AEROBIC DIGESTION OF WASTE ACTIVATED SLUDGE WITH ULTRASONIC PRETREATMENT

by

Monruedee Moonkhum

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in
Environmental Engineering and Management

Examination Committee: Prof. C. Visvanathan (Chairperson)
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(Industrial Environmental Management)
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Abstract

Ultrasound pretreatment is very attractive option to enhance the digestion efficiency of waste activated sludge (WAS). It is gaining popularity because of its ability to breakdown the recalcitrant particles, compact design and no additional chemical requirement.

The efficiency of the aerobic digestion of waste activated sludge containing 3% TS using ultrasonic pretreatment was determined at 2 different SRT of 10 and 20 days. WAS was sonicated for 150s with the ultrasonic density of 1.9 W/mL, at the frequency of 20 kHz and specific energy input of 9.5 kJ/kg TS. The ultrasonic pretreatment achieved the subsequent aerobic digestibility resulting better removal of Dissolved organic carbon (DOC). The DOC removal efficiency of part stream and full stream reactor improved by 26% and 28% respectively, at 10 days SRT compared to control reactor. Similarly, at 20 days SRT the efficiency of DOC removal of part stream and full stream reactor enhanced to 20% and 23% respectively, compared to control reactor. Correspondingly, VS removal of part stream and full stream reactor were found enhanced to 46% and 50% respectively at 10 days SRT in comparison to control reactor. Whereas at 20 days SRT VS removal efficiency were higher than control reactor by 32% and 36% respectively, for part stream and full stream reactor. TS removal efficiency of part stream and full stream reactor were found improved as well at 10 and 20 days SRT. Moreover, ultrasound pretreatment affected to enhance nitrification of part stream and full stream reactor. Due to the higher nitrate concentration was observed in part stream and full stream reactor. However, ultrasound pretreatment could not improved the dewater ability of digested sludge.

As removal efficiency observed from part stream reactor were observed as in the same range. Thus, part stream reactor can be the better choice due to economic reasons.

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List of abbreviation

a	Acceleration
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
cm	Centimeter
DO	Dissolve Oxygen
DS	Dissolve Solid
F	Force
HRT	Hydraulic Retention Time
J	Joule
Kg	Kilogram
kHz	Kilo Hertz
L	Liter
M	mass
mg	Milligram
mL	Milliliter
Mpa	Mega Pascal
NH_3	Ammonia
NO_3	Nitrate
OUR	Oxygen Uptake Rate
SBR	Sequencing Batch Reactor
SCOD	Soluble Chemical Oxygen Demand
SE	Specific Energy Input
SEM	Scanning Electron Microscope
SOUR	Specific Oxygen Uptake Rate
SRT	Solid Retention Time
TS	Total Solid
UASB	Up-flow Anaerobic Sludge Blanket
VS	Volatile Solid
W	Watt
WAS	Waste Activated Sludge
^oC	Degree Celsius
^oF	Degree Fahrenheit
^oK	Degree Kelvin
μ mpp	Micro Metre Peak to Peak

Chapter 1

Introduction

1.1 Background

Biological treatment processes, especially activated sludge processes, are most widely adopted for domestic wastewater treatment. During aerobic biological treatment, organic pollutants are mineralized into carbon dioxide and water with the generation of excess bacterial biomass, commonly known as waste activated sludge (WAS). An activated sludge process generates huge amount of sludge. The expense for of excess sludge treatment approximates 60% of the total expense wastewater treatment operating costs (Egemen et al., 2001).

The sewage sludge requires further treatment, particularly stabilization before land application, which is widely adopted practice for sludge disposal. The principal methods of sludge stabilization include alkaline treatment, composting, anaerobic and aerobic digestion. Anaerobic digestion is commonly employed in medium to large wastewater treatment facilities due to it is potential to generate methane gas as by-product. However, for small wastewater treatment plant, anaerobic digestion is not only expensive, but also complex to operate. Thus, aerobic digestion is often preferred due its cost effectiveness and simplicity.

The hydrolysis of sewage sludge especially WAS (or secondary sludge) is the bottleneck during aerobic digestion due to recalcitrant nature biological cell wall and membrane (Khanal et al., 2007). Thus, pretreatment is often required to break the cell wall and to enhance the digestibility. The main goal of sludge pretreatment is to rupture the cell wall and to facilitate the release of intracellular matter to the aqueous phase. This will accelerate the subsequent aerobic degradation and reduce the retention time needed during digestion (Pavlostathis and Gossett, 1986). These pretreatment include physical (e.g. ball milling, ultrasonic, etc.), chemical (ozone, hydrogen peroxide, acid and base), thermal or biological (e.g. enzymatic hydrolysis) etc. Physical pretreatment, particularly ultrasonic, is emerging as a popular method for WAS disintegration due to several inherent merits.

Ultrasonic is a sound wave with frequency above 20 kHz. When propagated into the sludge, it generates a repeating pattern of compression and rarefaction in the medium. The low pressure occurs in the rarefaction regions, where microbubbles are formed and grow to an unstable size before violently collapsing. The formation microbubbles and their violent collapse are known as cavitation. These bubbles implode rapidly thereby generating extremely strong hydrodynamic shear force in the slurry medium. This shear force can rupture bacterial cell wall and cell membrane and releases intracellular substances into liquid phase.

The anaerobic digestibility of ultrasound pretreated sludge has been studied by several researchers (Teihm et al., 2001; Hogan et al., 2004; Bougrier et al., 2004). However, studies on aerobic digestibility of ultrasonic pretreated sludge have been very limited (Khanal et al., 2007). Based on this premise, the goal of this research is to optimize the sonication condition for effective sludge disintegration and to evaluate the aerobic digestibity of ultrasonic pretreated WAS under different SRT of 10 and 20 days.

1.2 Objectives of study

The main goals of this study were two folds: to examine ultrasonic disintegration of WAS and to evaluate the aerobic digestion of ultrasonic pretreated WAS. The specific objectives include the following:

1. To optimize sonication condition to maximize WAS disintegration.
2. To examine the aerobic digestibility of full-stream (100% sonicated) and part stream (50% sonicated and 50% nonsonicated) at different solids retention time of 10 and 20 days.
3. To evaluate the quality of ultrasonic pretreated WAS following digestion with respect to pathogen counts, total phosphorus and TKN.

1.3 Scope of study

This study was based on Laboratory scale ultrasonication equipment used for pretreatment thickened waste activated sludge (TWAS) subsequent aerobic digester. The experimental was evaluated the efficiency of sludge disintegration using ultrasonic pretreatment. The horn size, sonication duration and sonication energy input to maximize sludge disintegration were optimized. Soluble chemical oxygen demand (SCOD) and microscopic examination were the indicator parameter of sludge disintegration efficiency. The evaluation of aerobic digester performance, the removal efficiency of Dissolved organic carbon (DOC), TS and VS, specific oxygen uptake rate (SOUR), concentration of NH_3 and NO^-_3 and dewaterability were examined at different sludge retention time (SRT) of 10 and 20 days to investigated the performance of aerobic digestion. The quality of digested sludge was evaluated as well by pathogen count, total phosphorus and TKN.

Chapter 2

Literature Review

2.1 Biological Process

The biological process is the most popular method to treat domestic wastewater such as activated sludge process, UASB, RBC and tricking filter. Activated sludge process is more efficient technology to meet stringent standard. Nevertheless, it results to generation of a considerable amount of waste activated sludge that has to be treated (Weemaes et al., 2000). The expense for excess sludge treatment has been estimated to be up to 60% of the total cost of a wastewater treatment plant (Egemen et al., 2001). Moreover the conventional disposal method of land filling requires a large quantity of area and causes secondary pollution problems. Therefore, an interest in methods to reduce the volume and mass of excess sludge has been growing rapidly. For the purpose of reducing the volume of sludge, anaerobic digestion has been widely used for the large scale industries since it generate the biogas and has high efficiency to treat waste activated sludge. However, in case of small and medium industry, aerobic digestion is mostly used due to low investment cost and simpler operation.

2.1.1 Activated Sludge Process (ASP)

The activated sludge process is the most widely used biological treatment process for wastewater (Kim et al., 2002). It facilitates the transformation of dissolved organic pollutants in the wastewater into biomass and these are finally converted into carbon dioxide and water by microorganism (Rocher et al., 1999). The major by-product of this process is waste activated sludge (WAS), which mainly consists of microbial biomass. This sludge contains high fractions of volatile solids (VS) and retain large amounts of water (>95% by weight) (Perez-Elvisa et al., 2006). It resulting in extremely large volumes of residual solids produced, and significant disposal costs. Moreover, activated sludge process can suffer from bulking sludge (Eikelboom et al., 1997), when excessive filamentous microorganisms limit or prevent good settling, thus reducing both the setting properties and the quality of the effluent.

2.1.2 Waste Activated Sludge (WAS)

Waste activated sludge is known to be more difficult to digest than primary sludge
Due to the cell wall and the .(2002 ,.Lafitteet al)cell membrane of prokaryotic organisms
and ,teichoic acids ,mposed of complex organic materials such as peptidoglycanis co
.(1993 ,.Pelczar et al)which are recalcitrant to biodegradation ,complex polysaccharides
The low digestibility and rate limiting cell lysis to cause require ment tion time a long reten
sludge consist of ,Generally .days during biological treatment 60-30in the range of
EPS a ,biomassn .d large amount of waterThe aqueous phase in sludge is separatedinto
Whereas .free water and bound water ,two categoriesXuan et al., (2004)parated it in se
:four forms

- Then it can be separated by .Water that is not attached to sludge solid :Free water .simple gravitation setting
- Interstitial water: Water that is trapped within the floc structure travels within the floc or cell. Water can be release when the floc is broken up or the cell is

destroying. In the mean time, water can be release with mechanical devices for example centrifuges.

- Water that assosiated with the solid particle and held on the surface :Vicinal water .ed by centrifugation or other mechanical methodof it and can not remov
- Water that attach particle with chemically bound nad can be :Water of hydration .(2004 ,.Xuan et al) removed only by thermo chemical method

2.2 Sludge Treatment

The great excess biomass is generated during biological wastewater treatment. There are several ways to treat excess sludge such as digestion, composting, lime stabilization etc. Sludge digestion is the most common process for waste activated sludge treatment. The anaerobic mesophilic process is the most widely used, due to the biogas evolved as by-product of such a process. However, it more suitable for the large and medium industries since it provides the high investment cost, and also complicate operation. The less common used is aerobic digestion. It is popular for smaller wastewater treatment plant due to low investment cost and simpler operation.

2.3 Aerobic Digestion

Aerobic digestion may be used for stabilization of primary sludge, and activated or trickling filter sludge. When a culture of aerobic heterotrophic microorganisms is placed in an environment containing a source of organic material, the microorganisms will remove and utilize most of this material. A fraction of the organic material removed is utilized for synthesis the new cell, resulting in an increase of biomass. The remaining material will be change into energy and oxidized to carbon dioxide, water and soluble inert material. Once the external source of organic material is exhausted, the microorganisms will begin endogenous respiration where cellular material is oxidized to satisfy the energy requirement for life support. If this condition is continued over an extended period of time, the total quantity of biomass will be considerably reduced and the remaining portion will exist at such a low energy state that it can be considered biologically stable and suitable for disposal in the environment.
The aerobic digestion process, as stated above consists of two steps; the direct oxidation of biodegradable matter and endogenous respiration where cellular material is oxidized. These processes can be illustrated in the following equations:

$$\text{Organic matter} + O_2 + NH_4 \longrightarrow CO_2 + H_2O + \text{Cellular material} \quad \text{Eq. 2.1}$$

$$\text{Cellular material} + O_2 \xrightarrow{\text{bacteria}} CO_2 + H_2O + NO_3 + \text{digested sludge} \quad \text{Eq. 2.2}$$

The first equation (Eq. 2.1) describes the oxidation of organic matter to cellular material. This cellular material is subsequently oxidized to digested sludge. The process described in the second equation (Eq. 2.2) is tropical of the endogenous respiration process and the predominant reaction in the aerobic system. The inclusion of primary sludge in the process can shift the overall reaction Eq. 2.1, because primary sludge contains little cellular material, so the final result may be an increase of total biomass. Therefore the aerobic process is recommended for excess activated sludge only where longer retention times are possible.

Using typical formula $C_5H_7NO_2$ as representative of the microorganisms. The stoichiometry of the aerobic process can be represented by the following equations:

$$C_5H_7NO_2 + 5O_2 \longrightarrow 5CO_2 + 2H_2O + NH_3 + \text{energy} \qquad \text{Eq. 2.3}$$

$$C_5H_7NO_2 + 7O_2 \longrightarrow 5CO_2 + 3H_2O + NO_3^- + H^+ + \text{energy} \qquad \text{Eq. 2.4}$$

Equation 2.3 represents a system inhibiting nitrification. Nitrogen appears in the form of ammonia. A system in which nitrification occur is represented by Eq. 2.4. These equations indicate that theoretically 1.42 g of oxygen is required per gram of active cell mass in the non-nitrifying system. Whereas 1.98 g of oxygen is required per gram of active cell mass when nitrification occur.

The actual oxygen requirement for aerobic digestion process depends on factors such as the operating temperature, inclusion of primary sludge and solid retention time.

The operating temperature of the aerobic digestion system is the main parameter in the process. Because of aerobic digestion is a biological process which effect from temperature. This can be estimated by the following equation:

$$(K_d)_T = (K_d)_{20^{\circ}c}\, \theta^{T-20} \qquad \text{Eq. 2.5}$$

The reaction rate constant (K_d) represents the reduction rate of volatile suspended solids during the digestion process. An increase in the reaction rate constant (K_d) generally occurs with increase in the temperature of the system and implies an increase in the digestion rate. Another concern in aerobic digestion is aeration. When the COD loads are much higher than the conventional activated sludge process, aeration must be very intensive.
Most aerobic digesters are operated as continuous flow, commonly mixed aeration reactors and design on the basis of volatile suspended solids (VSS) reduction.

Table 2.1 Advantage and disadvantage of aerobic digester (Metcalf and Eddy, 1991)

Advantages	Disadvantages
1. High volatile solids reduction rate 2. Lower BOD effluent 3. Odorless 4. Humus – like and more stable end product 5. Recovery more fertilizer values 6. Simpler operation 7. Lower capital cost	1. Energy cost 2. Poor dewatering 3. Affected by temperature, location, and type of tank material 4. Useless by-product

2.3.1 Aerobic Sludge Digestion Design Criteria

The performance of the aerobic digesters is measure by solid reduction, organic reduction, oxygen uptake rate and reduction of pathogen. The design criteria of aerobic sludge digestion are shown in the Table 2.2 below.

Table 2.2 Design criteria for aerobic digestion (Metcalf and Eddy, 1991)

Parameters	Range
SRT for waste activated sludge (day)	10-15
Solid Loading Rate (kg VS/m^3.day)	1.6-4.8
Oxygen Requirement (kg/kg)	2-4
Energy Requirements	
- Mechanical Aerator (W/m^3)	20-40
- Blower (m^3/m^3.minute)	0.02-0.04
DO Residual in Liquid (mg/L)	1-2
Reduction in VSS (%)	40-50

2.4 Sludge Pretreatments

For the purpose of reduction amount of excess sludge, aerobic digestion had been widely used in medium and small industries. Nevertheless, the efficiency of digestion has been limited by the hydrolysis and rate-limiting step due to the structure of secondary sludge consisted of cell wall and cell membrane. Therefore, long retention times and large digester volumes are required. To enhance the aerobic digestion, several method of pretreatment were study such as Enzyme addition for cell wall disruption (Thomas et al., 1993), heating (Tanaka et al., 1997), Ozonation (Weemaes et al., 2000; Scheminski et al., 2000), Alkaline addition (Lin et al., 1997), mechanical (Kopp et al., 1997), sludge thickening (Dohanyos et al., 1997), alkaline addition with sonication (Chiu et al., 1997; Jean et al., 2000) Sonication (Neis et al., 2000; Wang et al., 1999; Tiehm et al., 1997; Tiehm et al., 2001). The aim of them were release of the intracellular and extracellular substance of cells in the sludge solids into liquid phase, and this process was called sludge disintegration to facilitate subsequence sludge treatment. The comparison of sludge pretreatment was summarized in Table 2.3.

2.5 Ultrasonic Pretreatment

Ultrasound is a physical process has been used for sludge cell rupturing to release of intracellular materials. There are many advantages such as does not generates secondary toxic compound, disintegration many toxic and recalcitrant organic pollutants, and could break down complex compound into simpler forms. This is because of generation of the highly oxidative radicals hydroxyl (OH^o), hydrogen (H^o), and hydroperoxyl (HO_2^o) and hydrogen peroxide (H_2O_2) during ultrasound pretreatment, this oxidative lead to break down of the recalcitrant compounds (Adewuri, 2001).

In full-scale application, ultrasonication is applying for excess sludge prior to enter to aerobic digestion. When pretreat sludge with ultrasonication, the temperature of sludge is increased. These high temperatures have a positive impact affects on dewaterability (Neyens et al., 2003). Figure 2.1 shows the applying ultrasound in full scale.

Table 2.3 Comparison of sludge pretreatment (Perez-Elvira et al., 2006)

Pre-treatment method	COD solubilisation (times higher than without the pre-treatment)	Sludge removal after anaerobic digestion (%)	Biogas production (% higher compared to the conventional operation)	Pathogen reduction	Influence on the dewatering results	Advantages	Disadvantages
High Pressure homogenizers	18-20	23-64	Up to 300	Low	High	-No odor generation. -Easy to implement. -Better dewaterability.	-Low reduction of pathogens. -Clogging problems. -High tensions and erosion in the pump and homogenizing valve.
Ultrasonic homogenizers	6	40-70	10-60	Low	High	-No odor generation. -No clogging problems. -Easy to implement. -Better dewaterability.	-Erosion in the sonotrode. -high energy Consumption.
Thermal hydrolysis	10-20	60-80	Up to 400	Total	Very high	-Save energy. -Very good dewaterability -Best sludge disinfection.	-Heat exchangers. -Bad odor from gas streams.
Stirred ball mills	15	40-60	10	No	High	-Reliability of operation (high degree of research and development). -No odor generation.	-Huge erosion in the grinding chamber. -High energy losses. -Clogging problems. -Low degree of disintegration

Pre-treatment method	COD solubilisation (times higher than without the pre-treatment)	Sludge removal after anaerobic digestion (%)	Biogas production (% higher compared to the conventional operation)	Pathogen reduction	Influence on the dewatering results	Advantages	Disadvantages
Acid or alkaline hydrolysis	-	-	-	-	High	-Low energetic requirements. -Very good dewaterability	-Modification of the sludge composition. -Possible damage to active bacteria. -Bad odor. -Corrosion and fouling of the equipment. -Higher COD in the final effluent.
Pre-treatment using ozone	5	36	8	-	High	-Better dewaterability.	-High energy consumption. -Metals present in the initial sludge (Fe, Zn, Ag, Cu).
enzyme activity	-	-	-	-	-	-Low energy consumption -No stress on equipment.	-High cost. -The effect of enzyme pretreatment is not clear. -Bad odor.
Thermal+explosive	8-12	40-85	-	-	-	-Product can use as biofuel. -Phosphate generation. -Removal of N and heavy metals.	-Corrosion problems. -High operation and maintenance costs.

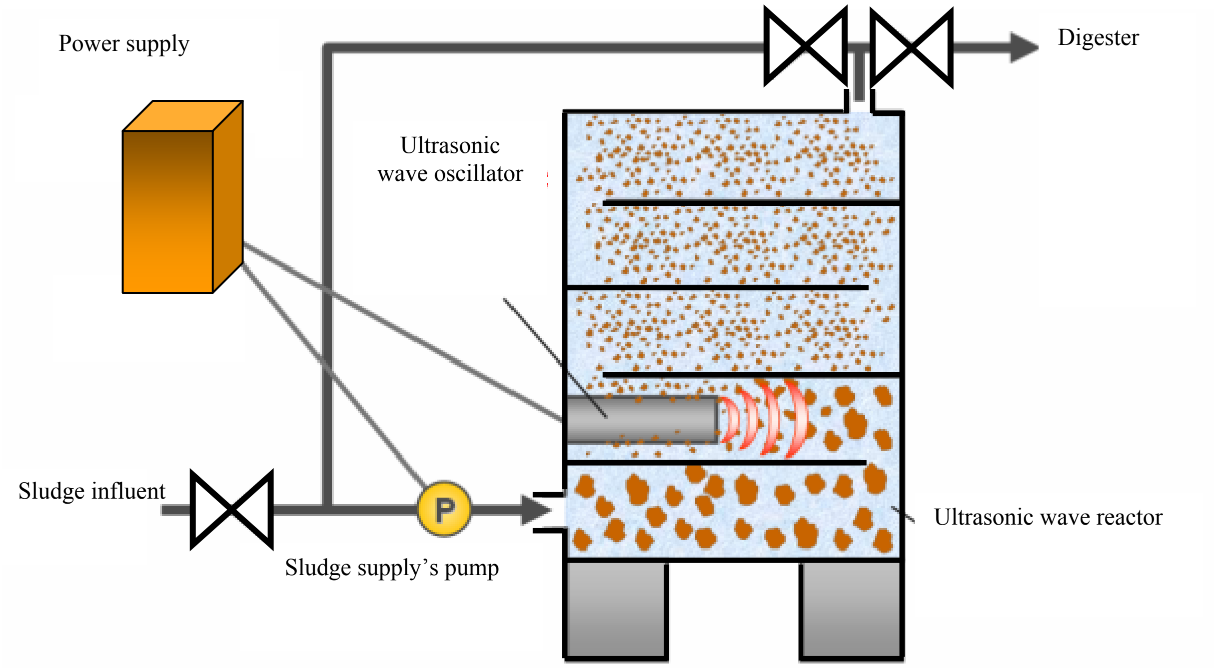


Figure 2.1 Flowchart of ultrasound pretreatment in full scale

Another location to applying ultrasonication is on recycled sludge to reduce the number of filamentous organisms to prevent sludge bulking. Excess temperature due to ultrasonication should be considered and avoided, when WAS is recycled to the biological treatment. As shown in Figure 2.2.

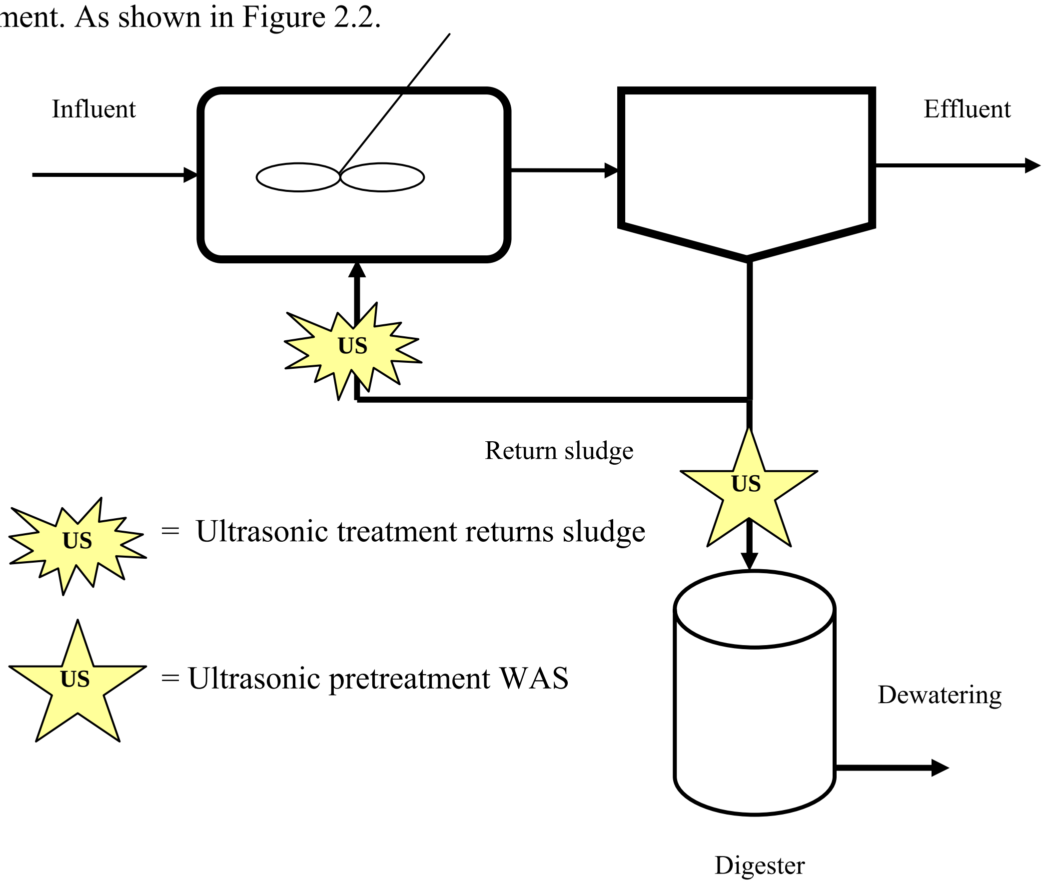


Figure 2.2 Location for apply ultrasonic treatment

The mechanism of cavitations plays an important role when applying ultrasounds to WAS. Affects of cavitations generated in sludge can be summarized as follows:

- High mechanical shear stress;
- Radical reactions: creation of OH^{o} and H^{o} radicals;
- Chemical transformation of substances;
- Thermal breakdown of volatile substances.

