precipitate P under raised pH condition. Since ammonia nitrogen and carbonate alkalinity were substantially reduced through nitrification pre-treatment, the subsequent lime addition increased the pH, thereby promoting the formation of P precipitate. The advantages of this process are: (1) adjustment of the N: P ratio to match

specific crop requirements, and (2) the final product of this process, calcium phosphate, can be used as a fertilizer and can be transformed into phosphate concentrates.

Ndegwa *et al.*, (2001) and Powers and Flatow (2002) used ferric chloride ($FeCl_3$) and alum ($Al_2(SO_4)_3$) as flocculants to determine their effects on the removal of solids and phosphorus in swine manure. Ndegwa *et al.*, (2001) achieved 76% suspended solids (SS) removal and 86% phosphorus removal with $FeCl_3$ at a dose level of 1500 mg/L, while alum at the same dose yielded 96% SS removal and 78% phosphorus removal.

Bromley *et al.*, (2002) conducted a pilot scale study to investigate the effectiveness of physical/chemical treatment on the removal of solids, organic matter, nutrients and microorganisms in swine liquid manure. The test included the preliminary settling of fresh manure for 24 hours, coagulation, and flocculation with alum, followed by settling in a sludge blanket clarifier. The clarified supernatant was then filtered through radially fluidizable glass bead media filters. The samples were tested for TSS, TP, TKN, COD, BOD_5 (5-day biochemical oxygen demand), and total and fecal coliforms. More than 95% removal was observed in both TSS and TP, while 40% TKN removal was measured. Significant microbial reduction was also observed.

Recent laboratory studies show that phosphorus content in swine manure can be reduced by recovering a portion of the phosphorous as a crystalline precipitate containing struvite (magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4.6H_2O$) (Beal *et al.*, 1999; Burns *et al.*, 2001; Kalyuzhnyi *et al.*, 2001, Nelson *et al.*, 2000; Wrigley *et al.*, 1992). By amending manures with a magnesium source to precipitate phosphorus, manure could be applied at a rate that meet crop needs for both nitrogen and

phosphorous, while avoiding the over-application of phosphorus. This would reduce manure handling costs. While investigators have examined phosphorus precipitation (e.g. struvite precipitation) in swine manures on a laboratory scale, little work has been done to develop this process for field scale application (Nelson *et al.*, 2000). The precipitated phosphorus can be utilized as fertilizer.

Calcium amendments reduced P solubility at high pH, however, at a slightly acidic pH range. Recently, Barrington *et al.*, (2004) investigated the possibility of using lime dust for precipitating phosphorus (TP) and solids (TS) from fresh swine manure. The effectiveness of fine limestone dust in precipitating swine manure total phosphorous and total solids was measured using 3 L and 1.30 m^3 volumes. Lime dust was mixed with 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 measured and removed to be sampled and analyzed for density, TS, TP, and pH. The sludge and supernatant mass 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.

2.4.1.4 Biological treatment processes

The main principle of biological nutrient removal is the removal of ammonia nitrogen through nitrification to nitrate and subsequent denitrification to nitrogen gas. Phosphorus is incorporated into the biomass and removed via the wasted activated sludge. To achieve enhanced biological phosphorus removal, an anaerobic zone in the activated sludge bioreactor is included, providing a selective advantage for certain bacteria that accumulate phosphorus beyond what is needed for biomass synthesis. Phosphorus can also be removed chemically through the addition of a precipitating agent (typically ferric chloride, alum, or other metal salts) at various points in the conventional wastewater treatment process train to convert soluble phosphate to particulate form. The polyphosphate is incorporated in the bacteria and is removed with the wasted activated sludge. Organic matter is oxidized during the growth of phosphorus accumulating bacteria, or other heterotrophic bacteria using oxygen or nitrate as an electron acceptor (Tchobanoglous and Burton, 1991).

2.4.1.4.1 Aerobic and anaerobic lagoons

Lagoons designed to treat manure can reduce organic content and nitrogen by more than 50 percent (Pader, 1986). Many different types of bubble or surface aerators can provide aeration for nutrient degradation and nitrogen removal. Aerators can be used in existing or new lagoons to reduce odour and ammonia volatilization by converting ammonia to nitrate. By selecting appropriate surface aeration equipment, or by placing air defusers above the bottom sludge zone, aeration can be designed to mix the whole lagoon or only the area above the sludge zone. When aeration is limited to the lagoon surface liquid, the bottom, or sludge zone, remains anaerobic. Thus, the benefits of anaerobic

decomposition of solids can be obtained while the upper portion may be aerated to reduce odour and ammonia volatilization at a reduced energy input.

Anaerobic lagoons are generally preferred over aerobic lagoons because of their greater ability to handle high organic load. Anaerobic lagoons are a useful size and cost compromise between storage basins and aerobic lagoons. Due to the tremendous area required for aerobic lagoons to treat livestock manure, almost all livestock lagoons are anaerobic (Pfost *et al.*, 2000). Nonetheless, incomplete anaerobic decomposition of organic material can result in offensive by-products, primarily hydrogen sulfide, ammonia, and intermediate organic acids, which can cause disagreeable odours. Therefore, proper design, size, and management are necessary to operate an anaerobic lagoon successfully.

2.4.1.4.2 Anaerobic digestion

Anaerobic treatment of high strength manure from animal feeding operations can be advantageous because of the lower energy requirement (generally a net gain of energy) and the lower production of manure biological solids. The disadvantage of anaerobic treatment is the lower growth rate of microorganisms, which can mean a slower startup to the process and slower recovery after operational errors.

Anaerobic digestion is a two stage process, carried out by two different types of microorganisms. In the first stage, a group of microbes referred to as "acid formers" breaks down the volatile portion of the manure solids (volatile solids) into volatile fatty acids (VFAs). The second group of microorganisms is the "methane formers." This group utilizes the VFAs produced by the first group as a food source, and reduces them further

to gases such as methane, carbon dioxide, hydrogen sulfide and others. For the anaerobic digestion of organic material, different groups of organisms have to interact during hydrolysis, fermentation, and methane formation. This requires a somewhat more advanced process control than aerobic wastewater treatment. Another disadvantage is that anaerobic treatment processes alone are generally not suited to removing nutrients such as nitrogen or phosphorus from wastewater (Tchobanoglous and Burton, 1991).

Anaerobic processes may play an important role in the removal of nitrogen and phosphorus (Tchobanoglous and Burton, 1991). For nitrogen removal, ammonia nitrogen resulting from the metabolism of nitrogenous organic compounds must be oxidized aerobically, after which the nitrogen may be removed anaerobically by denitrification. This is accomplished by recycling aerobic effluent back through an anaerobic denitrification process. Biological removal of phosphorus is sometimes accomplished through the use of anaerobic pre-fermenters, which produce volatile acids, and enhance the uptake of phosphorus by bacteria in subsequent aerobic operations.

Anaerobic digestion has been used for decades for the treatment of domestic sludges, animal manures and industrial manures (McCarty, 1992), and for treating the organic fraction of municipal solid manures (Chynoweth and Isaacson, 1987). Anaerobic digestion produces a useful energy form (methane) and a stabilized residue that can be subsequently applied to land as a soil amendment. Anaerobic lagoons have been used as an integral part of many swine production systems to provide practical treatment and storage of swine manure (Humenik *et al.*, 1980). Lagoons are typically earthen basins used to treat and store manure from pork production facilities. They rely on bacteria to

stabilize organic material. Lagoons are relatively simple to operate and maintain, and are relatively inexpensive compared to other treatment methods (ASAE, 1997). Lagoons become more odourous when overloaded due to sludge buildups, additional inputs, and cold weather (Ritter, 1989). Studies have been done in the past, and are currently being conducted, to determine and reduce the odour problems from anaerobic lagoons (Jiang *et al.*, 1995; Smith and Watts, 1994, Schmidt *et al.*, 1999, Heber *et al*, 2000, Chen *et al.*, 2003).

Conventional anaerobic digesters are based on continuously mixed (CSTR) technology and possess equal solid retention time (SRT) and hydraulic retention time (HRT). Some of the recently developed digesters include the anaerobic sequence batch reactor (ASBR), upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB), downflow anaerobic filter (DFAF), and packed anaerobic bed reactor (PABR) (SWET, 2001). Williams (1998), Wilkie (1999), Rim and Han (2000) and Iranpour *et al.*, (2000) investigated various anaerobic digesters under different conditions and then compared their results and the features of their respective digesters. Significant BOD and TSS reductions have been reported from the effluents produced by swine and dairy processing utilities using different anaerobic digesters (Hill *et al.*, 2002; Ross and Valentine, 1995).

One way to reduce the size of the anaerobic reactor is to actively retain solids. Ross *et al.*, (1992) combined anaerobic digestion with an ultrafiltration membrane separation that allows treated liquid to pass, but retains the solids within the reactor. This process was called ADUF (Anaerobic Digestion UltraFiltration). The membrane bioreactor offers three major advantages stemming from the fact that the membrane is a perfect separator

for solids. First, the membrane eliminates the possibility of uncontrolled biomass loss to the effluent and, therefore, a sudden washout of slow-growing anaerobic bacteria. Second, effluent quality is improved, since it does not contain suspended organic matter. Third, the volumetric loading can be increased to very high levels, since loss of biomass is impossible. Ross *et al.*, (1992) successfully applied the ADUF process for the treatment of maize-processing effluent. The main disadvantage of the membrane bioreactor is added costs: capital costs to install the membrane, energy costs to pump the water to and through the membrane, and replacement or cleaning costs to overcome membrane fouling (Rittmann and McCarty, 2000). An integrated system for the treatment of swine manures was developed on the basis of the ADUF process, where the anaerobic digestion with ultrafiltration for biomass retention is combined with downstream processing using ammonia stripping and reverse-osmosis. Such a process, termed BIOREK (Bioscan, AS, Denmark), has recently been developed to full-scale for the treatment of 40 m^3/d of liquid manure (1,100 sows) in Denmark (Norddahl and Rohold, 1998).

2.4.1.4.3 Sequencing batch reactors

A range of biological nutrient removal processes based on aerobic activated sludge treatment are being used for the treatment of animal manures. Many of these use sequencing batch reactor technology to achieve advanced nitrogen and phosphorus removal (Osada *et al.*, 1991; Bortone *et al.*, 1994; Maekawa *et al.*, 1995; Tilche *et al.*, 1999; Edgerton *et al.*, 2000; Ra *et al.*, 2000). The Sequencing Batch Reactor (SBR) displays great potential for increasing the profitability of the dairy industry by eliminating environmental problems associated with manure disposal. The Sequencing Batch Reactor

minimizes capital costs by incorporating both aerobic and anaerobic processes in a single reactor (Irvine and Ketchum, 1989). In Canada, SBR technology has been successfully used to treat high strength agricultural manures such as swine manure (Fernandez, 1994; Fernandez *et al.*, 1991; Fernandez and McKyes, 1991; Lo *et al.*, 1991). Juteau *et al.*, (2004) demonstrated an aerobic thermophilic treatment technology in SBR for high strength swine manures. By incorporating SBR technology into the animal farm manure management scheme, farms can continue to expand and to improve profitability, while also reducing the environmental and health risks associated with agricultural manures.

In British Columbia (Canada), a full scale Sequencing Batch Reactor manure treatment system has been operating since 1988 on a 220-sow (farrow to finish) unit in the city of Langley (BCMAFF, 1993). The SBR manure treatment system consisted of four components, or stages. A manure separator, a belt press made by SCS Biotechnology in England, removed coarse solids from the manure. An aerated pretreatment tank (16' * 14' * 18') pretreated the manure straight out of the barn. A 24' diameter, 12' deep concrete holding tank held 7-10 days production of manure and acted as a settling tank. The final stage was the SBR tank, a 16' by 16' by 18' deep concrete tank equipped with diffusers for aeration. Manure was flushed from the barns into the pretreatment tank where it was separated and aerated. It was pumped once daily from there to the holding tank for flow equalization and the settling of fine solids. Finally, manure was pumped from the holding tank to the SBR in four equal increments each day. Under optimum conditions, over 90% BOD_5 and TSS reductions were achieved. The nitrogen (total nitrogen, TN) and phosphorus (TP) reductions were 75 and 67%, respectively. Two

options were available to maintain the effectiveness of the SBR in winters: heating the tank to 15° C, or enclosing the tank in a building.

2.4.1.4.4 Biofiltration

The biological treatment system can be divided into suspended-growth and attach-growth systems (Tchobanoglous and Burton, 1991). In suspended-growth systems, microorganisms are maintained in suspension in the wastewater. In attached-growth (fixed-film) systems, microbial film is attached to an inert material. The activated sludge system (aeration and sedimentation tanks) is the main representative of the suspended-growth aerobic system. Attached-growth aerobic biological treatment systems include the trickling filter, the rotating biological contactor, fixed-bed nitrification reactors, etc. The principle of biofiltration is to have liquid and gaseous effluents pass through a filter containing an organic bed. Biofilters have been successfully used in wastewater treatment plants for the refining of organic matter in the effluents and for better odour control (Eckenfelder, 2000).

Research work done by Buelna *et al.*, (1993) and Hill *et al.*, (2002) indicated that biofilters (aerobic and anaerobic) can be used to reduce volatile solids, BOD and, to some extent, the microorganisms present in swine manures. Hill *et al.*, (2002) utilized a collimated UV beam on swine liquid manure effluent from biofilter treatment. Compared to the effluent from lagoon treatment, the biofilter effluent had fewer fecal coliforms and other enteric microorganisms.

2.4.1.4.5 Other technologies

2.4.1.4.5.1 Nutritional strategies

To reduce the nutrients (N and P) in swine manure, nutrient based strategies are available for farm producers (Murphy, 2003). Excretion of N and P in swine manure can be substantially reduced through a number of strategies, depending on individual farm situations. Murphy (2003) reported a number of nutritional strategies such as: (1) improving feed efficiency, (2) reducing feed wastage, (3) phase and split-sex feeding, (4) formulation on nutrient availability, (5) use of amino acids replacing protein, and (6) use of enzyme phytase. According to the same author, some strategies are quite simple and cost–effective, but some may increase feed costs.

2.4.1.4.5.2 Enzymes

Another technology that can be used to reduce the total P input in livestock rations is the use of enzymes. Phytase is an enzyme that has received much attention lately, because it is the enzyme that cleaves phosphate groups from the phytate molecule (Kornegay, 1996). It can be cultured rather easily using various fungi, such as *Aspergillus* sp., that produce exogenous phytase. This technology has been shown to reduce soluble P in swine manure by 15% compared to swine fed normal diets (Smith *et al.*, 2001). However, researchers are currently doing more studies to explain some drawbacks associated with this technique, especially with regard to swine manure (Smith *et al.*, 2001).

2.4.1.4.5.3 Constructed wetlands, aquatic plants, duckweed and algae/ bacteria

Constructed wetlands may also be used to remove nutrients from animal manure effluents (Reaves *et al.*, 1994; Hunt *et al.*, 1995; Kaldec and Knight, 1996) and for microbial reduction (McCaskey *et al.*, 1998). Phosphorus removal by wetlands has been well studied, quantified and reported (Kaldec, 1997; NRCS, 1992). Cronk (1996) investigated the performance of constructed wetlands to treat high strength dairy and swine manure, as well as wetland design, costs, and performance for the removal of total phosphorus (TP). In conclusion, she emphasized the effectiveness of wetlands only under conditions in which they are combined with pretreatment methods, such as solids separation, organic digestion or lagoon treatment. According to Cronk, wetlands are ineffective without pretreatment. Reddy *et al.*, (2001) reported treatment of swine manure in marsh-pond-marsh constructed wetlands. Two plant species of cattail (*Typha latifolia*,L.) and bulrushes (*Scirpus americanus*) were grown. Nitrogen removal was measured at 51 and 37%, at two different loading rates of 16 and 32 kg N $ha^{-1}day^{-1}$, respectively. Phosphorus removal ranged from 30 to 45%.

Lagoons with floating plants, such as water hyacinth and duckweed, have been investigated since the seventies and are currently in use on a large scale for the treatment of municipal manure throughout the world (Hillman and Culley, 1978; Alaerts *et al.*, 1996). Duckweeds such as *Lemna gibba* have been utilized to treat municipal wastewater in Israel and a very high Biochemical Oxygen Demand (BOD) removal (97%) has been reported (Oron and Porath, 1987). Duckweeds such as *Lemna sp.* may recover a high percentage of nitrogen from wastewater and may accumulate a protein content as high as 40%. This type of duckweed has been utilized to recover nitrogen and phosphorus from

anaerobic effluents from digested pig manure (Hernandez et al, 1997). Baumgarten *et al.*, (1999) utilized, in a photobioreactor, mixed cultures of algae (*Chlorella* sp.) and bacterial populations able to grow in high ammonia concentrations. The experiment indicated a promising alternative capable of reducing nitrogen (NH_4^+) and carbon contents (Total Organic Carbon, TOC). Villanueava *et al.*, (1994) tested the ability of cyanobacteria *phormidium* sp. to treat anaerobically digested swine manure.

2.4.1.4.5.3 Pellet technology

The nitrification of swine manure in lagoons has always been a difficult process because of the low growth rate of nitrifying bacteria and the lower number of nitrifiers (Nitrosomonas and Nitrobacter) present after anaerobic treatment (Wijfells *et al.*, 1993; Blouin *et al.*, 1989). The absence of adequate nitrifying bacteria may delay nitrification, even if a proper oxygen supply is available (Burton, 1992). In order to overcome this problem, Vanotti and Hunt (2000) developed a new technique in which pellets laden with nitrifying bacteria are used to enhance nitrification by increasing the concentration of nitrifying bacteria. Pellet technology, originally developed in Japan, removes ammonia-N from swine manure biologically. The nitrification rate achieved with this technology was three times greater than that obtained with the conventional activated sludge process (Tanaka *et al.*, 1991).

2.4.2 Ultraviolet Disinfection

UV disinfection is currently used in the drinking water, wastewater, and aquaculture industries. The development of UV technology for use in these industries has defined the operational parameters that influence the effectiveness of UV in water and wastewater

disinfection systems. The potential of ultraviolet irradiation for the disinfection of water and treated wastewater (municipal and industrial) has been studied and quantified extensively (Oliver and Carey, 1976; WPCF, 1986; Loge *et al.*, 2001; Temmer *et al.*, 2000; Craik *et al.*, 2000; Salgot *et al.*, 2002; Caretti and Lubello, 2002; Lubello *et al.*, 2002; Jeff Kuo *et al.*, 2003, and Yoon *et al.*, 2004). Limited literature review is available on the use of ultraviolet disinfection in treating animal manures (particularly swine manure). Hill and Sobsey (1998) and Hill *et al.*, (2002) have described the possibility of reusing agricultural wastewater after physical/chemical or biological treatment and disinfection with ultraviolet irradiations.

2.4.2.1 Mechanism of UV disinfection

Ultraviolet radiation (UV) is light energy between 100 and 400nm wavelength, between the X-ray and visible portions of the electromagnetic spectrum. In most UV disinfection applications, the short wave portion of the UV spectrum is used. This section is referred to as the optimum effective range and spans from 250-280nm. In general, UV radiation of microorganisms causes chemical bonds to form in cellular DNA (Deoxyribonucleic acid; the material inside the nucleus of cells that carries genetic information). This exposure interrupts normal DNA replication and organisms are killed or rendered inactive (Ultraviolet Applications Handbook, 2001; WPCF, 1986).

The degree of inactivation by UV is directly related to the UV dose as defined below:

$$D = I \times t \qquad [3]$$

Where:

D= UV dose ($mW.s/cm^2$);

I = intensity of the germicidal UV energy (mW/cm^2); and

t = exposure time (s)

2.4.2.2 Case studies

Hill *et al.*, (2002) investigated the effectiveness of biofilter and UV disinfection treatments on the removal of enteric bacteria in swine wastewater (manure). Microbial indicators such as *Salmonella* sp., fecal coliforms, E. *coli*, Enterococci, C. *perfrigens* sp., Somatic coliphages and F-specific coliphages were analyzed. Log_{10} reductions of 1.0 to 2.0 were determined after biofilter treatment, depending upon the temperature variations in the biofilter water occurring due to seasonal changes. Log_{10} reductions of 1.5 to 2.5 were achieved after collimated UV beam treatment with an average UV dose of 60 mJ/cm^2. Lower doses were not as effective. The presence of large particles (> 8μm), a high concentration of suspended solids and organic matter in swine manure, and UV-absorbing humic acids may provide shielding to microorganisms, and thus encourage their persistence under low and medium UV application doses (Bitton *et al.*, 1972; Parkar and Darby, 1995; Jolis *et al.*, 2001).

2.5 Future research needs

Future research based on the above literature review depends upon the following needs that have to be addressed:

- Limited literature review is available on the pilot scale level treatment of animal manures. Detailed pilot scale assessment studies are required to establish a state of the art technique for animal manure treatment and management;
- "Animal wastewater disinfection for reuse" is an area where thorough and comprehensive research is required. Land application methods are still employed widely across the world as a BMP (Best Management Practice) to reclaim manure produced from animal production units. Chlorination has been a widely acknowledged method of disinfection, but due to problems with byproducts (toxic), efforts should be made to evaluate other, relatively safe and cost effective alternatives, such as ozone and UV irradiations. Laboratory and pilot scale research studies are required to estimate the feasibility of these technologies for agricultural wastewater reuse;
- Physical/chemical treatment is described as effective in removing solids and phosphorus, while biological methods are effective in removing organic matter and nitrogen. Further research is needed to investigate the potential of combined treatments using both physical/chemical and biological processes. Advanced treatment with membrane technology is one other option which needs to be studied;
- Odours have been recognized as a major problem generated by confined animal production facilities. New treatment technologies must be developed in such a

way as to address the odour problem effectively along with other desired objectives; and

- The feasibility of options such as reuse of treated swine liquid manure in production facilities for cleaning the barns and for drinking animals.

3.0 MATERIALS AND METHODS

3.1 Materials

This project was conducted at 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 (liters). This means that approximately 75.7 m^3 (20,000 gallons) 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 inside storage tanks with a total storage capacity of approximately 20,000 gallons. The stored swine manure is directly pumped out to a lift station (pit) located next to the swine facility building. From there, it is further pumped out to a Composter Unit, where it is treated and reused through composting techniques.

3.1.1 Laboratory set-up and experimentation

The samples for the Laboratory experiments were collected in 20 L (0.02 m^3) buckets from the raw manure pit (lift station) using a submersible suction pump. All experiments were performed in the laboratories located in the Environmental Engineering Building, University of Alberta. The samples transported in the buckets from the farm were collected in a PVC barrel (0.57 m diameter and 0.9 m deep), with 55 gallons (0.2 m^3) capacity, set up in a cold room (temperature ~ 4°C) for storing the samples. Primary settlement (for 24 hours) was achieved in the PVC barrel. The samples of primary settled supernatant were collected with a pipette from the top of the manure level in the barrel.

The supernatant was further used in the jar test to simulate coagulation, flocculation and settling processes. The supernatant obtained from the jar test was then filtered (Fractionation test) using membrane filters of different pore sizes. The filtrates obtained from the filtration process, along with the primary settled and jar test supernatants, were tested for UV disinfection with a low–pressure UV lamp. Analysis work was conducted on all the samples: fresh raw manure, primary settled supernatant, jar test supernatant, filtrates, and finally, on the samples obtained after UV disinfection.

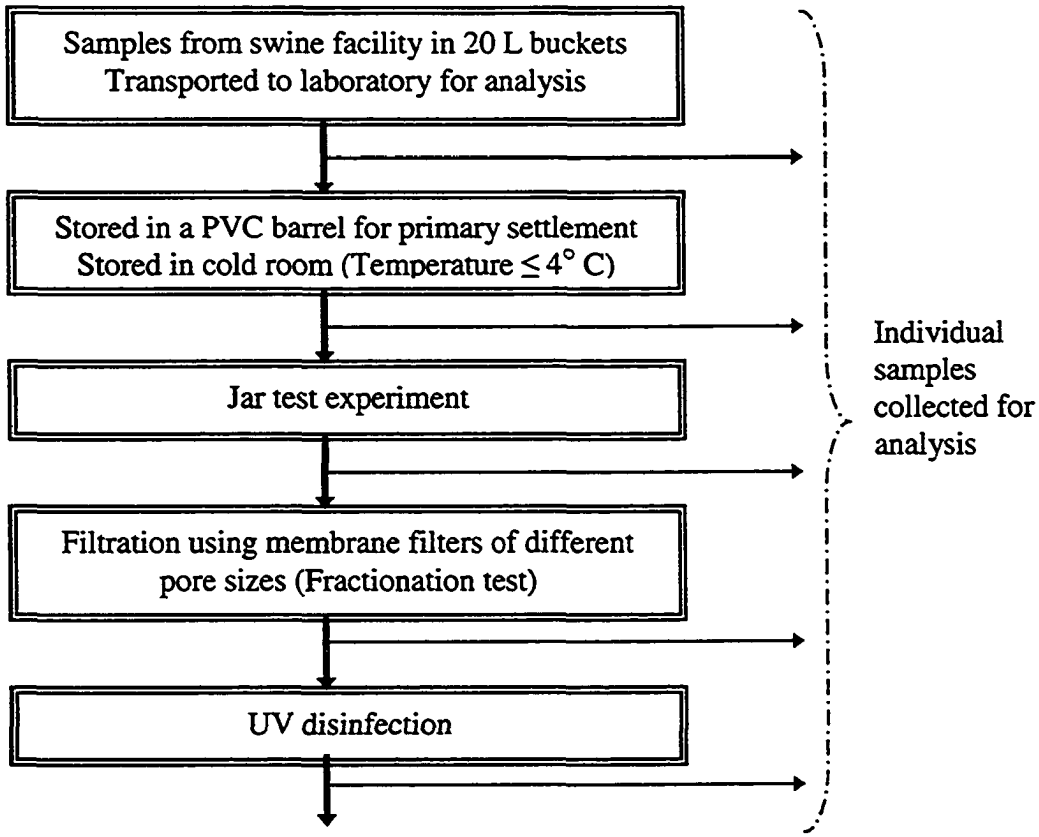


Figure 3.1 Flow chart indicating all the activity steps involved in laboratory experimentation.

The analysis work was aimed at determining the effects of physical/chemical treatment performed on swine manure in terms of solids and organic matter removal, and

microbial, nitrogen and phosphorus removal. Figure 3.1 shows a flow chart of all the activities involved in the laboratory experimentation with swine liquid manure.

3.1.1.1 Jar test experiment

Phipps & Bird™ (PB-700™ Jar tester) six-paddle stirrer with illuminated-base jar test set-up (Figure 3.2) was used to perform jar tests simulating the coagulation, flocculation, and settling processes achieved in the pilot-plant stationed at the University Research Farm.

Figure 3.2 Jar test apparatus.

The 24 hours settled supernatant was used as a sample in all the jar tests performed. Alum doses of 1200 mg/L and 1600 mg/L were used in all except for the last experiment, where a 60 mg/L alum dose was used because the raw manure was initially diluted by a factor of 50. To determine the effectiveness of the jar test, control samples (without alum) were involved in all of tests performed. The rapid and slow mixing speeds and times were 100 rpm and 100 s, and 20 rpm and 2 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 were used to collect the samples from each jar. All samples, except the control, were then mixed to make a composite sample. These samples were used further in the fractionation test and other analysis tests.

3.1.1.2 Fractionation test

A fractionation test was conducted to simulate the filtration step performed in the pilot plant. Millipore Isopore™ membrane filters were used to filter supernatants obtained after 24 hours settling and jar tests. These supernatants were filtered separately through a series of filters with pore sizes of 8 μm, 10 μm, 12 μm and 20 μm. The primary supernatant (24 hours settled) could not be filtered through the 8 μm filter because it clogged the filter. The filters with pore sizes of 5 μm and 2 μm were also tried, but were found to be easily clogged and hence were rejected.

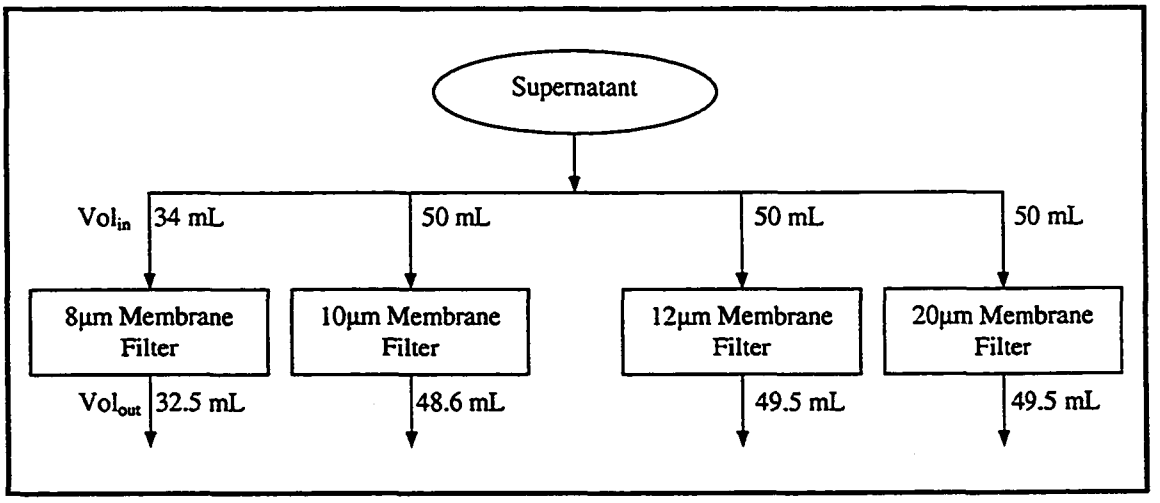


Figure 3.3 Schematic diagram of the fractionation process.

A schematic of the fractionation test is presented in Figure 3.3. The samples obtained after filtration were subsequently used for sample analysis and disinfection with UV irradiations.

A mass balance analysis was conducted on the total volume of supernatant used in the fractionation process. From the mass balance analysis, it was noted that the 8 μm filter retained more volume on its surface than did the others. The results obtained for all the filtrates also confirmed the purpose of the fractionation test.

It was observed, from the particle count analysis and initial UV experiments, that particles with sizes ranging from 2 μm to 8 μm were not removed by filtration and thus may hinder the effectiveness of UV irradiation by providing a shield to the microorganisms. To overcome this problem, the fractionation procedure was modified. The raw manure sample was diluted 1: 50 times and allowed to settle for 24 hours. A jar test experiment was performed on the supernatant obtained after the settling. Preliminary settling was negligible due to high dilution. After the jar test, primary and jar supernatants were filtered through a set of filters of different pore sizes. With this modification, we were able to filter these supernatants through 2μm and 5μm filters without any problem. Microbial Log_{10} reductions were significantly improved after this modification.

3.1.1.3 SEM (Scanned Electron Microscope) analysis

Scanned Electron Microscope (SEM) analysis was performed on all the membrane filters used in the fractionation test. The main purpose of performing SEM analysis was to physically verify the results obtained from the fractionation test and to see which types

of choking material (solids, organic or microbial mass) in the sample caused filter clogging.

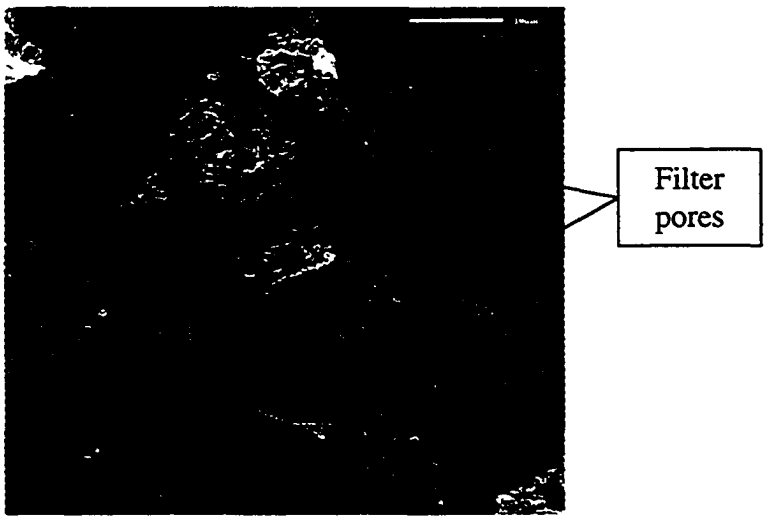


Figure 3.4 A membrane filter (pore size 20μm) after filtration with swine manure.

The SEM (Model # JSM6301FXV, Japan Electron Optics Ltd.) used in this project was located in a laboratory at the Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada. 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 demagnify the beam into a small-diameter probe. The demagnified probe is then scanned over the specimen. In order to get 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).

3.1.1.4 Ultraviolet (UV) disinfection

The use of ultraviolet (UV) irradiation for the disinfection of treated wastewaters has become accepted as an effective and economical alternative to chlorine or ozone use. According to WPCF (1986), disinfection by UV irradiation is a physical process that involves the transference of electromagnetic energy from a source (UV lamp) to an organism's cellular material, thereby affecting its existence.

In this project, a collimated beam apparatus manufactured by Calgon Carbon Corporation, Pittsburg, PA (Figure 3.5) was used to generate UV irradiations. The UV experiment was performed in a laboratory of the Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada (Figure 3.5).

Figure 3.5 Collimated beam apparatus for UV experiments.

The same samples obtained from the fractionation test were analyzed for UV inactivation. Both medium-pressure and low-pressure UV lamps were tested separately for their effectiveness on treated and filtered swine manure samples. Medium-pressure lamps are more effective in microbial inactivation than low-pressure lamps because of: (1) Higher intensity of radiations, and (2) Low photoreactivation (re-growth phenomenon of some microorganisms) (Bolton, 2001; Kallsvaart, 2001). Craik *et al.*, (2001) reported that low-pressure lamps were more effective in terms of germicidal effect compared to medium-pressure lamps. According to them, the selection of low-pressure or medium-pressure lamp depends primarily on economic considerations. There are fewer extraneous variables involved with the low-pressure lamp outputs, as compared to more variables associated with the medium-pressure lamp outputs. The use of a medium-pressure lamp requires more sophisticated instruments for output measurements, and these act as a constraint in experiments. The results obtained from low-pressure lamp are discussed in the Results and Discussion section.

The samples were first scanned in a spectrophotometer (Figure 3.6) to measure their transmittance. Glass plates containing 20 mL of each sample were placed under the central hub (cylindrical pipe extension used to concentrate UV irradiation over the sample; Figure 3.5) of the UV generator. Calculations for irradiance intensity, exposure times and some other factors were carried out in a Microsoft Excel file program provided by Bolton Photosciences Inc.[!!]

[!!] Dr. James R. Bolton, Adjunct Professor, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada; and President, Bolton Photosciences Inc., 628 Cheriton Cres. NW Edmonton, AB, Canada T6R 2M5. Website: www.boltonuv.com

The program provided the exposure time values for each sample directly once inputs such as transmittance, UV dose (mJ/cm^2) and irradiance (mW/cm^2) values were entered into the program. The effectiveness of UV irradiation on the treated swine manure samples was determined by performing fecal and total coliforms tests on the samples before and after disinfection. Figure 3.6 depicts the spectrophotometer and computer used for analyzing samples for transmittance and determining the exposure times for corresponding UV doses applied.

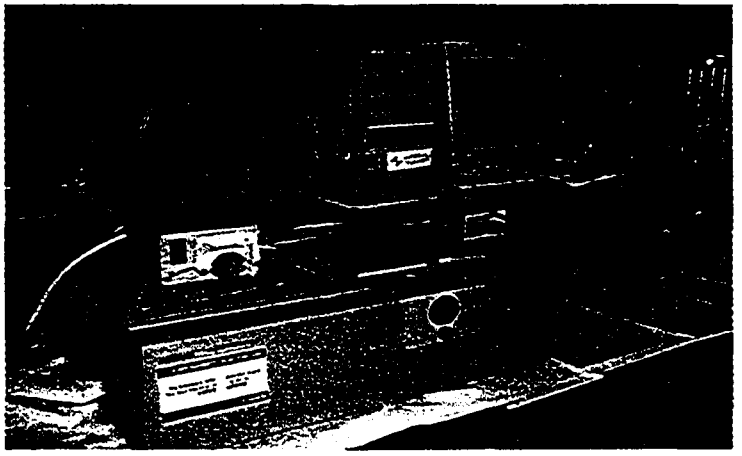


Figure 3.6 Spectrophotometer and computer system used in the UV experiment.

3.1.2 Pilot plant set-up

A pilot treatment plant was set up in a trailer unit adjacent to the manure storage tank (lift station) located beside the Swine Research Facility of the University of Alberta. The pilot plant comprised a customized sludge blanket clarifier with rapid and slow mixing chambers, rapid and slow mixers, patented Martin filters unit, two axial-flow auger pumps, three PVC storage tanks and PVC pipes and hoses for connections. The complete pilot plant layout is presented in Figure 3.7. Figure 3.8 depicts the manure treatment plant

set up inside the trailer to treat swine some of the liquid manure produced in the Swine Facility.

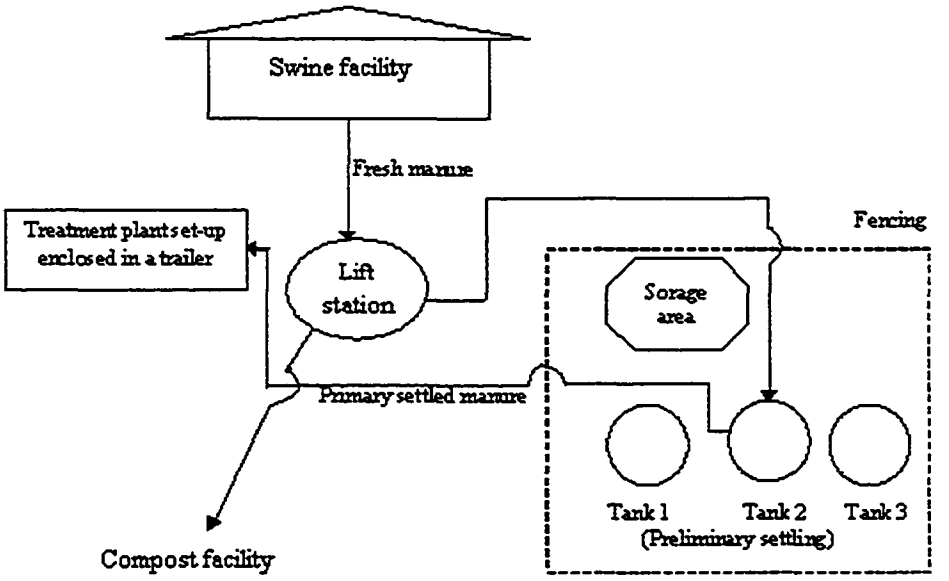


Figure 3.7 Schematic of pilot plant used for swine manure treatment.

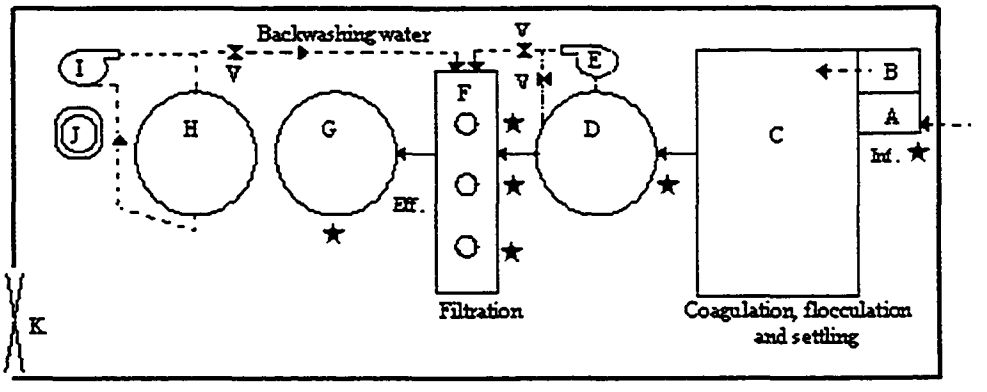


Figure 3.8 Top view (not scaled) of pilot plant set up (inside the trailer) for swine manure treatment. (A: rapid mixer chamber; B: slow mixer chamber; C: customized sludge blanket clarifier; D, G and H: Water storage tanks, F: Martin filters unit with three filter columns; E and I: pumps, J: compressor, K: trailer's opening door, V: Bypass valve). Solid arrows indicate the direction of liquid manure/supernatant flow and the dashed arrow indicates the water flow line for backwashing the filters. The asterisk sign indicates the sampling port locations).

3.1.2.1 Pilot plant operation

The pilot plant was operated manually. A submerged type suction pump was used to pump out 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 (~ 5000 gallons)) located nearly 25 m away from the lift station. The raw manure was normally left in the tank for a minimum period of 24 hours. The settled manure (supernatant) was then pumped from the settling tank to the rapid mixing chamber of the clarifier. A flexible hose (5 cm diameter) was used to transfer the manure from the raw manure pit to the preliminary settling tank and then to the clarifier. Separate hoses were used for fresh raw manure and settled manure to avoid mixing different manures and changing the manure characteristics.

3.1.2.2 Customized sludge blanket clarifier: Design and operation

The customized sludge blanket clarifier used in this project for coagulation, flocculation and settling (physical/chemical treatment) of the primary settled swine manure is shown in the Figure 3.9a and 3.9b. The clarifier design comprised four different chambers: the rapid mixing (coagulation) chamber, the slow mixing (flocculation) chamber, the froth and scum disposal chamber and the sludge blanket chamber. The rapid and slow mixing chambers (tanks) are shown in Figure 3.10. The design of the clarifier was custom engineered in that it consisted of three different chambers for coagulation, flocculation and settling, unlike the conventional sludge blanket clarifier where coagulation and flocculation are achieved in a common central compartment. The clarifier was manufactured entirely with aluminum metal.

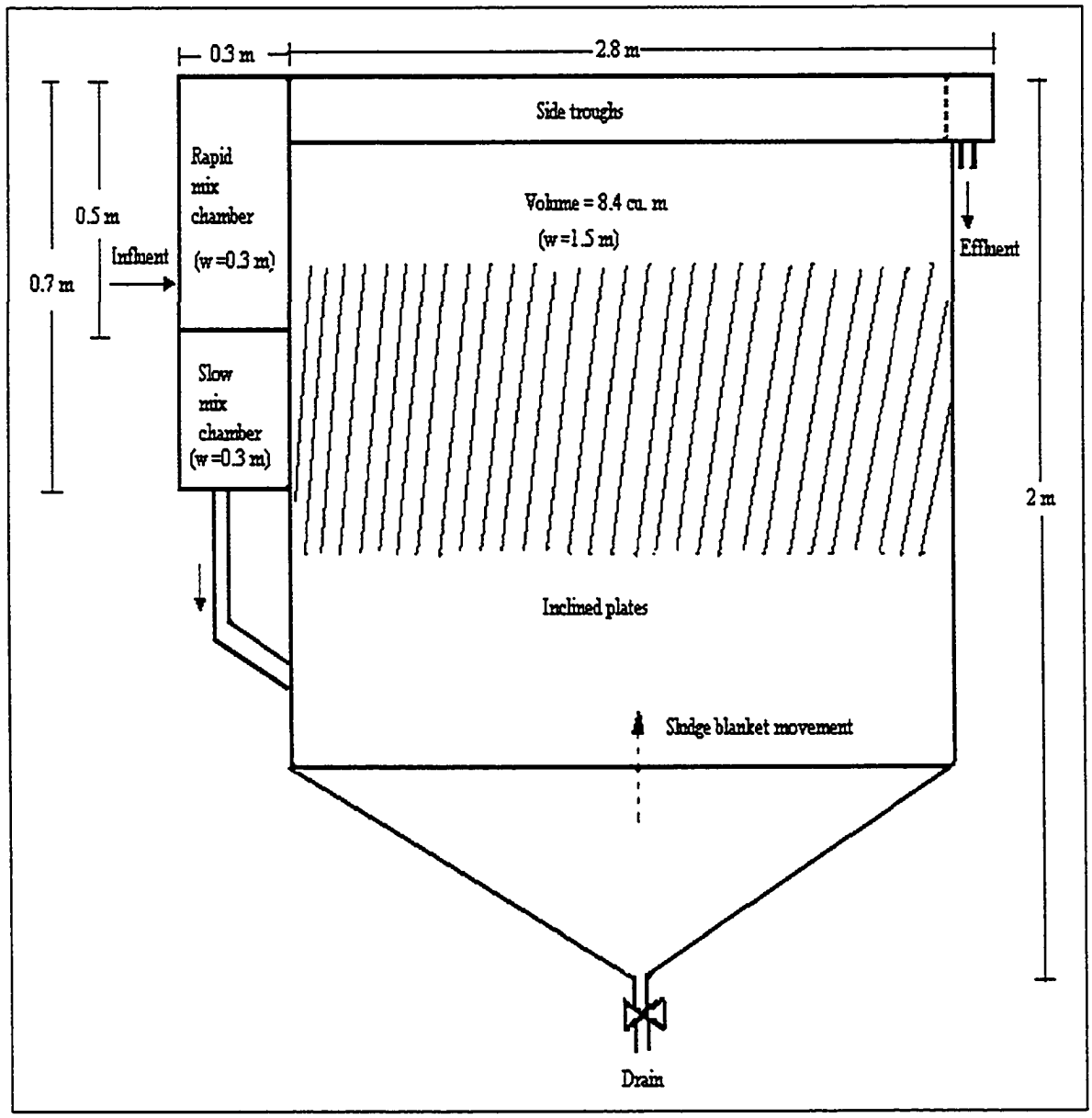


Figure 3.9a Cross-sectional view of sludge blanket clarifier.

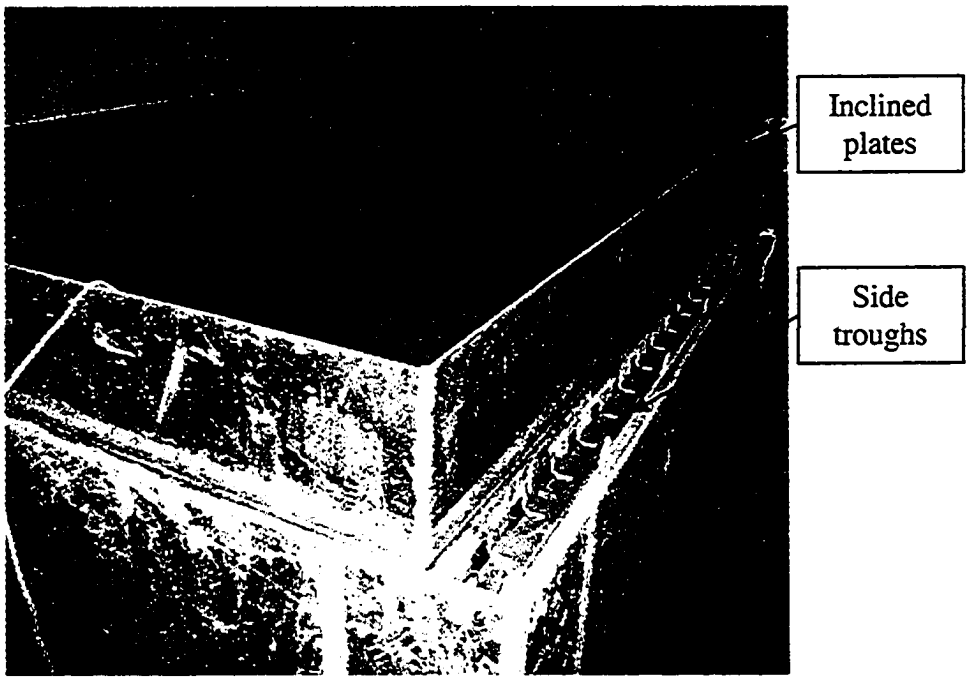


Figure 3.9b Customized sludge blanket clarifier.

The rapid mixing tank received the primary settled manure (supernatant) from the settling tank and alum (30% strength) was fed into the rapid mixing tank with a perilistic pump at a controlled flow rate and known concentration. The flow was controlled by a valve provided in the pipeline connected to the rapid mix tank. Rapid mixing (100 to 120 rpm) was provided using a paddle impeller attached to a motor. The alum reacted with the manure and flocs of different sizes were produced. The coagulated manure was then moved to the slow mixing tank under the action of gravity.

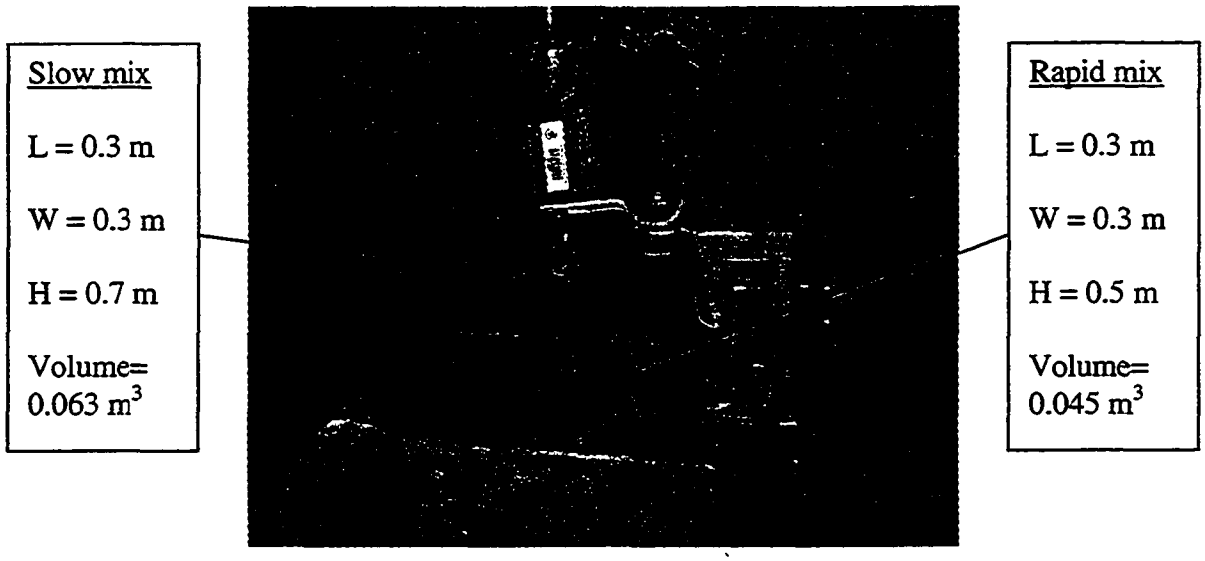


Figure 3.10 Rapid and slow mixing chambers with rotating impellers and motors.

Flocculation was achieved in the slow mixing tank. Slow mixing (20 to 40 rpm) was provided using a vertical paddle impeller attached to another motor. Gentle mixing enhances the formation of flocs, and hence flocculation. Due to the flocculation and the small size of the tank, froth formed and accumulated on top of the manure level in the tank. To avoid overflow, a froth and scum disposal tank was provided beside these chambers. The froth (scum layer) was usually removed manually with the help of a scoop. The flocculated manure was then moved to the sludge blanket tank through a pipe connecting the two tanks.

The flocculated manure entered the sludge blanket tank from the bottom. The level of manure was increased gradually until it reached the top. Side troughs were provided along the circumference of the tank. When the tank was completely filled, the manure fell, under gravity, into the side troughs through orifices provided on the walls separating the tank and the troughs. The troughs were further connected to a clarified manure

storage tank where the clarified supernatant (manure) was stored and subsequently used as influent for the filtration step.

Initially, the pilot plant operation was carried out for 24 hours without storing the clarified supernatant in order to build up the sludge blanket at the bottom of the tank. The level of the blanket was regularly checked by inserting a long graduated glass tube into the tank and then pulling it out, while blocking the airflow by pressing the thumb on one side of the tube. Once a sludge blanket is formed, the tube will suck some sludge into it, and thus, the sludge level in the tank can be measured. To enhance the settling process, and hence sludge blanket formation, inclined plate settlers were provided in the tank.

When the sludge blanket was developed, the plant was run at different flow rates and alum concentrations in order to determine the best running conditions for the clarifier. The quality of the effluent obtained after clarification was analyzed for each different flow rate and several different alum doses. Jar tests were performed in the laboratory to determine the best alum dose. From the initial test runs of the clarifier, it was noted that the scum layer developed above the manure level in the clarifier and its side troughs eventually increased the solids level in the effluent. To avoid this problem, the scum layer was removed regularly with the help of a scoop.

The clarifier worked very well. Most of the solids and phosphorus removal occurred during preliminary settling (for 24 hours) and the chemical treatment performed in the clarifier. The only drawback noted in operating the clarifier was its sensitivity to variations in the flow rates of swine manure. The quality of the clarified effluent deteriorated when the flow rate was increased over 10 gpm (gallons per minute) (~

0.00064m^3/s). Therefore, keeping this factor in mind, the clarifier was run at lower flow rates (8 and 5 gpm) and the best determined alum dose.

3.1.2.3 Patented Martin filters

The patented Martin filter columns were supplied by the John Martin Company of Wichita Falls, Texas. A total of three columns were used in this project and are shown in Figure 3.11a. Figure 3.11b depicts a dismantled Martin filter, with the concentric pipes shown individually.

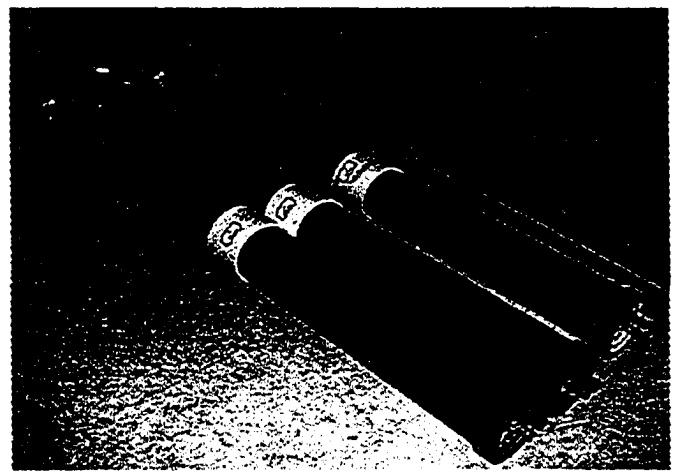


Figure 3. 11a Patented Martin filters (dismantled).

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 may 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 3.11b Parts of a Martin filter (overhauled).
(Courtesy: John Martin Company, Wichita Falls, TX, USA)

3.1.2.4 Martin filters operation

The filters worked on a down-flow (gravity) arrangement. The feed was provided from the top of the column and the filtered effluent was collected from the bottom in a storage tank. The clarified effluent that was stored in a tank after clarification in the sludge blanket clarifier was fed as influent to these filters. An auger type axial flow pump was used to supply the clarified supernatant to the filter columns. A flow control valve was provided to regulate the flow of supernatant into the columns. A flow meter across the main supply line and three pressure gauges were installed with each filter column to determine the instantaneous flow rate and pressures in the lines. Three sampling ports

(taps) were provided to obtain sample from each filter column. The filter operation was divided into two main modes: filtration and backwashing (Figures 3.12 and 3.13).

During filtration mode, the clarified effluent was pumped to the first filter column from the top. There were two main points of entry, namely the central and annular inlets, provided for the influent. The annular space surrounding the innermost pipe was filled with glass bead media. The liquid manure was filtered there and then moved downwards by gravity and 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 same connections existed between the second and third columns. A storage tank was provided next to the filtration unit to receive the final filtered effluent. The flow rates were selected to be approximately the same (5 and 10 gpm) (3.15 and 6.3 $*10^{-4}$ m^3/s) as the flow rate of the primary settled manure into the clarifier. This was done so that both clarification and filtration operations could be performed simultaneously.

During backwashing mode, the 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 and exited the unit from the top, then proceeding 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 guidelines provided by the filter manufactures. During the running of the pilot plant, in-line pressures and flow rates were continuously monitored to avoid any troubleshooting.