However, ultrasonic had disadvantages as well, such as digester fed with soicated sludge consumed higher level of alkali dose compared to digester fed with nonsonicated sludge. Moreover, this technology consumed energy which better to apply ultrasonication with anaerobic digestion. Due to anaerobic digestion can provide biogas that can convert to recalculate energy. In addition, during sonication cavitation phenomenon generated noise that can disturb operator.

These effects of sludge disintegration on aerobic digestion, resulting to reduction of sludge treated, enhancing sludge destruction rates, enhancing hydrolysis rates and quality of treated sludge in term of dewaterabilty and pathogen inactivated. Moreover, ultrasonic could increase organic loading rate as keeping hydraulic retention time constant

2.6 Mechanisms of Ultrasonic Disintegration

Ultrasound is a sound wave at a frequency above 20 kHz that out of hearing range of human. The hearing range of humans is between 16-20 kHz. When the ultrasound wave applies into the sludge the repeating pattern of compressions and rarefactions were generate. The low pressure happens in the rarefactions region (excessively large negative pressure) in which liquid or slurry is torn apart. Due to reduced pressure, microbubbles are formed in this region. These microbubbles are known as cavitations bubbles, essentially containing vaporized liquid and gas that had dissolved in the liquid. As the positive pressure cavitations bubbles are oscillate and growing to an unstable size prior to violently collapsing. Figure 2.3 shows the forming of cavitation.

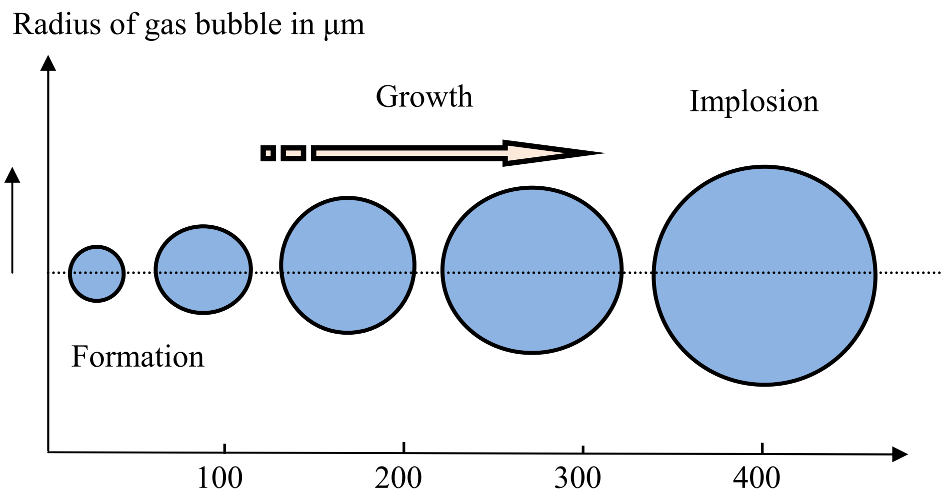


Figure 2.3 Illusion of cavitation formation

In addition, the sudden and violent collapse of huge numerous of microbubbles generates powerful hydro-mechanical shear forces in the bulk liquid surrounding the bubbles. The collapsing bubbles disrupt adjacent bacterial cells by extreme shear forces, rupturing the cell wall and membranes. The localized high temperature and pressure could also assist in sludge disintegration. At high temperatures, lipids in the cytoplasmic membrane are decomposed, resulting in holes within the membrane, through which intracellular materials are leaked to the aqueous phase (Wang et al., 2005). Mechanisms of the ultrasonic process are influenced by three factors such as supplied energy, ultrasonic frequency and characteristic of sludge.

Another mechanism that occurs while sludge is sonicating beyond cavitations phenomena is acoustic streaming. The main benefit of streaming in sludge processing is mixing, which facilitates uniform distribution of ultrasound energy within the sludge mass, convection of the liquid and distribution of any heating that occurs. Overall there are three regions of acoustic streaming. The figure of regions of acoustic streaming is shown in figure 2.4

- *Eckart streaming* (Region I) is the furthest from the horn, largest and has circulating currents that are defined by the shape of the container and the size of the wavelength of the acoustic wave in the liquid.

- *Rayleigh streaming* (Region II) is around horn has circulating currents and its size and shape are primarily defined by the acoustic tooling. This has much longer wavelengths than that of the acoustic wave in the liquid.

- *Schlichting streaming* (Region III) is the nearest the horn on size of the fluid acoustic boundary layer. This is a region where the tangential fluid velocity is near the velocity of the horn face. This layer is relatively thin. For example, at 20 kHz, the acoustic boundary layer for water at 20°C is less than 4 μm. All three regions play a critical role in mixing of the fluid.

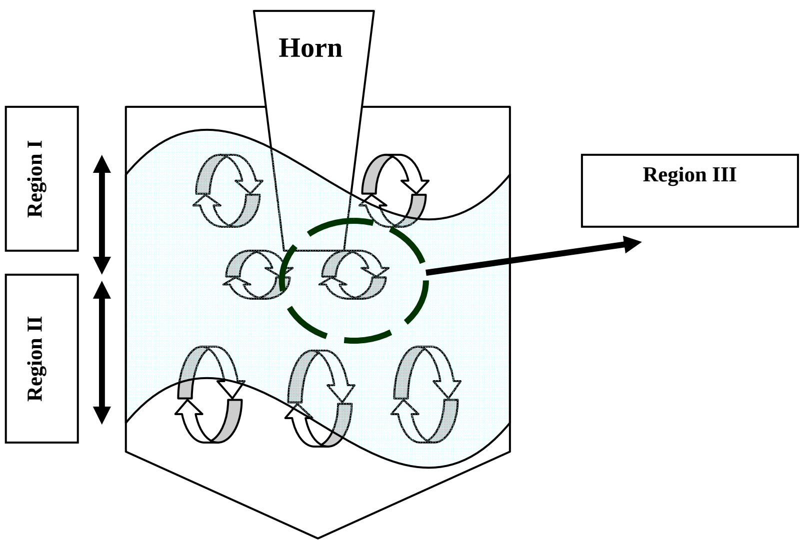


Figure 2.4 Regions of acoustic streaming

2.7 Components of Ultrasonic

Ultrasound unit consist of the converter (or transducer), booster and horn (or sonotrode). A converter basically converts electrical energy into ultrasound energy (or vibration). The booster is a mechanical amplifier that promote higher amplitude which generated by the converter. The horn is a specially designed tool that contributes the ultrasonic energy to the sludge bulk. The component of ultrasonic is shown in the Figure 2.5. The booster is designed and tuned to operate at a desired frequency. The booster often acts as a mounting component. The stack is mostly clamped at nodal points to hold. The two most common places to clamp the stack assembly are either at the converter or booster nodal ring. The same as the horn, which transfer the ultrasound wave to the sludge, often amplifies the motion even further. In addition, the horn is usually half a wavelength long, but full wavelength designs are also common depending on the application.

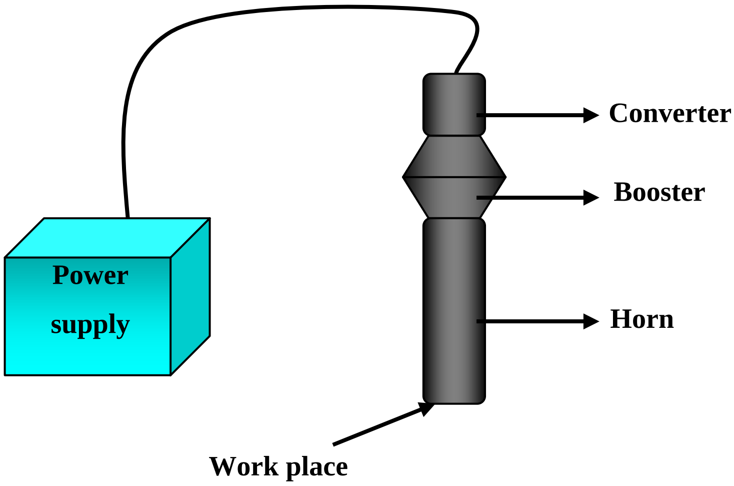


Figure 2.5 Component of ultrasonic

Thus, the main function of booster and horn are magnifying the amplitude of the ultrasonic motion. Because of ultrasonic processing desired large contact area. Thus a booster is often placed between the converter and the horn. The mass above and below the nodal plan (area with no motion) can be approximated by evaluating the booster and horn. Because of equilibrium and compatibility, the forces (F) above and below the nodal plan must be equal. However, when the mass (m_1) above the nodal plan is different from the mass below the nodal plan (m_2), the accelerations (a_1, and a_2) must also be different, resulting in different amplitudes of motion.

$$F_1 = F_2 \Rightarrow m_1 a_1 = m_2 a_2 \Rightarrow \frac{a_1}{a_2} = \frac{m_1}{m_2} \qquad \text{Eq 2.6}$$

The horn design usually not an issue the small faces, however the large block horns uniformity can be difficult to obtain. Often masses are added to the back drive of these horns or undercuts are made near the face of the horn where uniformity drops off. There are several designs of horns. Some of typical designs are shown in Figure 2.6. The donus shape was popular for using due to it can provide more area to propagate ultrasound wave and compact size.

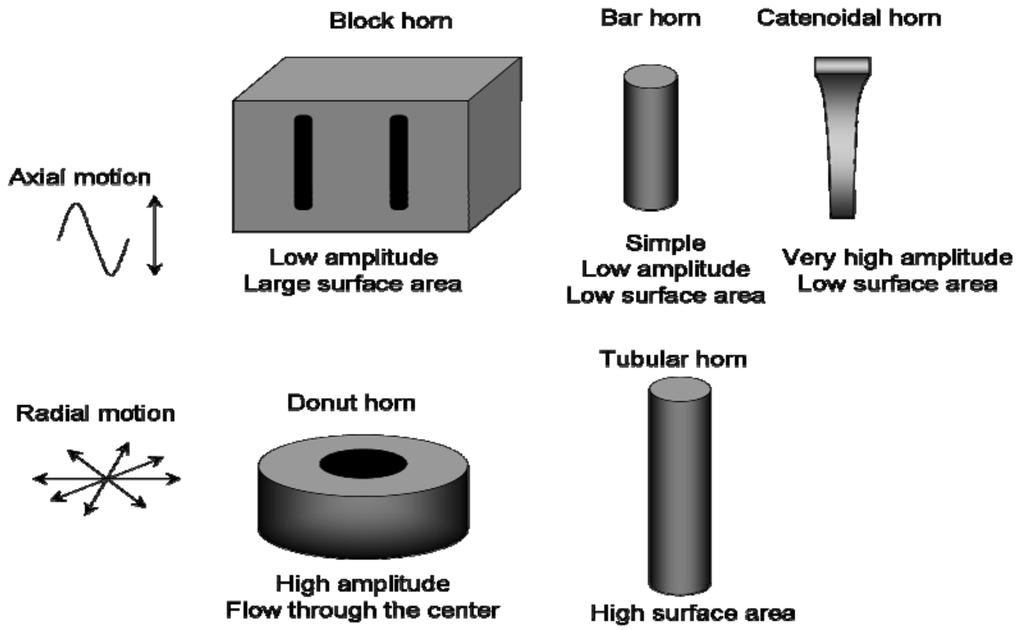


Figure 2.6 Examples of common horns used for liquid processing

2.8 Quantification of Energy/ Power Input

The economy was influence to ultrasound system. Since the ultrasonic consume the power (W or kW) or energy (J or kJ) input to achieve effective sludge disintegration. Thus, the maximum degree of disintegration is critical to evaluate by consider the quantification of energy/power input. This will be a key factor in selecting the ultrasound system for field application. The power or energy input needed to obtain a desired degree of sludge disintegration depends on both sludge characteristics (e.g., TS content, sludge viscosity, organic fraction, nature of sludge, i.e., fraction of primary and secondary sludge to be sonicated, etc.) and design of the horn, booster and converter. Nowadays, no rational model is available that accounts for all of these factors. Therefore, the efficiency energy and power input have to be investigate as laboratory scale and field-tested before apply with full-scale. The power or energy supplied for sludge disintegration can be expressed as following. However this energy cost can be compensating by biogas production (in case of anaerobic), reduction of sludge disposal cost and transportation.

2.8.1 Specific Energy Input (SE)

It is defined as the energy supplied per unit of mass of sludge solid (as TS) to achieve a certain degree of disintegration. This can be calculated using the following equation (Bougrier et al., 2005):

$$SE = \frac{P \times T}{TS \times V} \qquad \text{Eq 2.7}$$

Where,

SE = Specific energy input in kJ/kg TS
P = Ultrasonic power in kW
T = Ultrasonic duration in second (s)
V = Volume of sonicated sludge in liter (L)

TS = Total solids concentration in kg/L

2.8.2 Ultrasonic Dose

It relates to the amount of energy supplied per unit volume of sludge and is expressed as J/L or kJ/L. However, it does not depend on total solid concentration. The ultrasonic dose can not use to compare the sludge with different TS content. As long as the TS content remains fairly constant, the ultrasound density is a practical method of expressing the energy input for the disintegration of sludge on a volume basis.

$$Ultrasonic\ dose = \frac{P \times t}{V} \qquad \text{Eq 2.8}$$

2.8.3 Ultrasonic Density

Ultrasonic density relates to the power supplied per unit volume of sludge and has a unit of W/ml. Ultrasound density also relates power input to the volume of sludge, similar to ultrasound dose. However, ultrasound density does not take into account the sonication duration.

$$Ultrasonic\ density = \frac{P}{V} \qquad \text{Eq 2.9}$$

2.8.4 Ultrasonic Intensity

It relates to power supplied to sludge per unit of converter surface area and is expressed as W/cm^2. Ultrasonic intensity therefore reflects the power generating capacity of the converter. When amplitude of the ultrasound emitted by horn increases, power supplied to the sludge will increase.

$$Ultrasonici\ Intensity = \frac{P \times t}{A} \qquad \text{Eq 2.10}$$

Where:

A = Converter surface area (cm^2)

2.9 Evaluation of Ultrasound Disintegration Efficiency

Ultrasound pretreatment is destroyed the cell wall and cell membrane of microbes and release the intracellular materials to the aqueous phase. In addition, ultrasound also distributes to deagglomerate the biological flocs and disrupt large organic particles into smaller-size particles. The changes in physical, chemical and biological properties of ultrasonic pretreated WAS could be observe. Therefore it is necessary to quantify degree of disintegration of sludge. So far, data obtained from researches is not sufficient to fit the model to predict sludge disintegration. Because, degree of disintegration depends many variables associated with ultrasound pretreatment. Some of the variables are operating frequency, horn, booster and converter designs, types of sludge, TS content, organic fraction, operating temperature, ultrasonic density (or power density), etc. The most one of important affecting factor to the degree of sludge disintegration is Horn design and its design is often a proprietary. Therefore, it is harder to quantify many important operating conditions of ultrasound system. Most of previous researches are based on laboratory/bench-scale ultrasonic systems, which are usually inefficient. Direct use of such data for pilot or full-scale design could be very misleading. Therefore, for further study needed to scale up laboratory/bench data to pilot or full scale for facilitated practically applying.

The quantitative data provides much valuable information such as:

- Efficiency of a selected ultrasound system, particularly converter, booster and horn design;
- Assessment of minimum energy input needed for cell rupture;
- Various optimal operating data (TS content, sonication duration, ultrasonic density, frequency, amplitude, etc.) to maximize sludge disintegration;
- Overall operating cost of ultrasound system for sludge disintegration.
- Different parameters have been employed to evaluate sludge disintegration efficiency.

They can be collectively classified into three categories namely, physical (such as change in particle size distribution and microscopic examination), chemical (such as increase in soluble COD concentration and ammonia concentration, and release of protein) and biological (oxygen uptake rate and heterotrophic count) process. Detailed discussion of each category is presented in the following section.

2.9.1 Physical Evaluation

Particle size distribution, microscopic image, turbidity, and sludge dewaterability have been widely employed for simplicity as qualitative determine of sludge disintegration. Physical evaluation could investigate the sludge disintegration such a many previous researches such as in Table 2.4 below;

Table 2.4 Summarize the physical evaluation of ultrasound disintegration efficiency

Parameters	Sonication condition					Result	Reference
	Specific energy input (kJ/kgTS)	Frequency (Hz)	Time (min)	Density (W/mL)	Power Input (kW)		
Particle size distribution	-	20	1	0.18. 0.33, 0.52	1.5	Particle size = 47.7, 31.2, 17.8 μm	Mao et al., 2005
Particle size distribution	-	20	20	0.22,0.33, 0.44	0.11	Particle size =99, 22, 3 μm	Chu et al., 2001
Particle size distribution	660, 1,350, 6,950, 14,550	20	-	-	0.23	32, 19.6, 18.5, 17.6, 12.7 μm	Bougrier et al., 2005
Dewaterability	-	20	60	0.22,0.33, 0.44	0.11	Increase up to 490s from 197 at o.33 W/mL	Chu et al., 2001

Most of research above the reduction of particle size was proportion of increasing power density, sonication duration and specific energy input at the low frequency.

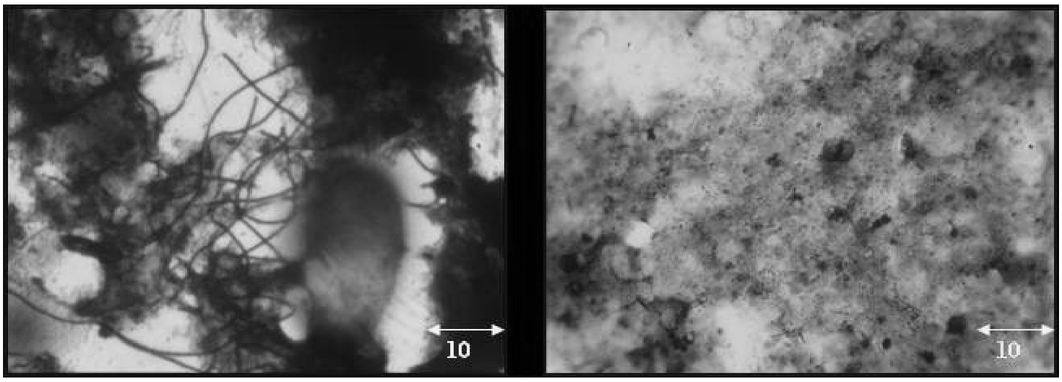


Figure 2.7 Microscopic observation of WAS; (left) before sonication; (right) after 2 min of sonication (1000 x)

- Khanal et al., (2007) used light microscope for investigate sludge disintegration, to observe the structural changes in flocs, disappearance of filaments etc., at constant power input of 1.5 kW and frequency of 20 kHz. However, researcher could be observing only floc-like structures entangled within a large numbers of filaments were seen prior to sonication which does not provide information at the cellular level. Within two minutes of sonication, the filaments and flocs were almost completely disintegrated and a more or less homogeneous texture was observed. As shown in Figure 2.7.
- Khanal et al., (2007) investigated the cellular level information of sludge during min of sonication, the structural integrity of flocs as well as filaments was significantly disrupted without appreciable destruction of bacterial cells. At a longer sonication duration of 10 min, nearly complete disintegration of flocs and filament-like structures with a very few scattered bacterial cells. When the sludge was sonicated for 30 min, more or less complete break-up of cell walls was observed with several punctured cells. As shown in Figure 2.8.

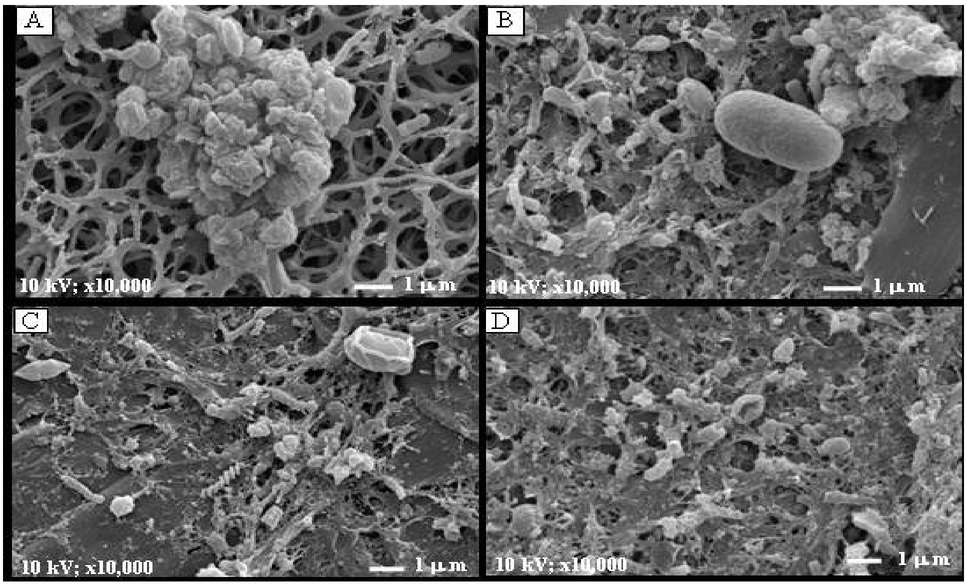


Figure 2.8 SEM images of WAS at different times, (A) 0 min; (B) 2 min; (C) 10 min and (D) 30 min

- Chu et al., (2001) was observed the floc structure with SEM. They found that after sonication at 0.33 W/mL up to 2h. The structural integrity of floc has almost completely broken down after 40 min of sonicaion

2.9.2 Chemical Evaluation

Chemical evaluation measures the soluble substance of WAS that released to liquid phase after applying ultrasound. All of released organic matter is measured together as an increase in soluble chemical oxygen demand (SCOD). SCOD consisted of organic debris, extracellular polymeric substance (EPS). Thus SCOD is a gross parameter to quantify the sludge disintegration. Some of previous studies of chemical evaluation were summarizing in Table 2.5.

- Wang et al. (1999) found that the release of soluble protein was significantly higher than the DNA and polysaccharide during sonication. The soluble protein concentration in the aqueous phase increased from 50 to 1,200, 3,000, 5,200 and 6,000 mg/L, respectively at sonication durations of 0 (control), 10, 20, 30 and 40 min.