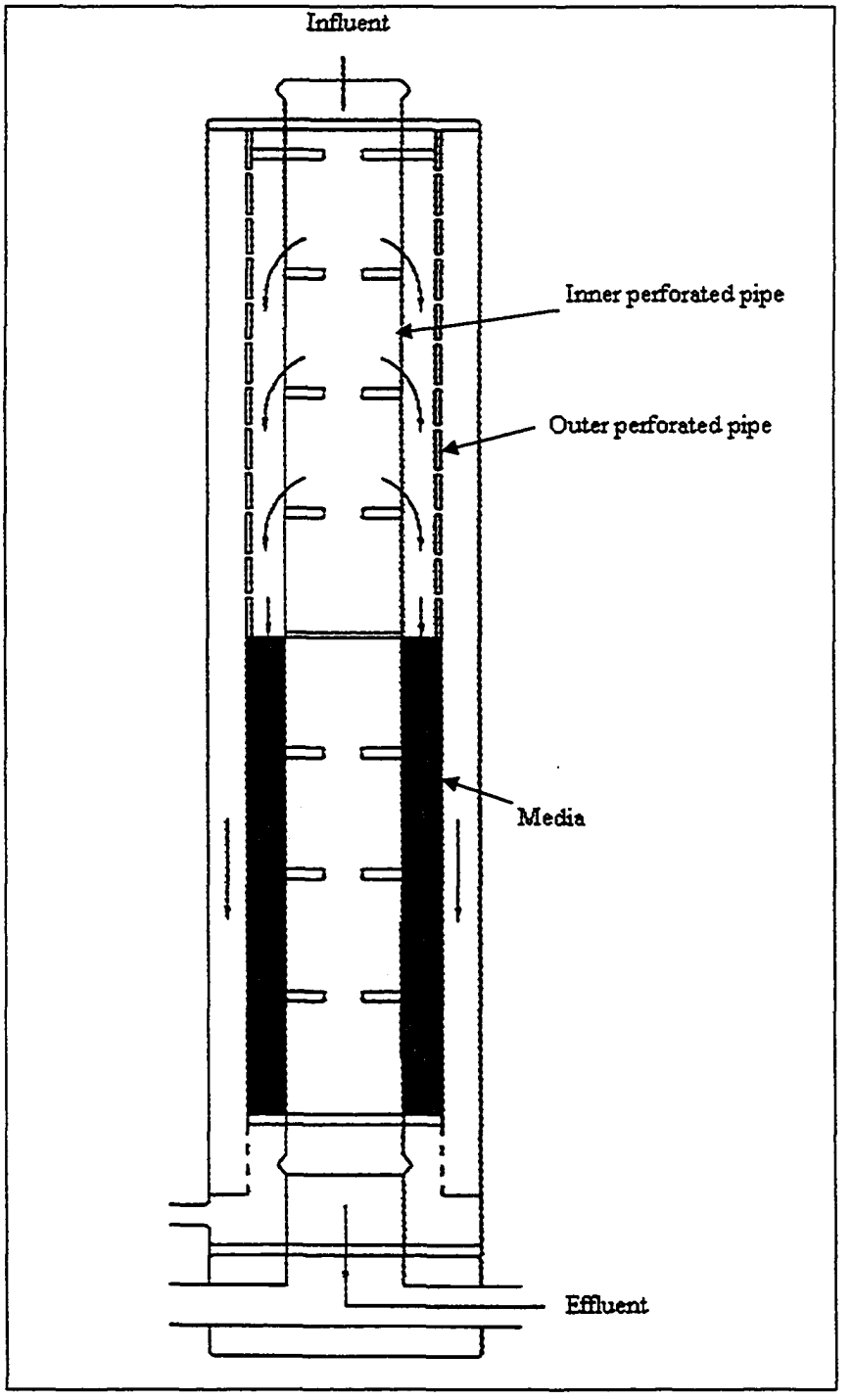


Figure 3.12 Martin filter during filtration mode.
(Adapted from Baxter *et al.*, 2001)

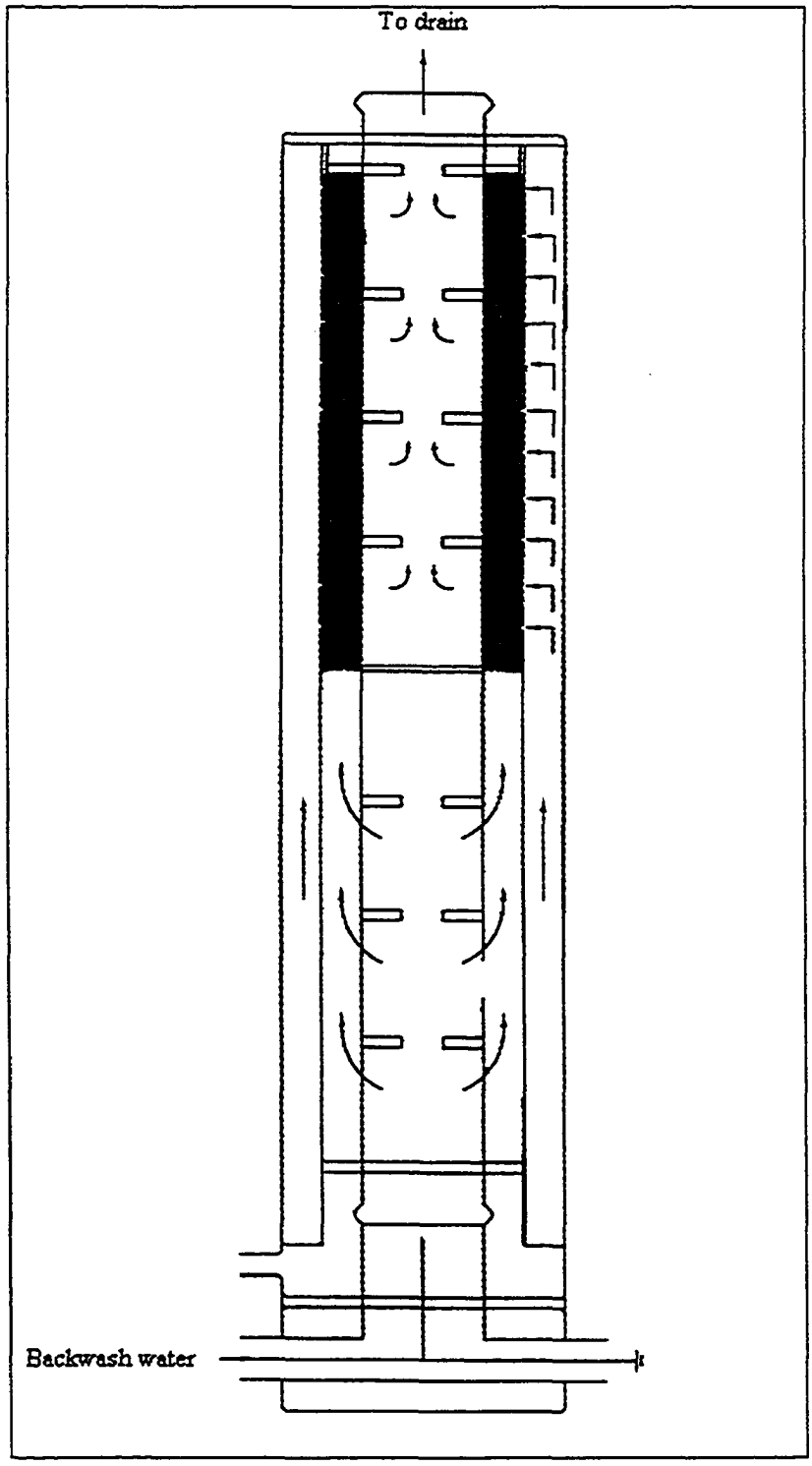


Figure 3.13 Martin filter during backwashing mode. (Adapted from Baxter *et al.*, 2001)

3.2 Methods

All of the quality parameters for swine liquid manure were analyzed according to the procedures described in the Standard Methods (APHA, 1995).

3.2.1 Total Suspended Solids (TSS)

3.2.1.1 General Discussion

The residue retained on the previously weighed standard glass fiber filter is dried to a constant weight at 103 to 105° C after a well-mixed sample was put through the filter. This residue is weighed as an increase in the weight of the filter that represents the measure of the total suspended solids (TSS) in that sample (APHA, 1995). 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 case of surface and ground waters, TSS is usually determined as turbidity, which represents very fine and colloidal suspended matter.

3.1.1.2 Apparatus

Gooch Crucibles, 25 mL capacity

Glass fiber filters, special 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 103 to 105° C

Desiccator, for moisture control provided with a color indicator or instrumental indicator *Vacuum Filtration assembly*, vacuum suction pump, volumetric flasks and holding unit for Gooch crucibles.

3.2.1.3 Procedure

a. *Set-up of filters in Gooch crucibles:* The crucibles were washed, rinsed and then dried in the oven for 10 to 15 minutes. Glass filters were then set on the crucible holding unit and filters were added. The filters were then wetted with deionized water (DI) with the vacuum already applied. They were then placed in the oven at 103 to 105° C for at least one hour and subsequently cooled in the desiccator for at least one hour to balance the temperature and weight. Crucibles were weighed before being used in filtration.

b. *Filtration step:* Different sample volumes of 2 mL, 5 mL and 10 mL were selected (depending upon the solids concentration levels and physical appearance of the raw samples) to ensure that more representative samples were used in each run. Several dilutions (5, 10 and 20 times) were also used as it was not always possible to filter the sample directly. Graduated cylindrical tubes were used to transfer samples instead of the usual volumetric pipettes because it was found that the tip of the pipette was very easily clogged with swine manure samples. A second reason for not using the volumetric pipettes was to avoid higher dilutions of samples which may have resulted in errors in TSS determination. The samples were then filtered through the Gooch crucibles.

c. *Sample analysis:* The crucibles were taken off the holding unit, placed in the oven for 24 hours, and then left to cool in the desiccator for at least one hour. After cooling,

the crucibles were weighed a second time to measure the increase in the weight of the filter. All the samples were analyzed in triplicate to ensure quality assessment and the final results were averaged.

d. Calculation:

$$TSS\ (mg/L) = \frac{(W_f - W_i) \times 1000}{sample\ volume\ (mL)}$$

Where:

W_i = Initial weight of the filter + Gooch crucible (before filtration), mg

W_f = Final weight of filter + Gooch crucible (after filtration), mg

3.2.2 Total Volatile Suspended Solids (TVSS)

3.2.2.1 General discussion

The volatile content of suspended solids can be determined by igniting the Gooch crucible with the filter at 550° C for 15 to 20 minutes (APHA, 1995; Sawyer *et al.*, 1994). Generally, volatile content accounts for 80% of the total suspended content in a sample. The test is conducted to determine the percentage of volatile and fixed solids in the total suspended content in a sample. Volatile solids are expressed as a percentage of total suspended solids.

3.2.2.2 Apparatus

Apparatus listed in the section 2.2.1.2. In addition:

Muffle furnace, to ignite the glass fiber filter at 550° C

3.2.2.3 Procedure

a. *Filter set-up and filtration:* The procedure was almost the same as that described in section 2.2.1.3 for TSS analysis. The only difference was that the crucibles needed to be dried in the muffle furnace instead of the oven before the filters were added to them. This was done to ensure the complete evaporation of any residue left from the previous tests.

b. *Sample Analysis:* The crucibles, after measuring the weights for TSS calculations, were placed in the muffle furnace at 550° C for 15 to 20 minutes. They were then put in the oven for an hour, and then into the desiccator for cooling to room temperature. Finally, the weights were taken.

c. *Calculation:*

$$TVSS\ (mg/L) = \frac{(W_f - W_{f'}) \times 1000}{sample\ volume\ (mL)}$$

Where:

W_f = Final weight of the filter + Gooch crucible (after filtration), mg

$W_{f'}$ = Final weight of filter + Gooch crucible (after ignition), mg

3.2.3 Total Dissolved Solids (TDS)

3.2.3.1 General discussion

The dissolved solids consist of those remaining after the filtered sample has been evaporated. A known volume of filtrate obtained after filtering a well-mixed sample through the glass fiber filter (used in TSS determination) is evaporated in a pre-weighed dish and dried to a constant weight at 180° 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 its specific conductance or conductivity. But in this project, TDS were measured by evaporating the filtered sample and then measuring the increase in the weight of the evaporating dish.

3.2.3.2 Apparatus

Evaporating dishes, 40 mL capacity

Gooch crucibles, 20 mL capacity

Glass fiber filters, special 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 180° C

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

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

3.2.3.3 Procedure

a. *Sample preparation and filtration:* All the samples were diluted before filtration. A number of dilutions (5, 10, 20, 25 and 50 times) were selected depending upon the quality of the raw swine manure sample. The same steps were followed for the filtration of samples as is described in section 2.2.1 (TSS determination), except that

higher volumes (100 to 200 mL) of sample were filtered and the filtrate was not discarded.

b. *Sample analysis:* A known volume (usually 25 mL) of filtrate was then transferred to previously weighed dishes and the dishes were left to evaporate overnight in the oven at 180° C. The dishes were cooled to room temperature in the desiccator for at least one hour and then weighed again. The samples were analyzed in triplicate.

c. *Calculation:*

$$TDS\ (mg/L) = \frac{(W_f - W_i) \times 1000}{sample\ volume\ (mL)}$$

Where:

W_i = Initial weight of the evaporating dish, mg

W_f = Final weight of evaporating dish + weight of residue, mg

3.2.4 Total Phosphorus (TP)

3.2.4.1 General discussion

Phosphorus in wastewater occurs mostly as orthophosphate (reactive phosphates), polyphosphate (condensed phosphates) and organically bound phosphate (APHA, 1995). Phosphorus analysis basically requires two steps for its determination: conversion of all phosphorus forms to dissolved orthophosphate (digestion) and then colorimetric determination of dissolved orthophosphate. In this project, the Ascorbic Acid Method (APHA, 1995) was used to determine the total phosphorus concentration levels in the raw and treated swine manure samples.

3.2.4.1 Apparatus

Spectrophotometer, Ultraspec® 2000 Pharmacia Biotech

Autoclave, for operation at 121° C, 137 kPa

Glassware, Acid washed glassware

3.2.4.2 Procedure

a. *Sample storage:* All the samples were preserved by adding a few drops of concentrated sulfuric acid to maintain the pH level below 2. The samples can be stored for 28 days in the cold room with temperature $\leq 4°$ C.

b. *Sample preparation:* All the raw samples were analyzed with a constant dilution factor of 100, while a dilution factor of 50 was used for the chemically treated and filtered samples. Blank and phosphate standard solutions (at least 3) were run each time to ensure the reliability of each test. For a quality check, all the samples were run in duplicate.

c. *Digestion:* 50 mL of each of the diluted samples was poured into Wheatman Bottles (125 mL) through volumetric pipettes. This was followed by the addition of one drop of phenolphthalein indicator solution: sulfuric acid (11N H_2SO_4) was added if red color appeared. Subsequently, 1 mL of 11N H_2SO_4 and 0.4 g (one scoop) of solid ammonium persulfate were added. The bottles were covered with aluminum foil paper. The samples were autoclaved for 30 minutes at 121° C and 137 kPa pressure and then cooled to room temperature. After cooling, one drop of phenolphthalein indicator solution was added (sulfuric acid to be added if red color appeared). Sodium hydroxide (5N NaOH) solution was added to each bottle until a light pink color appeared. Then, 50 mL of each sample was transferred to 250 mL Erlenmeyer flasks.

A few drops of 11N H_2SO_4 were added to all the samples to remove the pink color. This was followed by the addition of 8 mL of combined mixed reagent (Sulfuric acid, potassium antimonyl tartrate solution, ammonium molybdate and ascorbic acid) to each sample.

d. *Sample analysis:* The samples were then analyzed in the spectrophotometer at a wavelength of 880 nm. For better results, all the samples need to be analyzed within 10 to 30 minutes of the addition of reagent into the samples.

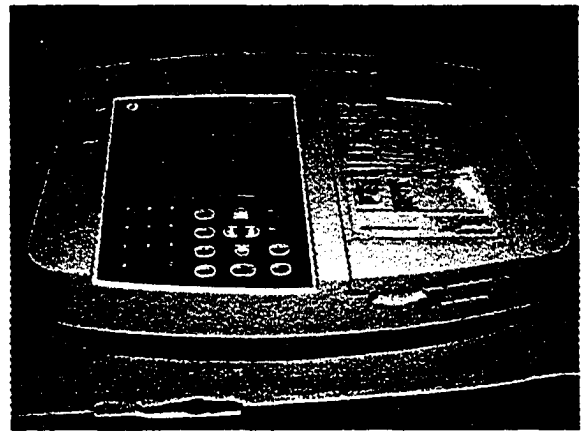


Figure 3.14 Spectrophotometer used for TP determination.

e. *Calculation:* A standard calibration curve was generated from the readings obtained from the standards. The phosphorus concentration for all the samples was then computed from this standard curve.

3.2.5 Total Kjeldahl Nitrogen (TKN)

3.2.5.1 General discussion

Nitrogen in the environment exists in two forms – organic and inorganic. All nitrogen in organic compounds is potentially organic nitrogen (Sawyer *et al.*, 1994). Inorganic

forms include ammonia nitrogen, nitrite and nitrate. Nitrogen determination in wastewater treatment plants is very important because it cuts the running cost of the plant by avoiding nitrification in the wastewater.

According to Sawyer *et al.*, (1994) the feces of animals contain appreciable amounts of unassimilated proteins (organic nitrogen). TKN includes both organic nitrogen and ammonia nitrogen. Keeping this point in mind, only the TKN test (rather than total nitrogen, nitrate and nitrite tests) was selected to determine the total organic and ammonia nitrogen in the swine manure samples. Estimating the availability of laboratory equipment and the accuracy desired, in terms of the range of nitrogen concentration in the samples, the volumetric method of analysis was selected. The test follows a three-step procedure – *Digestion, Distillation* and *Titration.*

3.2.5.1 Apparatus

Digestion apparatus, Tecator Kjeldahl 2020

Distillation apparatus, Tecator 1026

Titration apparatus, Mettler Toledo DL 50 autotitrator

3.2.5.2 Procedure

a. *Sample preparation:* Two sample dilutions (50 and 100 times) were performed, but the latter dilution yielded better and more consistent results. For accuracy, precision and quality assessment, blanks and standards were run each time along with regular samples and each sample was analyzed in duplicate.

b. *Digestion:* In this step, all the organic nitrogen converts into ammonia nitrogen. A Tecator Kjeldahl 2020 digestion apparatus was used for digestion. The operating

instruction manual "Tecator Application Note AN 300 for the determination of nitrogen according to Kjeldahl using block digestion and steam distillation" was followed.

Two Kjeltabs (tablets consisting of 3.4 g of K_2SO_4 and 0.4 g of $CuSO_4$) and one boiling rod were added to each boiling tube (250 mL). Kjeltabs act as a catalyst, increasing the boiling point of the acid (conc. H_2SO_4) during digestion and hence the decomposition of the organic nitrogen. 100 mL of each sample (after dilution) was added to the tubes. Then, under the fume hood, 12 mL of concentrated sulfuric acid was added carefully with a dispensing pump to each tube. All of these tubes were then placed into a stainless steel frame which held the tubes over the Kjeldahl 2020 digestion apparatus. The apparatus was set for 30 minutes to an hour to reach a temperature of 420° C. This was followed by a digestion period of 70 minutes, after which the samples were allowed to cool for about an hour.

Figure 3.15 Digestion apparatus.

c. *Distillation:* During distillation, all of the ammonia nitrogen is absorbed into an absorbent solution (4% boric acid), which can then be measured by titrating it with acid (0.005N HCl). The Tecator 1026 apparatus was used for distillation and the operating instruction manual "the Tecator Application Note AN 300" was followed. During distillation, 75 mL of DI water and 100 mL of 40% NaOH solution were taken into the Tecator 1026 and the steam was injected directly into the sample. 25 mL aliquot of 4 % boric acid in a 250 mL beaker was used as an absorbent to receive the condensate from the Tecator 1026. The beaker should be shaken gently while receiving the condensate.

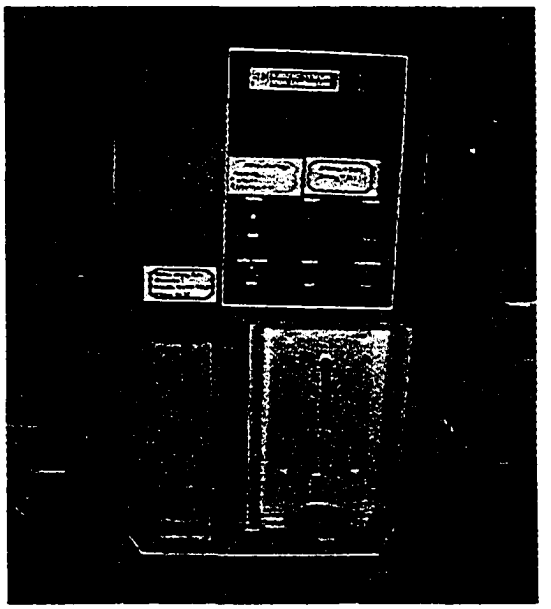


Figure 3.16 Distillation apparatus.

d. *Titration and sample analysis:* The titration was performed by a Mettler Toledo DL50autotitrator; 0.005 N HCl (hydrochloric acid) was used as a titrant. The operating manual "Tutorial: Mettler Toledo DL50/DL53/DL55 Titrators" was followed. The instrument (pH electrode) was calibrated with commercial pH buffers

each time it was used. The titrant was also calibrated with a standard solution of sodium carbonate (Na_2CO_3). Initially the end point was established by running the blank boric acid solution (25 mL boric acid + approximately 125 mL DI water) until a stable pH value was obtained. This value was inserted into the autotitrator programme for all pre-dispensing titrant volume options, enabling the autotitrator to stop dispensing titrant at the end point. The following sequence of samples was used for titration – blank boric acid sample (to establish end point), blank (DI water) samples, standards and then regular manure samples. The autotitrator was connected to a printer that gave us printed copies of the results.

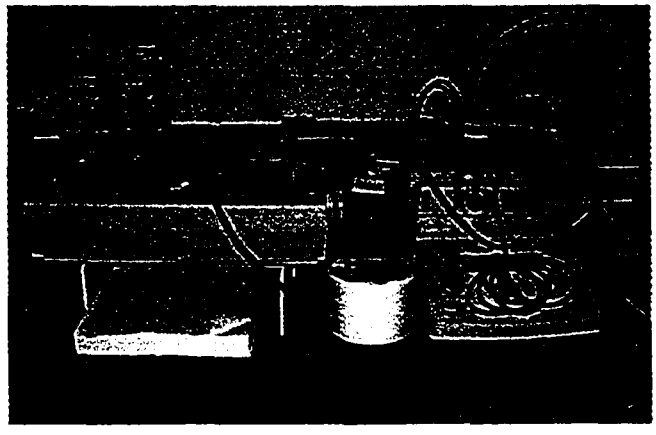


Figure 3.17 Auto-titrator and printer.

e. Calculation:

$$TKN\ (mg\ N/L) = \frac{(T-B)\times N\times 14.007\times 1000}{sample\ volume\ (mL)}$$

Where:

T = Volume of titrant used for sample, mL

B = Volume of titrant used for blank, mL

N = Normality of titrant to 4 decimal places

3.2.6 5-day Biochemical Oxygen Demand (BOD_5)

3.2.6.1 General Discussion

Determining five-day biochemical oxygen demand (BOD_5) involves the measurement of 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 5 to 7 days.

3.2.6.1 Apparatus

BOD incubation bottles, 300 mL

Air incubator, thermostatically controlled at 20 ± 1° C

Burette, 50 mL

Magnetic stirrer, to mix the sample during titration

3.2.6.2 Procedure

a. *Sample preservation and dilution buffer preparation:* Samples collected for BOD should not be preserved for long periods of time. Fresh samples can be preserved for 6 hours maximum in a temperature controlled room or refrigerator below 4° C. These guidelines were strictly followed. Some trial experiments were carried out to determine the best dilution for the swine manure sample. According to Standard Methods (APHA, 1995), the dilutions resulting in a residual DO of at least 1 mg/L and a DO uptake of at least 2 mg/L after a 5- day incubation period produce the most

reliable results. Out of three dilutions (6000, 3000 and 1500 times) performed, the middle one gave the most consistent and representative results. The blank samples (seed checks), standards (Glucose-glutamic acid) and the regular manure samples were run in triplicate to ensure quality and accuracy. Dilution buffer was prepared, according to the requirements of each run, by adding 1mL of phosphate (PO_4) buffer, $MgSO_4$ solution, $CaCl_2$ and $FeCl_3$ solutions to every 1L of DI water. The dilution buffer was saturated with DO by overnight aeration with organic-free oxygen before it was used the next day.

b. *BOD determination:* After the dilutions were complete, seeding was performed by adding 0.67 mL of seed developed from untreated swine manure to each bottle. This was followed by the addition of 10 mL of DI water in blank sample bottles; the same volume of standard solution and diluted samples were added to the other bottles. The dilution buffer was poured into the bottles very carefully so as to avoid any bubbles being left in the bottle that could possibly hinder the 5-day BOD results. 5-day BOD bottles were capped and kept for incubation in the temperature-controlled room at 20° C. The azide modification method was used to determine both 1-day and 5-day BOD. This method involved the addition of 1 mL of each of manganous sulfate solution and alkali-iodide-azide reagent to each bottle, followed by the addition of 1 mL of conc. H_2SO_4 and gentle mixing. Out of 300 mL of aliquot in the bottle, 201 mL was transferred to an Erlenmeyer flask and then titrated against standard sodium thiosulfate solution. Starch solution was used as an indicator. The titrant was calibrated each time the test was performed. The same procedure was repeated with 5-day BOD samples.

c. Calculation:

$$BOD\ (mg/L) = \frac{[(DO_1 - DO_5) - (DO_{sc1} - DO_{sc5})] \times 300\ (mL)}{sample\ volume\ (mL)}$$

Where:

DO_1 = 1-day DO of samples, mg/L

DO_5 = 5-day DO of samples, mg/L

DO_{sc1} = 1-day DO of seed check (blank) sample, mg/L

DO_{sc5} = 5-day DO of seed check (blank) sample, mg/L

3.2.7 Chemical Oxygen Demand (COD)

3.2.7.1 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.

3.2.7.1 Apparatus

Digester, HACH COD reactor

Spectrophometer, Pharmacia Biotech Novaspec II

COD vials, 10 mL

3.2.7.2 Procedure

a. *Sample preservation and preparation:* The samples for the COD test can be stored for 28 days in a temperature controlled room or refrigerator at a temperature of 4° C or less and a pH below 2. The samples should be allowed to reach room temperature before they are used for the test. The samples were diluted 50 times to get the best results.

b. *Digestion:* 3.5 mL of COD digestion reagent (mixture of 10.216 g $K_2Cr_2O_7$, 167 mL conc. H_2SO_4, 33.3 g $HgSO_4$ diluted in 1 L DI water), 2 mL of sulfuric acid reagent (10 g Ag_2SO_4 in 1 L conc. H_2SO_4) and 2 mL of sample were added to COD vials in sequence. The digester was set for 30 minutes to achieve a temperature of 140°C before the samples were put on it. The samples were digested for 2 hours and then cooled for a few minutes.

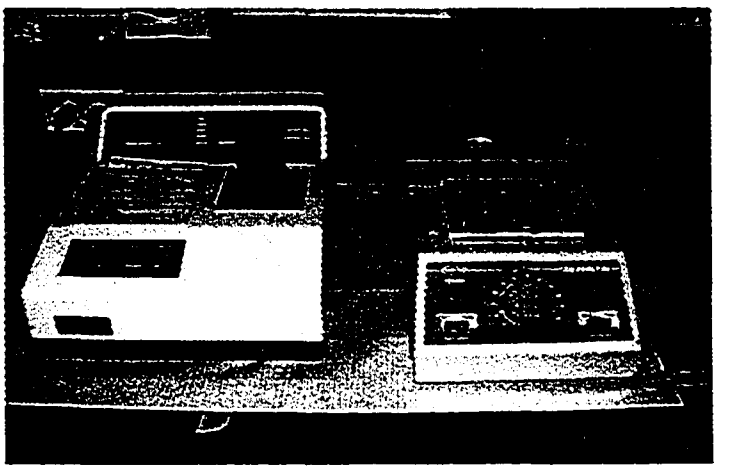


Figure 3.18 COD reactor with temperature probe and photospectrometer.

c. *Sample analysis and COD determination:* The Pharmacia Biotech Novaspec II spectrophotometer was used to measure the absorbance of each sample at 600 nm wavelength. Three COD standard solutions (potassium hydrogen phthalate, KHP) and

blanks were also run each time the test was performed. All the samples were analyzed in triplicate. A standard curve was drawn between absorbance and standard concentrations. COD concentrations were measured directly from the standard curve by incorporating the dilution factor.

3.2.8 Particle Counts (size distribution)

3.2.8.1 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 future modifications.

3.2.8.1 Apparatus

Particle Counter, HIAC ROYCO 8000 by Pacific Scientific Instrument

3.2.8.2 Procedure

a. *Sample preparation:* The samples were diluted adequately. Normally, a dilution factor of 100 was selected for raw manure samples, while the other samples were diluted 50 times 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 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 results on the screen of the electronic counter after taking the average of the three observations.

3.2.9 Fecal and Total Coliforms (FC / TC)

3.2.9.1 General discussion

The total coliform group has been used for many decades as an indictor of drinking water quality. This group is defined as gram-negative, non-spore-forming, rod-shaped, aerobic and facultative anaerobic bacteria that ferment milk sugar lactose and produce gas within 48 hours at 35°C. Fecal coliforms are a subset of the total coliform group. Fecal coliforms grow at elevated temperatures (44.5°C) within 24 hours. *E. coli* is a major subset of fecal coliform group (APHA, 1995).

3.2.9.2 Apparatus

Membrane filters, GN-6 grid, pore size 0.45 μm and diameter 47 mm

Filter holding assembly, to hold filters and facilitate filtration

Incubators, 35 ± 0.5 °C (for total coliforms) and 44.5 ± 0.5 °C (for fecal coliforms)

3.2.9.3 Procedure

a. *Membrane filtration technique:* The method 9222 (APHA, 1995) was followed for microbial analysis. The sample was diluted in a sequence of five dilutions (0.1, 0.01, 0.001 and so on) and then filtered through a 0.45 μm membrane filter set up in a filter holding assembly unit. These filters were then placed in a plate containing solid

nutrient media (agar) to grow microbial colonies. The m-Endo and m-FC media agars were used for the determination of total coliforms and fecal coliforms, respectively. The plates containing TC agar were stored in incubator at 35 ± 0.5 °C for 48 hours and the FC plates were stored at 44.5 ± 0.5 °C for 24 hours. At the end of their respective incubations, the colonies formed by the coliforms were counted and expressed as colony forming units (CFU) per mL in the sample. The plates were counted within the minimum to maximum countable range of 20 to 80 CFU/plate.

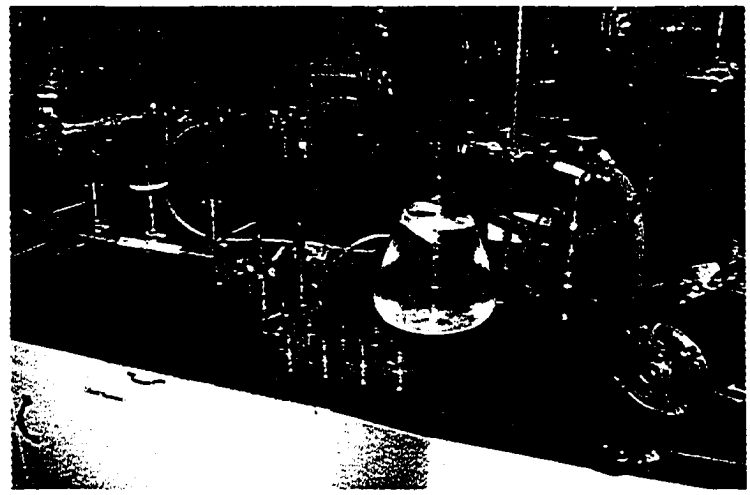


Figure 3.19 Filtration apparatus.

All the samples were run in duplicate and the average of the two specimens was taken in the final results.

4.0 RESULTS AND DISCUSSION

4.1 Pilot plant operation

4.1.1 Manure characteristics and the effect of preliminary settling

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; Loehr, 1977; Ra *et al.*, 1998; Powers and Flatow, 2002). Table 4.1 summarizes the raw and primary settled swine manure characteristics. It should be noted that swine manure characteristics vary substantially from sample to sample.

Table 4.1 Swine manure characteristics* (in mg/L).

Parameter	Raw Manure					Primary (24 hours) Settled Manure			
	Number of Runs	Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum
TSS	9	3945	1162	2217	5843	1843	301	1325	2267
TDS	6	4776	205	4475	4962	4791	153	4550	4901
TP	6	164	15	138	181	129	14	106	146
BOD_5	7	7315	842	6676	8762	6716	506	6071	7433
COD	6	11498	2691	9042	15585	9055	1836	7653	11958
TKN	5	1379	323	1026	1850	1492	244	1364	1928

*Based on samples taken during pilot plant operation.

Preliminary settling has been described as an effective and economic animal manure treatment process by many authors (Jett *et al.*, 1975; Pieters *et al.*, 1999; Gao *et al.*, 1993; Ndegwa *et al.*, 2001). Most of the previous work on preliminary settling has been conducted at the bench scale level and on wastewaters containing 1 to 7% total solids (TS) content. These studies concluded that low to medium strength wastewaters (containing 1 to 3% TS) settle more thoroughly in less time, as compared to high strength

(4% TS or above) wastewaters which take longer to settle. In addition, they concluded that the major portion of type II settling occurs during the initial hours. Further increases in solids reduction may be caused by the settling of fine particles which usually take a longer time to settle. In a pilot scale study, the % TSS removal efficiencies of 60 to 75%, depending upon the characteristics of raw manure, were achieved after 24 hours of settling in a tank (Zhu *et al.*, 2004). However, during this project we achieved approximately 53% of TSS and 22% of TP reduction after 24 hours of settling in a tank. These results were significant because a major portion of TSS and TP reduction occurred during preliminary settling of the raw manure. Moreover, this is also an important economical step, as it does not require the addition of any chemical or polymer.

4.1.2 Operational performance of clarifier

The custom designed sludge blanket clarifier ran successfully. An average of about 16% TSS and 30% TP were removed during the clarification step. Figure 4.1 explains the performance of the clarifier in terms of percent removal of TSS and TP at the two different flow rates used during the clarifier operation.

The performance of the clarifier was improved when the flow rate of the influent liquid manure was reduced from 8 gpm ($5.04* 10^{-4}$ m^3/s) to 5 gpm ($3.2* 10^{-4}$ m^3/s). This improvement can be attributed to the increase in the hydraulic retention time (HRT) of the slow and rapid mix tanks which occurred due to the decrease in influent flow rate. To run the clarifier simultaneously with the filtration unit, the influent flow rates to the clarifier and the filtration unit should be approximately equal. Therefore, the filtration

unit next to the clarifier was run at flow rates of 10 gpm and 5 gpm, respectively, in accordance with the flow rates of 8 gpm and 5 gpm for the clarifier.

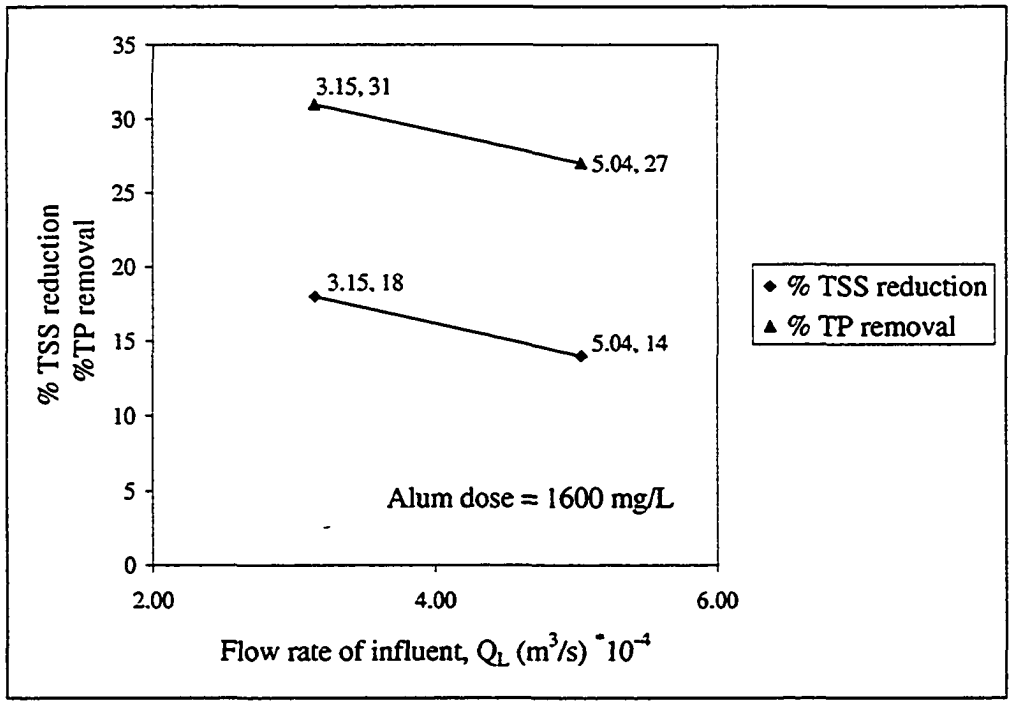


Figure 4.1 Performance characteristics of the clarifier.

4.1.3 Martin filters operation

A total of three filter columns was used in this project. Each filter used a glass bead media of different pore size. The three columns containing Mil-spec 5, 8 and 10 sized glass bead media were used in series in a coarse (higher void size) to fine (lower void size) arrangement. Filtration with a single filter containing Mil-spec 13 media was also tested against the in-series arrangement. Table 4.2 presents the relationship between Mil-spec size specifications, bead size and void size.

Table 4.2 Relationship between Mil-Spec, size of bead and corresponding void size

Mil-Spec	Bead size range (mm)	Void size range (μm)
4	0.42 - 0.59	29.4 - 41.3
5	0.30 - 0.42	21.0 - 29.4
8	0.15 - 0.21	10.5 -14.7
10	0.09 - 0.15	6.3 -10.5
12	0.05 - 0.10	3.5 – 7.0
13	0.04 - 0.09	2.8 - 6.3

Typical filter performance curves are shown in Figure 4.2. These curves represent the variations in the pressure head and flow rate during the filtration process. As previously discussed, two filtration options, (1) In-series, and (2) Single filter (Mil-spec 13) were investigated.

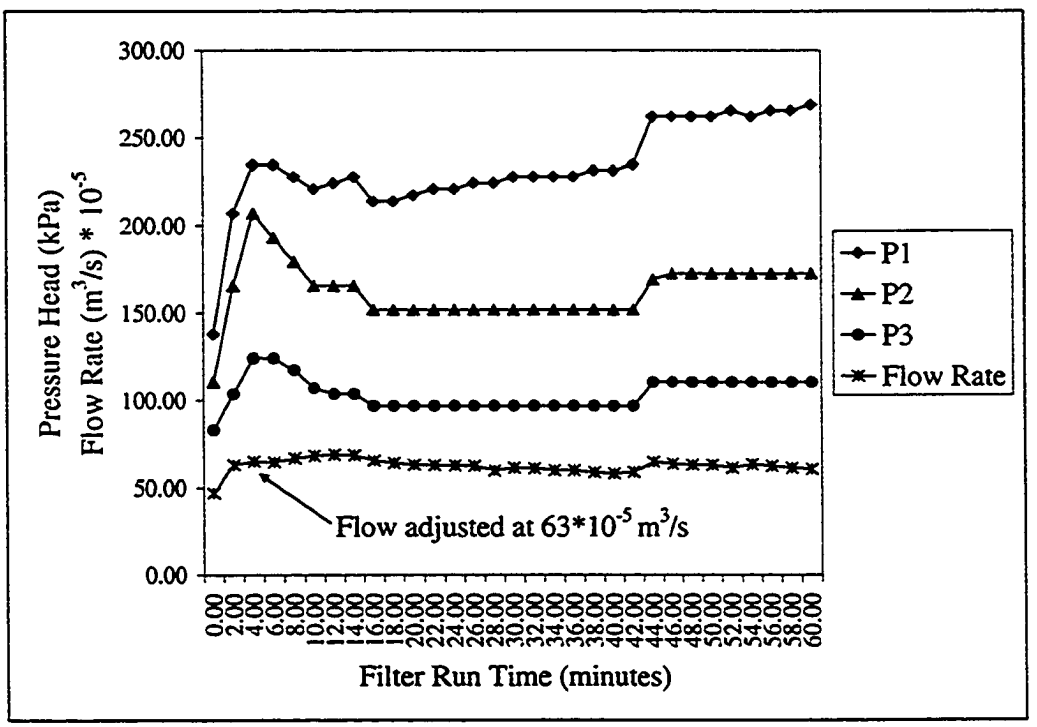


Figure 4.2 Operational performance curves for in-series arrangement (Scenario I) of Martin filters (P: Pressure Head; 1, 2 and 3 denote the number of filter; where, 1: Mil-spec 5, 2: Mil-spec 8 and 3: Mil-spec 10).

Scenario I involves the running of a set of three filters (containing media Mil-spec 5, 8, 10) in-series at an adjusted flow rate of 10 gpm ($6.3*10^{-4}$ m^3/s). It was found that clarifier performance was improved by reducing the influent flow rate from 8 gpm ($5.03*10^{-4}$ m^3/s) to 5 gpm ($3.15*10^{-4}$ m^3/s) (Figure 4.1). Filters were run at flow rates of 10 gpm and 5 gpm, corresponding to clarifier influent flow rates of 8 gpm and 5 gpm, respectively. Filter run time was 60 minutes (1 hour). It is clear from the operational results that in-line pressure (head) and flow rate are directly proportional to each other. At the start of filtration, both flow rate and pressure head will increase simultaneously to a point where one of these parameters (flow rate) is kept controlled. The middle portion of the pressure-flow rate curve is flat and rises at the end when the flow rate is increased slightly. Filters ran smoothly without any clogging problems.

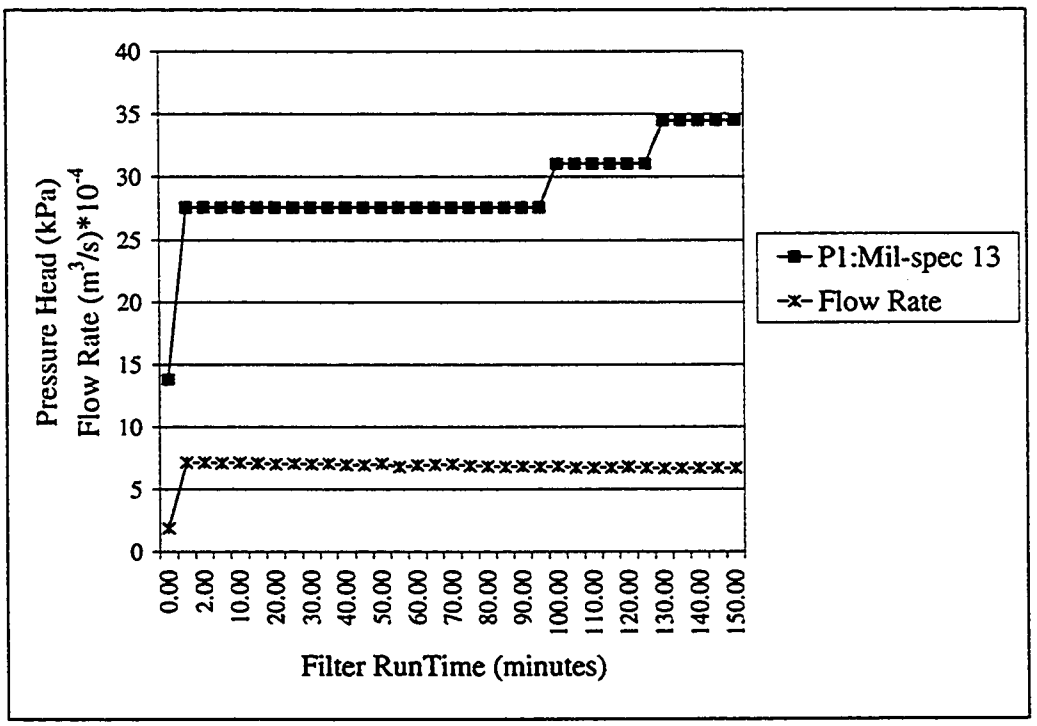


Figure 4.3 Operational performance curves for single Martin filter (Mil-spec 13) arrangement (Scenario II) (P: pressure head).

Figure 4.3 represents Scenario II, which involves the running of a single filter containing glass bead media of Mil-spec 13 and at a flow rate of 10 gpm ($6.3*10^{-4}$ m^3/s) which was regulated through a by-pass valve provided on the storage tank-filtration unit line. The effluent was collected in a storage tank next to the filtration unit. A slight increase in the pressure head was noticed in the last minutes of the filter run. This could possibly be due to partial clogging of the media pores with manure material.

4.2 Pilot plant results

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 respective instruments.

4.2.1 Type of coagulant and dose selection

Previous studies conducted by this group indicated that alum was a more effective coagulant than ferric chloride in removing suspended solids and phosphorus from liquid swine manure. 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). In another 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 (1,000 mg/L) with higher polymer doses (upto 200 mg/L) in order to match the results obtained from alum used alone at a rate of 1,600 mg/L. Consequently, it was decided not to use ferric chloride or polymer for treatment. The other factor which favored alum

selection was the fact that alum cost five time less than ferric chloride (according to supplier's information). An alum dose of 1,600 mg/L was concluded to be, and recommended as, the most effective and economical dose for the treatment. 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 3,000 mg/L, while it was only 15% at 100 mg/L alum (Zhu, 2003).

In this project, an alum dose of 1,600 mg/L was used most of the time during pilot plant operation. In laboratory experiments, alum doses of 1,600 mg/L and 1,200 mg/L were used for undiluted raw manure samples, while in another experiment, the alum dose was reduced to 60 mg/L when raw manure was diluted to 50 times with DI water in order to increase the transmittance efficiency for UV application.

4.2.2 Total suspended solids (TSS) and total phosphorus (TP) analysis

Figures 4.4 and 4.5 show the effect, on total suspended solids and total phosphorus concentrations, respectively, of the sequence of operations performed at the pilot plant. The samples were named according to the type of operation they underwent in the treatment chain, e.g., a sample obtained after clarification was named clarified supernatant, and similarly, Mil-spec specification was mentioned with the filtrate sample obtained after filtration through each of the three filter columns containing that specific

size media. Figure 4.6 shows the total suspended solids and total phosphorus removal efficiencies obtained during the pilot plant treatment operation.

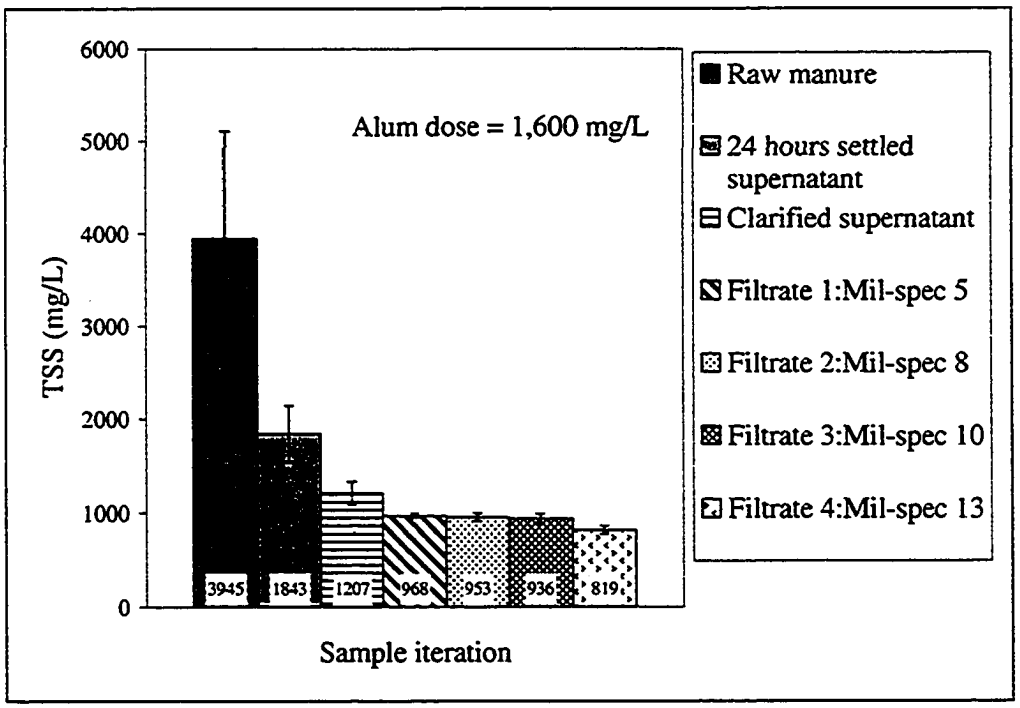


Figure 4.4 Effect of pilot plant treatment process on total suspended solids (TSS) in swine manure samples (Sample ID: Filtrate 4: Mil-spec13 represents scenario II where preliminary (24 hours) settled supernatant was passed through a single filter containing glass bead media with specification Mil-spec13).

Raw manure samples were collected from the lift station pit with the help of a dipping bucket arrangement. A suction pump was used to transfer raw manure to a nearby tank for preliminary settling. Raw manure was allowed to settle for 24 hours in the tank. The next day, samples were collected by the same method as was employed to collect raw manure samples. As settling occurs, large particles settle first, and settle down at the bottom of the tank, while small to medium size particles take longer to settle and continue to do so for a much longer period of time. Settling time depends on the type, strength, volume and other characteristics of the manure. In this project, primary settled

supernatant samples were always collected from the top 0.5 m depth of the tank, since settling occurs from top to bottom. This was also done to ensure consistency and accuracy in sample collection.

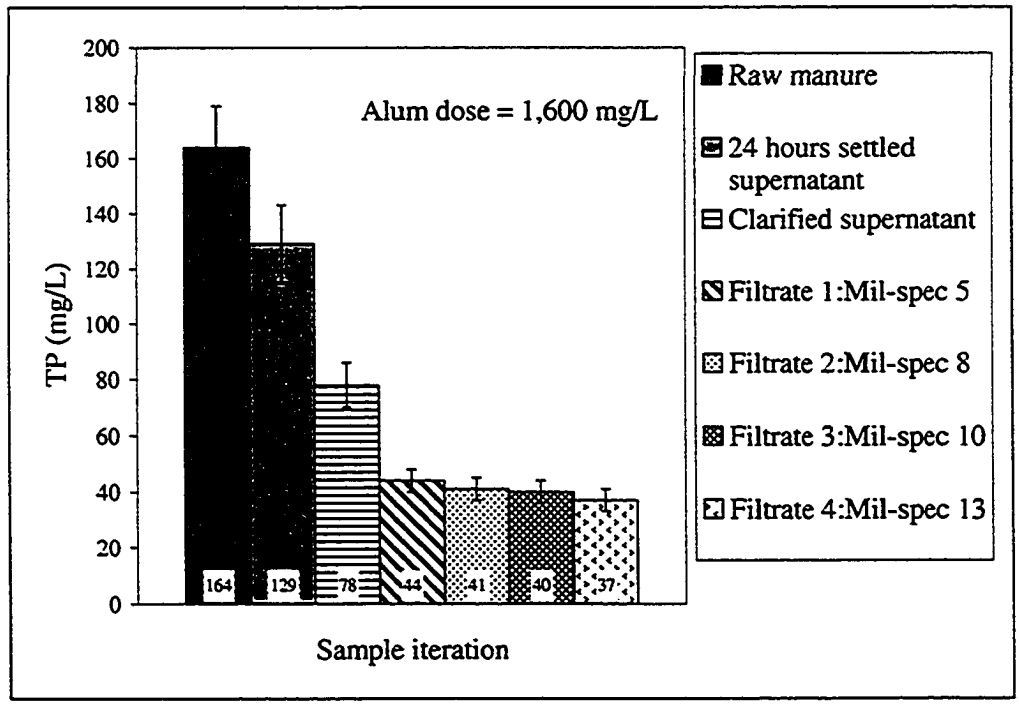


Figure 4.5 Effect of pilot plant operation on total phosphorus (TP) in swine manure samples.

Figure 4.6 indicates that the preliminary settling of raw liquid manure for 24 hours before any operation was very effective, and removed 53% of TSS and 22% of TP. 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 phosphorus in raw swine manure. The results confirmed the effectiveness of the preliminary settling treatment process for swine manure. Therefore, preliminary settling can be described as an important pre-treatment process in animal manure treatment.

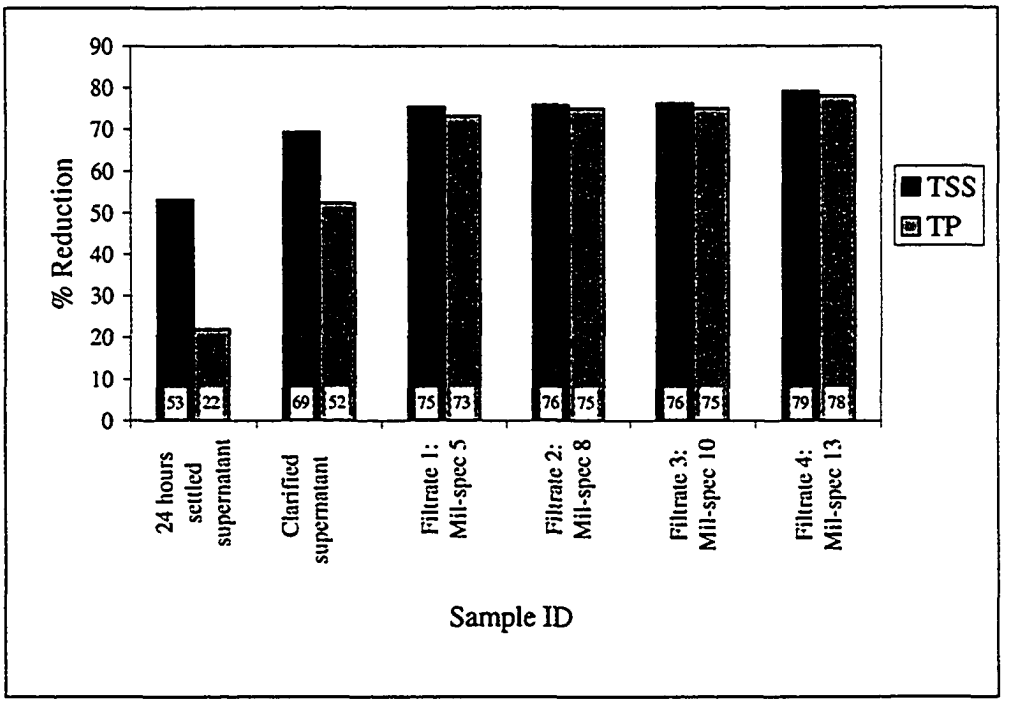


Figure 4.6 Percentage reduction (%) in total suspended solids and total phosphorus during pilot plant operation.

Clarification in the customized sludge blanket clarifier was the key operation in the pilot plant treatment chain. Clarification involved rapid mixing and coagulation in the rapid mix tank, flocculation in the slow mixing tank, and finally settling in the sludge blanket tank. The tank had several inclined plates to enhance settling. The clarified supernatant was obtained from the side troughs of the clarifier and collected in a PVC tank. The initial experiments observed the relatively poor performance of the clarifier. Therefore, in order to improve its performance, the clarifier was run for two days so that it could fully develop the sludge blanket. The flow rates, as already mentioned in section 4.1, were optimized to give better results. During the operation, it was observed that small chunks of scum, which had accumulated on the top of the clarifier, were moving along with the supernatant. This may have been a possible reason for less solids than

expected being removed. Thereafter, scum layers were removed regularly from the center and side troughs and, better results were obtained thereafter.

Another problem associated with the chemical treatment of animal manure is gas production. When alum reacts with the constituents of manure, it produces H_2S (Hydrogen sulfide) and NH_3 (Ammonia) gases along with the froth. To overcome difficulties with froth, the clarifier had a froth removal tank. Froth was removed manually with a scoop and was washed away with running water in the froth removal tank. Sprayed water may react with the froth to produce aerosols which can aggravate the gas problem in an enclosed unit, as was the case in the pilot plant. Since H_2S gas is heavier than air, it remains close to the bottom surface. A high power blower and two ventilating fans were used in the pilot plant (trailer) unit to evacuate the gases. Gas monitors were always activated by the operators to check the instantaneous changes in the gas levels in the unit.

During the clarification step (after preliminary settling), average removal efficiencies of 16% of TSS and 30% of TP were achieved. The removal efficiencies increased significantly when the clarifier was run at a low flow rate.

4.2.3 Total dissolved solids (TDS) analysis

Figure 4.7 presents the total dissolved solids (TDS) concentrations in different swine manure samples before and after treatment at the pilot plant.

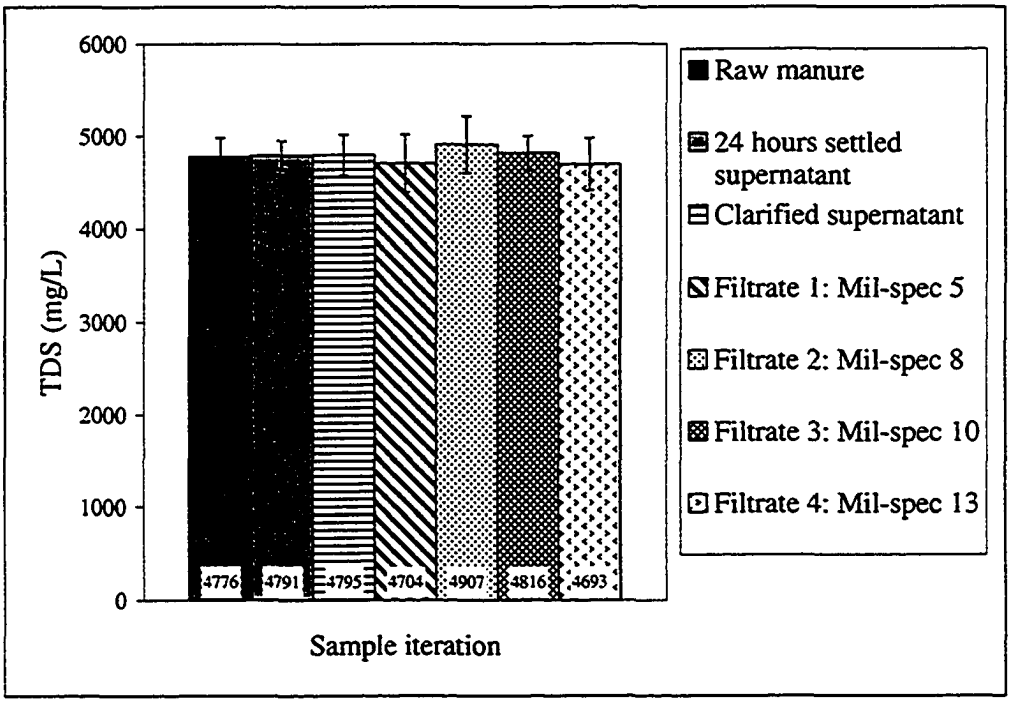


Figure 4.7 Effect of pilot plant treatment process on total dissolved solids (TDS) in swine manure samples.

The results indicate no significant decrease in TDS concentration after treatment. Total dissolved solids (TDS) comprise inorganic salts and small amounts of organic matter dissolved in water, many of which may not be considered contaminants (Sawyer *et al.*, 1994 and Tchobanoglous and Burton, 1991). Manure separation (by physical and chemical methods) is effective in reducing TSS, but it has very little effect on TDS concentration (TDS are usually removed through biological treatment) (Zhu, 2000). Some researchers have concluded that chemical treatment with aluminum and iron salts may increase the inorganic salt concentration in the treated samples, and thereby lead to an increase in the TDS concentration. In our experiments, the TDS values were fairly consistent for treated and untreated samples, ranging between 4,700 and 5,000 mg/L, with a mean and standard deviation of 4,776 and 205 mg/L, respectively.

4.2.4 5-day biochemical oxygen demand (BOD_5)/ chemical oxygen demand (COD)

Figures 4.8a and 4.8b show the BOD_5 and COD concentration variations in the treated and untreated swine manure samples obtained from the pilot plant. Sample analysis was carried out according to the procedures outlined in Standard Methods.