Table 2.5 Summarize the chemical evaluation of ultrasound disintegration efficiency

Frequency (kHz) Duration (min)	SE x 10-3 (kJ/kgTS)	Power (W)	TS (%)	VS reduction (%)	COD destruction (%)	CH_4 enhancing (%)	SRT (days)	Process	References
20 kHz 20-120 min	0.44 W/mL	110	0.82	-	40 times (SCOD/COD)	-	-	-	Chu et al., 2001
20 kHz 20 min	0.33 W/mL	-	0.94		6 – 38 (SCOD/TCOD)	104 – 260 (in 6 days)	-	Anaerobic (flocculated biosolid)	Chu et al., 2002
20 kHz	0 - 35		0.35-2	22.5 – 24.3	2.5 - 37	-	-		Dewil et al., 2006
22-27,40 kHz 2.5 & 10 min	30,000	200	2.2			8-17 times (soluble)	19	Anaerobic	Gronroos et al., 2005
20 kHz, 2,4,8,16,20,30 and 60 min	-	1500	1.5, 2, 2.5, 3	26-53	91 - 98	-	25 - 28	Aerobic	Akin et al., 2006
31 kHz 64 s	-	3600	-	50.3	-	28	22	Anaerobic	Tiehm et al., 1997
41, 207, 360, 616 & 3217 kHz 7.5-150 min	0 – 60,000	-	2.59	22.7-33.7	0 – 23.7	63.5 – 68.9	8	Anaerobic	Tiehm et al., 2001
9 kHz 10, 20, 30 & 40 min	-	200	3.3-4.0	-	29 - 39	12, 31, 64 & 69	1, 2, 3, 5, 7, 9, 11	Anaerobic	Wang et al., 1999

Therefore, quantification of sludge disintegration particularly WAS by protein measurement could be used reliably. However, for field application, protein measurement is still not common as none of the published studies employed protein measurement to assess the efficacy of ultrasonic sludge disintegration. The COD measurement will continue to be the method of choice for daily operation due to its simplicity.

2.9.3 Biological Evaluation

The determination of efficiency of ultrasonic disintegration could be conduct heterotrophic plate counts and specific oxygen uptake rate (SOUR). Since WAS mainly consists of heterotrophic bacteria, the measure of their survival during ultrasonic treatment.

- Chu et al. (2001) reported a survival ratio of viable bacteria after sonication to the original sample of 44% for heterotrophic bacteria at a sonication density of 0.33W/mL during 120 min of sonication. However, heterotrophic plate count is not a pragmatic method for judging the sludge disintegration efficiency in field applications.

The measurement of oxygen uptake rate is a good indicator of bioactivity of WAS. Due to the WAS mainly consists of aerobic and facultative bacteria. Since ultrasonic treatment disrupts the bacterial cells, the measurement of SOUR of sonicated WAS could be used to assess the effectiveness of sludge disintegration. Based on this premise, Khanal et al. (2007) examined the SOUR of WAS samples using 20 mL of sonicated sludge with a TS content of 1.5%, at different duration and synthetic substrate with SCOD of 500 mg/L containing all essential nutrients was used as the sole carbon source . The researcher observed that, the biological activity of sonicated sludge decreased rapidly during the first 16 min of sonication; then biological activity is decreased lower. The activity decreased by approximately 55% during sonicated duration at 16 min compared to a control (without sonication). This research suggests that sonication was effective in disintegrating the bacterial cells. It is important to point out that the release of SCOD may not be a true measure of effectiveness of sonication. Because of the rupturing of the bacterial cells does not necessarily release the intracellular matter only. However, it also exposes the cell content to exo-enzymes thereby enhancing efficient digestion. Thus, the use of oxygen-uptake rate could be a useful and practical tool to evaluate the cell disintegration.

Rai et al. (2004) coined the term degree of inactivation (DD_{OUR}) based on oxygen uptake rate (OUR) data, which the similar data of degree of disintegration (DD_{COD}) as discussed earlier. The DD_{OUR} can be calculated using the following equation 2.11 and 2.12 below:

$$DD_{OUR}(\%) = \left[1 - \frac{OUR_{sonicated}}{OUR_{original}}\right] \times 100 \qquad \text{Eq 2.11}$$

Where, $OUR_{sonocated}$: oxygen uptake rate of sonicated sludge.
$OUR_{original}$: oxygen uptake rate of the original sample (without sonication)

$$OUR = -\frac{d[O_2]}{dt} \qquad \text{Eq 2.12}$$

The DD_{OUR} increased rapidly with increase in specific energy input up to 40 kJ/gTS after that the slightly increase (Rai et al, 2004). At a specific energy input of 8 kJ/gTS, the

DD$_{OUR}$ was found to be negative. This means that the OUR of sonicated sludge was higher than that of the unsonicated. This was mainly because at low energy input, the microbial floc are into individual microbial cells, which eventually the biological activity still continuous. The measurement of oxygen uptake rate is relatively simple and takes only 20 min or less. Thus, DD$_{OUR}$ determination based on OUR measurement could be a very useful tool for field application to assess the ultrasonic disintegration of WAS sludge.

2.10 Factors Affecting Efficiency of Ultrasonic Disintegration

The WAS sludge disintegration is depended on several factors. These factors can be classified into three categories,

- Sludge characteristics;
- Sonication conditions; and
- Design of ultrasonic components.

Detailed discussion of each category is elucidated as below:

2.10.1 Sludge Characteristics

The sludge characteristics are an important factors affect to effectiveness of sludge disintegration, such as type of sludge (primary solids, waste activated sludge or animal manure, etc.), especially TS content, and particle size. High effectiveness of ultrasonic disintegration is observed at high concentrations of DS in the WAS (Tiehm et al., 2001; Onyeche et al., 2002; Neyens et al., 2004). This is because of more DS provided more sites for cavitation and provided more particles are exposed to the resulting shear force. Grönroos et al. (2005) reported the maximum SCOD concentration released at the highest dry solid (DS) content. However, the authors did not present the data in terms of mg SCOD/gDS, which made it difficult to understand whether sludge disintegration was efficient at higher solids content. Dewil et al. (2006) studied to evaluate the effect of TS contents on SCOD release at different specific energy inputs. The results are presented in Figure 2.9

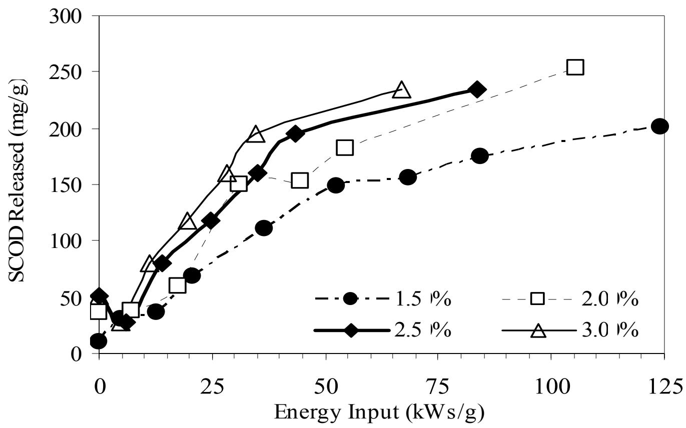


Figure 2.9 SCOD increased with different energy input

As evidence from the figure, SCOD release showed an increasing trend with increase in both TS content and energy input. However, the release in SCOD slowed down at an energy input of over 35 kWs/gTS for all TS contents. Wang et al. (2005) reported that the SCOD release increased from 3,966 to 9,019 mg/L when the TS content was increased from 0.5 to 1% during 30 min of sonication at an ultrasonic density of 1.44 W/mL.

These is because of higher TS content is more energy efficient for ultrasonic disintegration than the lower TS content.

Interestingly, higher SCOD release at higher TS content. It can be hypothesized that at higher TS content, the violent collapsing of micro-bubbles might have accelerated the particles in vicinity of the bubbles, which bombarded the adjacent particles. It is most likely that the abundance of particles at a higher TS content could have facilitated the sludge disruption due to particle-to-particle collision. However, the effect of the number of particles (TS contents) on the formation of cavitation bubbles in the sludge matrix is still unknown.

The composition of sludge matrix also affect to cell disintegration. It is believed that non-biological solids, such as primary sludge and animal manure, are relatively easy to disintegrate compared to biological sludge such as WAS due to the structure of WAS has cell wall and cell membrane that more difficult to digest by microorganism. However, no study evaluated the effects of different sludge types and particle size on ultrasonic disintegration.

2.10.2 Sonication Conditions

Frequency

Sludge disintegration was most effective at low frequency. This is demonstrated by the most pronounced reduction of median sludge particle size as well as the largest increase in turbidity of the sludge sample at low frequency (Tiehm et al., 2001). The destruction of sludge cell caused by cavitation phenomena, powerful hydromechanical shear forces and sonochemical reactions. The powerful hydromechanical shear forces were produced after ultrasound waves propagated to the sludge. While sonochemical degradation can occur in a board ultrasound frequency range from 20 kHz up to around 1 MHz the highest efficiency of sonochemical reactions was observed at frequency more that 100 kHz (Hua and Hoffmann, 1997; Petrier and Francony, 1997). The decreasing sludge disintegration efficiency observed at higher frequencies was attributed to smaller cavitation bubbles which do not allow the initiation of such strong shear forces.(Tiehm et al., 2001) High frequencies promote oxidation by radicals, whereas low frequencies promote mechanical and physical phenomena like pressure waves(Gonze et al., 1999)

Tiehm et al. (2001) found the DD_{COD} to be 13.9, 3.6, 3.1 and 1.0%, respectively at frequencies of 41, 207, 360 and 1,068 kHz and concluded that a frequency lower than 41 kHz would yield better sludge disintegration. The efficiency of sludge disintegration decreased with increasing frequency. Hence researcher expected the best disintegration results with the lowest ultrasound frequency of 20 kHz. However such a frequency could not be set with the device available. Sonochemical reactions are particularly predominant at a higher ultrasonic frequency 200 to 1000 kHz (Mark et al., 1998). Thus, nearly all sludge disintegration tests are conducted at the lower frequency range of 20 kHz (Wang et al., 2005; Bougrier et al., 2005). As review above, High efficiency of sludge disintegration is obtained at low frequency as 20 kHz.

Sonication time

Short sonication times resulted in sludge floc deagglomeration without the destruction of bacteria cells. Longer sonication brought about the break-up of cell walls, the sludge solids were disintegrated and dissolved organic compounds were released (Tiehm et al., 2001).

The specific energy input is proportional to sonication time. The longer sonication time means a higher specific energy input; thus resulting in higher SCOD release. Wang et al. (2005) examined the release in SCOD concentration at different sonication times of 5, 15 and 20 min at TS content of 3%, frequency of 20 kHz and ultrasonic density of 0.768 W/mL. The authors observed an increase in SCOD release from 2,581 to 7,509 mg/L, when the sonication time was increased from 5 to 15 min. However, when the disintegration was continued for 20 min, the SCOD release slowed down significantly with final SCOD concentration of 8,912 mg/L. Several studies also showed this trend (Wang et al., 2005; Akin et al., 2006).

Although the degree of solubilization increased with indirect proportion to the energy input. For example, Bougrier et al. (2005) achieved as much as twice that at an energy input of only 6,951 kJ/kg TS. In another study, DD_{COD} of 40% was obtained at a specific energy input of 60,000 kJ/kg TS (Tiehm et al., 2001); whereas Rai et al. (2004) reported DD_{COD} of 25% at energy input of 64,000 kJ/kg TS.
Grönroos et al. (2005) was observed a better sludge disintegration at the same specific energy input, when the sludge was sonicated at higher ultrasonic density for a short duration than a lower sonication density for a longer duration. These findings show that for efficient sludge disintegration, ultrasonic density is apparently more important than the sonication time.

Specific energy input

Disintegration of sludge requires high mechanical shear forces cause by jet stream during cavitation bubble implosion. The largest SCOD increase was obtained with the highest power, highest DS and longest treatment time used. However, the optimization of energy consumption is essential in ultrasonic assisted disintegration. The power was relate with treatment time. At the same energy consumption, high ultrasonic power together with short treatment time increasing larger SCOD than using low ultrasound power couple long treatment time (Gronroos et al., 2005).

The SCOD release must also be correlated with ultrasonic energy input (expressed as ultrasonic density, ultrasonic intensity or specific energy input). Such correlations will help to optimize the energy needs to achieve maximum sludge disintegration

Released SCOD and disintegration rate can also directly be expresses as a function of specific energy (SE) that is applied to the sludge (Dewil et al., 2006). In addition, the authors are obtained; there is a minimum SE required before destruction starts. There, this minimum lies at about 1500 kJ/KgTS

pH

In evaluating the effects of sonication conditions on sludge disintegration, parameters such as pH and temperature also become equally important. The SCOD release was found to increase when the sludge was sonicated at a higher pH as shown in Figure 2.10 (Wang et al., 2005).

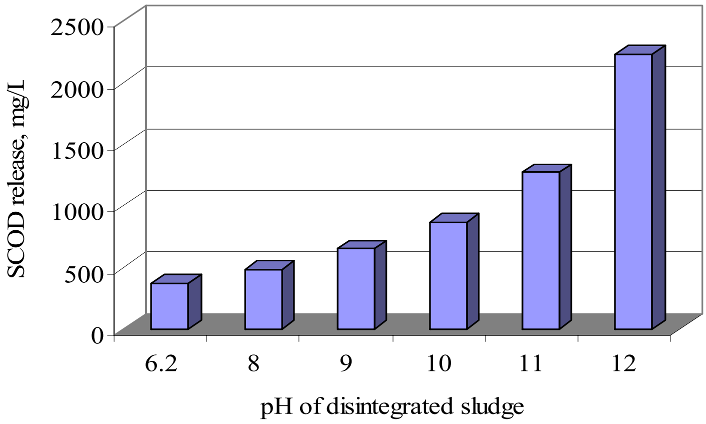


Figure 2.10 SCOD released at different pH

Due to alkaline condition facility for disrupting the sludge thus, raise the pH may have weakened the bacterial cell wall that distributes better destruction during ultrasonic pretreatment. Therefore, alkaline treatment of sludge followed by ultrasonic application could lower the energy cost of ultrasonic systems to achieve a desired degree of sludge disintegration. However, a thorough study is needed to examine the effect of alkaline addition on ultrasonic sludge disintegration.

Wang et al. (2005) examined the effects of pH, TS content, ultrasonic intensity and density on disintegration of biological sludge based on a kinetic model using a multi-variable linear regression method.

Temperature

Ultrasonic couple with heating increases higher SCOD. Sonication of sludge results in an increase in the temperature of the aqueous phase. The temperature increase depends on both sonication time and sonication density. Tiehm et al. (1997) observed an increased in sludge temperature from 15 to about 45°C during 64 seconds of sonication in a flow-through-type ultrasonic unit at frequency 31 kHz. Chu et al. (2001) observed an appreciable increase in sludge temperature when the sludge was sonicated for 120 seconds. The respective temperatures were 30, 42, 51 and 56^{o}C, at ultrasonic densities of 0.11, 0.22, 0.33 and 0.44W/mL. At a constant power density of 0.44W/mL, the sludge temperature increased from 19^{o}C to 30, 50 and 56^{o}C, when the sludge was sonicated for 0 (control), 20, 60 and 120s. Interestingly, the temperature increased at a rate almost proportional to the increase in ultrasonic density. The respective temperature increase rates were 0.15, 0.28, 0.43 and 0.51^{o}C/sec at ultrasonic densities of 0.11, 0.22, 0.33 and 0.44W/mL. As a matter of fact, ultrasonic density plays a more prominent role in temperature increase than the sonication time.

The solubilization of sludge could also be due to thermal effects resulting from the increase in sludge temperature during sonication. It is often difficult to quantify the contribution of thermal effects on the degree of sludge disintegration. In one study, SCOD release increased nearly 2.4 fold during sonication for 60 min at an ultrasonic density of 0.33W/mL without temperature control compared to sludge samples sonicated at a controlled temperature of 15°C (Chu et al., 2001). However, there was no data on final temperature of sonicated sludge. Grönroos et al. (2005) also reported a significant contribution of temperature on ultrasonic sludge disintegration.

Intensity

The ultrasonic intensity affect and useful on sludge characteristic. When applied as low intensity can be improved settling characteristic and solved foam problems. Higher intensity application cause the release of intracellular substance and aid digestion

2.10.3 Design of Ultrasonic Components

While there are many different ultrasonic manufacturers and designs, nearly all systems consist of two major components: (1) the power supply and (2) the stack assembly. In order to maximize the efficiency of operation, most systems operate at a particular frequency. The stack assembly is designed and manufactured to mechanically resonate at that frequency, similar to the ringing of a bell or strumming of a string, where the stored energy of the system is high compared to the energy loss of the system. The power supply then matches this frequency through an electro-mechanical system. The stack consists of three sub-components, the converter, the booster and the horn. The converter is simply a linear motor. The maximum displacement of the converter is usually rated in peak-to-peak displacement and is inversely proportional to the operating frequency. For example, at 20 and 40 kHz, the typical maximum amplitude is 20 and 10 μmpp, respectively. The limitation of the amplitude at higher frequency is primarily due to design constraints because of the desire to have a resonant system. In most systems, the converter is designed to be half the wavelength (λ) of the vibrations. It is important to note that because the converter consists of various components (i.e., back drive, piezo-electric ceramics and front drive that are manufactured from different materials), determining the amplitude of the entire converter is not a trivial task. In addition, the complexity of this problem is compounded by the fact that the piezo-electric ceramics have material constants (such as stiffness and displacement constants) which are load and voltage dependent.

Design of an efficient horn is extremely important to achieve an amplitude of 50 μmpp or higher. This is because strong cavitation is generated at higher amplitudes. Horn configuration becomes a major limiting factor when dealing with high amplitudes. This is because high amplitudes with some horn designs may cause significant structural damage. The horn design could essentially limit its ability to achieve greater cavitation levels and power outputs.Thus, the design of all these units may significantly affect the efficacy of ultrasonic systems for sludge disintegration. Such information is often proprietary so manufacturers do not normally share this.

2.11 Aerobic Digestibility of Ultrasonic Pretreated Sludge

Most of studied on ultrasonic pretreatment of WAS focus on anaerobic digestibility since it generated biogas. However, for small wastewater treatment system, anaerobic system employed both high capital investment cost and complex system to operate. Thus, aerobic system remains popular in the small waste water treatment plant because of lower capital investment cost and simpler to operate. Nevertheless, previous study on the effect of sonication on aerobic digestibility of WAS is barely available.

Khanal et al., (2006a) investigated the aerobic digestibility of WAS at different SRTs of 8, 10 and 15 days. The authors employed a 1.5 KW ultrasound unit at frequency of 20 kHz for sonicated 3% TS of sludge sample. The sludge sample was sonicated for 10 min. Result to gained VS removal efficiency from 13, 22 and 31% with SRTs in the digester fed with nonsonicated sludge was increase of 8, 10 and 15 days, respectively. For digester fed with sonicated sludge, the VS removal at SRTs of 8, 10 and 15 days were increase 20, 25 and 36%, respectively. Base on statistic analysis, the significantly different of sonication and nonsoniaction sample were detected. Interestingly, the effect of sonication on digestibility was more pronounced at the shorter SRT. Base on the result of the VS removal improved by 54, 23 and 16% for sonicated sludge with respect to the control at SRTs of 8, 10 and 15 days, respectively. The reduction in particle size of organic debris couple with rupturing of biological cell may have promoted to incessant improvement in VS reduction at longer SRT for the sonicated sludge.

2.12 Effect of Ultrasonic on Biosolids Quality

The biosolids quality refers to residual organics and pathogen levels after digestion. As mention above, ultrasonic pretreatment resulted in lower VS and SCOD levels in the digested biosolids. Khanal et al. (2007) investigated the specific oxygen uptake rates (SOUR) of both sonicated and unsonicated aerobically digested sludge at different SRTs and the results are presented in Figure 2.11.

Digested sludge from the digester fed with sonicated WAS was more stable than that from the control. This was evident from the fact that the former had a lower SOUR value than the latter as apparent from the figure. The SOUR data infers that the ultrasonic treated biosolids have less potential for vector attraction and odor emanation. This is particularly important when the biosolids are intended for land application.

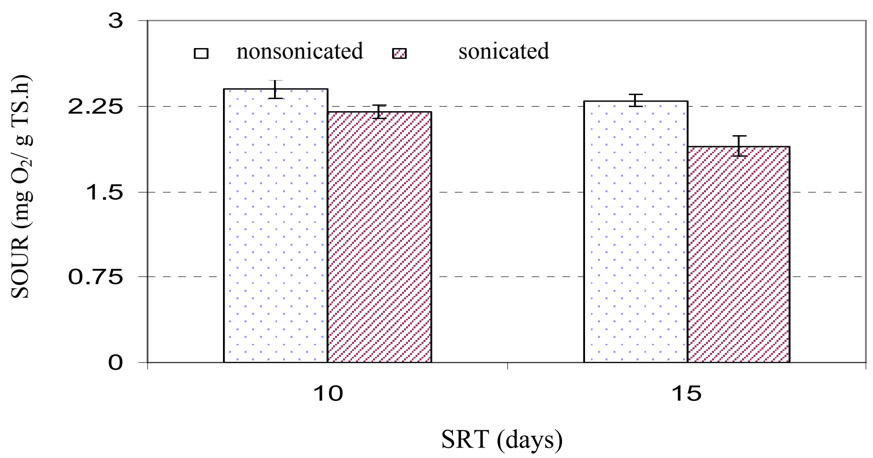


Figure 2.11 Specific oxygen uptake rate (SOUR) at different SRT

Khanal et al. (2007) determined bacteria levels, e.g. fecal coliform, *E. coli* and *Salmonella sp*. in sonicated and unsonicated, and digested and undigested sludge samples. The sludge samples were taken from the digesters operating at an SRT of 10 days. The results are presented in Table 2.5. The tested sludge had *Salmonella sp.* densities below detectable levels under all conditions.