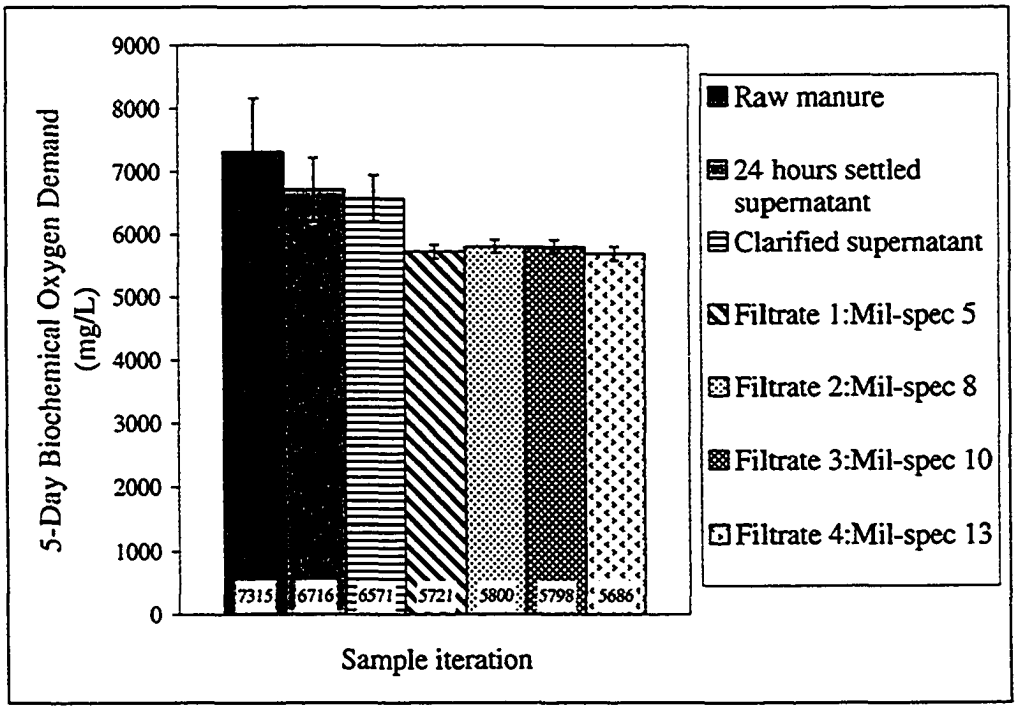


Figure 4.8a Effect of pilot plant operation on BOD_5 concentration in swine manure samples.

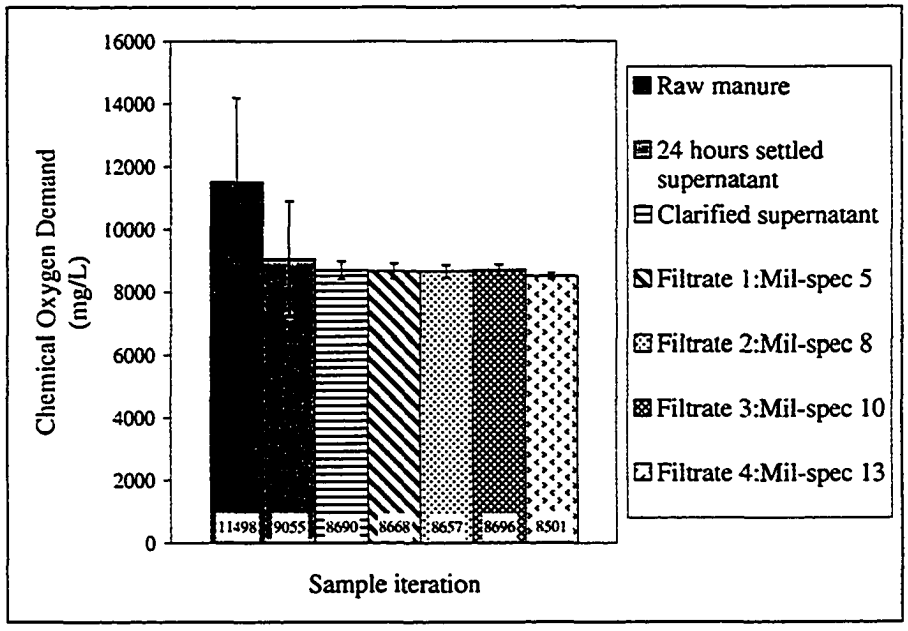


Figure 4.8b Effect of pilot plant operation on COD concentration in swine manure samples.

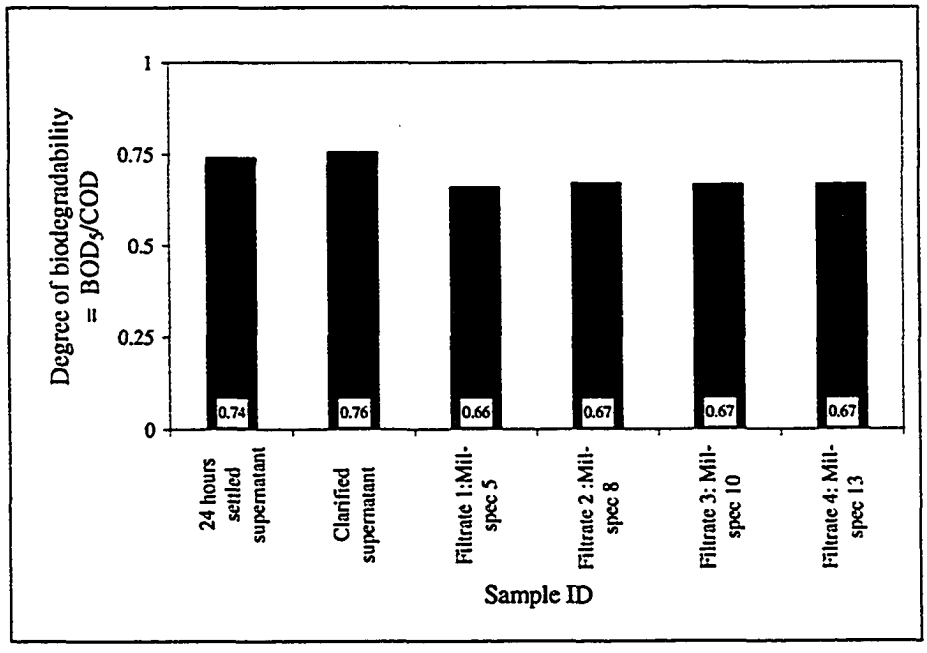


Figure 4.9 Effect of pilot plant treatment process on biodegradability (BOD_5/ COD) in swine manure samples.

Preliminary settling for 24 hours prior to any chemical treatment reduced BOD_5 and COD by 8 and 21%, respectively. BOD_5 and COD reductions during the clarification (chemical treatment in the clarifier) step were not quantitatively significant (< 5%). Since the treatment was totally physico-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. Total BOD_5 and COD removal efficiencies achieved by pilot plant treatment were approximately 22 and 26%, respectively. Figures 4.8a,b indicate that major portions of BOD_5 and COD reduction occurred during preliminary settling. After this step, COD remained almost constant, but BOD_5 was further reduced during filtration through the first (Mil-spec: 5) filter column, and remained constant thereafter. Figure 4.9 shows that the degree of biodegradability (BOD_5/ COD) decreases from 0.74 to 0.66 from the untreated influent (raw manure) to the treated effluent (clarified and filtered).

4.2.5 Total Kjeldahl nitrogen (TKN) analysis

Swine manure is a rich source of nutrients such as phosphors and nitrogen. Land application methods are utilized in such a way as to reap the maximum benefit from these naturally available nutrients (Loehr, 1977). Although manure utilization through land application in the agriculture sector is beneficial and economical, the problems such as odours, groundwater seepage and runoff to surface water channels need to be addressed. Manure treatment can be another alternative to achieve nutrient management through solid/liquid separation, to reuse treated liquid effluent in the facilities for cleaning and drinking purposes and to reduce the odour nuisances.

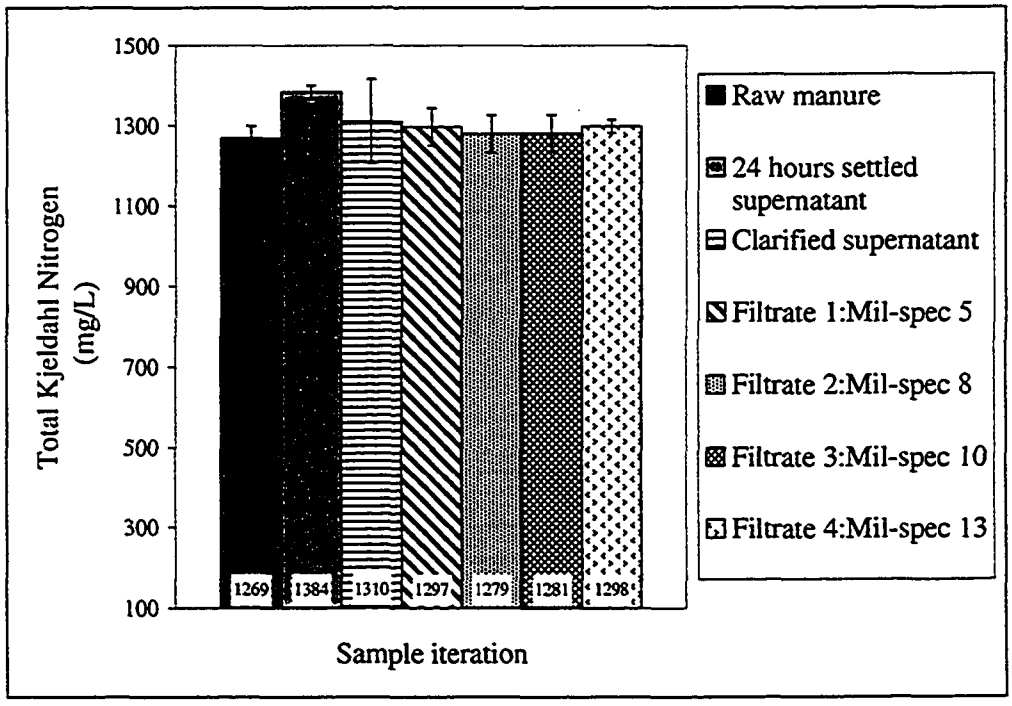


Figure 4.10 Effect of pilot plant treatment process on Total Kjeldahl nitrogen (TKN) in swine manure samples.

Pilot plant treatment was very effective in removing TSS and TP from fresh liquid manure, but it was less effective in removing TDS, fine organic matter and TKN. The ineffectiveness of alum in nitrogen removal in municipal and animal wastewaters has been described in the literature (Gilmour *et al.*, 2004; Zhu, 2003). The results obtained for TKN in untreated and treated swine manure samples are presented in Figure 4.10. TKN concentration in all the samples varied between 1,250 mg/L and 1,400 mg/L, with a mean value of 1,302 mg/L and a standard deviation of 37.4%. Analytically, it is obvious that there is no apparent trend in TKN reduction in the treated sample results. Some variation in the measurements may be attributed to personal and instrumental errors.

4.2.6 Particle size distribution/ particle count analysis

Fresh and treated swine manure samples obtained after pilot plant treatment were analyzed for particle size distribution and particle counts. The results are depicted in Figure 4.11. The majority of particles (up to 80 to 90%) fall within the particle size range of $\leq$ 10 μm. Raw manure contains more large sized (> 10 μm) particles, while filtered sample contains an almost negligible percentage of large 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. Moreover, it is also very useful for UV experiments. The effectiveness of UV treatment can be hindered by fine particles that act as protective shields for pathogenic microorganisms.

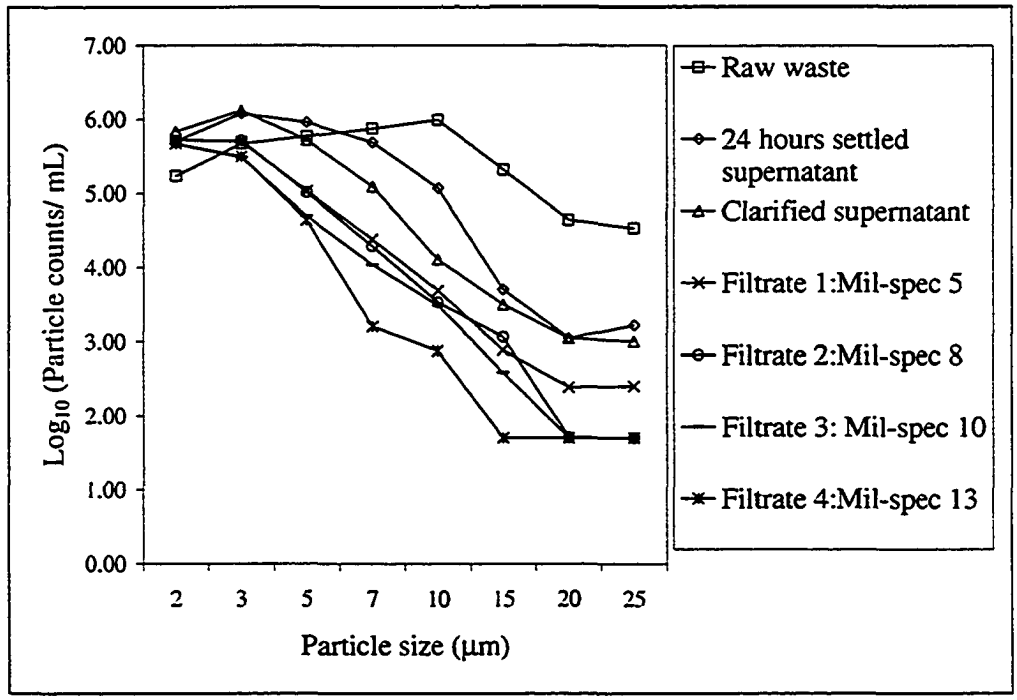


Figure 4.9 Particle size distribution and particle counts analysis in pilot plant treated swine manure samples.

4.2 Laboratory results

In the laboratory, primary settled supernatant (after 24 hour settling) samples were used to perform jar tests and filtration/fractionation experiments, as explained in Methods and Materials section 3.1.1.1.

4.2.1 Total suspended solids (TSS) and total phosphorus (TP) analysis

Laboratory experiments and analysis work were conducted to confirm and compare the results obtained from the pilot plant treatment. The treatment process chain adapted for the pilot plant operation was simulated in the laboratory by performing jar tests for coagulation, and flocculation and settling, followed by filtration through a series of membrane (polycarbonate) filters of different pore size.

Raw manure brought from the pilot plant was stored in a PVC barrel for preliminary settling for 24 hours. Primary settled supernatant was further used for jar tests and filtration through membrane filters. The supernatant obtained from the jar tests was filtered through the same size membrane filters. All the samples obtained before and after the treatment were analyzed according to the procedures described in Standard Methods. For sensitivity and quality assessment, the samples were tested in triplicate and duplicate. Figures 4.12 and 4.13 show the variations in TSS and TP levels of untreated and treated (in the laboratory) swine manure samples.

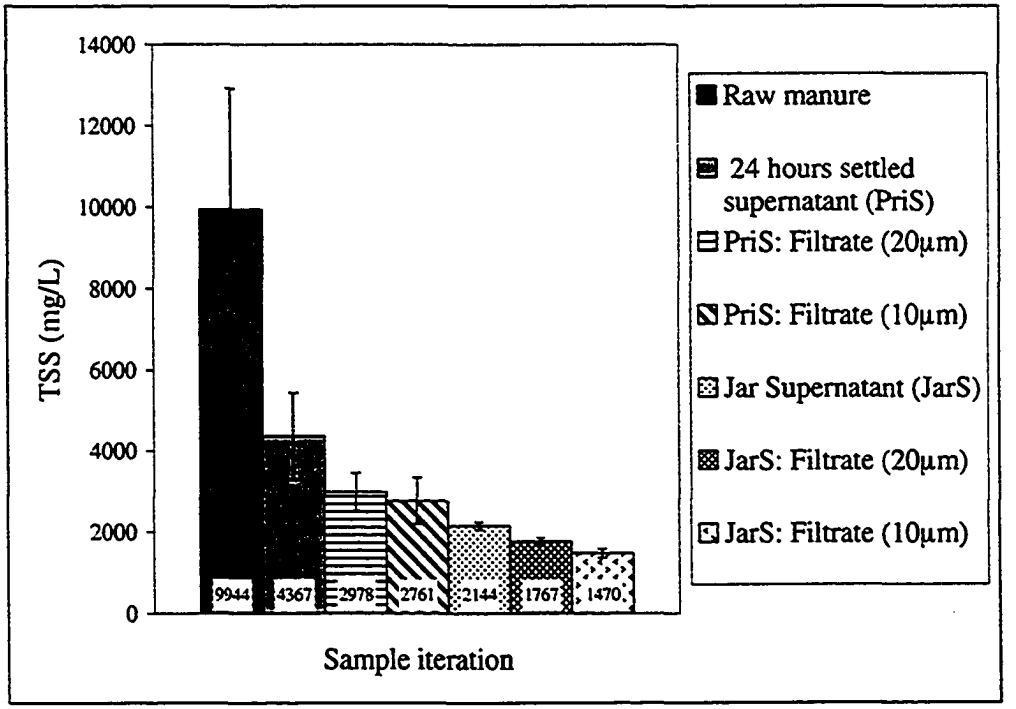


Figure 4.10 Effect of laboratory treatment process on total suspended solids (TSS) in swine manure samples (Alum doses = 1600 mg/L, 1200 mg/L; results obtained from two different doses, averaged and presented here).

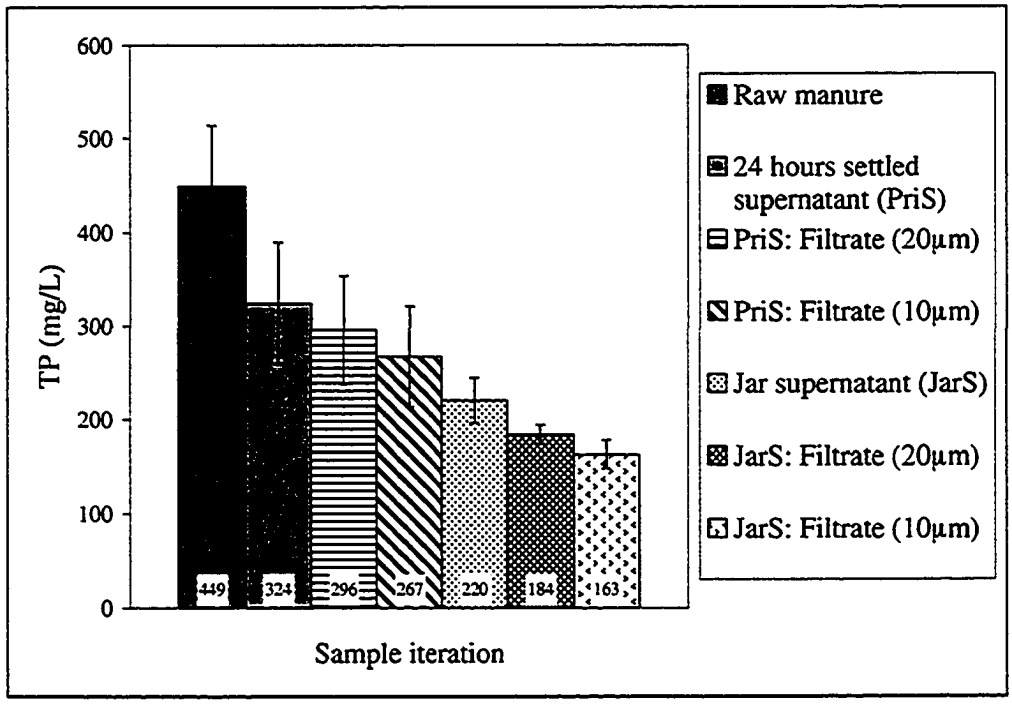


Figure 4.11 Effect of laboratory treatment process on total phosphorus (TP) in swine manure samples (Alum doses = 1600 mg/L, 1200 mg/L).

As demonstrated by Figure 4.14, preliminary settling (laboratory treatment) removed an average of 56% TSS and 28% TP, as compared to 53% TSS and 22% TP in the case of pilot plant treatment. Solid concentrations in the samples brought for laboratory (Jar test) analysis were significantly higher as compared to the samples brought during pilot plant treatment. The raw manure coming out of the swine unit remained inside the lift station (raw manure collection pit) for a few days due to some maintenance problems in the delivery pump system and lines. Consequently, the stagnated manure contained comparatively a higher solid content. In the case of pilot plant treatment, there were less variations observed in solid concentration. As evident from the results, there was insignificant effect of higher solid content on preliminary settling in the samples brought for Jar test that those brought during pilot plant operation. Both treatments achieved nearly same removal efficiencies after preliminary settling.

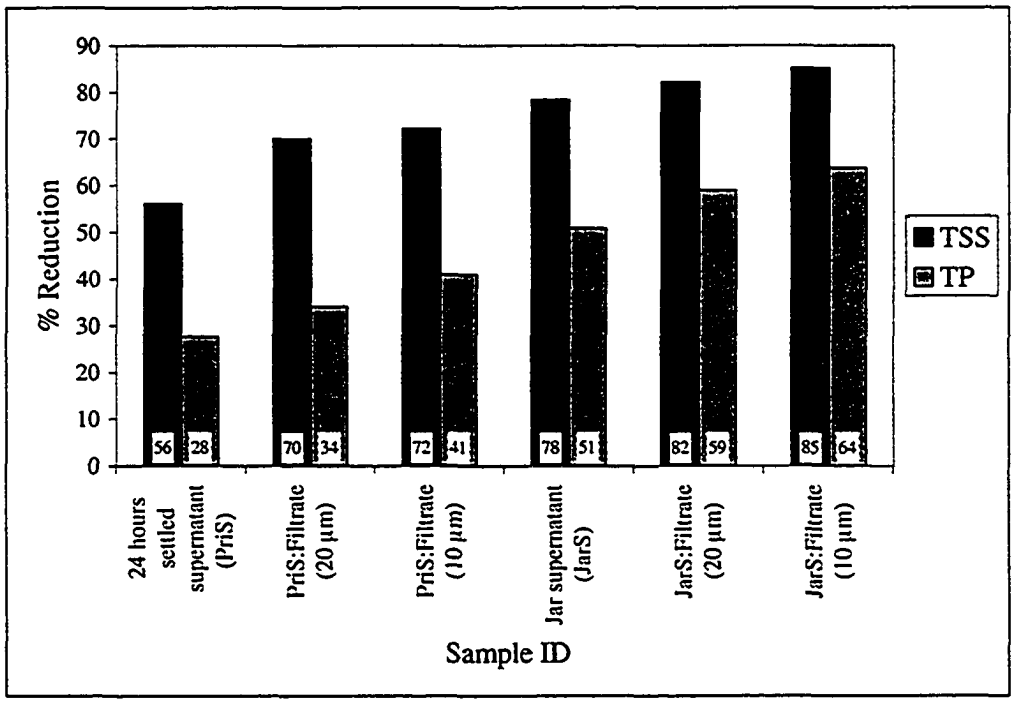


Figure 4.12 Percentage (%) reduction in TSS and TP of different swine manure samples treated in the laboratory.

Primary settled supernatant was filtered separately through membrane polycarbonate filters (diameters: 10µm and 20µm) to estimate the TSS and TP removal efficiencies without any chemical use. Maximum TSS and TP removals of 72 and 41% respectively were achieved after filtration through a 10µm filter. Although a significant portion of TSS (72%) was removed without using alum, TP reduction (41%) was low and required the use of alum to achieve higher treatment efficiency.

Jar tests were performed using alum doses of 1600 mg/L and 1200 mg/L. The results presented in Figures 4.12, 4.13 and 4.14 are the averaged results obtained from the jar tests performed with these two alum doses. Removal efficiencies of 78% in TSS and 51% in TP were achieved after alum treatment. The jar supernatant was filtered through the same size membrane filters as was the primary settled supernatant. The removal

efficiencies were significantly improved to 85 and 64%, in TSS and TP, respectively. Partially effective preliminary settling due to relatively high solids content might cause less TSS and TP removal as compared to what was achieved during pilot plant treatment. As a whole, a comparison of TSS and TP removal trends, in both pilot plant and laboratory treatments, indicates similar patterns, and points to the effectiveness of the treatment system analyzed in this project.

4.2.2 Fractionation test

A fractionation test was performed on the filtered swine manure samples to determine the particle size/phosphorus concentration relationship or, in other words, to estimate how much phosphorus was associated with what size range of particles. The procedure for the fractionation test is described in Methods and Materials section 3.1.1.2. The fractionation test was performed only once, and the results are not averaged over multiple iterations, as were the other results (TSS, TP etc.) from the laboratory and pilot plant operations. Table 4.3 demonstrates the P concentration values (total and soluble fractions) in all untreated and treated swine manure samples. Glass fiber filters of 1μm pore size were used to separate the soluble portion of phosphorus from the total volume. Table 4.4 describes the P concentration/particle size relationship in laboratory treated samples. This study provided us with ideas and objectives for successive treatment operations designed specifically to remove certain size ranges of solid particles for better TSS and TP removal efficiencies. The results listed in Table 4.4 clearly indicate that the majority of phosphorus (> 80%) is associated with the particles of size less than 10μm that account for 70 to 80% of the total particles in swine manure samples. Therefore,

treatment operations must include filtration media that can effectively remove particles of size ≤ 10 μm.

Table 4.3 Total and soluble phosphorus levels in untreated (raw) and treated swine manure samples.

Sample ID	Total P (mg/L)			Soluble P (mg/L)		
	P_{in}	P_{out}	P_{total}	P_{in}	P_{out}	P_{sol}
Raw manure	n/a	n/a	444	n/a	n/a	396
Primary Supernatant (PriS)	n/a	n/a	392	n/a	n/a	345
PriS (20 μm filtrate)	392	355	n/a	345	325	n/a
PriS (10 μm filtrate)	392	328	n/a	345	308	n/a
Jar Supernatant (JarS)	n/a	n/a	256	n/a	n/a	171
JarS (20 μm filtrate)	256	228	n/a	171	162	n/a
JarS (10 μm filtrate)	256	196	n/a	171	148	n/a

Note: P – phosphorus; n/a - not applicable.

Table 4.4 Phosphorus (total and soluble) concentration/ particle size relationship in swine manure samples.

Type of sample	Particle size range (μm)	Total P (mg/L)	% Total P associated	Soluble P (mg/L)	% Soluble P associated
(PriS) filtrates (No alum)	$X_1 \geq 20$	37	9.4	20	5.8
	$20 > X_2 \geq 10$	27	6.9	17	4.9
	$X_3 < 10$	328	83.7	308	89.3
(JarS) filtrates (Alum used)	$X_1 \geq 20$	28	10.9	9	5.3
	$20 > X_2 \geq 10$	32	12.5	14	8.2
	$X_3 < 10$	196	76.6	148	86.5

Note: (1) PriS - 24 hours settled supernatant or primary settled supernatant; JarS - Jar supernatant; X - fraction variable e.g., $X_1 \geq 20$ indicates the phosphorus concentration associated with particles with size $\geq$ 20 μm. (2) The values are derived from the P concentration values presented in Table 4.3.

4.2.3 Total dissolved solids (TDS) analysis

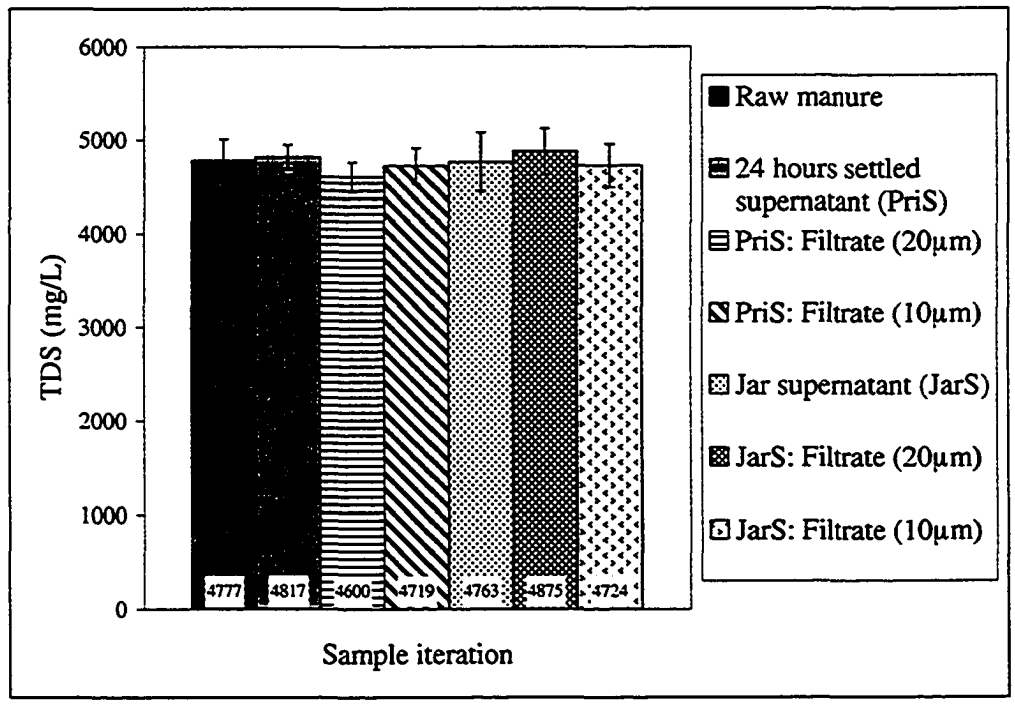


Figure 4.13 Effect of laboratory treatment process on total dissolved solids (TDS) in swine manure samples (Alum doses = 1600 mg/L, 1200 mg/L).

The total dissolved solids (TDS) results presented in Figure 4.15 were fairly similar to those obtained in the pilot plant operation. This indicates that the treatment system was not effective in removing TDS.

4.2.4 Chemical oxygen demand (COD) analysis

COD results for the samples treated in the laboratory are presented in Figure 4.16. Because of a time shortage, BOD_5 tests were not carried out for these samples. At the same time, lengthy and time consuming UV experiments were commenced. Since it has already been mentioned that the samples brought for the laboratory experiments were highly concentrated, it follows that the COD values for these samples were also high. The values were 2 to 3 times higher than those obtained from the pilot plant operation. The

same glass fiber filter (1μm pore size) was used to separate the soluble COD fraction from the total as was used to determine soluble phosphorus. The percentage of soluble COD in total COD ranged from 60 to 75%.