Table 2.6 Pathogen levels in sludge under different treatment conditions

Pathogen types	Pathogen levels (MPN/g TS by dry weight)			
	Nonsonicated feed sludge	Sonicated feed sludge	Nonsonicated digested sludge	Sonicated digested sludge
Fecal coliform	3.4 x 106	1.7 x 106	98,000	57,000
E. coli	1.5 x 106	870,000	98,000	29,000
Salmonella sp.	< 1.1	< 1.1	< 1.1	< 1.1

Fecal coliform and *E. coli* levels dropped by 42% and 70%, respectively for sonicated digested sludge compared to unsonicated ones. The biosolids must meet one of the requirements: either density of fecal coliform less than 1,000 MPN/g total solids (dry weight basis); or density of *Salmonella* sp. less than 3 MPN/4 g total solids (dry weight basis)

Chapter 3

Methodology

3.1 Introduction

This study was focus on aerobic digestibility of waste activated sludge with ultrasonic pretreatment obtain from Thammasart University (Rangsit campus) domestic wastewater treatment plant. The optimum sonication condition will be investigated followed by aerobic digestion. The research plan is shown in Figure 3.1

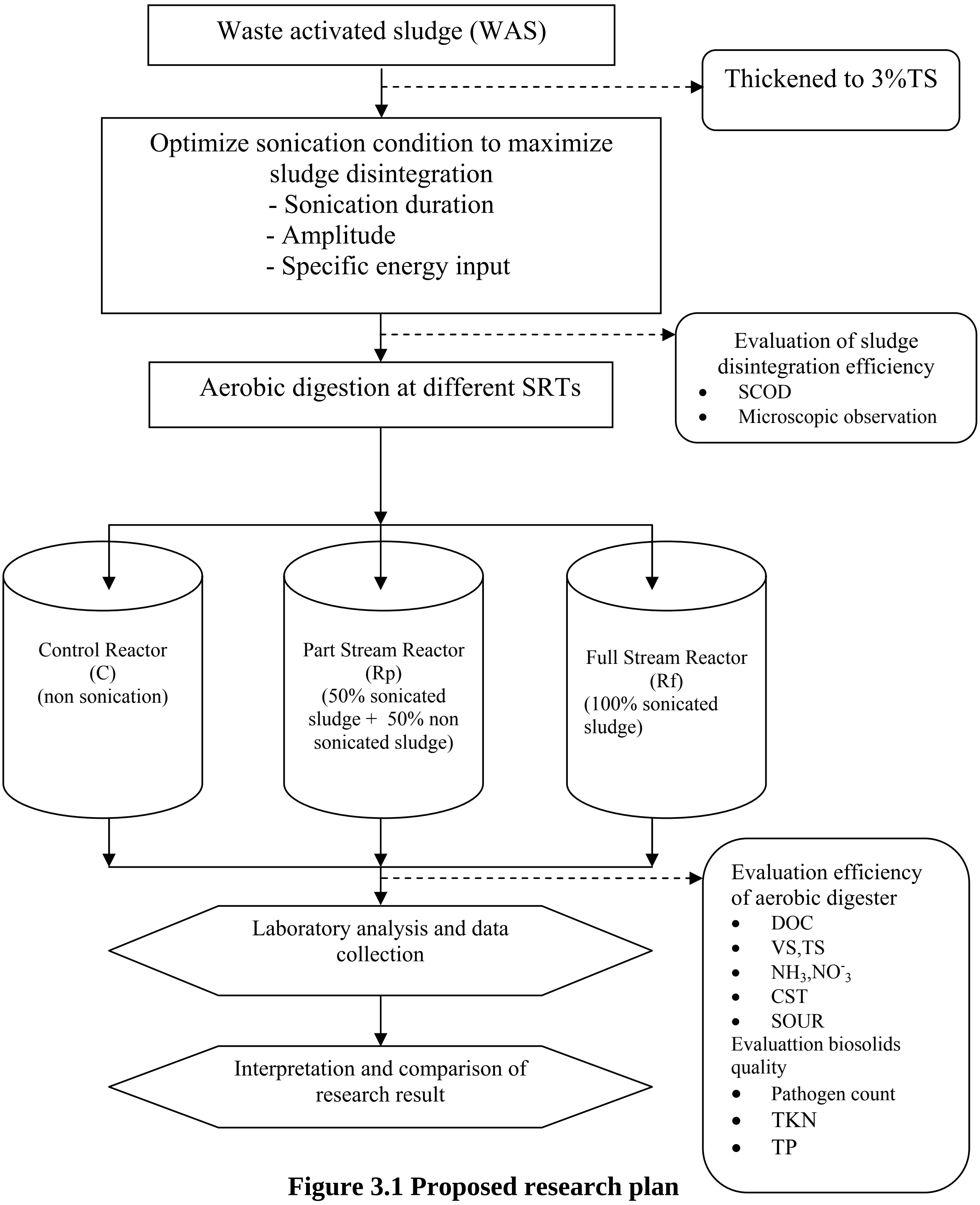


Figure 3.1 Proposed research plan

3.2 Waste activated sludge

The settled waste activated sludge (WAS) or return sludge was collected from Thammasart University wastewater treatment plant on a weekly basis and analyzed immediately for SCOD, TS, VS, pH, TKN, NH_3. The sludge sample was stored at 4 ^oC storage room prior to use to prevent biodegradation. Sludge sample will be concentrated to 3% by centrifugation (at 3000 to 5000 RPM for 4-5 minutes) for sonication and subsequent digestion studies. The 3% TS has been selected to optimize the disintegration efficiency during sonication, while abating oxygen transfer limitations during aerobic digestion (Khanal et al., 2007).

3.3 Ultrasonic equipment

The thickened WAS sample was sonicated using Sonics Sonicator (VC750 model, Newtown, CT, USA) with maximum power output of 750 W and constant frequency of 20 kHz. The sonication unit is equipped with three different horns, small (1.2 cm), medium (2.5 cm) and large (3.8 cm). The power input can be set independently from 250-750 W. The amplitude can also be set independently from 1-100%. The ultrasonic equipment is shown in Figure 3.2

Figure 3.2 Ultrasonic equipment

3.4 Sonication chamber

The sonication chamber known as Rosett cell was employed for sonication using small horn. At the bottom of the chamber has three open loops to reduce the temperature generated during sonication. The chamber was made up of glass, with total volume of 300 mL. The configuration of Rosett cell is shown in Figure 3.3a. For sonication using medium and large horns, stainless steel sonication chamber, fabricated at Environmental Engineering Laboratory, AIT was employed. The sonication chamber has a total volume of 610 mL. The design of the stainless steel is shown in the Figure 3.3b. The stainless steel chamber for small horn was made as well by using the same shape as mention above with smaller size.

Figure 3.3a Rosett cooling cell

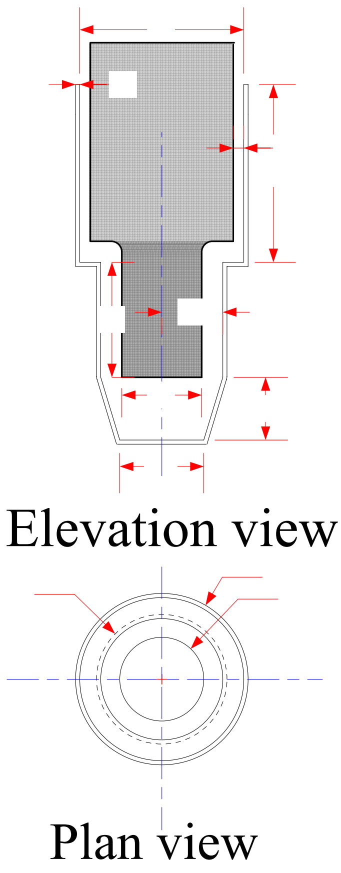


Figure 3.3b Stainless steal chamber (unit is cm)

3.5 Sonication horn

There are three horns were used in this study namely small, medium and large horn. Each horn was differed by the surface area. The surface areas of small, medium and large horn are 4.5, 20 and 45 cm^2 respectively. Figure 3.4 shows the different horn used in this study.

Figure 3.4 Small horn (left), Medium horn (middle) and Large horn (right)

3.6 Evaluation of sludge disintegration efficiency

The effectiveness of sludge disintegration was determined base on physical evaluation (Microscopic examination and Particle size analysis), Biological evaluation (Specific oxygen uptake rate (SOUR) or degree of inactivation) and chemical evaluation (SCOD, NH_3 release).

3.6.1 Optimize sonication condition

Selection of suitable horn: 100 mL TWAS was sonicated in a batch mode using three different horns as discussed in Section 3.3 at different sonication time of 0 (control), 30, 60, 120, 240 and 480 seconds. The amplitude will be kept constant at 25% for all sonication. The SCOD release at different sonication duration will be determined. The SCOD release will be plotted against sonication time for all three horns. The horn that releases the highest SCOD will be chosen for all the subsequent sonication tests.

Selection of optimal specific energy input: 100 mL of TWAS obtained from Section 3.2 was sonicated with a selection horn as discussed above at different power input of 50, 100, 150 and 190W. Different sonication times of 0 (control), 30, 60, 120, 240 and 480 seconds were investigated at each amplitude. The SCOD release at each power input was determined at different sonication duration. The SCOD release was plotted against specific energy input for each power input. The specific energy input to the sludge was calculated using the following equation:

$$E = (P.t)/(V.TS) \qquad \text{Eq 3.1}$$

Where;
E = Specific energy input (kWs/g TS)
P = Power input (kW)
t = Sonication time in seconds (s)
V = Volume of sludge sonicated (L)
TS = Total solids (g/L)

Then the effective sonication duration that releases the highest SCOD was chosen for all sonication testing.

3.7 Evaluation of aerobic digestibility

The performance of aerobic digester was observed performance base on SCOD, TS and VS removal, NH_3 and NO_3^-, and SOUR of the digested biosolids. Sour was examined to investigate the bioactivity of digested biosolids. The dewaterability and pathogen count (fecal coliform, *E. coli* and *Salmonella* sp.) of the digested biosolids were determined.

3.7.1 Aerobic digesters setup

Three laboratory scale aerobic digesters were fabricated using a transparent acrylic cylinder 1400 mm internal diameter and 3800 mm high, covered both ends by acrylic. The top part covered with removable plate and provided with two ports the first one for feeding the ultrasonic pretreated sludge, withdrawing digested sludge and measuring pH, DO, and temperature. The second port on the cover is for supplying the oxygen.

All three digesters had a total volume of 5.8L and a working volume of 3L. Extra head space is being provided as a precautionary measure to avoid overflow, should sludge foaming of sludge occur during digestion. The digesters were aerated using compressed air through porous circle pipe with 5.5 mL O_2/min to maintain adequate mixing and dissolved oxygen level. The reactor set-up is shown in Figure 3.5.

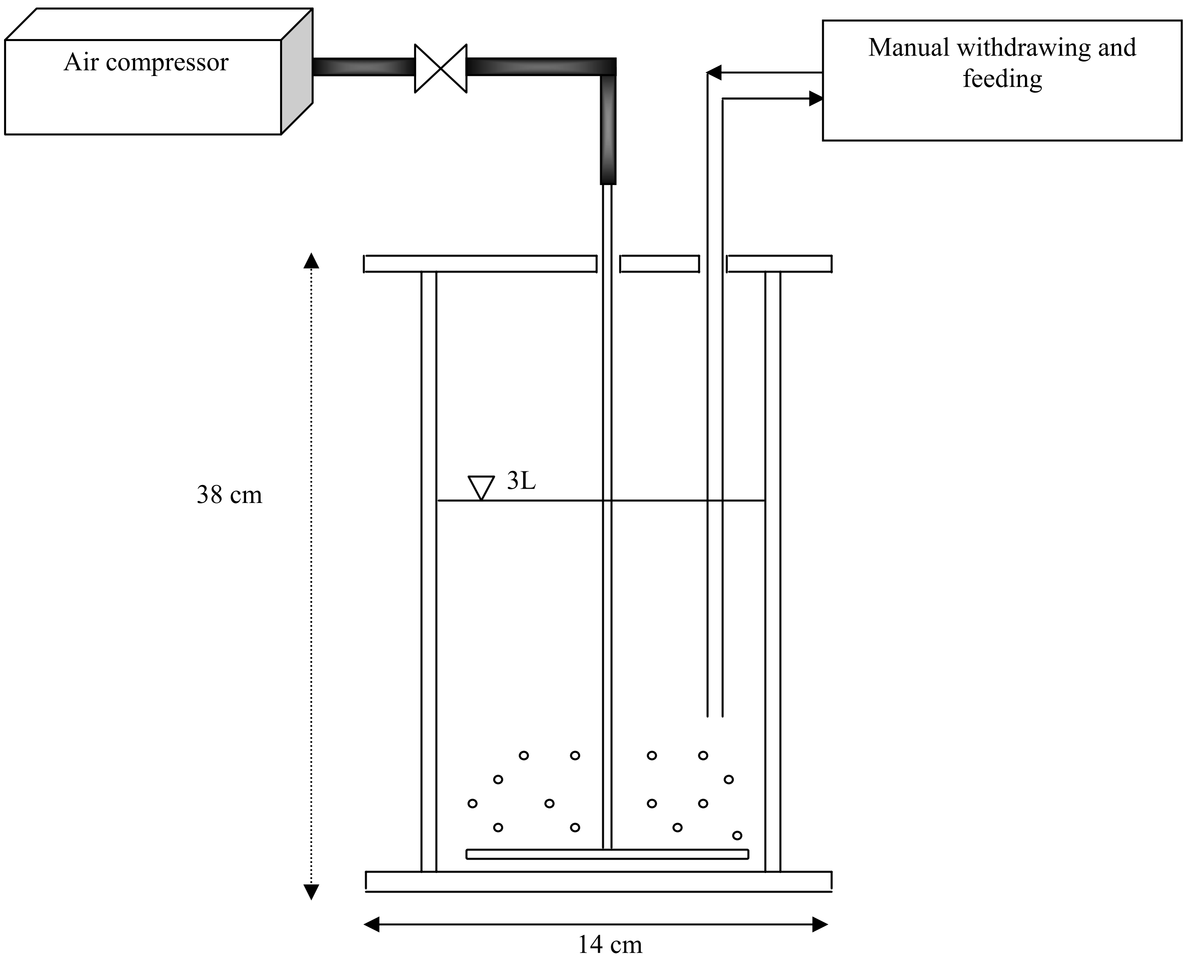


Figure 3.5 Reactor set-up

3.7.2 Digester start-up and operation

Digester start-up: All three laboratory-scale digesters, namely control reactor (C), part stream reactor (Rp) and full stream reactor (Rf) were initially started with nonsonicated TWAS at SRT of 20 days and temperature of $25\pm2^{o}C$. SCOD, NH_3, TS, VS and SOUR of digester content were monitored on a weekly basis; while pH was measured every 12 hours interval, until the reactor has reached a steady-state condition. If the pH drops below 6.8, 1N NaOH solution was added into the reactor to maintain a pH of 7 ± 0.2. The steady state is believed to reach when the collected data do not vary more that 5%. After steady state, all digesters were operated for a minimum of one week to collect enough steady state data.

Digester operation: Sludge 150 and 300 mL were withdrawn and feed every 12 hour at SRT of 20 and 10 days respectively. Digested sludge collected from each 12 hour was kept in container with tight cover during batch operation of the day to prevent evaporation. Then, effluent sample immediately stored sample at 4 ^{o}C storage room and mix well prior to take sample for analyze. The analysis will be conducted once a day after semi-batch completed.

Then, three of reactors were continuous operated at 10 days of SRT. The aerobic digester operating condition is shown in Table 3.1

Table 3.1 Aerobic digester operation condition

Parameters	Range
TS	3%
SRT	10 and 20 days
Aerate flow	5.5 ml/min
Temperature	25 ^{o}C ±2 ^{o}C
pH	7 ± 0.2
Do	> 2 mg/L
Operation system	Semi-batch operation (feeding and withdrawing every 12 hour)

Rp: Digested sludge was mixed well and withdraws as 150 and 300 mL per day prior to feed the sonicated sludge. (50% of sonicated sludge and 50% of nonsonicated). Feeding sludge was fed into the digester each 12 hours at different SRT of 20 and 10 days respectively.

Rf: Digested sludge was mixed well and withdraws as 150 and 300 mL per day prior to feed the sonicated sludge. (100% of sonicated sludge). Feeding sludge was fed into the digester each 12 hours at different SRT of 20 and 10 days respectively.

The overview of experimental set up is shown in Figure 3.6.

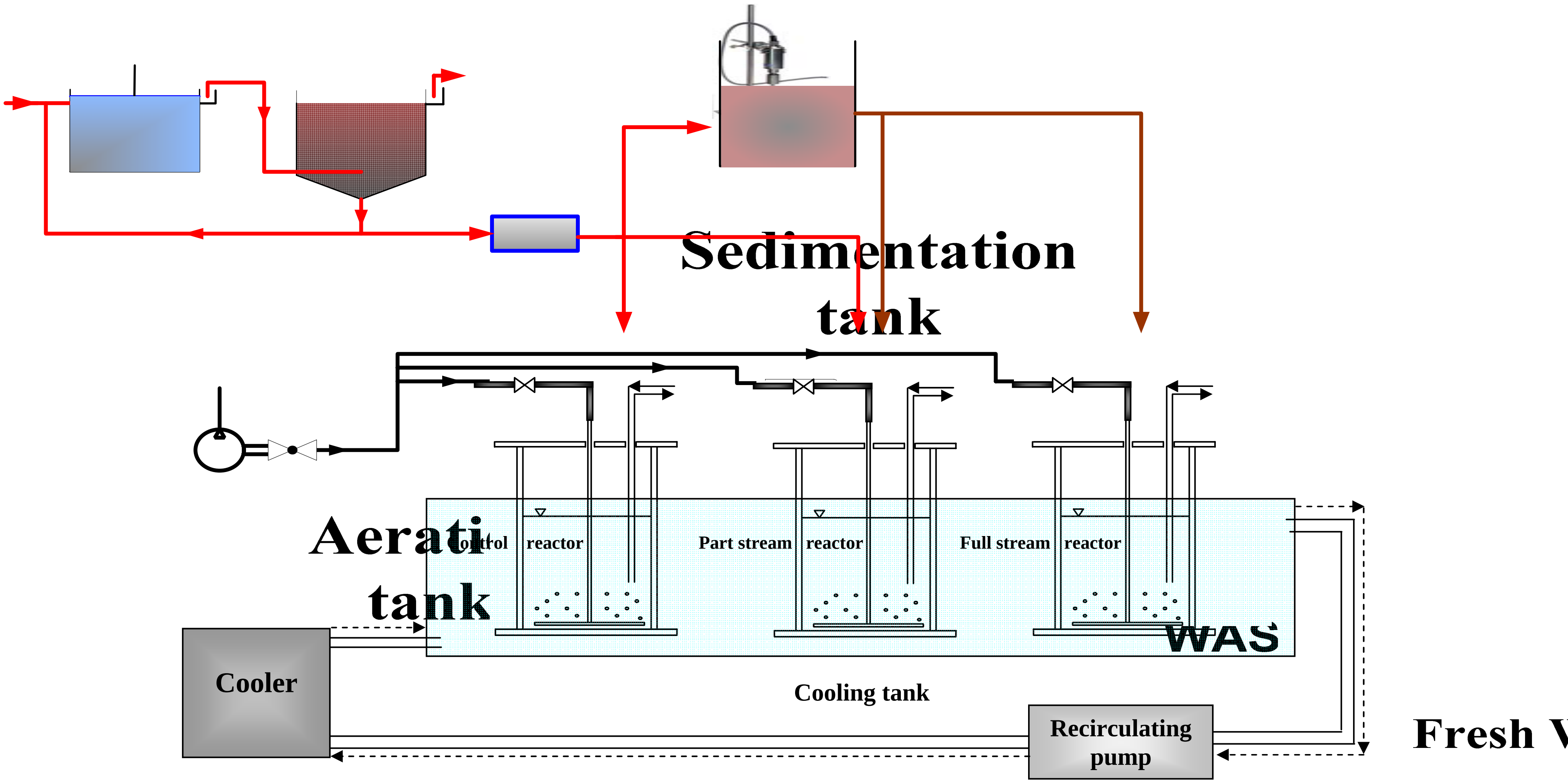


Figure 3.6 Overview of experimental set up

3.8 Analytical method and data collection

For each of experimental, all of apparatus were calibrated regularly.

3.8.1 Analytical method for evaluate sludge disintegration

Microscope examination: Visual observation of sonicated sludge using light microscope (Olympus-CX40RF200 Model, Japan) was furnish information on structural or morphological change in particle structure base on visual observation using light microscope. The visual observation the changed of particle structure was examined for each sample of horn size, sonication duration and sonication energy input.

SCOD in supernatant were determined among the standard method (1998). Due to the sonication could be ruptured the sludge to facilitate the release more SCOD. Thus, sludge disintegration efficiency increase proportion with SCOD release.

3.8.2 Analytical method for performance of aerobic digester

Dissolved organic carbon (DOC), NH_3, NO_3^-, TS, VS, DO, pH, TKN and pathogen count (fecal coliform, *E. coli* and *Salmonella* sp.) were determined among the standard method (1998) to investigate the effectiveness of aerobic digesters. Including SOUR, dewaterability and sludge morphology. Sludge morphology observation was examined for each sample of horn size, sonication duration, sonication energy input. The detail of parameter analysis the efficiency of digestibility is summarized in Table 3.2

SOUR was examined to investigated the bioactivity of sonication WAS. Since ultrasonic pretreatment disrupts the sludge. Thus after sonication SOUR should be decrease.

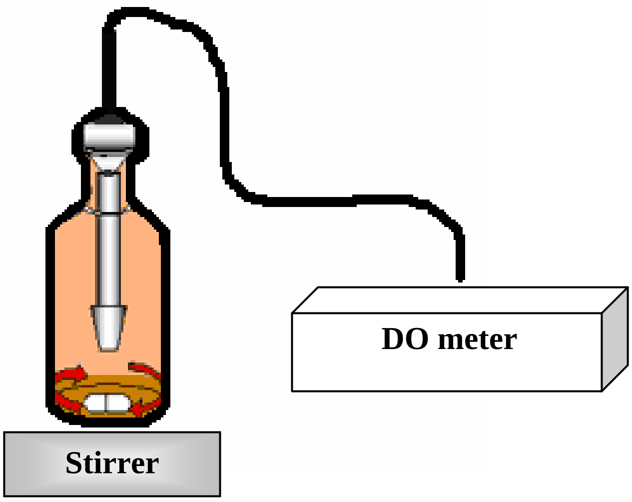


Figure 3.7 Schematic representations of SOUR apparatus

$$SOUR = (M/VSS)*60 \text{ min/h} \quad (\text{mg oxygen /g VSS})/\text{h} \qquad \text{Eq 3.2}$$

Where M = Oxygen consumption rate mg/L.min
VSS = Volatile suspended solid g/L

Dewaterability was determined using capillary suction apparatus to investigate the filtration of the sludge sample. The capillary suction apparatus consisted of sludge column contained in the sample cylinder which is centered in the middle in the two of concentric electrodes at diameter D1 and D2 resting on a Whatman-17 filter paper. A timing device is started when the water front reaches the inner electrode at D1 and is stopped when the water reaches the outer electrode at D2. The time elapsed is the Capillary Suction Time (CST). The schematic representation of CST apparatus is shown in Figure 3.8.

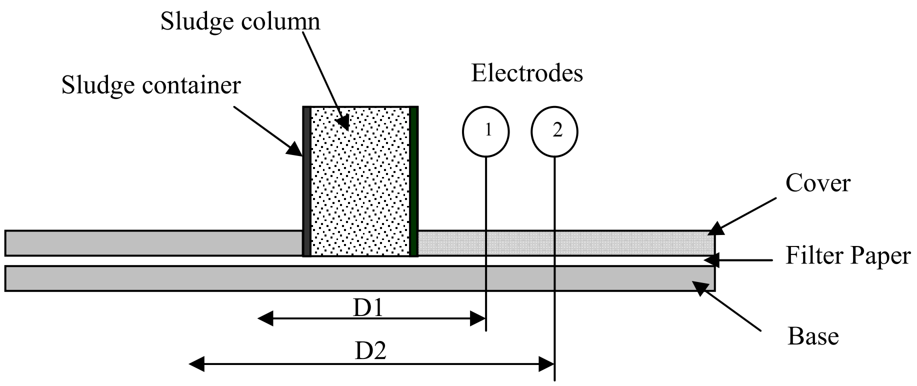


Figure 3.8 Schematic representations of CST apparatus

Table 3.2 Parameter analysis the efficiency of digestibility

Parameter	Analytical method	Analytical equipment	Interference	Frequency per week
SCOD (mg/L)	Closed Reflux Method	Closed reflux apparatuses and centrifuge	Cl^-, NO_2^-, Br^-, F^- and other reagent that activates the silver ion.	2 (3 times after reaching steady state condition)
Ammonia-N (mg/L)	Distillation and titration method	Distillation and titration apparatus	Ca_2^+,Fe_2^+ Mg_2^+,S_2^-, volatile alkaline compounds and residual chlorine.	2 (3 times per week after steady state)
NO_3^- (mg/L)	Chromatography separation	Ion Chromatograph	Nitrite	1 (3 times per week after steady state)
pH	pH meter	pH meter	-	Every 6 hours
DO (mg/L)	Hach Potable LDO	Do meter	H_2S, N_2	Daily
VS (mg/L)	Ignition at temperature 550^{o}C	Oven and analytical balance	Loss of ammonium carbonate and volatile organic matter during drying	2 (3 times after reaching steady state condition)
TS (mg/L)	Evaporation and dry at temperature 103-105^{o}C	Oven and analytical balance	Large, floating particles or submerged agglomerates of no homogenous materials, visible floating oil and grease etc.	2 (3 times after reaching steady state condition)
SOUR (mg O_2/g TS-hr)	-	DO meter, BOD bottle	-	2 (3 times per week after steady state)
Sludge morphology	Light microscope	Light microscope	-	1 (after reaching steady state)

Parameter	Analytical method	Analytical equipment	Interference	Frequency per week
Dewaterability (s)	Capillary suction time	Capillary suction apparatus	Temperature	2-3 (after reaching steady state condition)
Pathogen count	Plate count	Incubator	-	after reaching steady state condition
TKN	Kejeldahl method	Digestion, Distillation and titration apparatus	-	after reaching steady state condition
TP	Digestion	Digestion and spectrophotometer	SS	after reaching steady state condition

Note : The method of determination was following Method for the Examination of Water and Wastewater. (20^{th} Ed.), APHA et al., (1998)

All of collected data was compared and interpreted for each batch of SRT using the statistic analysis program including report the information with table, graph and another suitable form.