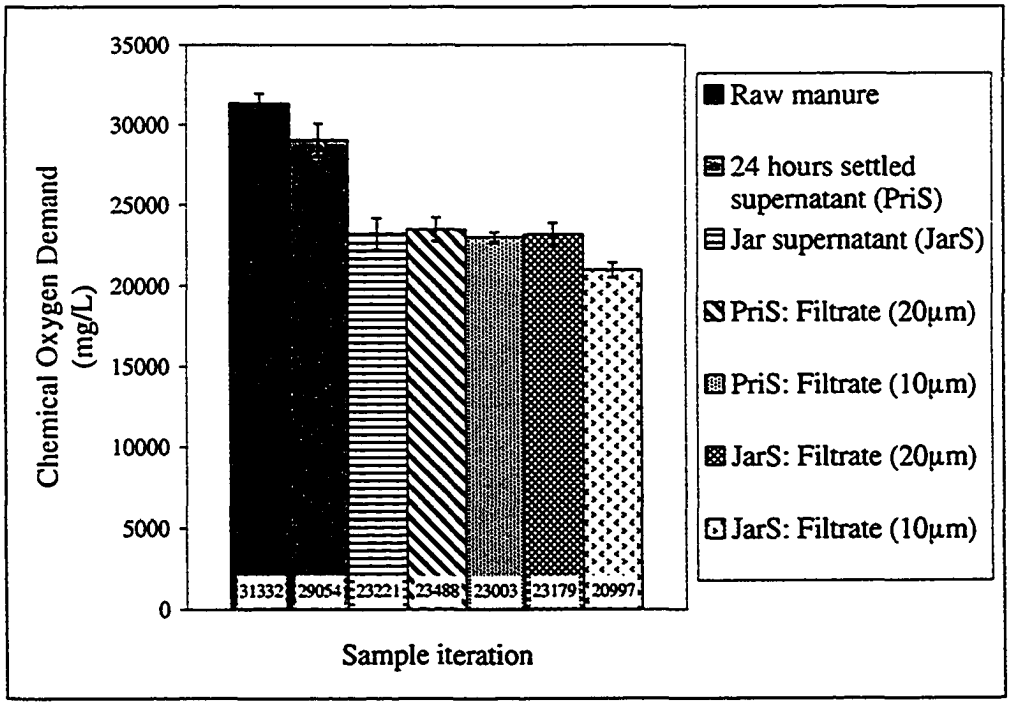


Figure 4.14 Effect of laboratory treatment process on chemical oxygen demand (COD) in swine manure samples (Alum doses = 1600mg/L, 1200 mg/L).

Because of the high solid content of fresh manure, preliminary settling was not effective and did not remove much COD. A jar test or alum addition removed about 20% COD from the primary settled supernatant. COD remained fairly constant for the filtered samples (filtrates) of primary settled and jar supernatants. COD was reduced further under Scenario II (using media Mil-spec 13) by 10%, adding to the total of approximately 30% from raw manure.

4.2.5 Total Kjeldahl nitrogen (TKN) analysis

Figure 4.17 shows the TKN values in the samples treated in the laboratory. Physical/ chemical treatment with alum coagulation and filtration was not effective in removing nitrogen from swine manure. The treatment could only achieve approximately 15% TKN removal from raw manure. Treatment systems should also include any biological processes that could effectively remove organic matter (BOD) and TKN.

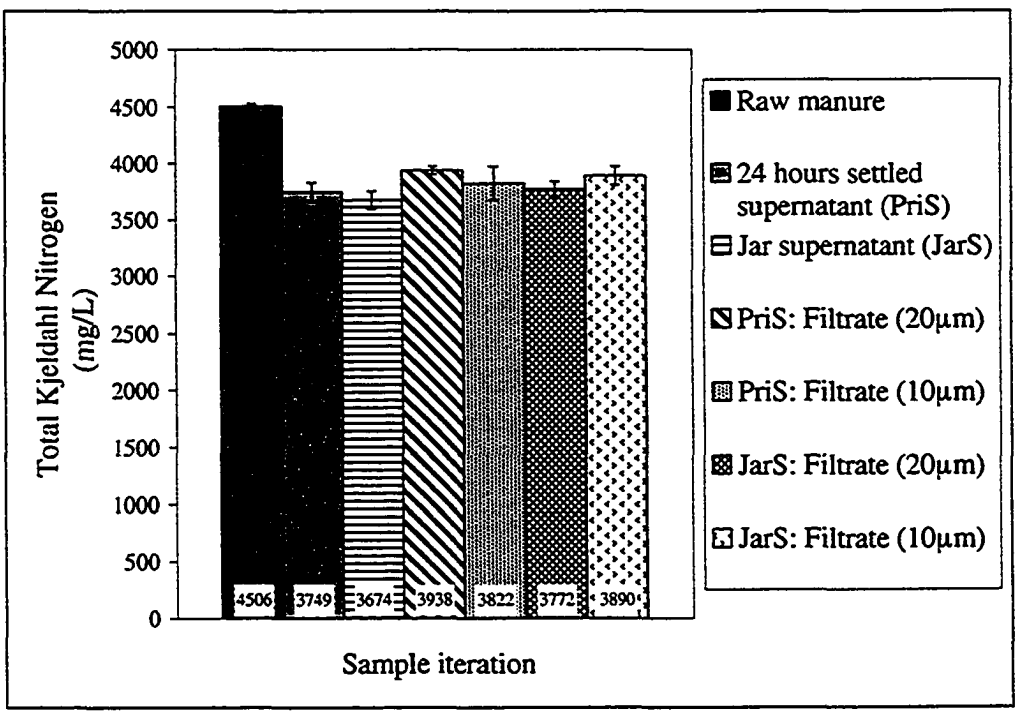


Figure 4.15 Effect of laboratory treatment process on total Kjeldahl nitrogen (TKN) in swine manure samples.

4.2.6 Particle size distribution/ particle counts analysis

Figure 4.18 illustrates the effectiveness of physical/chemical treatment in removing solid particles of size ≥ 8 μm. 1.5 to 3 Log_{10} inactivations were observed. The test

provided useful information about particle size and counts before UV experiments on the treated samples were commenced.

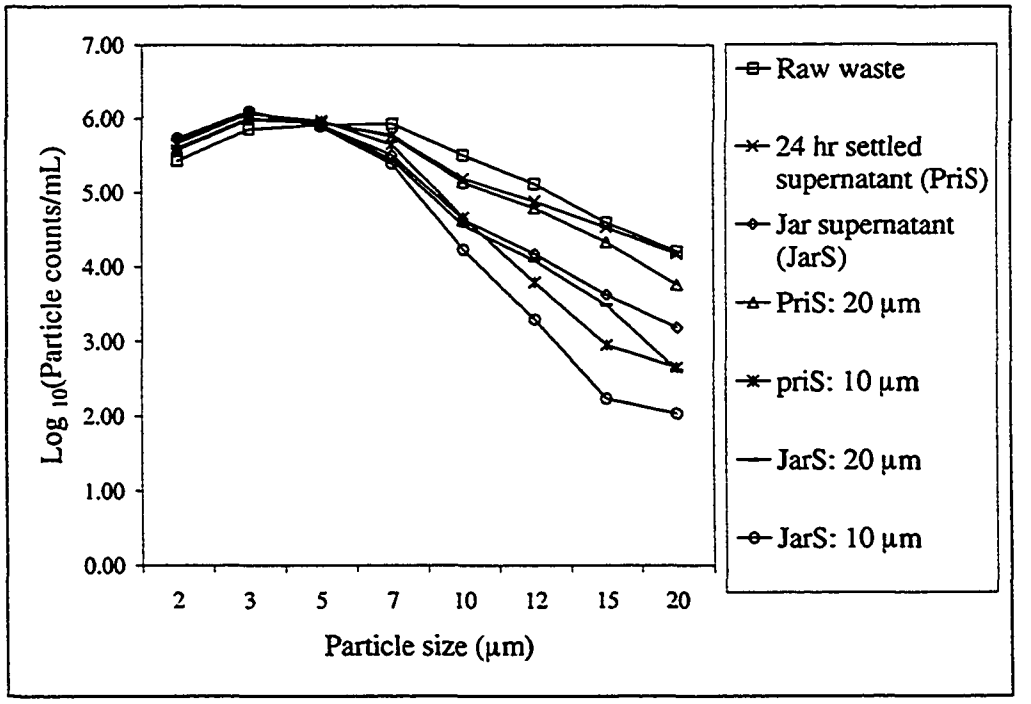


Figure 4.16 Particle size distribution and particle count analysis in laboratory treated swine manure samples.

4.3 Microbial analysis

Animal manure contains numerous pathogenic bacteria and other microorganisms. Nutrients present in animal manures have been widely utilized for land application and other reuse techniques in the agriculture sector. Some of the primary concerns regarding these practices are: the possible risk of pollution in ground and surface water, air pollution (odours) and human health problems resulting from the presence of many types of pathogenic microorganisms (Riddell and Rodvang, 1992; Sri Ranjan *et al.*, 2001; Sims *et al.*, 2000; Cole *et al.*, 1999). Therefore, new reuse technologies (or strategies) must be developed to eliminate, or effectively reduce, the pathogens in animal wastewaters.

Modern practices include ozone and UV (ultraviolet) irradiations applications for water and wastewater treatment, along with traditional techniques such as chlorination.

In this project, ultraviolet irradiations are evaluated for their effectiveness against the pathogens typically found in swine manure. In the past, the same group has tested chlorine for of its ability to rid swine manure of pathogens. Chlorination was found to be effective on the filtered samples brought from the pilot plant. A complete kill (inactivation) was achieved at a chlorine dose of 100 mg/L and 10 minutes of contact time using total coliforms (TC) and fecal coliforms (FC) as microbial indicators. However, very high chlorine doses (up to 500 mg/L) were used for the effective inactivation of pathogens in the supernatant obtained from the jar test in the laboratory. Therefore, it was decided to evaluate other alternatives for disinfection because chlorine demands were determined to be very high for the treatment. UV was selected to be tested in the next phase.

4.3.1 Effect of physical/chemical treatment on microbial populations

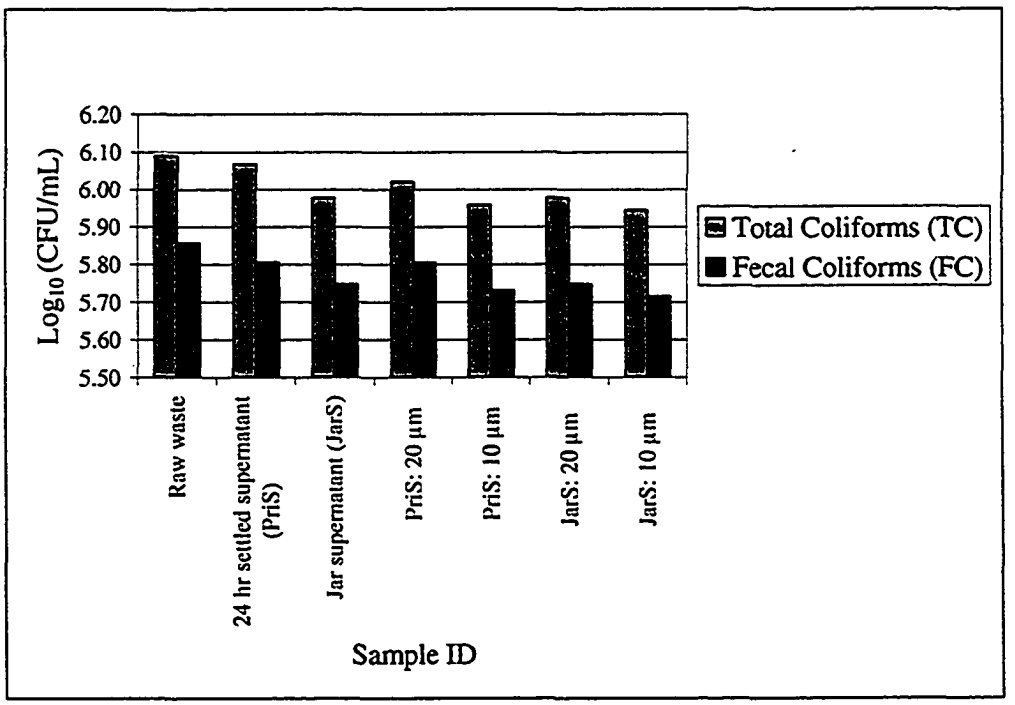


Figure 4.17 Effect of alum treatment and filtration on total and fecal coliforms (TC/FC) in swine manure samples.

Figure 4.19 explains the effect of physical/chemical treatment on microbial populations in the swine manure samples. There was no significant effect noticed after alum treatment and filtration. The need for other established disinfection methods to reduce pathogens was clearly indicated.

4.3.2 UV application

UV in the form of a collimated beam from a low pressure intensity lamp was applied to the samples treated in the laboratory. The samples were then analyzed for total and fecal coliforms to determine the effectiveness of the UV.

4.3.2.1 Experiment #1

In experiment #1, raw manure was brought from the farm swine unit and allowed to settle for 24 hours in a PVC barrel, as described in the Methods and Materials section. The fresh swine manure was not diluted. The supernatant obtained after preliminary settling was used to perform the jar test. Both of the supernatants, *i.e.* the 24 hours settled supernatant (PriS) and the jar supernatant (JarS), were passed through membrane filters of two different sizes (10 μm and 20 μm). The effect of this treatment on the microbial populations of these samples was insignificant (Figure 4.19). As chlorination had already been tested in the first phase of this project, UV was applied at various doses to determine its effectiveness on swine microbes.

Figure 4.20 shows the inactivation curves for all the samples treated at various levels of UV dose applied as a collimated beam from a low pressure intensity lamp. Widely accepted microbial indicators, total coliforms (TC) and fecal coliforms (FC), were used.

It is apparent from the microbial inactivation curves that UV doses with values exceeding 50 mJ/cm^2 were quite effective against the microbial population, but that the lower doses were found to be inefficient. The highest UV dose of 80 mJ/cm^2 achieved a 3 to 3.5 $\log_{10}$ inactivation (N_0/N) in total coliforms (TC), while a reduction of approximately 2.5 was observed in fecal coliforms (FC) for filtered jar supernatant (JarS) and primary settled supernatant (PriS).

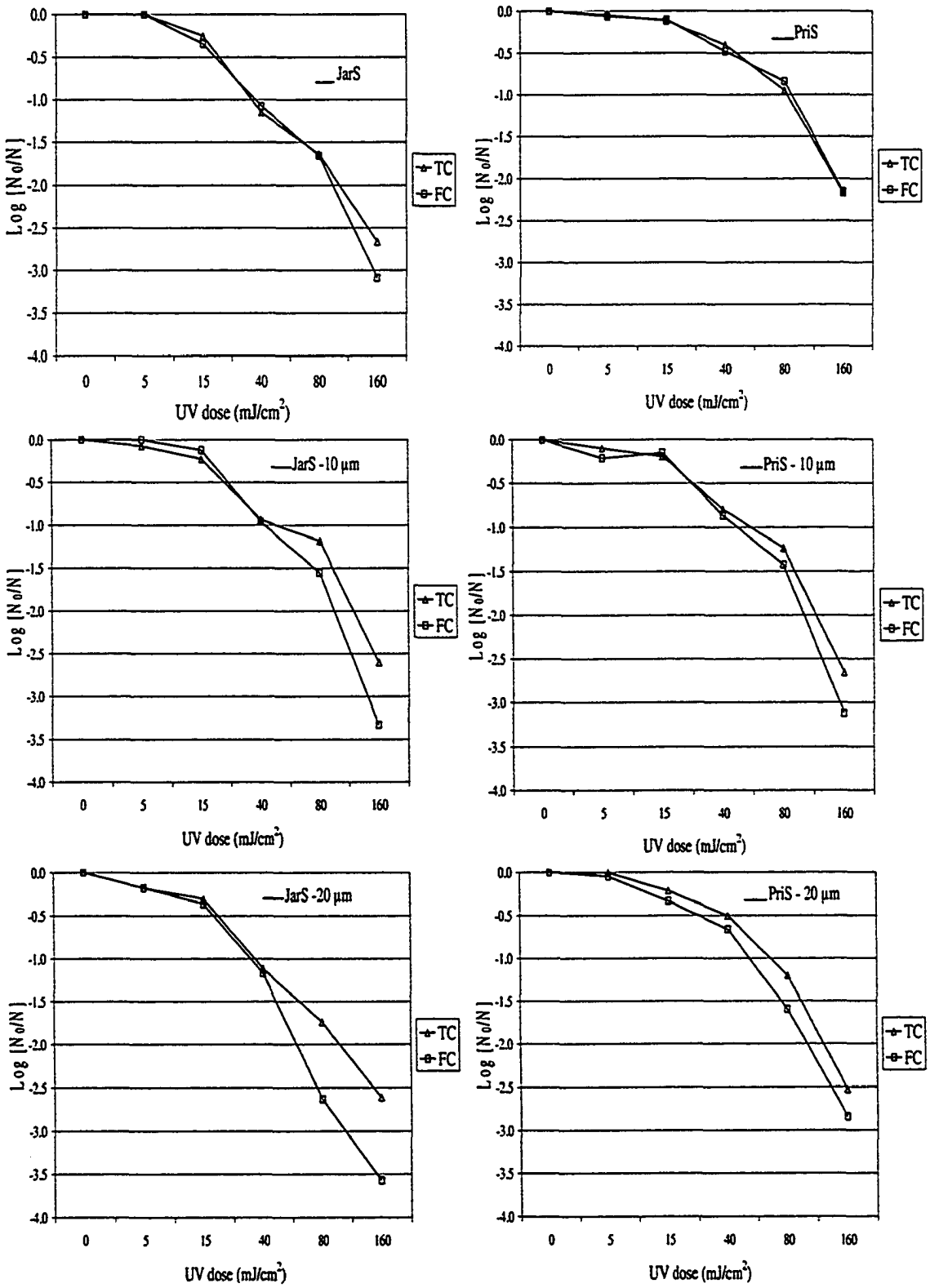


Figure 4.18 Log_{10} inactivation (N_0/N) curves for 24 hours settled supernatant (PriS), jar supernatant (JarS) and their filtrates (10 µm and 20 µm).

A typical dose-response curve is depicted in Figure 4.21 and, characteristically, possesses two important parts: (1) first order kinetics, which is noticed at lower doses, and (2) a tailing region, which occurs after a certain optimum level of dose is reached. The first order region illustrates the immediate effect of UV irradiations on microbial populations, and therefore, the inactivation curve falls steeply towards an optimum effective region where the dose-response effect is quite high. The tailing region appearing after the optimum dose level is reached indicates the minimum dose-response effect behavior. Table 4.5 demonstrates the experimental parameters that were employed to carry out the experiment.

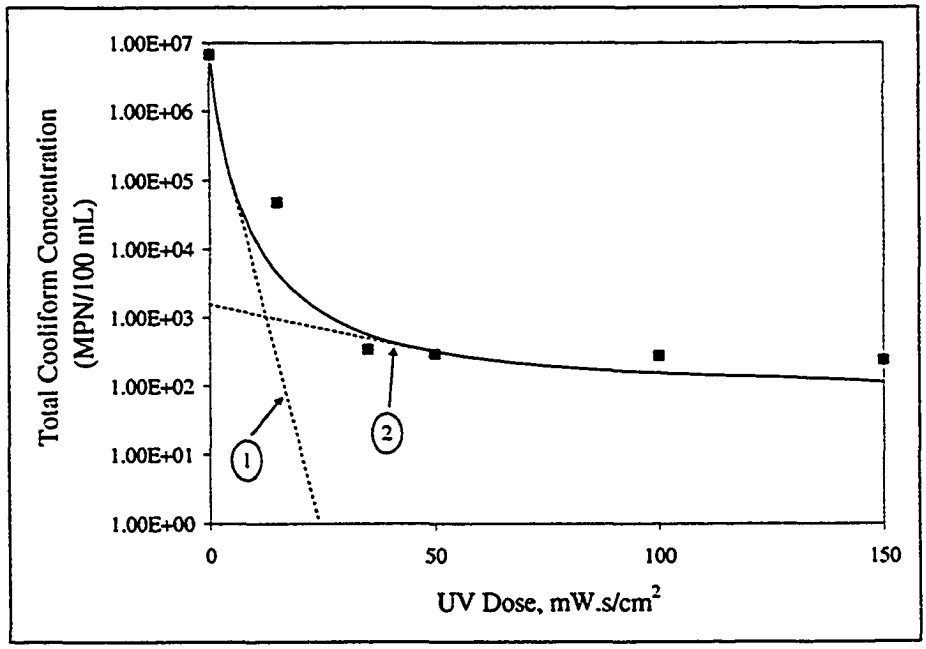


Figure 4. 19 Graphical representation of a UV disinfection model developed to describe the first order kinetics (1) and tailing effect (2) in wastewater secondary effluents (Reproduced from Loge *et al.*, 2001).

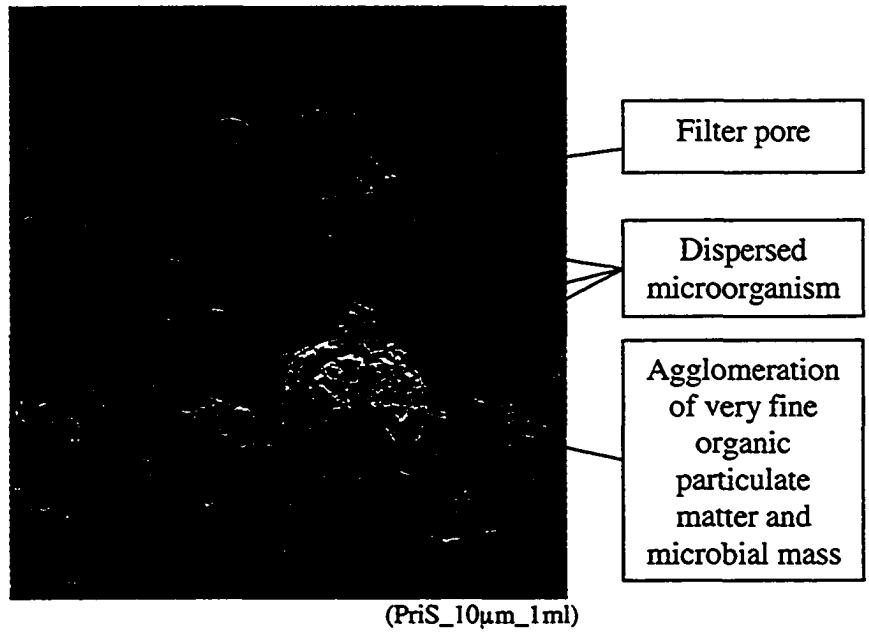
Table 4.5 Experiment #1: Process parameters.

Sample ID	UV absorbance @ 254 nm	UV dose (mJ/cm^2)	Exposure time (min/s)
PriS	4.10153	5	4 min 34 s
		15	13 min 42 s
		40	35 min 52 s
		80	73 min 1 s
		160	171 min
PriS 10 μm	4.08461	5	4 min 36 s
		15	13 min 48 s
		40	38 min 17 s
		80	74 min 14 s
		160	151 min 40 s
PriS 20 μm	4.10222	5	4 min 58 s
		15	14 min 55 s
		40	36 min 33 s
		80	74 min 44 s
		160	147 min
JarS	4.12634	5	4 min 33 s
		15	13 min 40 s
		40	36 min 28 s
		80	73 min 46 s
		160	149 min 1 s
JarS 10 μm	4.04565	5	4 min 37 s
		15	13 min 51 s
		40	36 min 56 s
		80	74 min 49 s
		160	153 min 1 s
JarS 20 μm	4.12634	5	5 min 41 s
		15	15 min 4 s
		40	38 min 30 s
		80	76 min 21 s
		160	153 min 24 s

Comparing the inactivation curves obtained from experiment #1 with the typical UV disinfection model curve shown in Figure 4.21 indicates that the former does not show first order kinetics and tailing phenomena, but rather consists of a flattening region at the beginning where the dose-response effect is significantly less.

This phenomenon is referred as "*shoulder effect*". In Figure 4.21, the optimum dose level is about 20 mW-s/cm^2, whereas in our case, it may be close to the maximum dose *i.e.* 160 mJ/cm^2, which is comparatively very high. Since we did not apply higher doses (> 160 mJ/cm^2), the tailing effect was not observed.

The "*shoulder effect*" could be caused by high UV absorbance due to a high concentration of organic matter, that is, dissolved solids and fine particles (< 8 μm) that may have shielded microorganisms against the UV action. For effective UV action on microorganisms in this type of wastewater, the absorbance should not be more than 2 (Bolton, 2001). Table 4.5 shows that the average UV absorbance of all the samples was approximately equal to 4.0977, almost double the extreme value (*i.e.* 2.0) required for effective UV action. It is obvious that more effective treatment is required to reduce dissolved solids, BOD and fine particles. Another alternative would be to dilute the swine manure to bring its absorbance into the desired range. SEM (Scanning Electron Microscope) analysis was performed on the membrane filters used for filtering primary settled and jar supernatants. The results confirmed our viewpoint that fine particles provided protective shields to microorganisms, thus rendering lower doses of UV ineffective. Figures 4.22 and 4.23 depict SEM pictures of membrane filters showing microorganisms, organic mass and fine solid (colloidal) particles dispersed separately and agglomerated with one another. The agglomerated mass of microorganisms, organic matter and colloidal particles prevents the UV rays from penetrating through, and thus protects the microorganisms from inactivation.



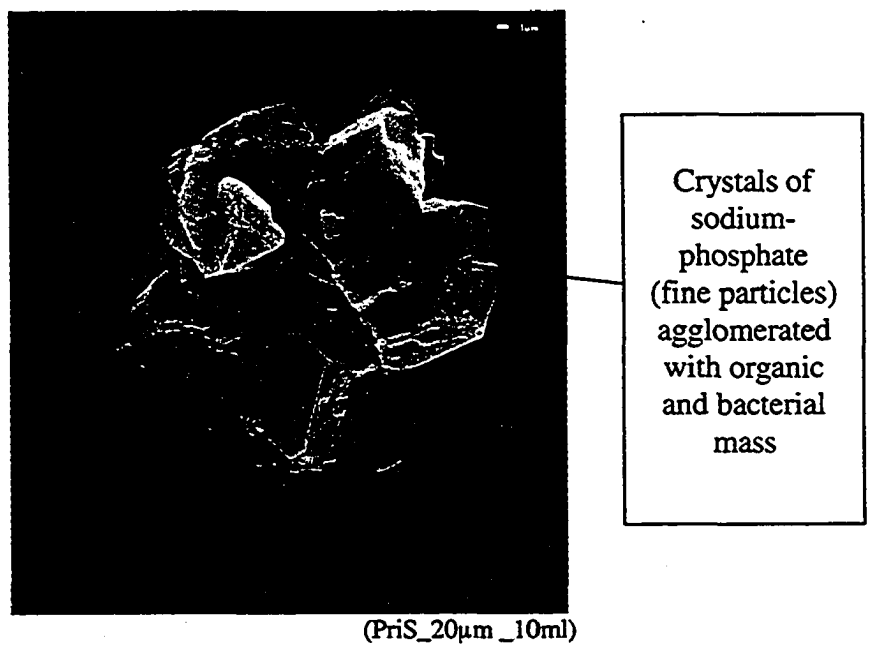
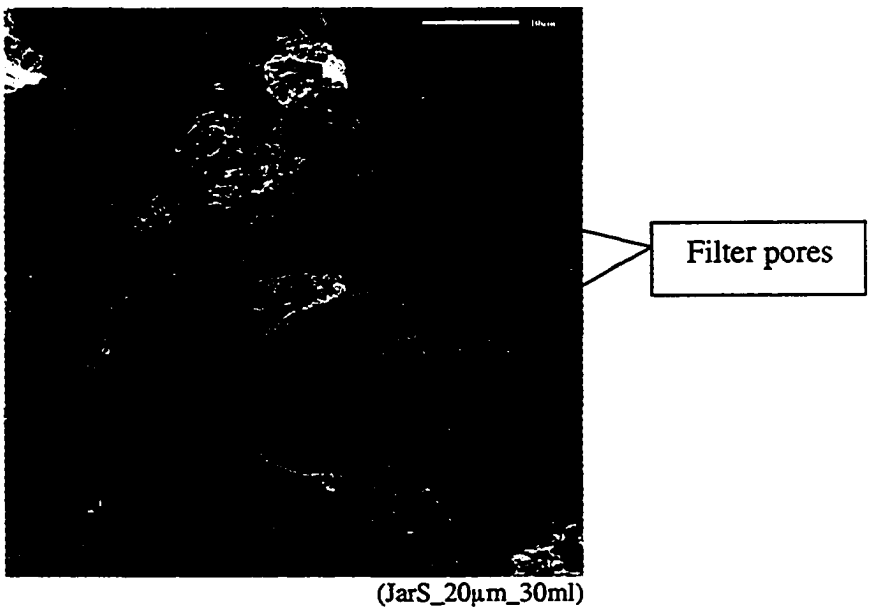


Figure 4.20 SEM picture showing very fine particles agglomerated with microbial mass and dispersed microorganisms on the membrane filters. (Parenthesis denotes Sample ID_filter pore size_volume of sample filtered).