Chapter 4

Results and Discussion

This chapter was presented the results and discussion mainly obtained from two phases of lab scale experimental. The first experimental, the sonication condition was optimized. The SCOD and microscopic examination were conducted to evaluate the efficiency of ultrasound disintegration. The second experimental, the efficiency of aerobic digester was evaluated by dissolved organic carbon (DOC) and TS/VS removal efficiency, NH_3 and NO_3 concentration, SOUR, and CST. Moreover, the quality of biosolid was investigated as well.

4.1 Optimization of Ultrasonic pretreatment condition.

4.1.1 Horn optimization

Waste Activated Sludge (WAS) from Thammasart University was collected and centrifuged at 2000 rpm for 2 minutes to concentrate sludge to 3 % of TS. The concentration of sludge selected for the experiment was 3% because ultrasonic disintegration of higher TS content is more energy efficiency compared to lower TS content. Wang et al. (2005) reported that SCOD release increased from 3,966 to 9,019 mg/L when the TS content was increased from 0.5 to 1 % during 30 min of soniction at an ultrasonic density of 1.44 W/mL. However, some previous studies reported that an aerobic digester operating at 4% TS content showed critical odor emission problems due to the oxygen transfer limitation. (Hertle and de Waal, 2003). WAS which had 3% of TS was sonicated with small, medium and large horn at 190W of power input and each horn was sonicated as different sonication duration at 0 (control), 30, 60, 120, 240 and 480 seconds. The optimization of sonication condition was measured by SCOD. In addition physical and microbiological changes in sludge at each sonication condition was observed using microscope.

As presented in Figure 4.1, results showed that the large horn was the best horn which could release the highest SCOD at 30.4 kJ/kg TS of specific energy input for each sonication duration of 0, 30, 60, 120, 240 and 480 s. Then, the large horn was selected for the rest of experiments. The SCOD released of each horn were showed in Table 4.1.

Table 4.1 SCOD released at each horn during sonication at different time

Specific energy input (kJ/kg TS)	Sonication duration (s)	SCOD released (mg/L) of each horn size		
		Large	Medium	Small
0	0	79.2	79.2	79.2
1.9	30	1584	864	360
3.8	60	2592	1368	1512
7.6	120	3744	2736	2160
15.2	240	5832	3936	4392
30.4	480	6480	6264	5148

The SCOD release increase with increasing sonication duration as shown in Figure 4.1.

The continuous releasing of SCOD shows the better disintegration achieved at a longer sonication time. This is because there was adequate opportunity for sludge cell and debris to come under perpetual attack of collapsing cavitation bubbles. Moreover, at 3% of TS facilitated the sludge disruption due to particle to particle collision and the violent collapsing of micro-bubbles might have accelerated the particles in vicinity of the bubbles, which bombarded the adjacent particles.

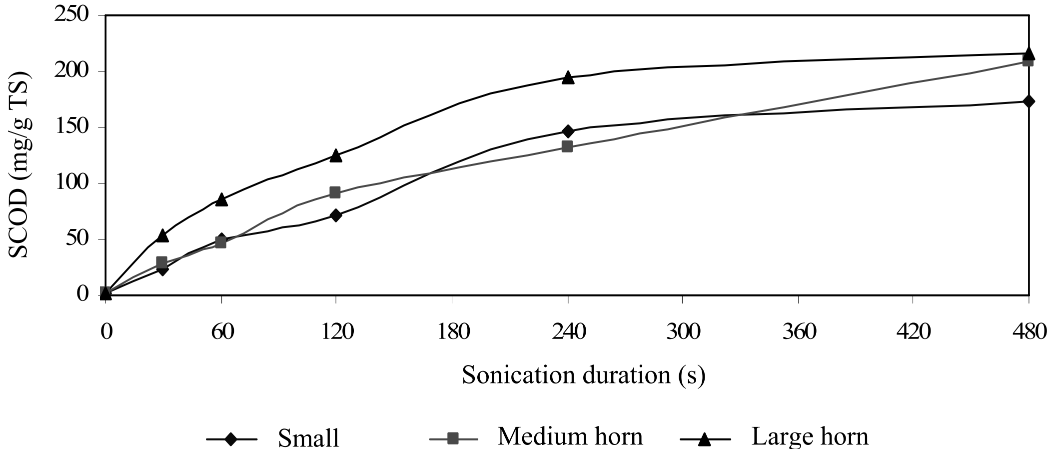


Figure 4.1 SCOD released at each horn versus sonication duration

Applying sonication into WAS, another effect of sonication was temperature raising and changing of sludge characteristic. The temperature of each horn was found increasing proportionally with the sonication duration and power input. Moreover dissolve solid could increase the temperature. The temperature rising at each sonication duration was showed in Table 4.2. The excess temperature was generated by the cavitation bubbles in the container during sonication. When acoustic energy was propagated to sludge, cavitation bubbles are formed. Then suddenly implode and locally resulting in very extreme condition of temperature (~ 5000 K) (Raf Dewil et al., 2006).

Table 4.2 Temperature raising of sonicated sludge at each horn during sonication at different time

Specific energy input (kJ/kg TS)	Sonication duration (s)	Temperature raising (^{o}C) of each horn size		
		Large	Medium	Small
-	Control	-	-	-
1.9	30	11	11	12
3.8	60	21.5	18	12
7.6	120	34	21	25
15.2	240	45	36	36
30.4	480	55	39.5	52.5

Figure 4.2 shows the temperature rising for each horn versus different sonication duration. When WAS was exposed by ultrasonic pretreatment, an increasing of temperature was measured immediately after sonication.

The large horn generated the highest temperature at every condition. The second order was the small horn which could generate temperature higher than the medium horn. The medium horn rivaled the least temperature increasing. This is because the large horn has more effective area that could propagate more ultrasound wave to disintegrated sludge.

Small horn could generate higher temperature compared to medium horn. Although it had less effective area but it had longer shape that can immerse deeper into sludge and provide Rayleigh streaming region (Region II) as mention in chapter 2. This region can propagate ultrasound wave as well. This increase in temperature must be avoided when ultrasonic pretreatment was used for feeding of aeration digester to prevent confusing in increment of efficiency. If sonicated sludge feeding had high temperature prior to digestion, the efficiency of digester will be having positive effect due to thermal treatment also. Hence, the water jacket for the chamber was advised to use in this case to control the temperature of sonicated sludge.

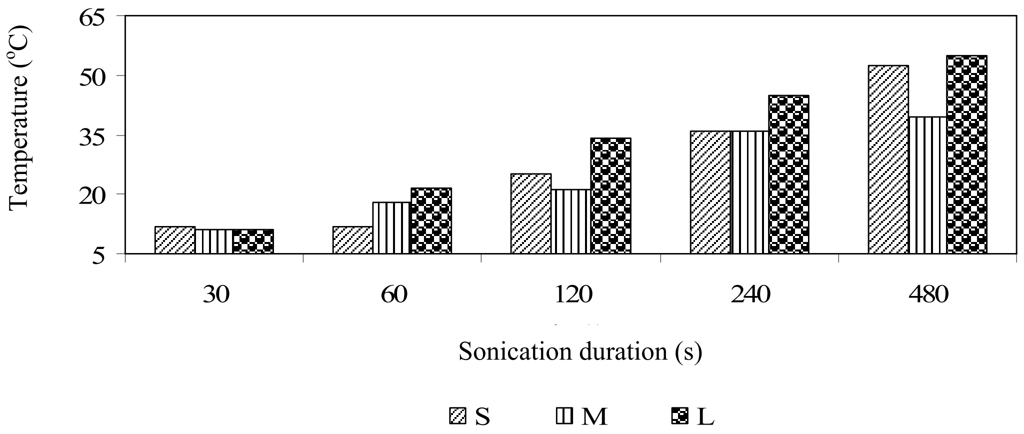


Figure 4.2 Temperature rising at each horn versus sonication duration

4.1.2 Sonication condition optimization

SCOD was used to investigate, sonication duration and the optimum specific energy input. The real application need to optimize the specific energy input for cost–effective. Sludge sample was sonicated with the large horn at different power input of 50, 100, 150 and 190 W. Each power input was sonicated at sonication duration of 0, 30 60, 120 and 240 s. The specific energy input is proportional to sonication time. The longer time means a higher specific energy input used. Moreover, it results into higher SCOD release (Wang et al., 2005). As shown in Figure 4.3, the highest increase in SCOD value was obtained with the highest power input and longest treatment time. In addition, dissolved solid is one of factor that affects SCOD release, the highest dissolve solid was released with highest SCOD but in this study was conducted at solid content of 3%. Since the disintegration of sludge presupposes high mechanical shear force cause by jet streams during cavitation bubble implosion (Gronroos et al., 2006). That why the better disintegration requires high ultrasonic power. Figure 4.3, is illustrates effect of power input and treatment time to SCOD release. However, specific energy input has to be considered for energy consumption for economic reason. The highest power of 190 w and the short time of 45 s were selected because at this point shown the double effects of ultrasonic pretreatment. However, Then the selected specific energy input is 3.8 (kJ/Kg TS). In addition, It is better to select the higher power input dose and less duration. Due to the shorter sonication duration could be prevented the effect of temperature increasing during sonication. The SCOD released was increased with time and start to slow down at 240s.

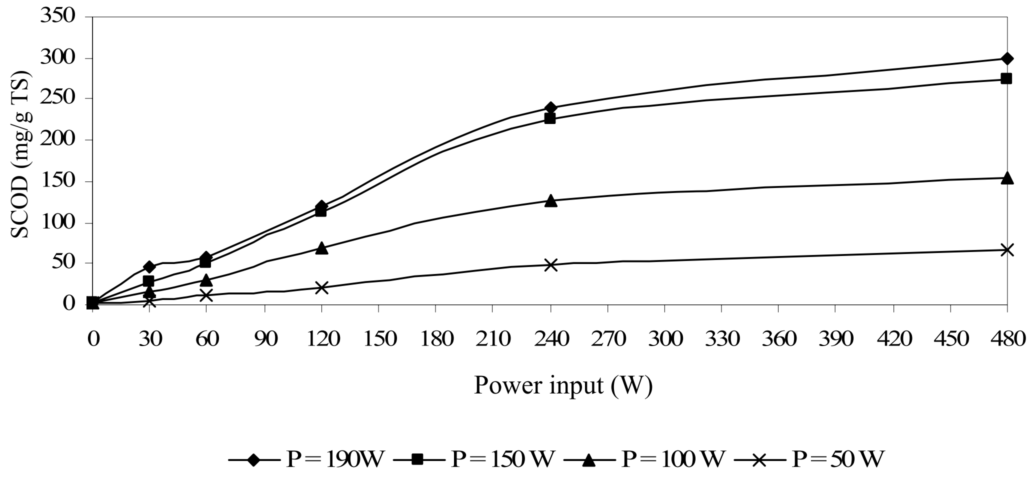


Figure 4.3 SCOD released at different power input as each sonication duration

Figure 4.4 shows the SCOD release at various specific energies for different ultrasonic densities. Form this figure, when the specific energy input was increased up to about 2 kWs/gTS, the SCOD release was increased rapidly at all ultrasonic densities as well. Thereafter, increment in the SCOD release was slowed down up to 4 kWs/gTS of the specific energy input. Once more, the SCOD release was found to be increased rapidly with increasing specific energy input from 4 kWs/gTS to12 kWs/gTS. The beyond 12 kWs/gTS, increment of SCOD was retarded with increasing specific energy. When the specific energy and SCOD release were considered together, specific energies of 2 kWs/gTS and 12 kWs/gTS were found to be the critical values for the effective SCOD release. However, the specific energy was selected at 12 kWs/gTS for effective SCOD released and effective energy using as well.

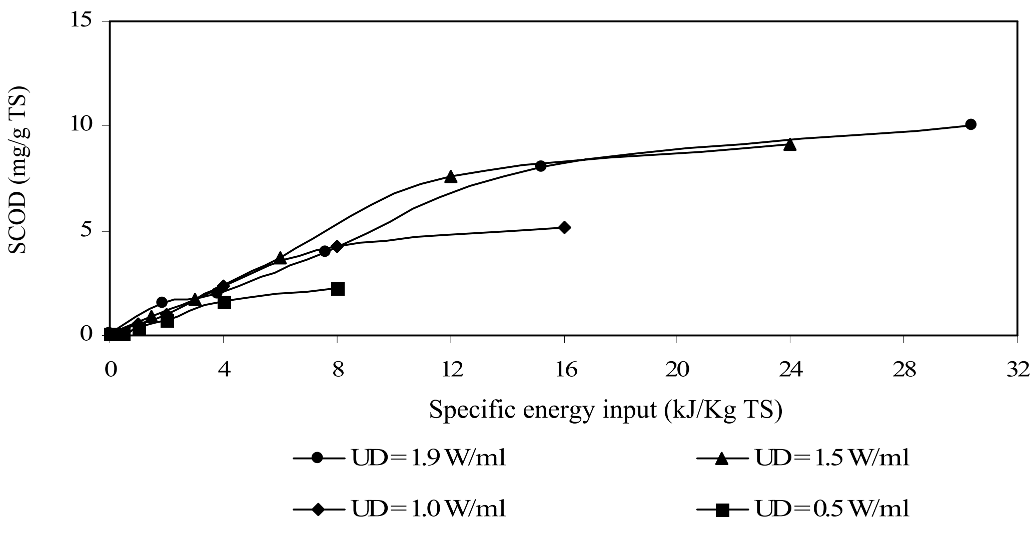


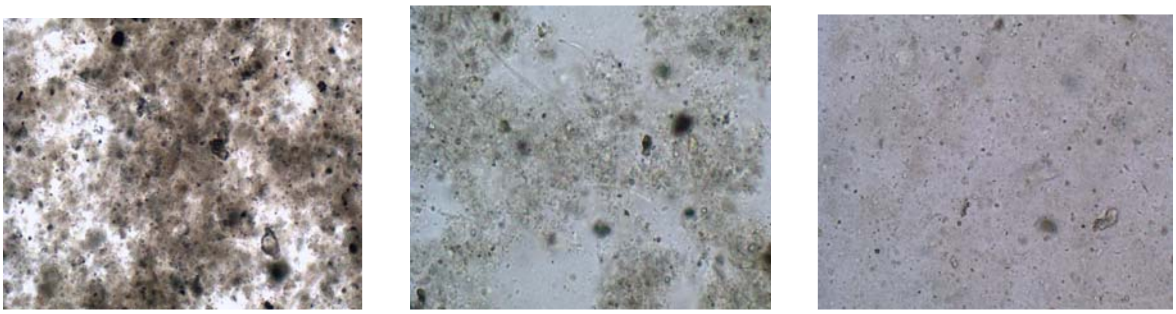
Figure 4.4 SCOD released versus specific energy input

After operating reactor for 1 month at 20 days SRT, both of part stream and full stream digester did not show the significant improvement of VS reduction. As showed in the

Figure 4.12. Then, sonication duration was tripled from the previous duration which expected to observe the effective of ultrasonic pretreatment. Thus, sonication condition of 3.8 kJ/kg TS with 150s of sonication duration using the large horn was selected for rest experiments.

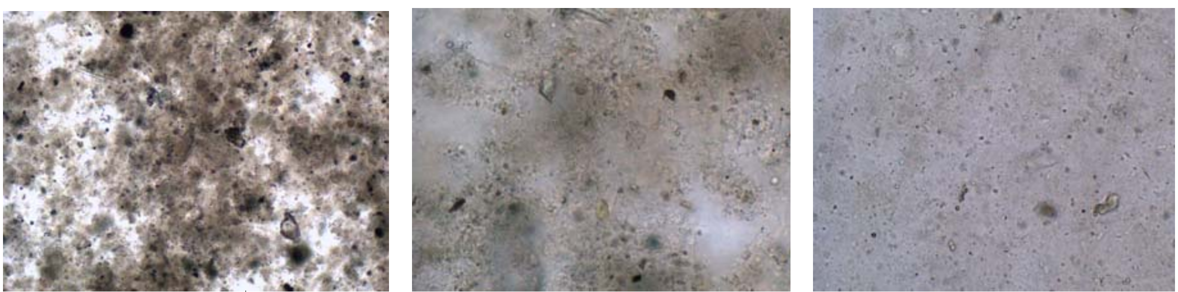
4.1.3 The characteristic of sonicated sludge at different power input, sonication duration and horn

Sludge sample from horn optimization, specific energy input optimization and sonication optimization shown the changing in characteristics after sonication at different condition. Ultrasonic pretreatment can reduce the size of WAS (Yoon et al., 2004). According to light microscopic observation with 40 magnifications reveled that higher power input and longer sonication duration showed finer particle. This indicating that the efficiency of sludge disintegration is depends on sonication duration and power input. This study found that the longest of sonication duration, the highest power input could provide more sludge disintegration compared to control as shown in Figure 4.5 and 4.6 respectively. At different horn size, this study found that each horn size could provide the same efficiency to disintegrate sludge as presented in Figure 4.7



Control 30 s 480 s

Figure 4.5 Characteristic of sonicated sludge at different sonication duration by large horn at 1.90 w/mL of ultrasonic density and 3% TS. (X 40)



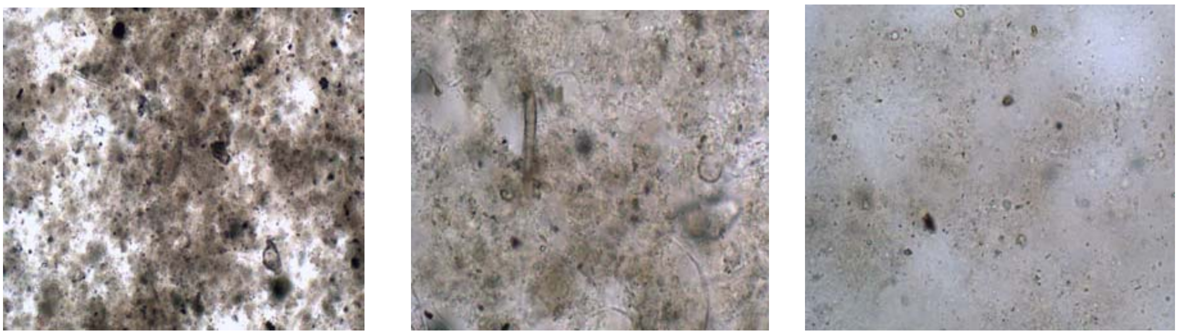
Control 0.5 w/mL 1.9 w/mL

Figure 4.6 Characteristic of sonicated sludge with large horn at different ultrasonic density, 240 s of sonication duration and 3% TS by the large horn. (X 40)

Small horn Medium horn Large horn

Figure 4.7 Characteristic of sonicated sludge with different horn at 1.9 w/mL of ultrasonic density, 480 s and 3% TS. (X 40)

At short sonication duration and low amplitude ultrasonic pretreatment can only broke down the sludge floc to separate sludge cell but it could not broke down cell of sludge. In the other hand, at longer sonication duration and higher amplitude the ultrasonic pretreatment can provide more sludge disintegration. Especially for longest sonication duration (240s) and highest ultrasonic density 1.9 w/mL, the characteristic was changed significantly and easier observe compared to the shortest sonication duration (30s) and lowest ultrasonic density 0.5 w/mL as shown in Figure 4.8.



Control 30 s, 50 w 240 s, 190 w

Figure 4.8 Characteristic of sonicated sludge with the large horn at 3% TS at 30 s and 0.5 w/mL of ultrasonic density and 240 s and 1.9 w of ultrasonic density (X40)

4.2 Effect of Ultrasound on Aerobic digestibility of Waste Activated Sludge (WAS)

Three aerobic digesters, each of 3 L working volume were operated at SRT of 10 and 20 days to investigate the effect of ultrasound pretreatment on aerobic digestion of WAS. The TS content of feed sludge (WAS) at each SRT was maintained at 3% TS, and the WAS was sonicated at 150s at power density of 1.9 W/mL. The digesters were maintained under completely mixed conditions through aeration at a rate of 5.5 L/min. The pH of all digesters was controlled at the neutral range by adding 1 N NaOH twice a day. The digesters were maintained at $25 \pm 2\ ^{o}C$ using water bath.

The main goal of ultrasonic pretreatment is to destroy the cell wall and cell membrane of microbe and release the intracellular materials to the aqueous phase. In addition, ultrasound helps to deagglomerate the biological flocs and disrupt organic particles thereby releasing intracellular organics to the liquid phase. Thus, the evaluation of aerobic digester were based on TS/VS and DOC removal efficiency, SOUR of digested biosolids, and effluent ammonia and nitrate concentration.

4.2.1 Dissolved Organic Carbon (DOC)

The DOC removal efficiency for part stream and full stream bioreactor were 67%, 90% and 93% respectively, at 10-days. Whereas, at 20-days SRT the efficiency of part stream and full stream were found at 71%, 90% and 93% respectively. Figure 4.9 shows the increasing of DOC removal efficiency with time. Figure shows that the DOC removal efficiency of part stream and full stream bioreactor were significant higher than control bioreactor. However, the SRT do not effected to DOC removal efficiency. As shown in the graph, the DOC removal did not changed with the different SRT. The DOC removal efficiency of part stream and full stream digester improved by as much as 26% and 28% at 10-d SRT and the removal efficiency of DOC were improved 20% and 23% for part stream and full stream reactor respectively, at 20-d SRT compared to control reactor.

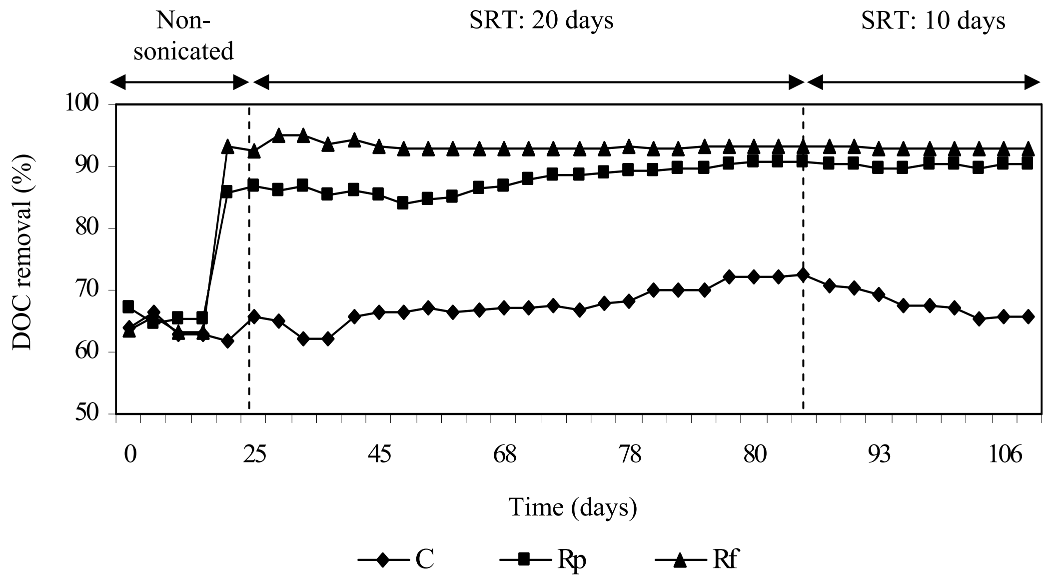


Figure 4.9 DOC removal efficiency at different SRT

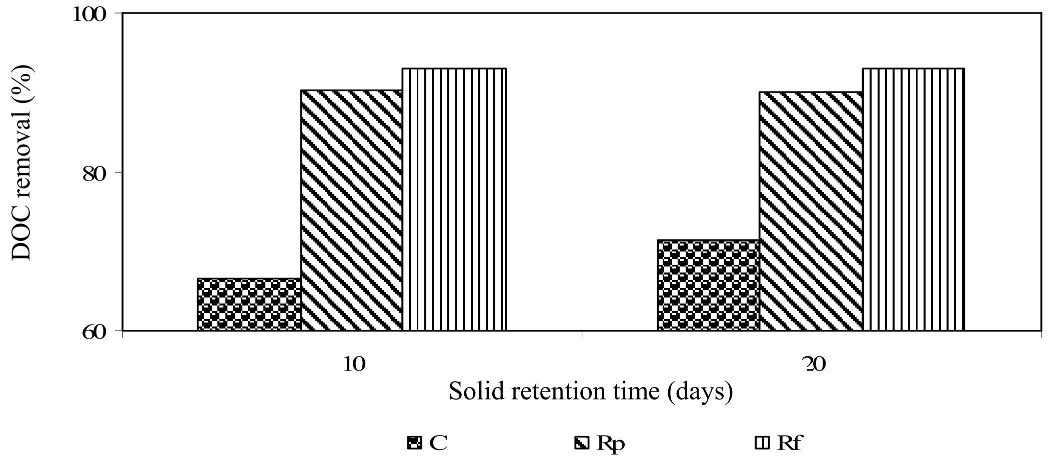


Figure 4.10 Average DOC removal efficiency at different SRT

As shown in Figure 4.10. Both 10-d and 20-d SRT full stream reactor shows the higher of DOC removal efficiency than part stream reactor. Figure showed that ultrasonic pretreatment can provide more soluble organic which facilitate for digestion. In addition at 10-d SRT, both of part stream and full stream reactor were showed the better removal efficiency of DOC than 20-d SRT. As determined by statistically analysis at the significant $p < 0.05$, the differences were found between variable of full stream and part stream reactor in this analysis. Except for part stream reactor, the removal efficiency of it was present in the same percentage. As the result of statistically analysis using one way ANOVA was not showed the differences at the significant $p<0.05$ between 10-d SRT and 20-d SRT of part stream reactor.

4.2.2 Total solids and Volatile solids removal

Ultrasonic pretreatment was achieved TS/VS removal efficiency of part stream and full stream bioreactor as shown in figure 4.11. Figure shows that TS removal efficiency of control, part stream and full stream digester were 6%, 11% and 12% respectively, at 10 days SRT and the removal efficiency of part stream and full stream reactor were11%, 17% and 18% respectively, at 20 days SRT. The TS removal efficiency of part stream and full stream digester improved higher than control digester by as much as 46% and 50% respectively, for 10-d SRT and the efficiency of part stream and full stream reactor higher than control reactor by 32% and 36% respectively, for 20-d SRT.

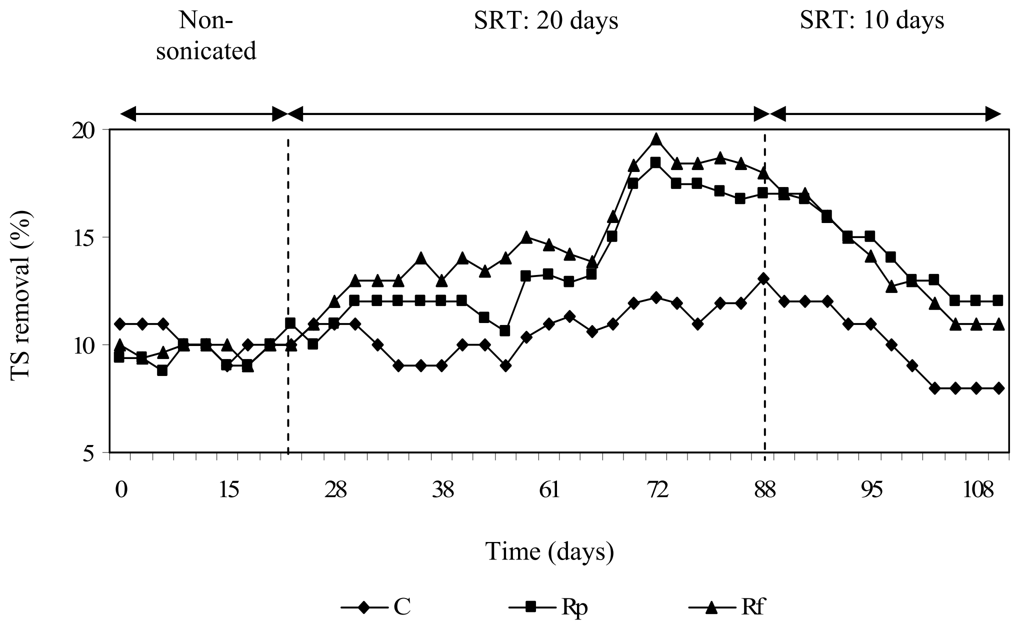


Figure 4.11 TS removal efficiency of aerobic digester at different SRT

Whereas VS removal efficiency for part stream and full stream digesters operated at 10-d were 11%, 17% and 17% respectively. As well as 20-d SRT the VS removal efficiency for part stream and full stream digesters were 19%, 24% and 24% respectively. Similarly at 10-d SRT, VS removal efficiency of part stream and full stream digester higher than control reactor by 35% and 38% respectively. While the efficiency of part stream and full stream digester for 20-d SRT higher than control reactor by 21% and 23% respectively. As shown in Figure 4.12.

All aerobic digester operated at 20-d SRT showed the higher rate of TS/VS removal than 10-d SRT. This showed that the digester was operated well at the longer time of 20 days SRT. Furthermore, full stream digester shows the better performance than past stream at both 10-d SRT and 20-d SRT. As determined by statistically analysis at the significant $p < 0.05$, the significant differences were found between variable of control, part stream and full stream reactor in this analysis.

However, TS and VS removal efficiency of part stream and full stream bioreactor were improved as the same range. This is indicating that only 50% of sonicated feed sludge is sufficiency to improve the aerobic digestibility. Thus, part stream reactor was the best option for this study since it achieved the TS/VS removal efficiency equal to full stream digester while consumed energy only 50%. As this advantage of ultrasonic pretreatment, it automatically reduces in cost of biosolids transportation and disposal. Due to the less amount of digested sludge produced.

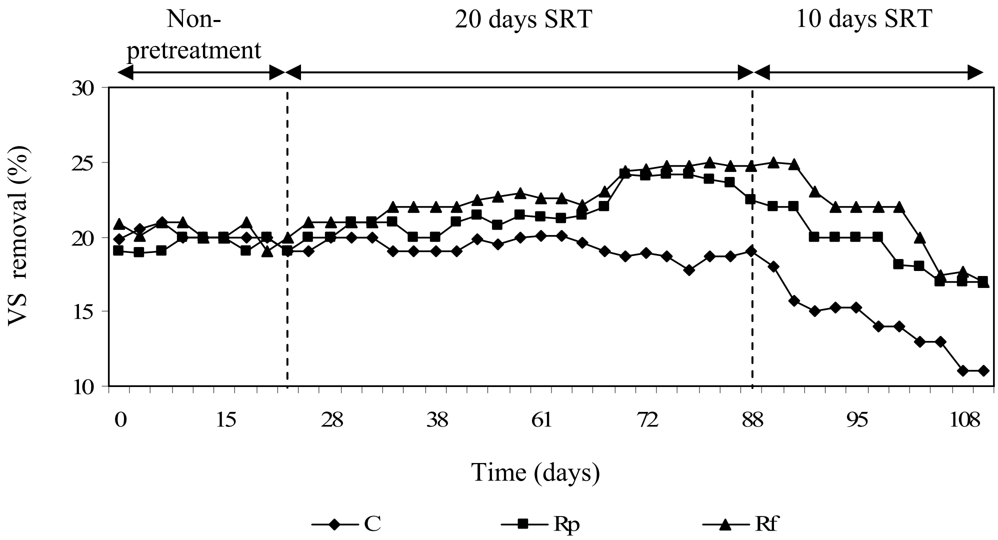


Figure 4.12 VS removal efficiency of aerobic digester as 20 SRT

4.2.3 Specific oxygen uptake rate (SOUR)

The investigation on SOUR indicates the stability of the digested sludge. Biosolids with low SOUR indicates better sludge stability (Khanal et al., 2007). As the apparent from Figure 4.13, the longer time of 20-d SRT presented the better quality of biosolids than 10-d SRT. At 10-d SRT, SOUR of control, part stream and full stream reactor were 9, 8 and 6 mg O_2/g TS-hr respectively. SOUR of control, part stream and full stream reactor were 8, 6 and 3 mg O_2/g TS-hr respectively, for 20-d SRT.

SOUR value of part stream and full stream was found reduced lower than control reactor by 30% and 60% respectively. This can proved that ultrasonic pretreatment was significant reduced the bioactivity in full stream reactor. This is because ultrasound wave can explode active cell. Then, it affected to the reduction of oxygen uptake rate of cells which can link to the lower amount of fecal coliform as mention on topic below. At 10-d SRT, lowering the SOUR of all three bioreactors showed increasing trend. SOUR of part stream and full stream reactor was found reduced lower than control reactor by 15% and 37% respectively.

All of aerobic digester operated at 20-d SRT produced the better quality of biosolids than 10-d SRT. This could be indicated by the lower level of SOUR. Also, full stream digester presents the better performance than past stream digester at both of 10-d SRT and 20-d SRT. As determined by statistically analysis at the significant p< 0.05, the significant differences were found between variable of control, part stream and full stream reactor in this analysis.

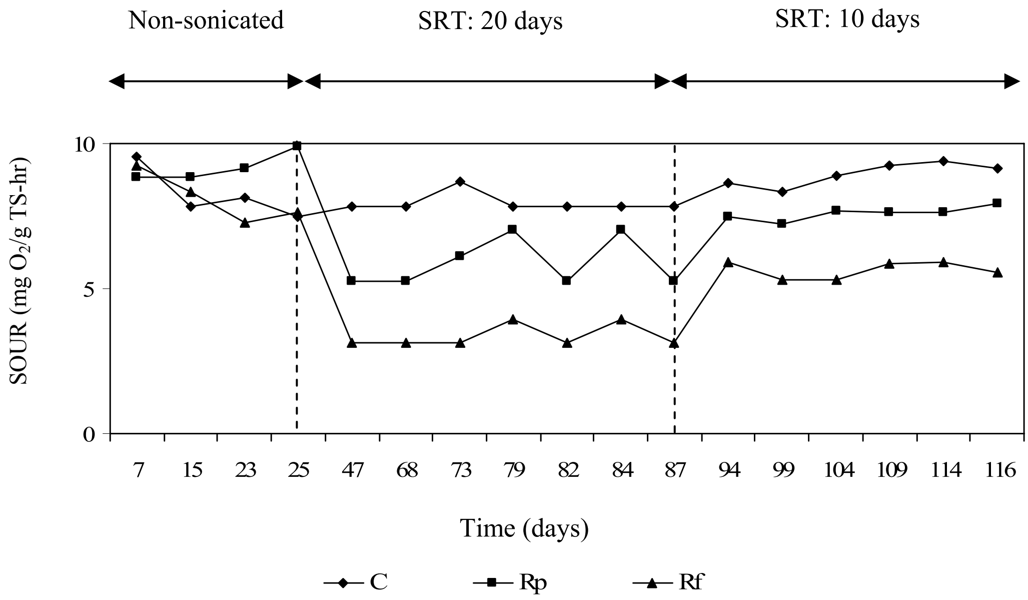


Figure 4.13 Specific oxygen uptake rate (SOUR) at different SRT

4.2.4 Ammonia level and nitrate release.

The predominance reactions of aerobic digester were ammonification and nitrification. Thus, ammonia and nitrate concentration were regularly monitored in this study. Ammonia concentration in digested sludge of control, part stream and full stream reactor were 9, 5 and 3 mg/L respectively, at 10-d SRT. Whereas at 20-d SRT, ammonia concentration of control, part stream and full stream reactors were 11, 10 and 6 mg/L respectively. As shows in Figure 4.14

Ammonia levels in digested sludge of part stream and full stream reactor operated at 10-d SRT were increased higher than control reactor by 53% and 55% respectively. Whereas at 20-d SRT ammonia values of part stream and full stream reactor were higher than control reactor by 11% and 48% respectively. Moreover, 10-d SRT is shows the lower amount of ammonia than 20-d SRT. This is obvious because at shorter SRT, more TKN was available for subsequence hydrolysis, thereby releasing more ammonia. Figure 4.15 shows the relation between ammonia and TKN in biosolids at different SRT.

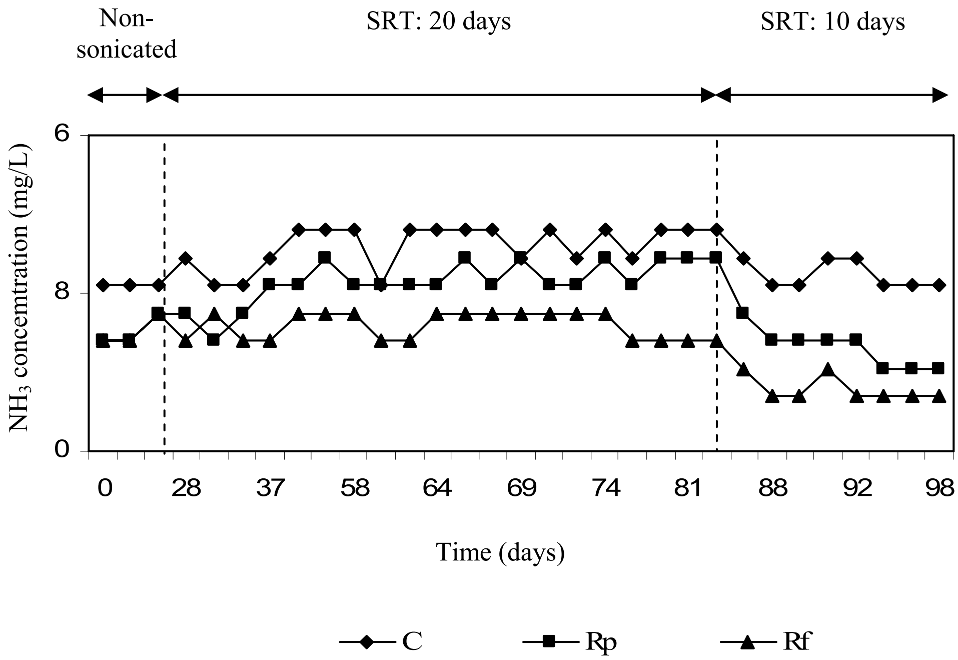


Figure 4.14 NH_3 removal efficiency at different SRT

The ammonification increased with aerobic digester fed with sonicated sludge because during sonication biological cell was disintegrated. Then, cell intracellular organic nitrogen was released into the aqueous phase which was subsequently hydrolyzed to ammonia during digestion (Khanal et al., 2007).

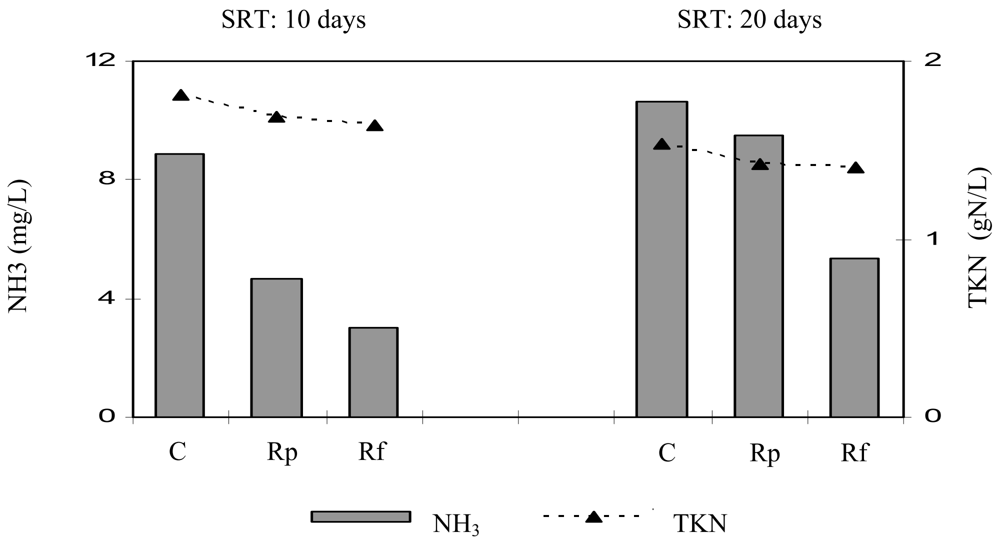


Figure 4.15 NH_3 level compared to TKN level at different SRT

As apparent from Figure 4.16, nitrate concentration was increased because resulting in nitrification reaction during aerobic digestion. An increasing of nitrate concentration was related to the reduction of ammonia concentration because during nitrification ammonia was oxidized to nitrate (Ros et al., 2002). In this study, nitrate level of control, part stream and full stream reactor operated at 10-d SRT were 619, 866, and 916 mg/L respectively.

Whereas the lower concentration of nitrate was found at 20-d SRT. The nitrate concentration of control, part stream and full stream reactor operated at 20-d SRT were 356, 766, and 797 mg/L respectively.

Nitrate concentration of part stream and full stream reactor were found higher than control reactor by 28% and 32% respectively, at 10-d SRT. Similarly at 20-d SRT nitrate concentration of part stream and full stream reactor were found higher than control reactor was higher by 53%, 55% respectively.

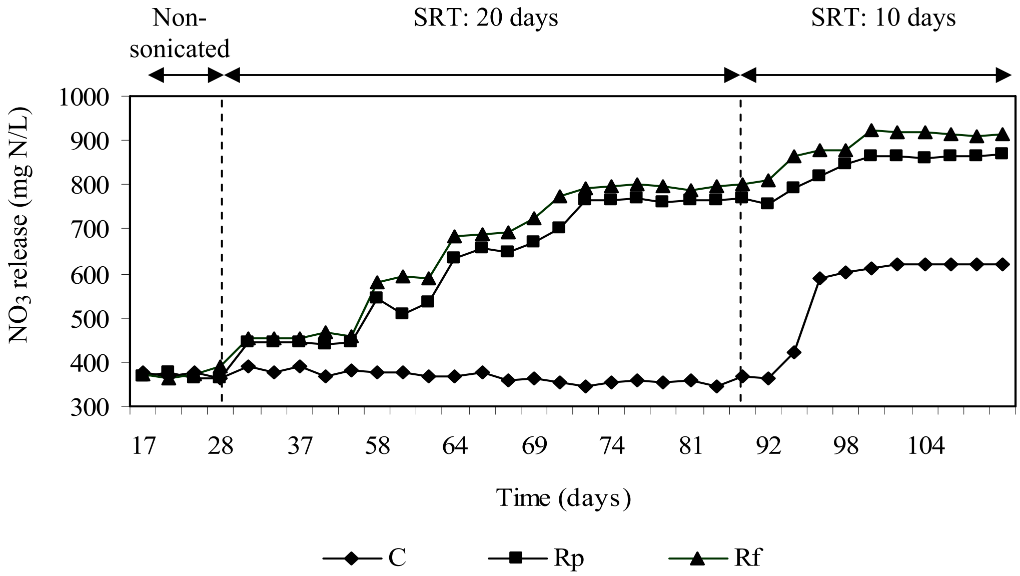


Figure 4.16 NO_3 release of aerobic digester at different SRT

The quantity of nitrate released relate to ammonia reduction. As shown in Figure 4.17 that the higher nitrate concentration occurred with the lower ammonia concentration. Because nitrogen bacteria oxidized ammonia to nitrate during aerobic condition.

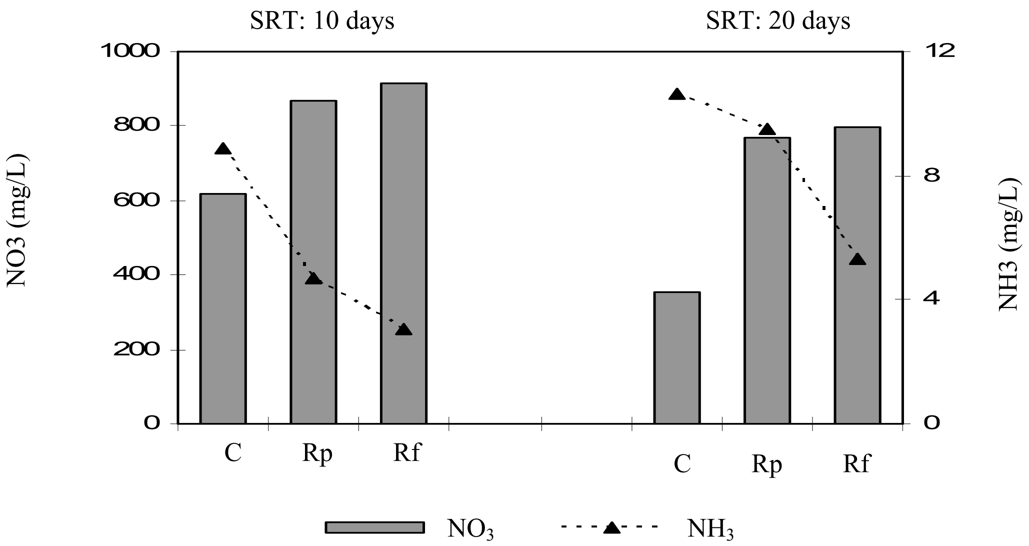


Figure 4.17 NO_3 release of aerobic digester at different SRT

At 10-d SRT, aerobic digesters showed the better performance than 20-d SRT. As the higher rate nitrification was enhanced more at 10-d SRT for all three of digester. In addition, full stream digester shows the higher performance than past stream at both 10-d SRT and 20-d SRT. As determined by statistically analysis at the significant $p < 0.05$, the significant differences were found between variable of control, part stream and full stream reactor in this analysis.

4.2.5 Capillary Suction time (CST)

CST is the parameter normally used to analyze the dewatwerability of digested sludge. Most of previous study found that ultrasonic pretreatment decreases the dewaterability of sludge. The dewaterability is deteriorated more by increased ultrasonic density and duration. The CST was increased from 82s to 344s using an ultrasonic density of 0.528 w/mL for 5 min to disintegrate sludge at 3% of TS (Wang et al, 2006). This is because of during digestion biopolymers are released from sludge floc into aqueous phase. Moreover Wang et al, (2006) reported that when sludge cells releases biopolymer into solution, it creases difficulties in sludge dewatering because most of biopolymer consist of water. In addition, when floc was disrupted by ultrasonic, it became smaller providing more surface area for the water adsorption.

Moreover, dewaterability of sludge can be affected by the water retained by EPS. Keiding et al, (1997) found that activated sludge floc consists of EPS, dispersed bacteria and a large amount of water. The EPS are mainly composed of proteins, polysaccharides and small quantity of DNA and have a significant affinity with water. Then the dewaterability of sludge decreases (Forster, 1993). However, in this study EPS was not determined.
Contradictory to the above finding, some researcher has reported that the CST values of digested sludge were decreased after ultrasonic pretreatment with lower of ultrasonic density and shorter duration (Erdincler and Vesilind, 2000). It has been reported that applying an ultrasound density of 0.11 w/mL for 10 min could decrease the CST from 197.4s to 188.2s.

This study showed that ultrasonic density of 1.9 w/mL for 150s could increase CST of raw sludge from 50s to 1182s. Ultrasonic pretreatment revealed 24 fold increment in CST. Figure 4.18 shows significant increase in CST after an increasing of CST of sludge after sonication.

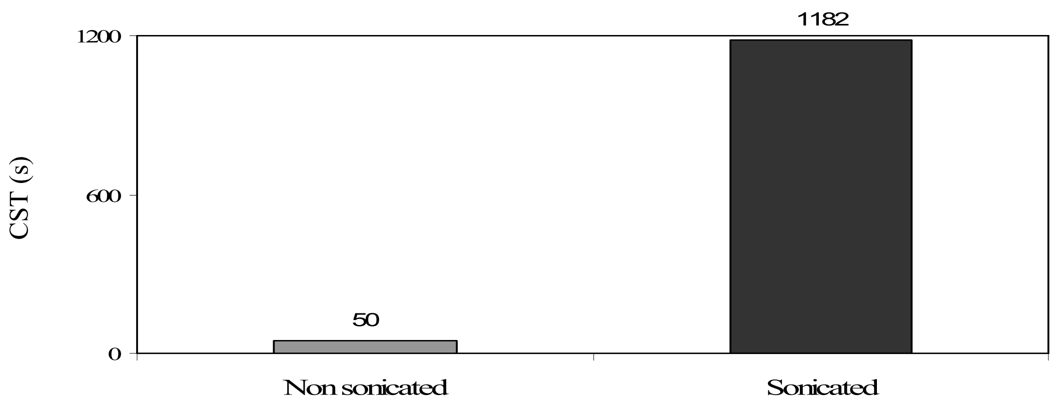


Figure 4.18 CST of sonicated sludge compared to non sonicated sludge

The CST of aerobic digested sludge of part stream and full stream reactor were increased compared to control reactor. Since ultrasonic breaks down sludge cell facilitating subsequence hydrolysis, particle size became smaller making it easy to clog the pore of CST filter paper.