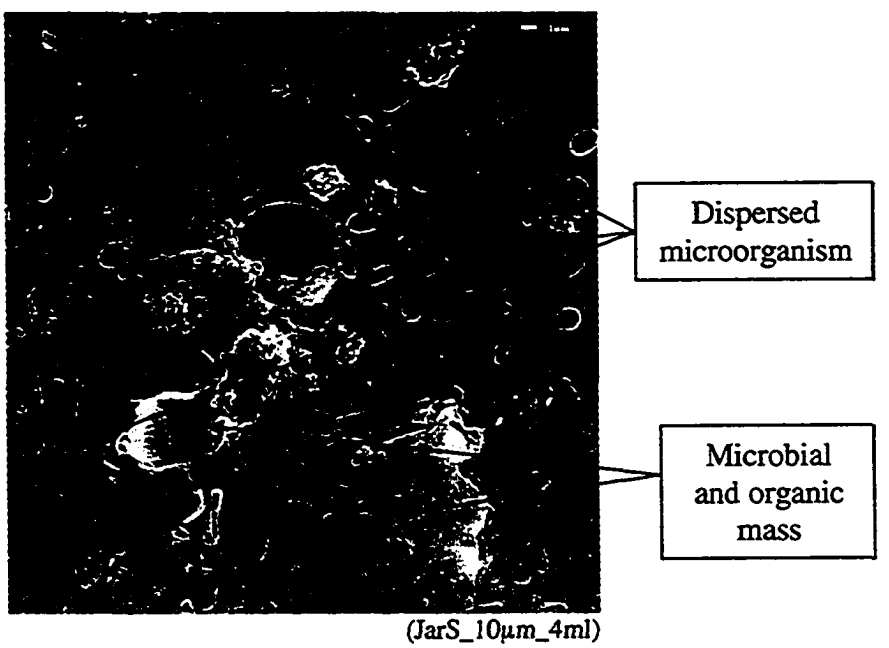


Figure 4.21 SEM picture showing very fine particles agglomerated with microbial mass and dispersed microorganisms on the membrane filters. (Parenthesis denotes Sample ID_filter pore size_volume of sample filtered).

4.3.2.2 Experiment #2

There was a problem in experiment #1 with what is termed "*shoulder effect*". In experiment #2, this problem was effectively eliminated by diluting the raw manure by a ratio of 1:50 with DI water. The diluted manure was left for natural settlement for 24 hours in a PVC barrel and then a jar test was performed on the supernatant obtained after 24 hours of settling. Since the manure was diluted 50 times with DI water, it is conceivable that the alum dose used for the jar test would have to be considerably less than previous doses. Thus, a nominal alum dose of 60 mg/L was used. As the manure was previously diluted, we were able to filter the jar supernatant through 5 μm and 2 μm polycarbonate membrane filters. This made it possible to further remove fine particles of size less than 8 μm. Figures 4.24 and 4.25 show the particle size distributions and particle counts for raw and treated samples in experiment #2. Remaining particles with size ranging from 2 μm to 5 μm (shown in Figures 4.24 and 4.25) may be due to particle counter standard error (instrumental), or inefficient filtration. Table 4.6 shows the phosphorus concentrations in raw manure and treated manure samples. Because of the high dilution, the percentage P removal was not as high as found in previous field and laboratory experiments.

Table 4.6 Phosphorus concentrations (mg/L) in raw and treated swine manure samples.

Sample ID	Without alum		With alum	
	P conc. (mg/L)	% Removal	P conc. (mg/L)	% Removal
Raw manure	197	0	197	0
Primary supernatant	196	0.5	196	0.5
Jar supernatant	n/a	n/a	131	34
Filtrate:10 μm	196	0.5	122	38
Filtrate: 5 μm	193	2.1	115	42
Filtrate: 2 μm	187	7.1	100	49

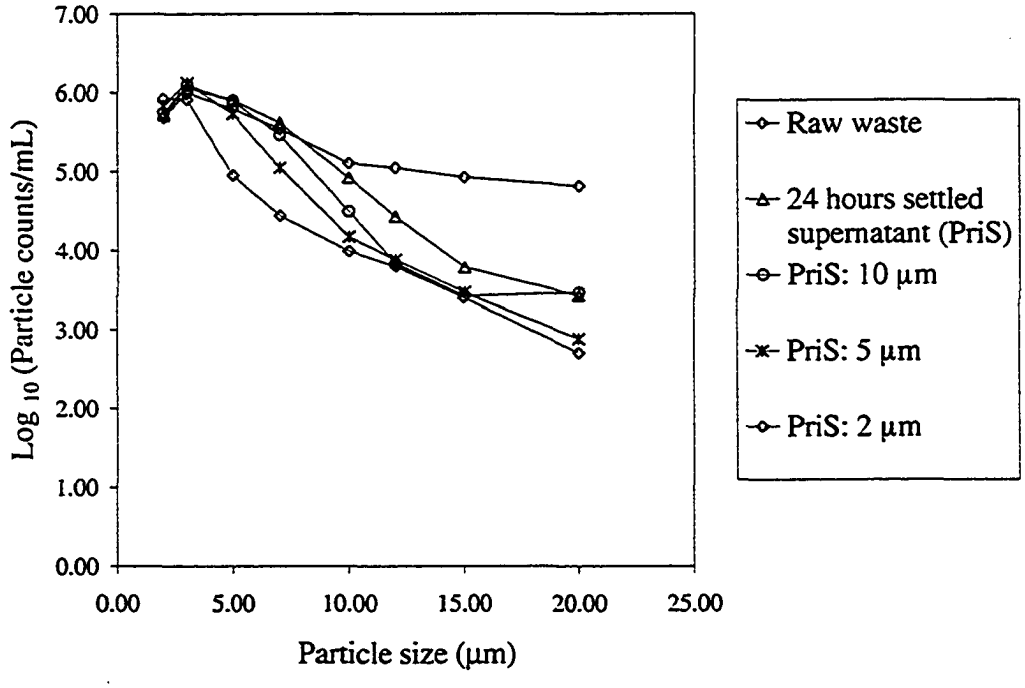


Figure 4.22 Particle size distribution and particle count analysis for Experiment #2.

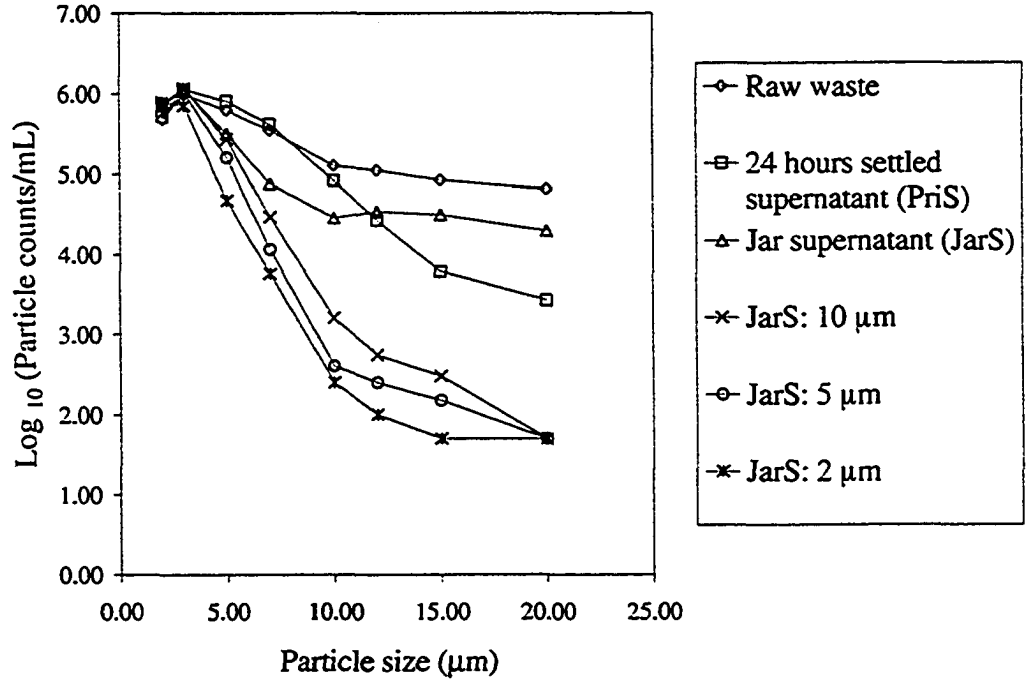


Figure 4.23 Particle size distribution and particle count analysis for Experiment #2.

The process parameters for the UV experiment are shown in Table 4.7. It should be noted that the UV absorbance values in experiment #2 are within the UV effective range (0.5 - 2.0). Consequently, the results obtained from the second UV experiment are free of "*shoulder effect*". The inactivation curves shown in Figures 4.26 and 4.27 look similar, with a standard disinfection model curve (shown in Fig 4.21) and others mentioned in the literature depicting the typical first order kinetics phenomenon.

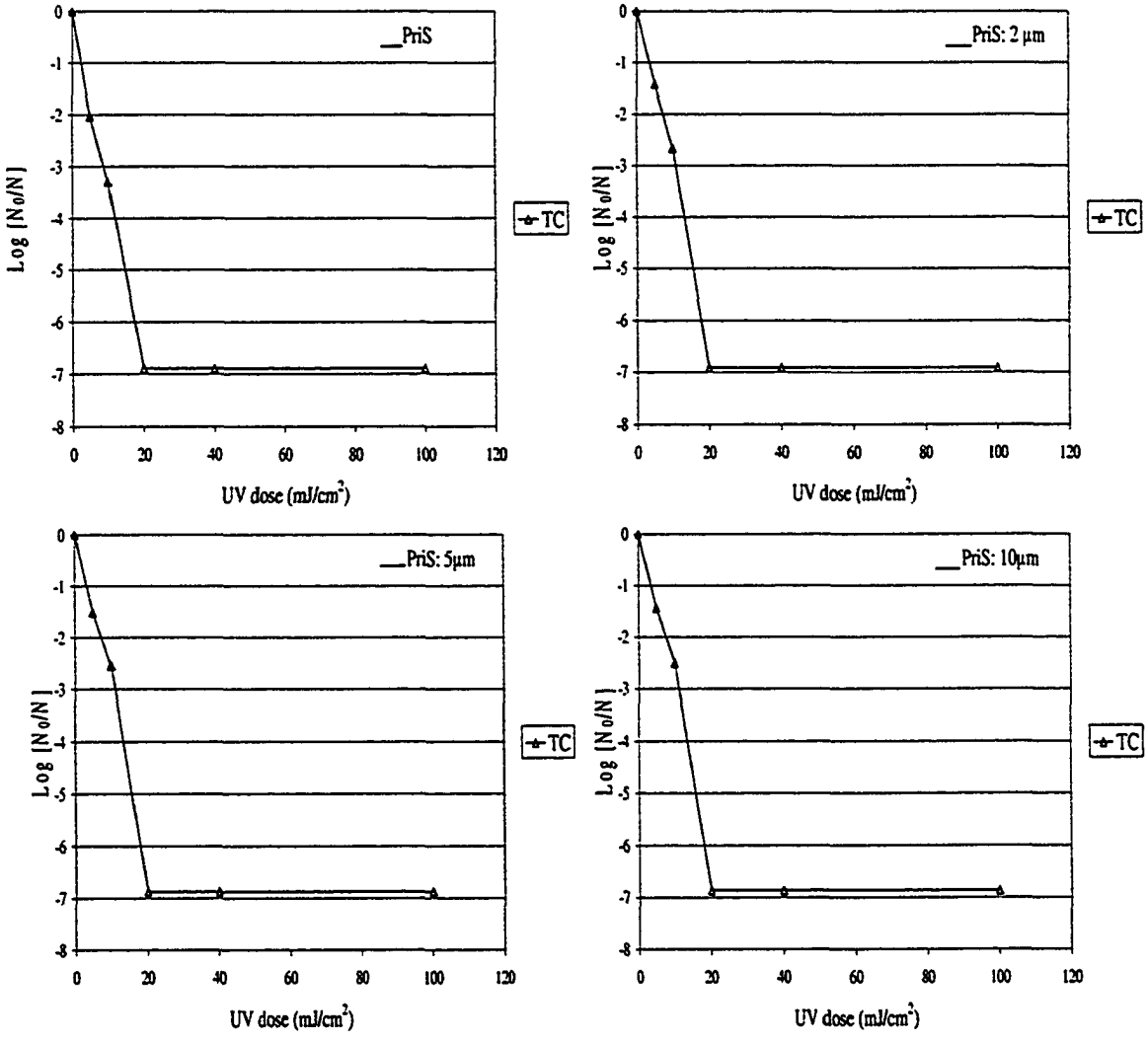


Figure 4.24 Log_{10} inactivation curves for 24 hours settled supernatant (PriS) and its filtrates (2 µm, 5 µm and 10 µm).

Table 4.7 Experiment #2: Process parameters (* further diluted 1:2)

Sample ID	UV absorbance @ 254 nm	UV dose (mJ/cm^2)	Exposure time (min/s)
PriS	1.67357	5	1 min 52 s
		10	3 min 43 s
		20	7 min 26 s
		40	14 min 53 s
		100	35 min 49 s
PriS: 2 µm	1.72917	5	1 min 49 s
		10	3 min 38 s
		20	7 min 15 s
		40	14 min 30 s
		100	36 min 44 s
PriS: 5 µm	1.90765	5	1 min 59 s
		10	3 min 57 s
		20	7 min 54 s
		40	15 min 48 s
		100	39 min 4 s
PriS: 10 µm*	1.48566	5	1 min 36 s
		10	3 min 12 s
		20	6 min 23 s
		40	12 min 46 s
		100	31 min 50 s
JarS	1.10788	5	1 min 15 s
		10	2 min 29 s
		20	4 min 58 s
		40	9 min 56 s
		100	25 min 30 s
JarS: 2 µm	1.64644	5	1 min 42 s
		10	3 min 23 s
		20	6 min 46 s
		40	13 min 32 s
		100	34 min 30 s
JarS: 5 µm	1.34973	5	1 min 27 s
		10	2 min 55 s
		20	5 min 49 s
		40	11 min 38 s
		100	28 min 46 s
JarS: 10 µm	1.42288	5	1 min 29 s
		10	2 min 59 s
		20	5 min 58 s
		40	11 min 55 s
		100	30 min 16 s

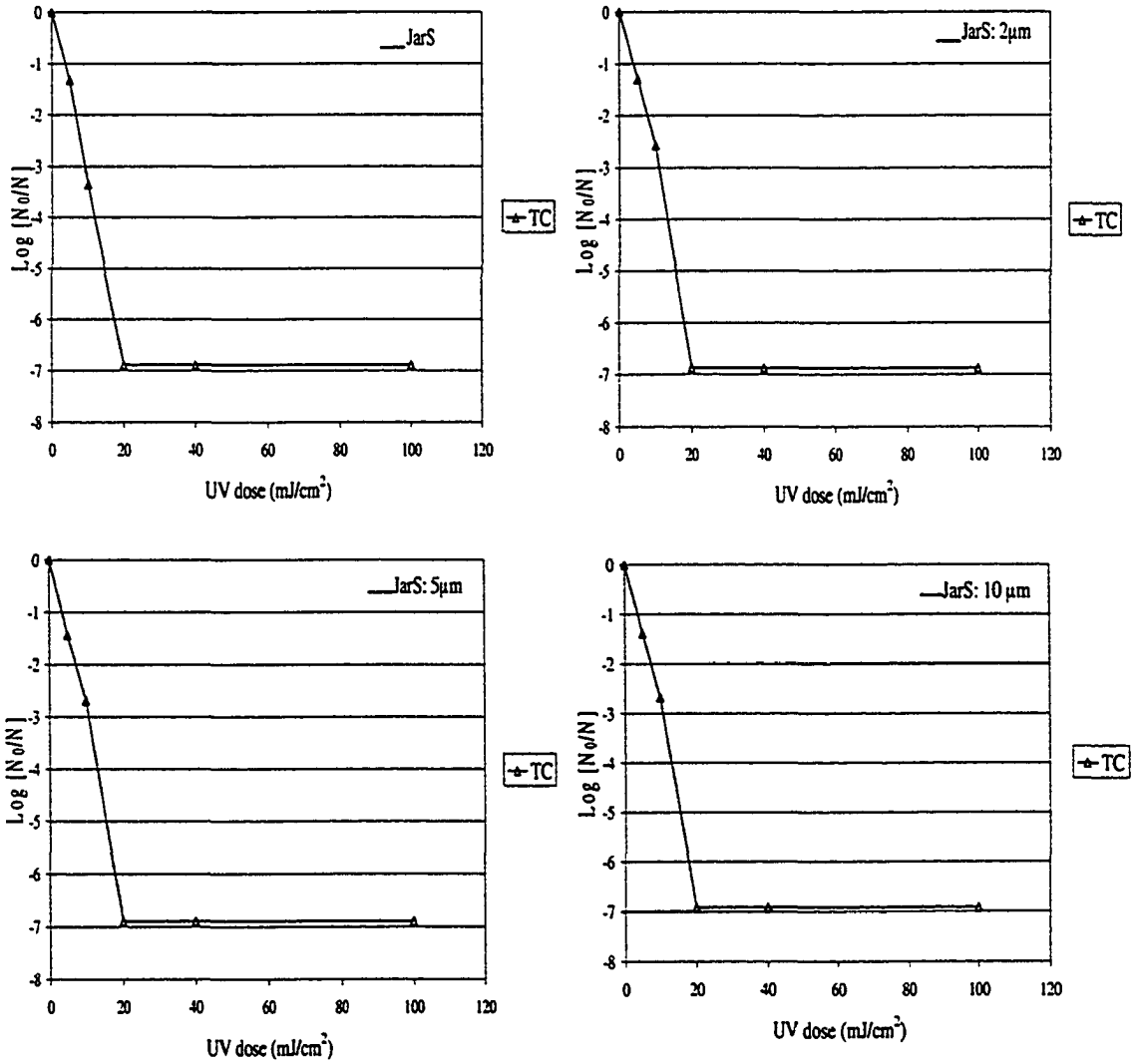


Figure 4.25 Log_{10} inactivation curves for jar supernatant (JarS) and its filtrates (2 µm, 5 µm and 10 µm).

Inactivation curves obtained from UV experiment #2 (Figures 4.26 and 4.27) demonstrate complete inactivation at an average dose of 20 mJ/cm^2, and at higher doses. Hill *et al.*, (2002) developed inactivation curves for E. *coli*, enterococci, *C. perfringens* spores, and somatic coliphages (in swine manure treated by aerobic biofilter) by doing several UV experiments with a low pressure intensity UV lamp at doses ranging from 0 to 15 mJ/cm^2. They achieved a 2.5 to 3 log_{10} reduction in E. *coli* at an average UV dose

of 13 mJ/cm^2. In our case, a $\log_{10}$ inactivation (N_0/N) between 2 and 3 was achieved at a UV dose of 10 mJ/cm^2. All inactivation curves developed for swine manure samples appear similar. The minimum most-effective UV dose is approximately equal to 20 mJ/cm^2, where complete inactivation is observed in all samples.

The effectiveness of UV on treated effluents depends upon the sample's absorbance of the UV light. The absorbance value is directly dependent on the concentration of suspended and dissolved solids, salts and organic content in the sample. Therefore, the treatment should be able to remove them effectively in order to ensure that the effect of the UV light on the microorganisms is maximized.

5.0 CONCLUSIONS AND RECOMMENDATIONS

In this project, the effectiveness of physical/chemical treatment was evaluated using flushed swine manure supplied by the Swine Research and Technology Center located at the University of Alberta, Edmonton Research Station. Both pilot scale and laboratory scale treatment operations were carried out and the results obtained in both settings were analyzed for comparison and confirmation. Finally, ultraviolet (UV) disinfection was applied to the samples treated on the laboratory scale. The following points conclude this research project:

- Swine manure characteristics vary substantially from sample to sample.
- Natural settling, or preliminary settling prior to any treatment was found to be very effective for livestock manures.
- Alum was chosen as the best performing coagulant, as it yielded the maximum TSS and TP removal at the lowest cost incurred.
- TSS and TP removal efficiencies were 79 and 78% respectively for pilot plant treatment, and 85 and 64% respectively for laboratory based (jar test) treatment. The results obtained from the pilot plant, and the laboratory, were found to be consistent.
- Physical/chemical treatment was not very effective in reducing TDS, TKN and BOD_5 in swine liquid manure.
- Both clarifier and Martin filter units performed well. Clarification was responsible for major TSS and TP reductions, while filtration removed more fine solid particles.

- Particle count analysis indicated that most of the particles present in untreated and treated swine manure samples were less than 8μm in size. Therefore, any treatment prior to UV disinfection should be able to effectively remove these particles.
- SEM analysis confirmed the results obtained from particle counting. SEM images demonstrated that fine solid particles (size $\leq$ 5μm) agglomerated with organic matter may shield microorganisms against UV action. This can also be verified by diluting the samples to keep the absorbance in the effective UV range.
- Ultraviolet (UV) disinfection is an effective alternative to conventional disinfection techniques. The results obtained from UV experiments were very promising. Almost complete inactivation (5 to 6 $\log_{10}$ inactivation) was observed in all treated swine manure samples (raw manure diluted to 1:50), with an average UV dose of 20 mJ/cm^2.

Based on the conclusions stated above, the following recommendations are made for further investigations:

- Initial investigations concluded that alum, when used alone, was the most cost-effective coagulant. It may not be cost-effective when used on a large scale, e.g. WWTPs. Therefore, further research could be conducted regarding the use of a combination of alum and polymers.
- Since this project was aimed at using the swine manure effluent obtained after treatment for land applications, more emphasis was placed on the management

of solids and nutrients. Although TSS and TP were successfully removed, the desired results were not obtained for TKN removal. Nitrogen is considered to be one of the main sources of surface and ground water pollution. The treatment system needs an additional step to manage the nitrogen present in swine manure.

- The reuse of agricultural manure is an idea currently growing in popularity in the agriculture sector. Solids, nutrients, organic matter and pathogens should be eliminated, or effectively reduced, in order to reuse manure in agro facilities. The option of combining the physical/chemical and biological methods may further improve the results.
- Fine glass bead media (> Mil-spec 13) may be used in Martin filters to facilitate the removal of those particles with size less than 5μm. This can improve the UV absorbance, and hence, result in more effective UV inactivation.
- A thorough dose-response (inactivation) study could be conducted at lower UV doses, as almost complete inactivation was observed at a UV dose of 20 mJ/cm^2.

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APPENDIX – A

UV Experiment #1

Dated: Feb 19, 2004
Sample ID: PriS (24-hours settled supernatant) (Diluted 1:2)
Petri dish diameter: 5 cm
Lamp Ht from water level In Petri dish 23.5 cm

Scale	Reading x-axis	Reading y-axis
-3.0	0.11	0.07
-2.5	0.14	0.12
-2.0	0.16	0.15
-1.5	0.17	0.16
-1.0	0.18	0.17
-.05	0.18	0.17
0	0.2	0.2
0.5	0.2	0.18
1.0	0.19	0.18
1.5	0.18	0.18
2.0	0.17	0.17
2.5	0.16	0.16
3.0	0.14	0.16

Absorbance: 3.84753
Irradiance @ center: 0.2 mW/cm^2
Petri factor: 0.747
UV dose: 160 mJ/cm^2
Exposure time: 2 hr 51 s
Initial temperature: 17° C
Final temperature: 19.5° C

Dated: Feb 19, 2004
Sample ID: PriS (24-hours settled supernatant) (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.11	0.078
-2.5	0.16	0.13
-2.0	0.17	0.16
-1.5	0.18	0.18
-1.0	0.19	0.19
-.05	0.2	0.19
0	0.2	0.2
0.5	0.2	0.2
1.0	0.19	0.2
1.5	0.19	0.2
2.0	0.17	0.19
2.5	0.17	0.18
3.0	0.16	0.18

Absorbance: 3.84753
Irradiance @ center: 0.2 mW/cm^2
Petri factor: 0.895
UV dose: 40 mJ/cm^2
Exposure time: 35 min 52 s
Initial temperature: 14.5° C
Final temperature: 18°

Dated: Feb 19, 2004
Sample ID: PriS (24-hours settled supernatant) (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.19
2.0	0.18	0.17
2.5	0.16	0.15
3.0	0.15	0.11

Absorbance: 4.10153
Irradiance @ center: 0.2 mW/cm^2
Petri factor: 0.936
UV dose: 5 mJ/cm^2
Exposure time: 4 min 34 s
Initial temperature: 14° C
Final temperature: 15° C

Dated: Feb 19, 2004
Sample ID: PriS (24-hours settled supernatant) (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.2	0.2
1.5	0.19	0.19
2.0	0.18	0.19
2.5	0.16	0.15
3.0	0.15	0.11

Absorbance: 3.84753
Irradiance @ center: 0.2 mW/cm^2
Petri factor: 0.936
UV dose: 15 mJ/cm^2
Exposure time: 13 min 42 s
Initial temperature: 14.5° C
Final temperature: 18° C

Dated: Feb 19, 2004
Sample ID: PriS (24-hours settled supernatant) (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.2	0.2
1.5	0.19	0.19
2.0	0.18	0.19
2.5	0.16	0.15
3.0	0.15	0.11

Absorbance: 3.84753
Irradiance @ center: 0.2 mW/cm^2
Petri factor: 0.936
UV dose: 80 mJ/cm^2
Exposure time: 1 hr 1 s
Initial temperature: 17° C
Final temperature: 19.5° C

Dated: Feb 19, 2004
Sample ID: PriS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.18	0.19
2.0	0.17	0.18
2.5	0.16	0.16
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.2 mW/cm^2
Petri factor: 0.930
UV dose: 160 mJ/cm^2
Exposure time: 2 hr 27 s
Initial temperature: 16° C
Final temperature: 20° C

Dated: Feb 19, 2004
Sample ID: PriS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.18	0.19
2.0	0.18	0.18
2.5	0.16	0.16
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.859
UV dose: 5 mJ/cm^2
Exposure time: 4 min 58 s
Initial temperature: 20.5° C
Final temperature: 20.5° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.18	0.19
2.0	0.18	0.18
2.5	0.16	0.16
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.859
UV dose: 15 mJ/cm^2
Exposure time: 14 min 55 s
Initial temperature: 20.5° C
Final temperature: 20° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.14	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.19
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.18	0.18
2.0	0.17	0.17
2.5	0.16	0.15
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.20 mW/cm^2
Petri factor: 0.915
UV dose: 80 mJ/cm^2
Exposure time: 1hr 14 min 44 s
Initial temperature: 20.5° C
Final temperature: 20° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.19	0.19
1.5	0.19	0.19
2.0	0.18	0.18
2.5	0.17	0.16
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.20 mW/cm^2
Petri factor: 0.935
UV dose: 40 mJ/cm^2
Exposure time: 36 min 33 s
Initial temperature: 19° C
Final temperature: 19.5° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.11	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.19	0.19
1.5	0.19	0.18
2.0	0.18	0.18
2.5	0.16	0.15
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.20 mW/cm^2
Petri factor: 0.929
UV dose: 5 mJ/cm^2
Exposure time: 4 min 36 s
Initial temperature: 15° C
Final temperature: 17.5° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.11	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.2	0.2
0.5	0.2	0.2
1.0	0.19	0.19
1.5	0.19	0.18
2.0	0.18	0.18
2.5	0.16	0.15
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.20 mW/cm^2
Petri factor: 0.929
UV dose: 15 mJ/cm^2
Exposure time: 13 min 48 s
Initial temperature: 15° C
Final temperature: 18.5° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.12	0.17
-2.5	0.16	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.19	0.2
-.05	0.2	0.2
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.19
2.0	0.18	0.18
2.5	0.16	0.16
3.0	0.15	0.11

Absorbance: 4.10222
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.859
UV dose: 160 mJ/cm^2
Exposure time: 2 hr 31 min 40 s
Initial temperature: 17° C
Final temperature: 20° C

Dated: Feb 20, 2004
Sample ID: PriS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.19
-2.0	0.18	0.19
-1.5	0.19	0.19
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.16	0.10

Absorbance: 4.10222
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.851
UV dose: 40 mJ/cm^2
Exposure time: 38 min 17 s
Initial temperature: 21° C
Final temperature: 20.5° C

Dated: Feb 21, 2004
Sample ID: PriS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.11	0.17
-2.5	0.17	0.19
-2.0	0.19	0.19
-1.5	0.19	0.2
-1.0	0.2	0.21
-.05	0.2	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.2
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.17	0.13
3.0	0.15	0.075

Absorbance: 4.08461
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.874
UV dose: 80 mJ/cm^2
Exposure time: 1hr 14 min 14 s
Initial temperature: 18.5° C
Final temperature: 20.2° C

Dated: Feb 21, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.19	0.2
-1.5	0.19	0.2
-1.0	0.2	0.21
-.05	0.21	0.21
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.2
1.5	0.19	0.19
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.15	0.099

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.893
UV dose: 5 mJ/cm^2
Exposure time: 4 min 36 s
Initial temperature: 13.5° C
Final temperature: 16.5° C

Dated: Feb 21, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.19	0.2
-1.5	0.19	0.2
-1.0	0.2	0.21
-.05	0.21	0.21
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.2
1.5	0.19	0.19
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.15	0.099

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.893
UV dose: 15 mJ/cm^2
Exposure time: 13 min 40 s
Initial temperature: 13° C
Final temperature: 17° C

Dated: Feb 21, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.19	0.2
-1.5	0.19	0.2
-1.0	0.2	0.21
-.05	0.21	0.21
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.2
1.5	0.19	0.19
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.15	0.099

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.893
UV dose: 40 mJ/cm^2
Exposure time: 36 min 28 s
Initial temperature: 16° C
Final temperature: 19.5° C