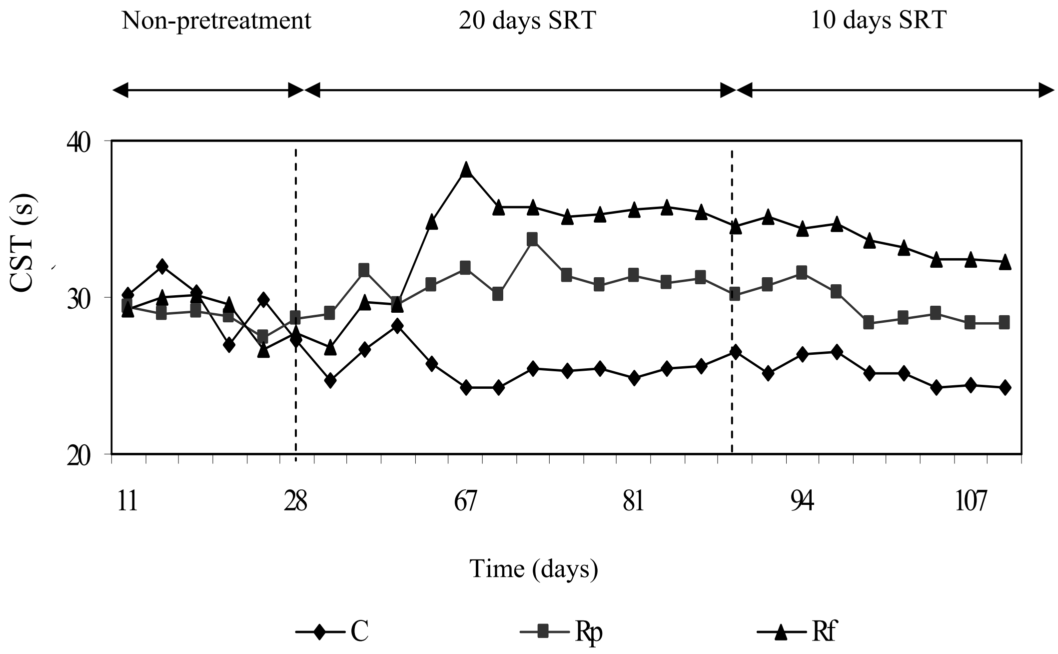


Figure 4.19 CST of aerobic digester at different SRT

As illustrated in Figure 4.19, the CST of part stream and full stream reactor were increased by 16% and 28% respectively at 20 days SRT. Similarly at 10 days SRT, the CST of part stream and full stream reactor were increased by 14 % and 24 % respectively. Full stream reactor showed higher CST than part stream reactor due to full stream feeding was better disintegration which facilitated to digestion making particle size become smaller. Researcher also found that digested sludge at a longer SRT created higher CST value. Because at the longer SRT contributed more hydrolysis.

4.2.6 pH

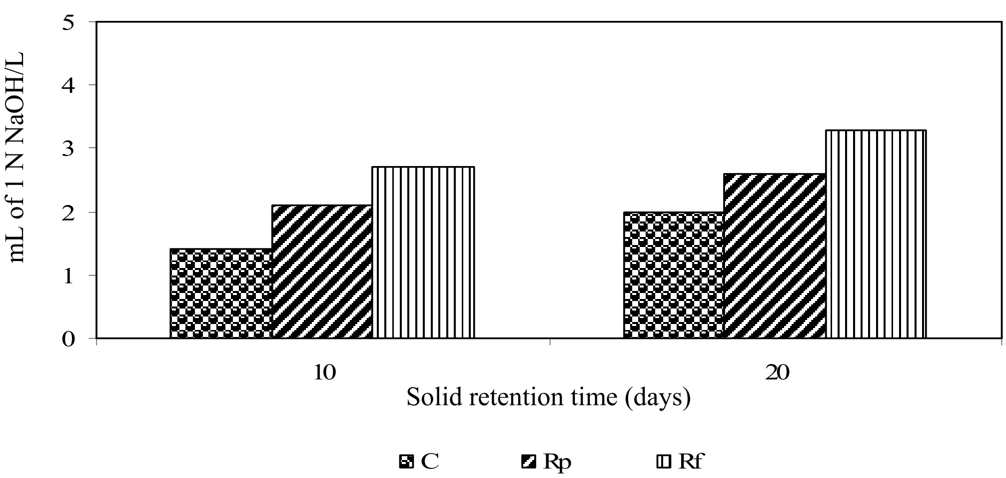


Figure 4.20 Alkali dosing requirement at each different SRT

Aerobic digestion is always plagued by drop in pH due to the ammonification reaction taking place. Then biomass consumes bicarbonate alkalinity. Therefore, all reactors were maintained at the neutral range of pH by adding 1N NaOH solution twice a day.

Figure 4.20 showed amount of NaOH solution needed to maintain a neutral pH (7$\pm$2) for full stream reactor and part stream reactor. This is indicating that sonicated sludge releases more ammonia than non sonicated sludge. Thus, full stream reactor was found to require double amount of NaOH solution for pH adjustment.

In summary, the full stream digester was present the best performance at 10-d SRT. Due to the highest rate removal of DOC and TS/VS, the lower SOUR level, the better dewaterability and higher rate of ammonification and nitrification compared to part stream and control. As determined by statistically test at the significant $p< 0.05$, the significant differences were found between variable of each parameter in this analysis. However the performance of part stream reactor was in the same range of full stream but lower a little bit as the significant differences by determination with statistically test. Thus, for the real applying, part stream digester is the best option for aerobic digester of WAS with ultrasonic pretreatment.

4.3 Effects of ultrasonic on biosolids quality

4.3.1 TKN level

Ultrasonic pretreatment affected the sludge by disintegrated cells and released more intracellular organic nitrogen into aqueous phase with facilitated for nitrification (Khanal et al., 2007), resulting in dropping of nitrogen in the form of TKN in biosolids. As presented in Figure 4.21, TKN level of part stream and full stream reactor were less than control reactor at both of 10-d and 20-d SRT. Thus, TKN can be useful indicator for organic nitrogen reduction measuring which effect from ultrasonic pretreatment. Moreover, it useful for indicate the quality of biosolids for applying as soil conditioner.

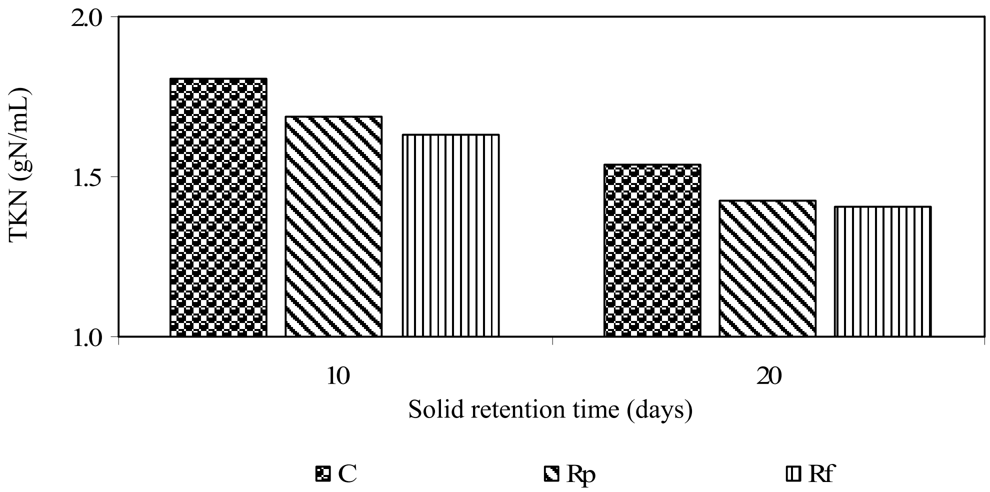


Figure 4.21 TKN level at different SRT

4.3.2 Phosphorus level

Ultrasound pretreatment did not provide the significant in term of changing in Phosphorus concentration of the sludge. As shown in Figure 4.22, the phosphorus level of part stream and full stream digester were in the same range after digestion at 10-d and 20-d SRT.

Phosphorus concentration is uptakes by active cell during aerobic digestion. At the 10-d SRT, sludge cell could uptake higher dose of phosphorus level compared to at 20-d SRT. Because at 10-d SRT was observed higher level of active cell as mention on the topic of SOUR above.

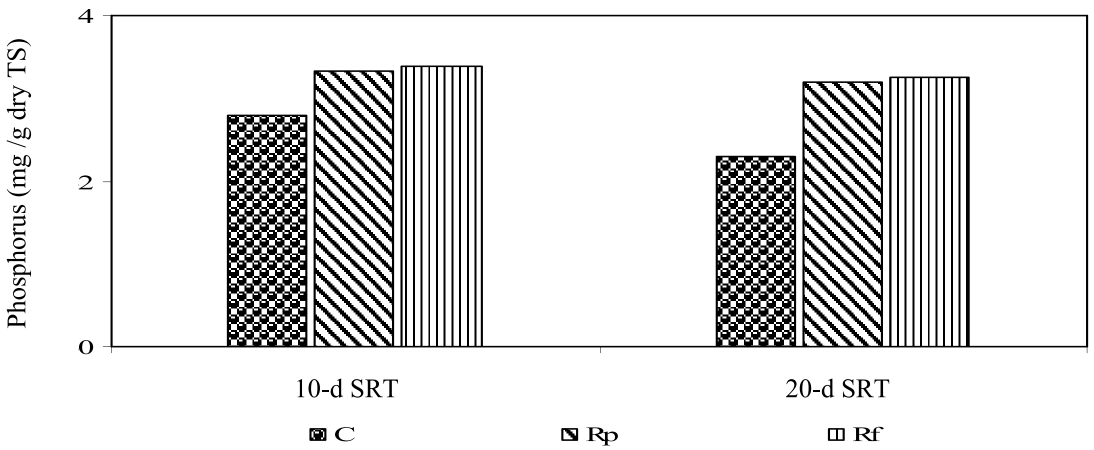


Figure 4.22 Phosphorus level at different SRT

4.3.3 Pathogen level in biosolids

The biosolids quality was investigated focusing on pathogen count. Major group of pathogens analyzed were fecal coliform, *E. coli and Salmonella sp.* These parameters are important when the biosolids are intended for land application. The pathogen level from the digester operating at an SRT 20 days are showed in the Table 4.3.

Table 4.3Pathogen level of each aerobic digester

Pathogen type	Pathogen level (by dry weight)		
	C	Rp	Rf
Fecal coliform (MPN/g TS)	$4x10^4$	$1.8x10^4$	$0.47x10^4$
E. coli (MPN/g TS)	$3.3x10^2$	$11x10^2$	$3.2x10^2$
Salmonella sp. (CPU/g TS)	< 100	< 100	< 100

All tested sludge from three of reactors had *Salmonella sp.* density below 100 CPU/g TS. Both part stream and full stream reactor were able to reduce the density of fecal coliform by 45% and 88% respectively compared to control reactor. This showed that digested sludge from the digester fed with sonicated sludge was more stable than biosolids from the control reactor. This table also showed the positive effect of ultrasonic pretreatment on fecal coliform reduction. However, *E. coli* level was not affected by ultrasound pretreatment since it level were in the same range for three of reactors. This showed that at power input 0.19 kW affected only for fecal coliform reduction not involved in reduction of *E. Coli.* However, some previous study was applied ultrasound wave at higher of specific energy input which could reduced the pathogen level in biosolids. Khanal et al. (2007) found that ultrasonic pretreatment could reduce the level of fecal coliform and *E. coli* as 42% and 70% respectively. Using ultrasonic power input of 1.5 kW, frequency of 20 kHz and TS content of 3%. The experiments were conducted at room temperature of $22 \pm 1^{o}C$ with 10-d of SRT.

Pathogen level at 10-d SRT was not investigate as ultrasound pretreatment did not showed any effect to pathogen reduction at 20 days SRT. Moreover, SOUR of 10-d SRT was higher than 20-d SRT. This is means that biosolids of 10-d SRT consists higher quantity of active cell which can be assumed as pathogenic organism as present in Figure 4.13.

Chapter 5

Conclusions and Recommendations

This study investigated the efficiency of ultrasound pretreatment on the aerobic digestion of waste activated sludge (WAS). This study was focused on optimized the sonication condition and investigate the efficiency of aerobic digester with ultrasonic pretreatment.

5.1 Conclusions

5.1.1 Horn optimization and sonication condition optimization.

- Large horn is the best horn of this study compared to small and medium horn since it can propagate the higher dose of ultrasound wave. Thus, it resulting in released the highest SCOD at 6480 mg/L. The sonication condition of specific energy input 30.4 kJ/kg TS and 480s were used. While the medium and small horn released SCOD at 6264mg/L and 5148 mg/L, respectively as the same condition.
- The sonication condition of this study was selected at sonication time of 150s, ultrasonic density of 1.9 W/mL and specific energy input of 9.5 kJ/kg TS. As this condition can provide high level of SCOD, which can observe the significant improving of aerobic digester.
- The characteristic of sonicated sludge easily to observe the differential by microscopic, when observed the different of the highest condition and the lowest condition.

5.1.2 Aerobic digestibility

- The efficiency of aerobic digester can improve by ultrasonic pretreatment. As the removal efficiency of DOC and TS/VS were significant increased when compared to control digester. Although, full stream reactor was showed the better performance but part stream reactor is the best choice for the real applying. Because the performance of part stream and full stream were in the same range but part stream reactor was used less energy.
- Ammonia and nitrate concentration were a regular measuring. Due to ammonification and nitrification were the predominates reaction for aerobic digester. Ultrasonic pretreatment can release more organic nitrogen with facilitated for ammonification subsequence nitrification. Thus nitrate concentration of part stream and full stream bioreactor found higher than control reactor.
- Adding 1 N NaOH solution needed more for aerobic digestion of waste activated sludge with ultrasonic pretreatment due to ultrasonic pretreatment enhanced ammonification. The full stream reactor request higher about 2 times.
- Ultrasonic pretreatment did not improved the dewaterability of WAS after digestion both at 10 days and 20 days SRT. However, at 10 day SRT biosolids has better dewaterability than 20 days SRT.
- At 10-d SRT all aerobic digesters were present the better performance than 20-d SRT. As the higher rate removal of DOC and TS/VS, more stable of digested sludge, and better dewaterability of sludge.
- Biosolids of reactor fed with sonicated sludge at 10-d SRT had higher level of TKN nitrogen than 20-d SRT. Whereas total phosphorus of reactor fed with sonicated sludge do not effect by SRT.

5.2 Recommendations for further study

Recommendations for further study are as follows:

- Cost-benefit analysis of ultrasonic pretreatment need to be conduct to justify the economics of the process in full-scale application
- Energy balance of aerobic digestion system can be investigated since energy consumption is the most important parameter for real field application.
- Thermophilic aerobic digester (TAD) is recommended. The experiments can be conducted in thermophilic temperature to see the effect of temperature in sludge disintegration and pathogen killed off (Mason et al., 1992).

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Appendix A: Experimental data

Table A-1 DOC of aerobic digester at different SRT

SRT	Date	C	Rp	Rf
Non sonication	0	64.07	67.29	63.68
	3	66.27	64.75	65.73
	14	62.69	65.23	63.10
	17	62.69	65.23	63.10
20-d SRT	23	61.74	85.82	93.16
	25	65.54	86.93	92.34
	26	64.89	86.05	95.15
	29	62.12	86.73	95.11
	36	62.04	85.27	93.48
	38	65.88	86.02	94.18
	45	66.58	85.41	93.39
	57	66.43	84.03	92.76
	60	67.16	84.62	92.90
	63	66.57	85.06	92.91
	65	66.69	86.30	92.95
	68	67.00	86.79	92.96
	71	67.03	87.81	92.99
	74	67.62	88.45	92.97
	75	66.62	88.60	93.00
	77	67.69	88.95	93.00
	78	68.33	89.42	93.04
	74	69.96	89.33	93.03
	75	69.93	89.50	93.02
	77	70.04	89.64	93.04
	78	72.27	90.46	93.06
	80	72.14	90.62	93.11
	82	71.99	90.75	93.07
	86	72.44	90.69	93.11
10-d SRT	89	70.77	90.34	93.16
	91	70.47	90.44	93.07
	93	69.28	89.66	93.01
	96	67.53	89.67	92.99
	98	67.46	90.44	92.97
	102	67.16	90.36	92.99
	104	65.18	89.67	92.99
	106	65.62	90.44	92.97
	108	65.78	90.36	92.99

Table A-2 TS/VS of aerobic digester at different SRT

SRT	Time (day)	TS removal (%)			VS removal (%)		
		C	Rp	Rf	C	Rp	Rf
Non sonication	3	11	9	10	20	19	21
	6	11	9	9	21	19	20
	8	11	9	10	21	19	21
	12	10	10	10	20	20	21
	16	10	10	10	20	20	20
	20	9	9	10	20	20	20
20-d SRT	23	10	9	9	20	19	21
	26	10	10	10	20	20	19
	27	10	11	10	19	19	20
	28	11	10	11	19	20	21
	29	11	11	12	20	20	21
	31	11	12	13	20	21	21
	34	10	12	13	20	21	21
	36	9	12	13	19	21	22
	38	9	12	14	19	20	22
	42	9	12	13	19	20	22
	45	10	12	14	19	21	22
	58	10	11	13	20	21	23
	62	9	11	14	19	21	23
	63	10	13	15	20	21	23
	64	11	13	15	20	21	23
	66	11	13	14	20	21	23
	68	11	13	14	20	21	22
	70	11	15	16	19	22	23
	72	12	17	18	19	24	24
	73	12	18	20	19	24	25
	76	12	17	18	19	24	25
	79	11	17	18	18	24	25
	82	12	17	19	19	24	25
	86	12	17	18	19	24	25
10-d SRT	88	13	16	18	19	22	25
	89	12	16	18	17	20	24
	91	12	16	16	16	21	25
	93	11	15	16	16	21	23
	93	11	15	15	15	20	22
	95	10	14	14	15	19	20
	97	9	14	13	13	19	20
	99	8	13	13	12	18	19
	102	6	12	12	11	17	18
	103	6	11	12	10	16	17
	108	6	11	12	11	17	18
	113	6	11	12	11	16	17
	115	6	11	12	11	16	18
	117	6	11	12	11	16	17

Table A-3 SOUR of aerobic digester at different SRT

SRT	Time (day)	SOUR		
		C	Rp	Rf
Non sonication	7	9.542	8.824	9.266
	15	7.807	8.824	8.340
	23	8.115	9.153	7.273
20-d	25	7.453	9.875	7.624
	47	7.826	5.255	3.144
	68	7.826	5.255	3.144
	73	8.696	6.131	3.144
	79	7.826	7.007	3.930
	82	7.826	5.255	3.144
	84	7.826	7.007	3.930
	87	7.826	5.255	3.144
10-d SRT	94	8.637	7.457	5.897
	99	8.331	7.216	5.281
	104	8.872	7.679	5.289
	109	9.231	7.624	5.870
	114	9.405	7.644	5.897
	116	9.134	7.941	5.567

Table A-4 Ammonic and nitrate concentration of aerobic digester at different SRT

SRT	Date	Ammonia concentration (mg/L)			Nitrate concentration (mg/L)		
		C	Rp	Rf	C	Rp	Rf
Non sonicated	17	8	6	6	376	367	371
	21	8	6	6	369	378	365
	24	8	7	7	377	364	374
20-d SRT	28	10	7	6	364	363	392
	31	8	6	7	391	443	455
	34	8	7	6	378	446	453
	37	10	8	6	392	442	454
	40	11	8	7	370	442	467
	43	11	10	7	380	446	459
	58	11	8	7	377	542	579
	59	8	8	6	379	508	594
	61	11	8	6	368	536	589
	64	11	8	7	369	634	684
	67	11	10	7	376	657	687
	68	11	8	7	358	647	692
	69	10	10	7	365	669	722
	70	11	8	7	353	702	774
	73	10	8	7	343	765	793
	74	11	10	7	356	765	795
	75	10	8	6	357	769	801
	79	11	10	6	352	762	796
	81	11	10	6	357	766	789
	83	11	10	6	347	766	799
	86	10	10	4	366	769	801
10-d SRT	88	10	8	4	364	757	809
	89	10	8	4	421	793	863
	91	10	7	4	588	820	877
	92	8	6	3	601	846	878
	94	8	6	3	613	867	923
	96	10	6	4	620	866	921
	98	10	6	3	619	861	919
	100	8	4	3	620	867	915
	102	8	4	3	620	865	912
	104	8	4	3	619	868	915
	106	8	4	3	619	870	912

Table A-5 CST of aerobic digester at different SRT

Time (day)	CST of digested sludge (s)		
	C	Rp	Rf
11	30	29	29
14	32	29	30
18	30	29	30
25	27	29	30
27	30	27	27
28	27	29	28
29	25	29	27
35	27	32	30
49	28	30	30
66	26	31	35
67	24	32	38
68	24	30	36
69	25	34	36
75	25	31	35
79	26	31	35
81	25	31	36
85	25	31	36
88	26	31	36
90	26	30	34
92	25	31	35
94	26	32	34
97	26	30	34
99	25	28	33
101	25	28	33
103	24	28	32
107	24	28	32
108	24	28	32
110	24	28	32
112	24	28	32
114	24	28	32

Table A-6 TKN in biosolids of aerobic digester at different SRT

SRTs	TKN (g N/L)		
	C	Rp	Rf
10	1.8$\pm$0.01	1.7$\pm$0.01	1.6$\pm$0.01
20	1.5$\pm$0.01	1.4$\pm$0.01	1.4$\pm$0.01

Table A-7 Total phosphorus in biosolids of aerobic digester at different SRT

SRT	Phosphorus (mg P/g dry TS)		
	C	Rp	Rf
10 days SRT	32.3 $\pm$1.3	33.2 $\pm$0.2	33.3 $\pm$0.5
20 days SRT	32.8 $\pm$0.1	33.3 $\pm$1.7	33.4 $\pm$0.8

Appendix B: Statistic analysis

Oneway

ANOVA

Parameter		Sum of Squares	df	Mean Square	F	Sig.
TS 20-d SRT	Between Groups	149.333	2	74.667	216.774	.000
	Within Groups	5.167	15	.344		
	Total	154.500	17			
VS 20-d SRT	Between Groups	126.778	2	63.389	570.500	.000
	Within Groups	1.667	15	.111		
	Total	128.444	17			
NH_3 20-d SRT	Between Groups	86.893	2	43.447	79.800	.000
	Within Groups	8.167	15	.544		
	Total	95.060	17			
NO_3 20-d SRT	Between Groups	727589.8	2	363794.889	16120.90	.000
	Within Groups	338.500	15	22.567		
	Total	727928.3	17			

Parameter		Sum of Squares	df	Mean Square	F	Sig.
TS 10-d SRT	Between Groups	126.778	2	63.389	1141.000	.000
	Within Groups	.833	15	.056		
	Total	127.611	17			
VS 10-d SRT	Between Groups	152.111	2	76.056	311.136	.000
	Within Groups	3.667	15	.244		
	Total	155.778	17			
NH_3 10-d SRT	Between Groups	108.671	2	54.336	118.810	.000
	Within Groups	6.860	15	.457		
	Total	115.531	17			
NO_3 10-d SRT	Between Groups	301800.4	2	150900.218	21134.66	.000
	Within Groups	107.099	15	7.140		
	Total	301907.5	17			
SOUR 20-d SRT	Between Groups	80.608	2	40.304	91.208	.000
	Within Groups	6.628	15	.442		
	Total	87.236	17			
SOUR 10-d SRT	Between Groups	33.082	2	16.541	161.058	.000
	Within Groups	1.541	15	.103		
	Total	34.623	17			
CST 20-d SRT	Between Groups	324.333	2	162.167	239.262	.000
	Within Groups	10.167	15	.678		
	Total	334.500	17			
CST 10-d SRT	Between Groups	197.721	2	98.861	3212.076	.000
	Within Groups	.462	15	.031		
	Total	198.183	17			