Dated: Feb 21, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.19	0.19
-1.5	0.2	0.2
-1.0	0.2	0.21
-.05	0.21	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.19
2.0	0.18	0.18
2.5	0.17	0.15
3.0	0.15	0.088

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.888
UV dose: 80 mJ/cm^2
Exposure time: 1 hr 13 min 46 s
Initial temperature: 17° C
Final temperature: 20.2° C

Dated: Feb 21, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.12	0.17
-2.5	0.17	0.19
-2.0	0.19	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.21
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.2
1.5	0.19	0.19
2.0	0.18	0.17
2.5	0.16	0.15
3.0	0.15	0.099

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.879
UV dose: 160 mJ/cm^2
Exposure time: 2 hr 29 min 1 s
Initial temperature: 19.5° C
Final temperature: 20.2° C

Dated: Feb 21, 2004
Sample ID: JarS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.19	0.19
-1.5	0.2	0.2
-1.0	0.2	0.2
-.05	0.21	0.2
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.15	0.091

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.873
UV dose: 5 mJ/cm^2
Exposure time: 4 min 41 s
Initial temperature: 15.5° C
Final temperature: 18° C

Dated: Feb 21, 2004
Sample ID: JarS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.19	0.19
-1.5	0.2	0.2
-1.0	0.2	0.2
-.05	0.21	0.2
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.15	0.091

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.873
UV dose: 15 mJ/cm^2
Exposure time: 14 min 4 s
Initial temperature: 15.8° C
Final temperature: 18.5° C

Dated: Feb 21, 2004
Sample ID: JarS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.19	0.19
-1.5	0.2	0.2
-1.0	0.2	0.2
-.05	0.21	0.2
0	0.21	0.21
0.5	0.21	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.17	0.14
3.0	0.15	0.091

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.873
UV dose: 40 mJ/cm^2
Exposure time: 37 min 30 s
Initial temperature: 17° C
Final temperature: 20° C

Dated: Feb 21, 2004
Sample ID: JarS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.14	0.17
-2.5	0.17	0.18
-2.0	0.19	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.19
2.0	0.18	0.17
2.5	0.17	0.15
3.0	0.15	0.1

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.869
UV dose: 80 mJ/cm^2
Exposure time: 1 hr 15 min 21 s
Initial temperature: 19° C
Final temperature: 19.5° C

Dated: Feb 21, 2004
Sample ID: JarS- Filtrate: 20 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.12	0.17
-2.5	0.17	0.19
-2.0	0.19	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.21	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.17	0.16
2.5	0.16	0.12
3.0	0.15	0.07

Absorbance: 4.12634
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.860
UV dose: 160 mJ/cm^2
Exposure time: 2 hr 32 min 24 s
Initial temperature: 20° C
Final temperature: 20° C

Dated: Feb 22, 2004
Sample ID: JarS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.18
-2.5	0.17	0.19
-2.0	0.19	0.19
-1.5	0.19	0.2
-1.0	0.2	0.21
-.05	0.21	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.16
2.5	0.17	0.13
3.0	0.15	0.071

Absorbance: 4.04565
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.870
UV dose: 5 mJ/cm^2
Exposure time: 4 min 37 s
Initial temperature: 11° C
Final temperature: 14° C

Dated: Feb 22, 2004
Sample ID: JarS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.16	0.13
3.0	0.15	0.082

Absorbance: 4.04565
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.859
UV dose: 80 mJ/cm^2
Exposure time: 1 hr 14 min 49 s
Initial temperature: 17° C
Final temperature: 20° C

Dated: Feb 22, 2004
Sample ID: JarS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.16	0.13
3.0	0.15	0.082

Absorbance: 4.04565
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.859
UV dose: 15 mJ/cm^2
Exposure time: 13 min 51 s
Initial temperature: 12° C
Final temperature: 15.5° C

Dated: Feb 22, 2004
Sample ID: JarS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.13	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.21
0	0.21	0.21
0.5	0.2	0.2
1.0	0.2	0.19
1.5	0.19	0.18
2.0	0.18	0.17
2.5	0.16	0.13
3.0	0.15	0.082

Absorbance: 4.04565
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.859
UV dose: 40 mJ/cm^2
Exposure time: 36 min 56 s
Initial temperature: 13.5° C
Final temperature: 18° C

Dated: Feb 22, 2004
Sample ID: JarS- Filtrate: 10 µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.12	0.17
-2.5	0.17	0.18
-2.0	0.18	0.19
-1.5	0.19	0.2
-1.0	0.2	0.2
-.05	0.2	0.2
0	0.21	0.21
0.5	0.2	0.2
1.0	0.19	0.19
1.5	0.18	0.18
2.0	0.17	0.16
2.5	0.16	0.12
3.0	0.14	0.069

Absorbance: 4.04565
Irradiance @ center: 0.21 mW/cm^2
Petri factor: 0.840
UV dose: 160 mJ/cm^2
Exposure time: 2 hr 33 min 1 s
Initial temperature: 20.5° C
Final temperature: 21° C

APPENDIX – B

UV Experiment #2

Dated: Apr 27, 2004
Sample ID: PriS (24-hours settled supernatant)
Petri dish diameter: 5 cm
Lamp Ht from water level In Petri dish 23.3 cm

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.118
-2.5	0.187	0.182
-2.0	0.197	0.199
-1.5	0.205	0.207
-1.0	0.212	0.217
-.05	0.218	0.229
0	0.240	0.240
0.5	0.225	0.234
1.0	0.211	0.227
1.5	0.194	0.215
2.0	0.182	0.203
2.5	0.168	0.184
3.0	0.151	0.119

Absorbance: 1.67357
Irradiance @ center: 0.240 mW/cm^2
Petri factor: 0.8
UV dose: 5 mJ/cm^2
Exposure time: 1 min 52 s
Initial temperature: 14° C
Final temperature: 15° C

Dated: Apr 27, 2004
Sample ID: PriS (24-hours settled supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.118
-2.5	0.187	0.182
-2.0	0.197	0.199
-1.5	0.205	0.207
-1.0	0.212	0.217
-.05	0.218	0.229
0	0.240	0.240
0.5	0.225	0.234
1.0	0.211	0.227
1.5	0.194	0.215
2.0	0.182	0.203
2.5	0.168	0.184
3.0	0.151	0.119

Absorbance: 1.67357
Irradiance @ center: 0.240 mW/cm^2
Petri factor: 0.8
UV dose: 10 mJ/cm^2
Exposure time: 3 min 43 s
Initial temperature: 12° C
Final temperature: 14° C

Dated: Apr 27, 2004
Sample ID: PriS (24-hours settled supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.118
-2.5	0.187	0.182
-2.0	0.197	0.199
-1.5	0.205	0.207
-1.0	0.212	0.217
-.05	0.218	0.229
0	0.240	0.240
0.5	0.225	0.234
1.0	0.211	0.227
1.5	0.194	0.215
2.0	0.182	0.203
2.5	0.168	0.184
3.0	0.151	0.119

Absorbance: 1.67357
Irradiance @ center: 0.240 mW/cm^2
Petri factor: 0.8
UV dose: 20 mJ/cm^2
Exposure time: 7 min 26 s
Initial temperature: 12° C
Final temperature: 15° C

Dated: Apr 27, 2004
Sample ID: PriS (24-hours settled supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.118
-2.5	0.187	0.182
-2.0	0.197	0.199
-1.5	0.205	0.207
-1.0	0.212	0.217
-.05	0.218	0.229
0	0.240	0.240
0.5	0.225	0.234
1.0	0.211	0.227
1.5	0.194	0.215
2.0	0.182	0.203
2.5	0.168	0.184
3.0	0.151	0.119

Absorbance: 1.67357
Irradiance @ center: 0.240 mW/cm^2
Petri factor: 0.8
UV dose: 40 mJ/cm^2
Exposure time: 14 min 53 s
Initial temperature: 14° C
Final temperature: 18° C

Dated: Apr 27, 2004
Sample ID: PriS (24-hours settled supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.094	0.124
-2.5	0.169	0.172
-2.0	0.202	0.194
-1.5	0.212	0.214
-1.0	0.221	0.220
-.05	0.234	0.231
0	0.234	0.234
0.5	0.220	0.234
1.0	0.205	0.232
1.5	0.188	0.225
2.0	0.174	0.211
2.5	0.161	0.191
3.0	0.106	0.142

Absorbance: 1.67357
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.852
UV dose: 100 mJ/cm^2
Exposure time: 35 min 49 s
Initial temperature: 14° C
Final temperature: 19° C

Dated: Apr 27, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.127
-2.5	0.201	0.175
-2.0	0.211	0.203
-1.5	0.221	0.209
-1.0	0.232	0.218
-.05	0.236	0.227
0	0.234	0.234
0.5	0.221	0.231
1.0	0.207	0.224
1.5	0.192	0.218
2.0	0.180	0.206
2.5	0.169	0.186
3.0	0.145	0.140

Absorbance: 1.10788
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.862
UV dose: 5 mJ/cm^2
Exposure time: 1 min 15 s
Initial temperature: 7° C
Final temperature: 10° C

Dated: Apr 27, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.127
-2.5	0.201	0.175
-2.0	0.211	0.203
-1.5	0.221	0.209
-1.0	0.232	0.218
-.05	0.236	0.227
0	0.234	0.234
0.5	0.221	0.231
1.0	0.207	0.224
1.5	0.192	0.218
2.0	0.180	0.206
2.5	0.169	0.186
3.0	0.145	0.140

Absorbance: 1.10788
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.862
UV dose: 20 mJ/cm^2
Exposure time: 4 min 58 s
Initial temperature: 7° C
Final temperature: 11° C

Dated: Apr 27, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.127
-2.5	0.201	0.175
-2.0	0.211	0.203
-1.5	0.221	0.209
-1.0	0.232	0.218
-.05	0.236	0.227
0	0.234	0.234
0.5	0.221	0.231
1.0	0.207	0.224
1.5	0.192	0.218
2.0	0.180	0.206
2.5	0.169	0.186
3.0	0.145	0.140

Absorbance: 1.10788
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.862
UV dose: 40 mJ/cm^2
Exposure time: 9 min 56 s
Initial temperature: 9° C
Final temperature: 14° C

Dated: Apr 27, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.183	0.127
-2.5	0.201	0.175
-2.0	0.211	0.203
-1.5	0.221	0.209
-1.0	0.232	0.218
-.05	0.236	0.227
0	0.234	0.234
0.5	0.221	0.231
1.0	0.207	0.224
1.5	0.192	0.218
2.0	0.180	0.206
2.5	0.169	0.186
3.0	0.145	0.140

Absorbance: 1.10788
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.862
UV dose: 10 mJ/cm^2
Exposure time: 2 min 29 s
Initial temperature: 8° C
Final temperature: 10° C

Dated: Apr 27, 2004
Sample ID: JarS (Jar supernatant)

Scale	Reading x-axis	Reading y-axis
-3.0	0.198	0.087
-2.5	0.208	0.152
-2.0	0.214	0.187
-1.5	0.221	0.204
-1.0	0.230	0.215
-.05	0.235	0.229
0	0.236	0.236
0.5	0.216	0.230
1.0	0.199	0.224
1.5	0.191	0.217
2.0	0.177	0.206
2.5	0.164	0.194
3.0	0.138	0.162

Absorbance: 1.10788
Irradiance @ center: 0.236 mW/cm^2
Petri factor: 0.832
UV dose: 100 mJ/cm^2
Exposure time: 25 min 30 s
Initial temperature: 13° C
Final temperature: 20° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.195	0.134
-2.5	0.207	0.180
-2.0	0.214	0.199
-1.5	0.225	0.211
-1.0	0.232	0.225
-.05	0.237	0.232
0	0.234	0.234
0.5	0.221	0.230
1.0	0.203	0.226
1.5	0.191	0.218
2.0	0.179	0.205
2.5	0.165	0.190
3.0	0.139	0.146

Absorbance: 1.72917
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.868
UV dose: 5 mJ/cm^2
Exposure time: 1 min 49 s
Initial temperature: 9° C
Final temperature: 12° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.195	0.134
-2.5	0.207	0.180
-2.0	0.214	0.199
-1.5	0.225	0.211
-1.0	0.232	0.225
-.05	0.237	0.232
0	0.234	0.234
0.5	0.221	0.230
1.0	0.203	0.226
1.5	0.191	0.218
2.0	0.179	0.205
2.5	0.165	0.190
3.0	0.139	0.146

Absorbance: 1.72917
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.868
UV dose: 10 mJ/cm^2
Exposure time: 3 min 38 s
Initial temperature: 10° C
Final temperature: 14° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.195	0.134
-2.5	0.207	0.180
-2.0	0.214	0.199
-1.5	0.225	0.211
-1.0	0.232	0.225
-.05	0.237	0.232
0	0.234	0.234
0.5	0.221	0.230
1.0	0.203	0.226
1.5	0.191	0.218
2.0	0.179	0.205
2.5	0.165	0.190
3.0	0.139	0.146

Absorbance: 1.72917
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.868
UV dose: 20 mJ/cm^2
Exposure time: 7 min 15 s
Initial temperature: 12° C
Final temperature: 15° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.195	0.134
-2.5	0.207	0.180
-2.0	0.214	0.199
-1.5	0.225	0.211
-1.0	0.232	0.225
-.05	0.237	0.232
0	0.234	0.234
0.5	0.221	0.230
1.0	0.203	0.226
1.5	0.191	0.218
2.0	0.179	0.205
2.5	0.165	0.190
3.0	0.139	0.146

Absorbance: 1.72917
Irradiance @ center: 0.234 mW/cm^2
Petri factor: 0.868
UV dose: 40 mJ/cm^2
Exposure time: 14 min 30 s
Initial temperature: 14° C
Final temperature: 18° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.197	0.133
-2.5	0.204	0.178
-2.0	0.213	0.200
-1.5	0.220	0.216
-1.0	0.232	0.225
-.05	0.236	0.235
0	0.235	0.235
0.5	0.224	0.225
1.0	0.205	0.220
1.5	0.197	0.216
2.0	0.184	0.208
2.5	0.174	0.197
3.0	0.162	0.178

Absorbance: 1.72917
Irradiance @ center: 0.235 mW/cm^2
Petri factor: 0.872
UV dose: 100 mJ/cm^2
Exposure time: 36 min 44 s
Initial temperature: 16° C
Final temperature: 19° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.188	0.125
-2.5	0.206	0.179
-2.0	0.216	0.201
-1.5	0.224	0.212
-1.0	0.232	0.222
-.05	0.238	0.234
0	0.235	0.235
0.5	0.233	0.236
1.0	0.206	0.228
1.5	0.194	0.221
2.0	0.183	0.212
2.5	0.170	0.190
3.0	0.148	0.140

Absorbance: 1.90765
Irradiance @ center: 0.235 mW/cm^2
Petri factor: 0.880
UV dose: 100 mJ/cm^2
Exposure time: 39 min 4 s
Initial temperature: 10° C
Final temperature: 18° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.191	0.122
-2.5	0.205	0.183
-2.0	0.213	0.203
-1.5	0.220	0.210
-1.0	0.226	0.217
-.05	0.234	0.229
0	0.236	0.236
0.5	0.219	0.237
1.0	0.206	0.233
1.5	0.192	0.225
2.0	0.179	0.216
2.5	0.168	0.209
3.0	0.145	0.194

Absorbance: 1.90765
Irradiance @ center: 0.236 mW/cm^2
Petri factor: 0.866
UV dose: 5 mJ/cm^2
Exposure time: 1 min 59 s
Initial temperature: 17° C
Final temperature: 18° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.191	0.122
-2.5	0.205	0.183
-2.0	0.213	0.203
-1.5	0.220	0.210
-1.0	0.226	0.217
-.05	0.234	0.229
0	0.236	0.236
0.5	0.219	0.237
1.0	0.206	0.233
1.5	0.192	0.225
2.0	0.179	0.216
2.5	0.168	0.209
3.0	0.145	0.194

Absorbance: 1.90765
Irradiance @ center: 0.236 mW/cm^2
Petri factor: 0.866
UV dose: 10 mJ/cm^2
Exposure time: 3 min 57 s
Initial temperature: 17° C
Final temperature: 18° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.191	0.122
-2.5	0.205	0.183
-2.0	0.213	0.203
-1.5	0.220	0.210
-1.0	0.226	0.217
-.05	0.234	0.229
0	0.236	0.236
0.5	0.219	0.237
1.0	0.206	0.233
1.5	0.192	0.225
2.0	0.179	0.216
2.5	0.168	0.209
3.0	0.145	0.194

Absorbance: 1.90765
Irradiance @ center: 0.236 mW/cm^2
Petri factor: 0.866
UV dose: 20 mJ/cm^2
Exposure time: 7 min 54 s
Initial temperature: 16° C
Final temperature: 18° C

Dated: Apr 27, 2004
Sample ID: PriS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.191	0.122
-2.5	0.205	0.183
-2.0	0.213	0.203
-1.5	0.220	0.210
-1.0	0.226	0.217
-.05	0.234	0.229
0	0.236	0.236
0.5	0.219	0.237
1.0	0.206	0.233
1.5	0.192	0.225
2.0	0.179	0.216
2.5	0.168	0.209
3.0	0.145	0.194

Absorbance: 1.90765
Irradiance @ center: 0.236 mW/cm^2
Petri factor: 0.866
UV dose: 40 mJ/cm^2
Exposure time: 15 min 48 s
Initial temperature: 15° C
Final temperature: 18° C

Dated: Apr 28, 2004
Sample ID: PriS- Filtrate: 10µm (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.161	0.106
-2.5	0.204	0.166
-2.0	0.211	0.196
-1.5	0.218	0.207
-1.0	0.225	0.217
-.05	0.231	0.227
0	0.237	0.237
0.5	0.222	0.237
1.0	0.209	0.230
1.5	0.196	0.221
2.0	0.189	0.216
2.5	0.172	0.216
3.0	0.152	0.209

Absorbance: 1.48566 (1:2) **Original absorbance:** 2.64854
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.850
UV dose: 100 mJ/cm^2
Exposure time: 31 min 50 s
Initial temperature: 11° C
Final temperature: 18° C

Dated: Apr 28, 2004
Sample ID: PriS- Filtrate: 10µm (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.167	0.151
-2.5	0.199	0.160
-2.0	0.209	0.194
-1.5	0.216	0.206
-1.0	0.221	0.217
-.05	0.232	0.229
0	0.237	0.237
0.5	0.226	0.236
1.0	0.210	0.231
1.5	0.196	0.223
2.0	0.185	0.216
2.5	0.173	0.209
3.0	0.152	0.194

Absorbance: 1.48566
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.848
UV dose: 40 mJ/cm^2
Exposure time: 12 min 46 s
Initial temperature: 18° C
Final temperature: 19° C

Dated: Apr 28, 2004
Sample ID: PriS- Filtrate: 10µm (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.167	0.151
-2.5	0.199	0.160
-2.0	0.209	0.194
-1.5	0.216	0.206
-1.0	0.221	0.217
-.05	0.232	0.229
0	0.237	0.237
0.5	0.226	0.236
1.0	0.210	0.231
1.5	0.196	0.223
2.0	0.185	0.216
2.5	0.173	0.209
3.0	0.152	0.194

Absorbance: 1.48566
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.848
UV dose: 20 mJ/cm^2
Exposure time: 6 min 23 s
Initial temperature: 18° C
Final temperature: 19° C

Dated: Apr 28, 2004
Sample ID: PriS- Filtrate: 10µm (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.167	0.151
-2.5	0.199	0.160
-2.0	0.209	0.194
-1.5	0.216	0.206
-1.0	0.221	0.217
-.05	0.232	0.229
0	0.237	0.237
0.5	0.226	0.236
1.0	0.210	0.231
1.5	0.196	0.223
2.0	0.185	0.216
2.5	0.173	0.209
3.0	0.152	0.194

Absorbance: 1.48566
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.848
UV dose: 10 mJ/cm^2
Exposure time: 3 min 12 s
Initial temperature: 19° C
Final temperature: 20° C

Dated: Apr 28, 2004
Sample ID: PriS- Filtrate: 10µm (Diluted 1:2)

Scale	Reading x-axis	Reading y-axis
-3.0	0.167	0.151
-2.5	0.199	0.160
-2.0	0.209	0.194
-1.5	0.216	0.206
-1.0	0.221	0.217
-.05	0.232	0.229
0	0.237	0.237
0.5	0.226	0.236
1.0	0.210	0.231
1.5	0.196	0.223
2.0	0.185	0.216
2.5	0.173	0.209
3.0	0.152	0.194

Absorbance: 1.48566
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.848
UV dose: 5 mJ/cm^2
Exposure time: 1 min 36 s
Initial temperature: 19° C
Final temperature: 20° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.175	0.178
-2.5	0.203	0.204
-2.0	0.211	0.212
-1.5	0.218	0.221
-1.0	0.226	0.230
-.05	0.233	0.234
0	0.239	0.239
0.5	0.230	0.238
1.0	0.213	0.233
1.5	0.196	0.227
2.0	0.185	0.220
2.5	0.171	0.211
3.0	0.154	0.195

Absorbance: 1.64644
Irradiance @ center: 0.239 mW/cm^2
Petri factor: 0.870
UV dose: 5 mJ/cm^2
Exposure time: 1 min 42 s
Initial temperature: 11° C
Final temperature: 13° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.175	0.178
-2.5	0.203	0.204
-2.0	0.211	0.212
-1.5	0.218	0.221
-1.0	0.226	0.230
-.05	0.233	0.234
0	0.239	0.239
0.5	0.230	0.238
1.0	0.213	0.233
1.5	0.196	0.227
2.0	0.185	0.220
2.5	0.171	0.211
3.0	0.154	0.195

Absorbance: 1.64644
Irradiance @ center: 0.239 mW/cm^2
Petri factor: 0.870
UV dose: 10 mJ/cm^2
Exposure time: 3 min 23 s
Initial temperature: 9° C
Final temperature: 12° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.175	0.178
-2.5	0.203	0.204
-2.0	0.211	0.212
-1.5	0.218	0.221
-1.0	0.226	0.230
-.05	0.233	0.234
0	0.239	0.239
0.5	0.230	0.238
1.0	0.213	0.233
1.5	0.196	0.227
2.0	0.185	0.220
2.5	0.171	0.211
3.0	0.154	0.195

Absorbance: 1.64644
Irradiance @ center: 0.239 mW/cm^2
Petri factor: 0.870
UV dose: 20 mJ/cm^2
Exposure time: 6 min 46 s
Initial temperature: 9° C
Final temperature: 13° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.175	0.178
-2.5	0.203	0.204
-2.0	0.211	0.212
-1.5	0.218	0.221
-1.0	0.226	0.230
-.05	0.233	0.234
0	0.239	0.239
0.5	0.230	0.238
1.0	0.213	0.233
1.5	0.196	0.227
2.0	0.185	0.220
2.5	0.171	0.211
3.0	0.154	0.195

Absorbance: 1.64644
Irradiance @ center: 0.239 mW/cm^2
Petri factor: 0.870
UV dose: 40 mJ/cm^2
Exposure time: 13 min 32 s
Initial temperature: 11° C
Final temperature: 16° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 2µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.190	0.149
-2.5	0.204	0.195
-2.0	0.212	0.205
-1.5	0.219	0.214
-1.0	0.229	0.223
-.05	0.237	0.232
0	0.236	0.236
0.5	0.221	0.231
1.0	0.208	0.227
1.5	0.195	0.220
2.0	0.183	0.213
2.5	0.172	0.206
3.0	0.156	0.188

Absorbance: 1.64644
Irradiance @ center: 0.236 mW/cm^2
Petri factor: 0.865
UV dose: 100 mJ/cm^2
Exposure time: 34 min 30 s
Initial temperature: 14° C
Final temperature: 19° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.163	0.106
-2.5	0.198	0.155
-2.0	0.208	0.194
-1.5	0.216	0.206
-1.0	0.223	0.216
-.05	0.231	0.227
0	0.237	0.237
0.5	0.226	0.237
1.0	0.213	0.234
1.5	0.199	0.228
2.0	0.187	0.221
2.5	0.174	0.214
3.0	0.160	0.204

Absorbance: 1.34973
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.855
UV dose: 5 mJ/cm^2
Exposure time: 1 min 27 s
Initial temperature: 8° C
Final temperature: 11° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.163	0.106
-2.5	0.198	0.155
-2.0	0.208	0.194
-1.5	0.216	0.206
-1.0	0.223	0.216
-.05	0.231	0.227
0	0.237	0.237
0.5	0.226	0.237
1.0	0.213	0.234
1.5	0.199	0.228
2.0	0.187	0.221
2.5	0.174	0.214
3.0	0.160	0.204

Absorbance: 1.34973
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.855
UV dose: 10 mJ/cm^2
Exposure time: 2 min 55 s
Initial temperature: 8° C
Final temperature: 11° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.163	0.106
-2.5	0.198	0.155
-2.0	0.208	0.194
-1.5	0.216	0.206
-1.0	0.223	0.216
-.05	0.231	0.227
0	0.237	0.237
0.5	0.226	0.237
1.0	0.213	0.234
1.5	0.199	0.228
2.0	0.187	0.221
2.5	0.174	0.214
3.0	0.160	0.204

Absorbance: 1.34973
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.855
UV dose: 5 mJ/cm^2
Exposure time: 5 min 49 s
Initial temperature: 10° C
Final temperature: 13° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.163	0.106
-2.5	0.198	0.155
-2.0	0.208	0.194
-1.5	0.216	0.206
-1.0	0.223	0.216
-.05	0.231	0.227
0	0.237	0.237
0.5	0.226	0.237
1.0	0.213	0.234
1.5	0.199	0.228
2.0	0.187	0.221
2.5	0.174	0.214
3.0	0.160	0.204

Absorbance: 1.34973
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.855
UV dose: 40 mJ/cm^2
Exposure time: 11 min 38 s
Initial temperature: 11° C
Final temperature: 15° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 5µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.191	0.114
-2.5	0.204	0.174
-2.0	0.213	0.200
-1.5	0.220	0.208
-1.0	0.228	0.217
-.05	0.235	0.230
0	0.238	0.238
0.5	0.229	0.236
1.0	0.217	0.231
1.5	0.203	0.222
2.0	0.190	0.213
2.5	0.178	0.204
3.0	0.167	0.180

Absorbance: 1.34973
Irradiance @ center: 0.238 mW/cm^2
Petri factor: 0.861
UV dose: 100 mJ/cm^2
Exposure time: 28 min 46 s
Initial temperature: 13° C
Final temperature: 18° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 10µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.186	0.137
-2.5	0.202	0.187
-2.0	0.211	0.201
-1.5	0.219	0.210
-1.0	0.226	0.221
-.05	0.234	0.231
0	0.237	0.237
0.5	0.229	0.237
1.0	0.218	0.231
1.5	0.204	0.226
2.0	0.192	0.217
2.5	0.179	0.209
3.0	0.168	0.191

Absorbance: 1.42288
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.874
UV dose: 5 mJ/cm^2
Exposure time: 1 min 29 s
Initial temperature: 17° C
Final temperature: 18° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 10µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.186	0.137
-2.5	0.202	0.187
-2.0	0.211	0.201
-1.5	0.219	0.210
-1.0	0.226	0.221
-.05	0.234	0.231
0	0.237	0.237
0.5	0.229	0.237
1.0	0.218	0.231
1.5	0.204	0.226
2.0	0.192	0.217
2.5	0.179	0.209
3.0	0.168	0.191

Absorbance: 1.42288
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.874
UV dose: 10 mJ/cm^2
Exposure time: 2 min 59 s
Initial temperature: 17° C
Final temperature: 18° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 10µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.186	0.137
-2.5	0.202	0.187
-2.0	0.211	0.201
-1.5	0.219	0.210
-1.0	0.226	0.221
-.05	0.234	0.231
0	0.237	0.237
0.5	0.229	0.237
1.0	0.218	0.231
1.5	0.204	0.226
2.0	0.192	0.217
2.5	0.179	0.209
3.0	0.168	0.191

Absorbance: 1.42288
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.874
UV dose: 20 mJ/cm^2
Exposure time: 5 min 58 s
Initial temperature: 16° C
Final temperature: 17° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 10µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.186	0.137
-2.5	0.202	0.187
-2.0	0.211	0.201
-1.5	0.219	0.210
-1.0	0.226	0.221
-.05	0.234	0.231
0	0.237	0.237
0.5	0.229	0.237
1.0	0.218	0.231
1.5	0.204	0.226
2.0	0.192	0.217
2.5	0.179	0.209
3.0	0.168	0.191

Absorbance: 1.42288
Irradiance @ center: 0.237 mW/cm^2
Petri factor: 0.874
UV dose: 40 mJ/cm^2
Exposure time: 11 min 55 s
Initial temperature: 13° C
Final temperature: 17° C

Dated: Apr 28, 2004
Sample ID: JarS- Filtrate: 10µm

Scale	Reading x-axis	Reading y-axis
-3.0	0.171	0.118
-2.5	0.200	0.173
-2.0	0.209	0.198
-1.5	0.217	0.206
-1.0	0.223	0.215
-.05	0.231	0.225
0	0.238	0.238
0.5	0.233	0.235
1.0	0.220	0.231
1.5	0.206	0.225
2.0	0.192	0.217
2.5	0.179	0.209
3.0	0.168	0.195

Absorbance: 1.42288
Irradiance @ center: 0.238 mW/cm^2
Petri factor: 0.857
UV dose: 100 mJ/cm^2
Exposure time: 30 min 16 s
Initial temperature: 11° C
Final temperature: 18° C