ANOVA

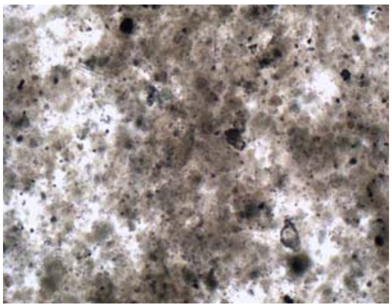
DOC 10-d SRT	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2547.023	2	1273.512	3101.780	.000
Within Groups	6.159	15	.411		
Total	2553.182	17			

ANOVA

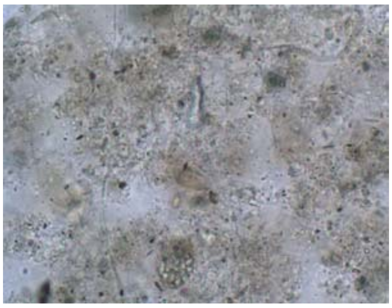
DOC 20-d SRT	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1656.214	2	828.107	1500.502	.000
Within Groups	8.278	15	.552		
Total	1664.492	17			

Appendix C: Observation of sludge disintegration at different condition

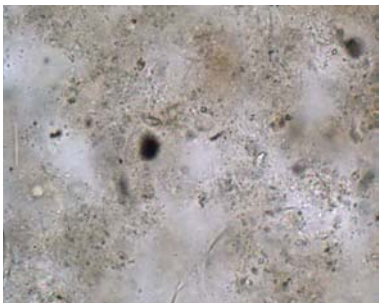
Characteristic of sonicated sludge at each sonication duration of small horn at power input 190 W and 3% TS.(x40)



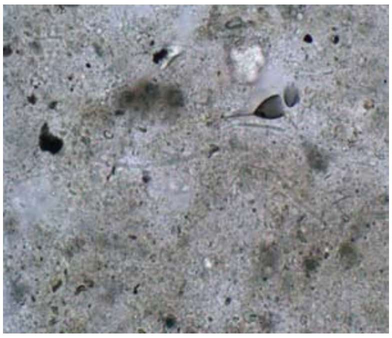
Control



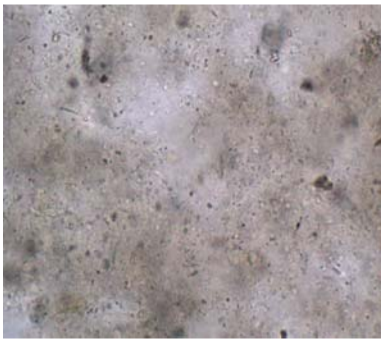
30 s



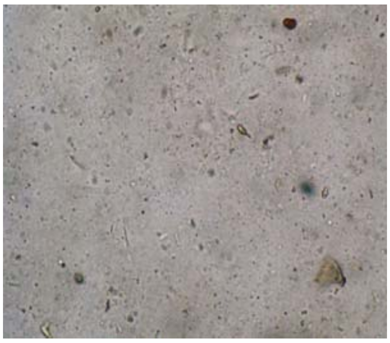
60 s



120 s

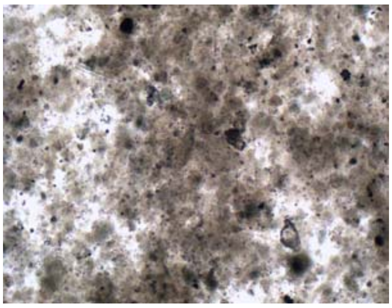


240 s

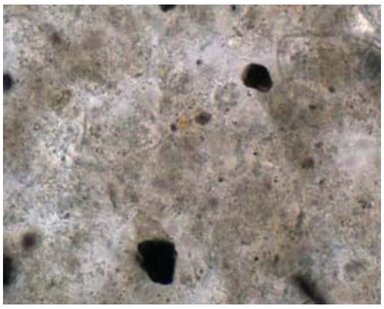


480 s

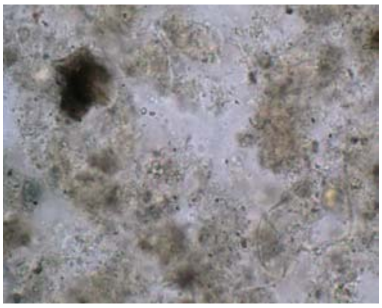
Characteristic of sonicated sludge at each sonication duration of medium horn at power input 190 W and 3% TS. (x40)



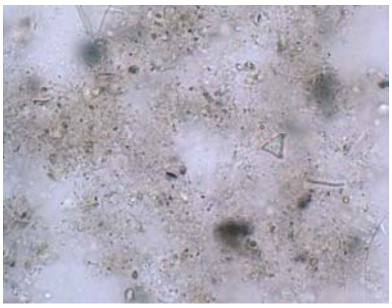
Control



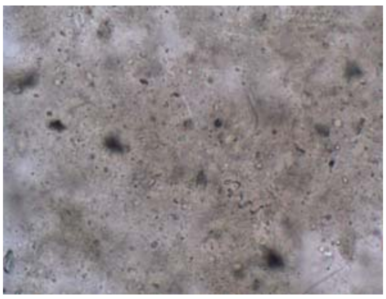
30 s



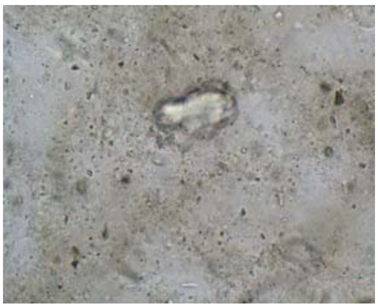
60 s



120 s

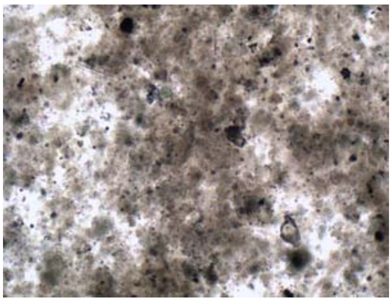


240 s

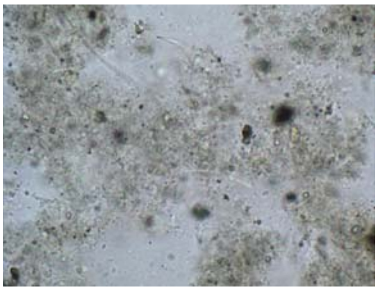


480 s

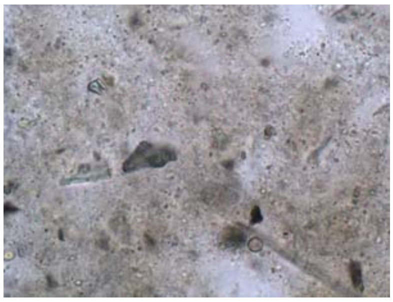
Characteristic of sonicated sludge at each sonication duration of large horn at power input 190 W and 3% TS. (x40)



Control

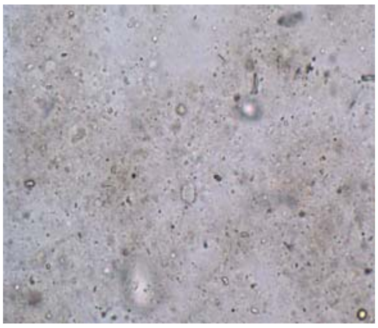


30 s



60 s

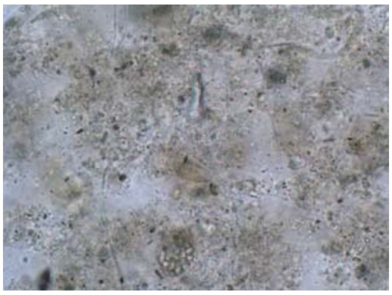
120 s



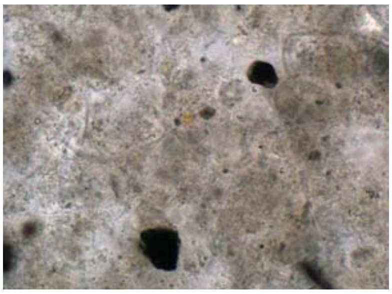
240 s

480s

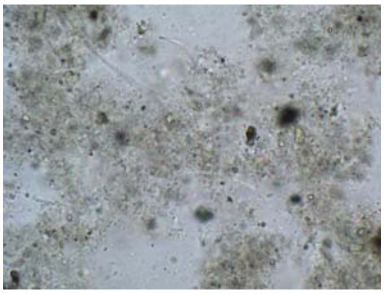
Characteristic of sonicated sludge at each horn at power input 190 W, 30 s and 3% TS. (x40)



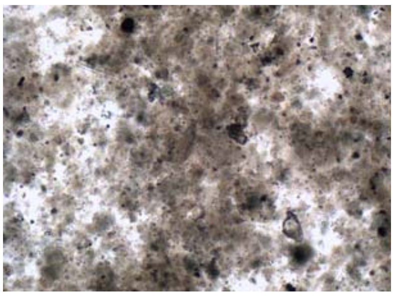
Small horn



Medium horn

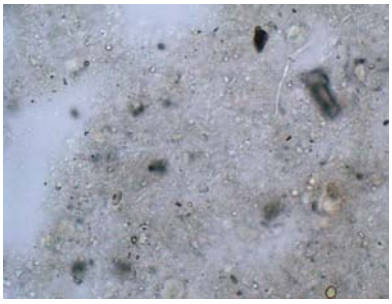


Large horn

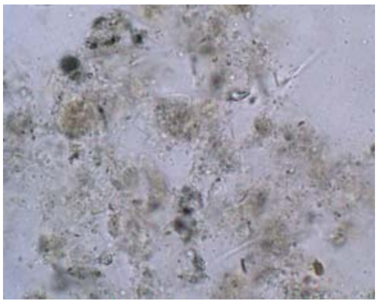


Control

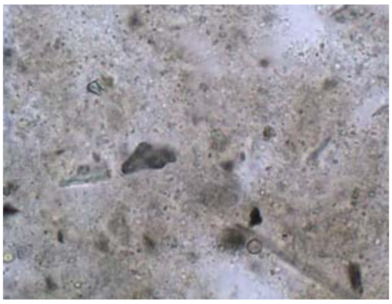
Characteristic of sonicated sludge at each horn at power input 190 W, 60 s and 3% TS. (x40)



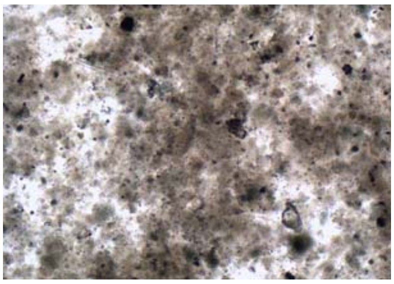
Small horn



Medium horn

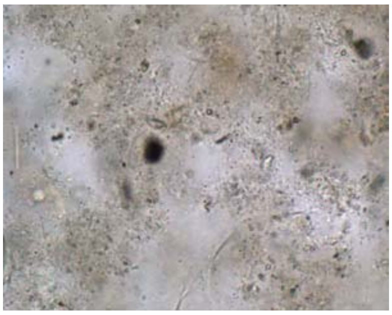


Large horn

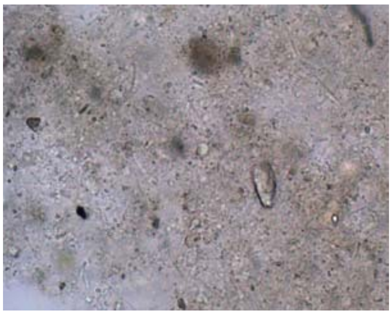


Control

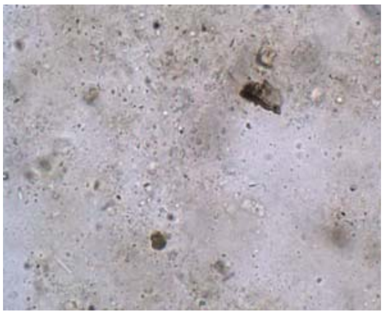
Characteristic of sonicated sludge at each horn at power input 190 W, 120 s and 3% TS. (x40)



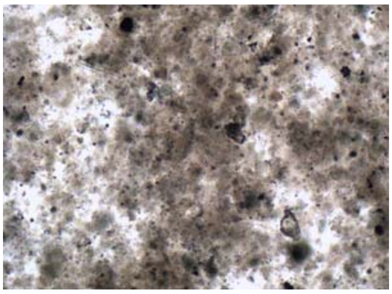
Small horn



Medium horn

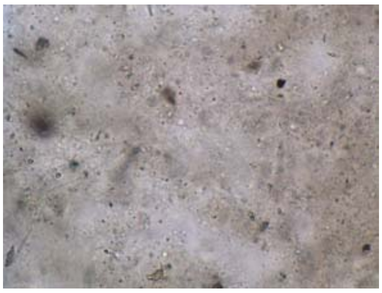


Large horn

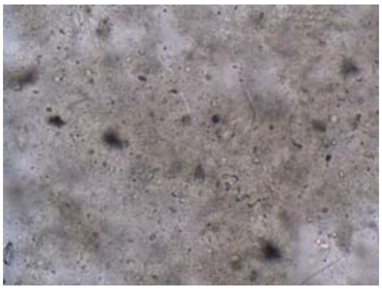


Control

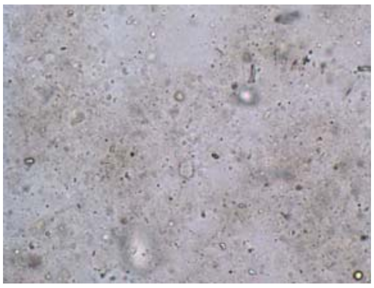
Characteristic of sonicated sludge at each horn at power input 190 W, 240 s and 3% TS. (x40)



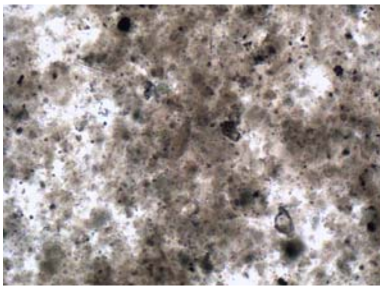
Small horn



Medium horn

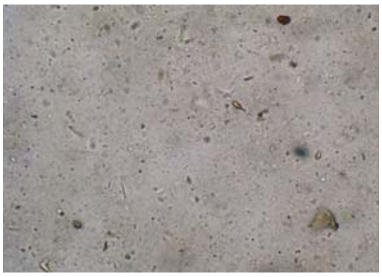


Large horn



Control

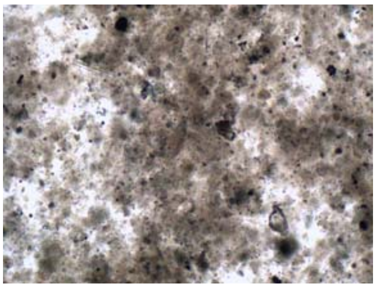
Characteristic of sonicated sludge at each horn at power input 190 W, 480 s and 3% TS. (x40)



Small horn

Medium horn

Large horn

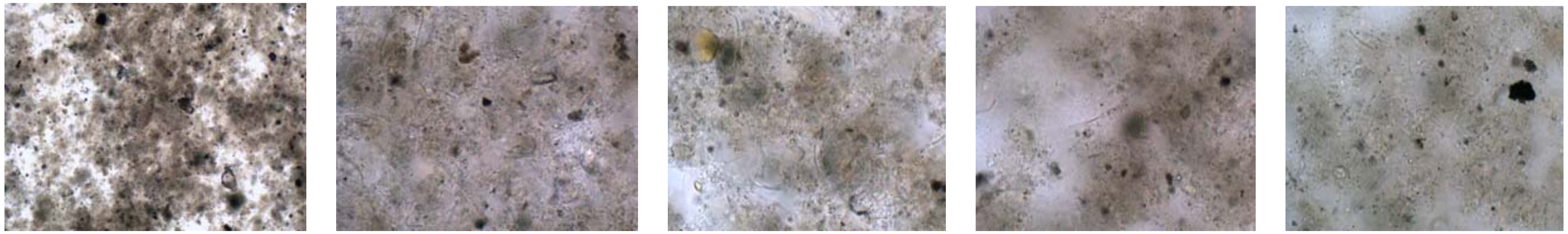


Control

Characteristic of sonicated sludge with large horn at each power input, 30 s and 3% TS. (x40)

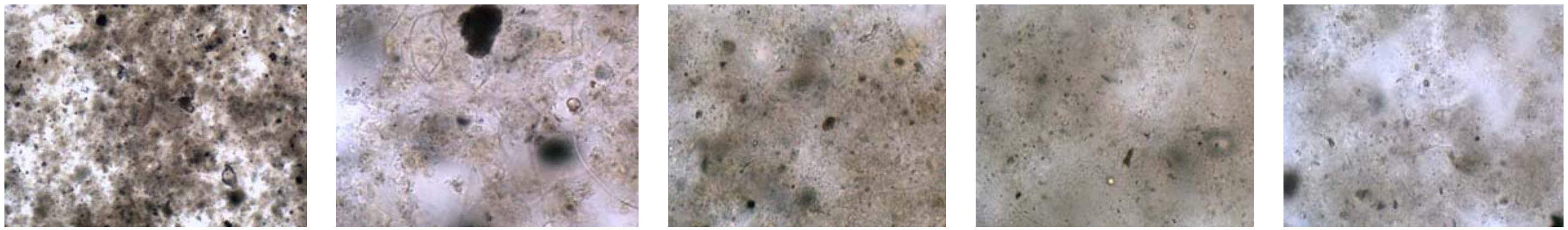
Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each power input, 60 s and 3% TS. (x40)



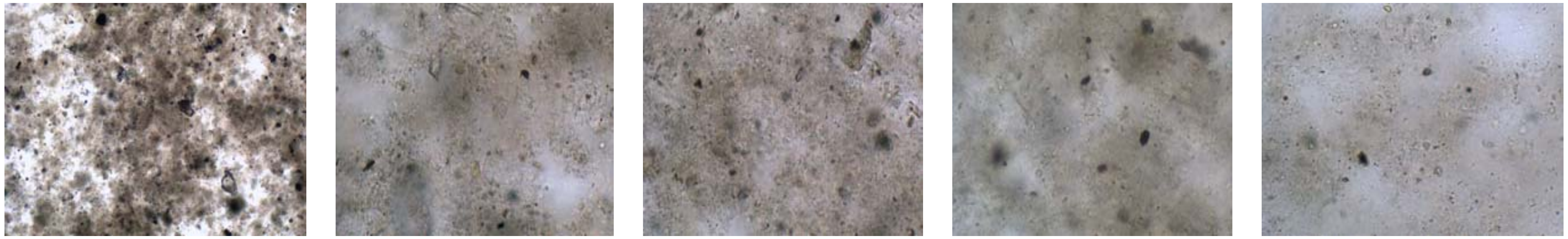
Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each power input, 120 s and 3% TS. (x40)



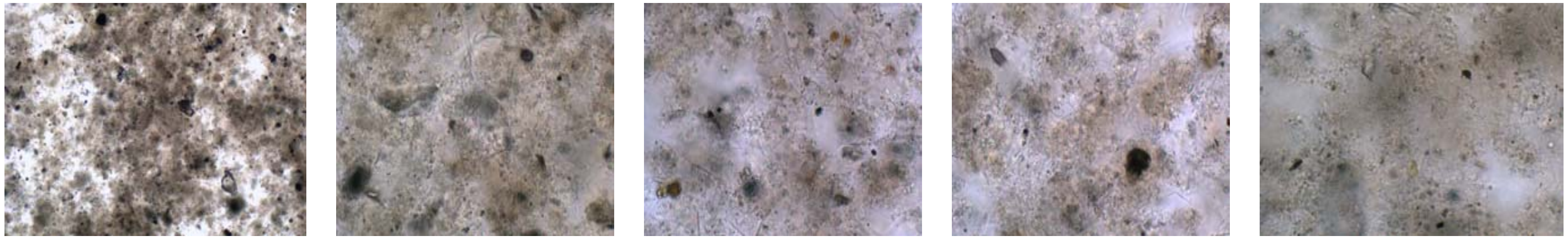
Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each power input, 240 s and 3% TS. (x40)



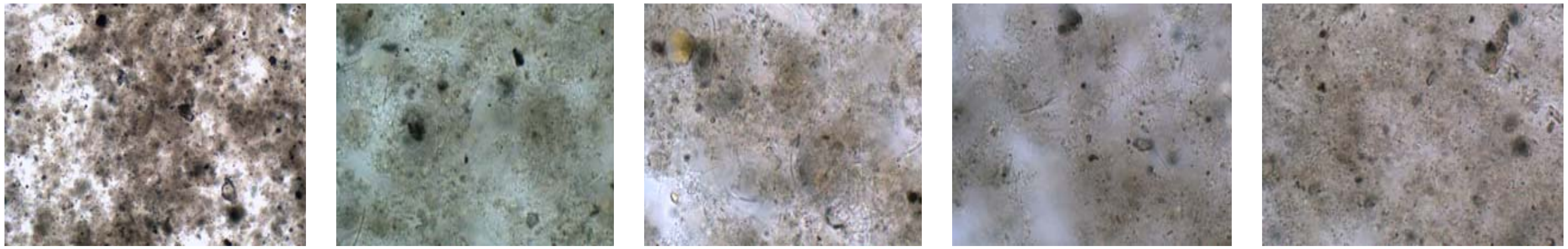
Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each duration, power input 50W and 3% TS. (x40)



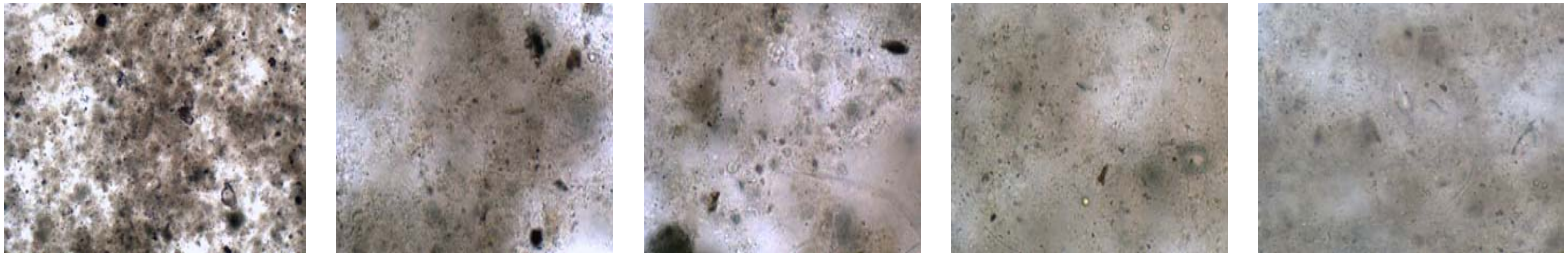
Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each duration, power input 100W and 3% TS. (x40)



Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each duration, power input 150W and 3% TS. (x40)



Control 50W 100W 150W 190W

Characteristic of sonicated sludge with large horn at each duration, power input 190W and 3% TS. (x40)

Control 50W 100W 150W 190W

Aerobic Digestion of Waste Activated Sludge with Ultrasonic Pretreatment

by

Monruedee Moonkhum

Examination Committee:

Prof. C. Visvanathan (Chairman)
Dr.Thammarat Koottatep
Dr. Animesh Dutta
Dr. Samir Kumar Khanal

Contents

Activated Sludge Process

Domestic wastewater

EQ tank

Aeration

Sedimentation

Return sludge

Excess sludge

Problem Statement

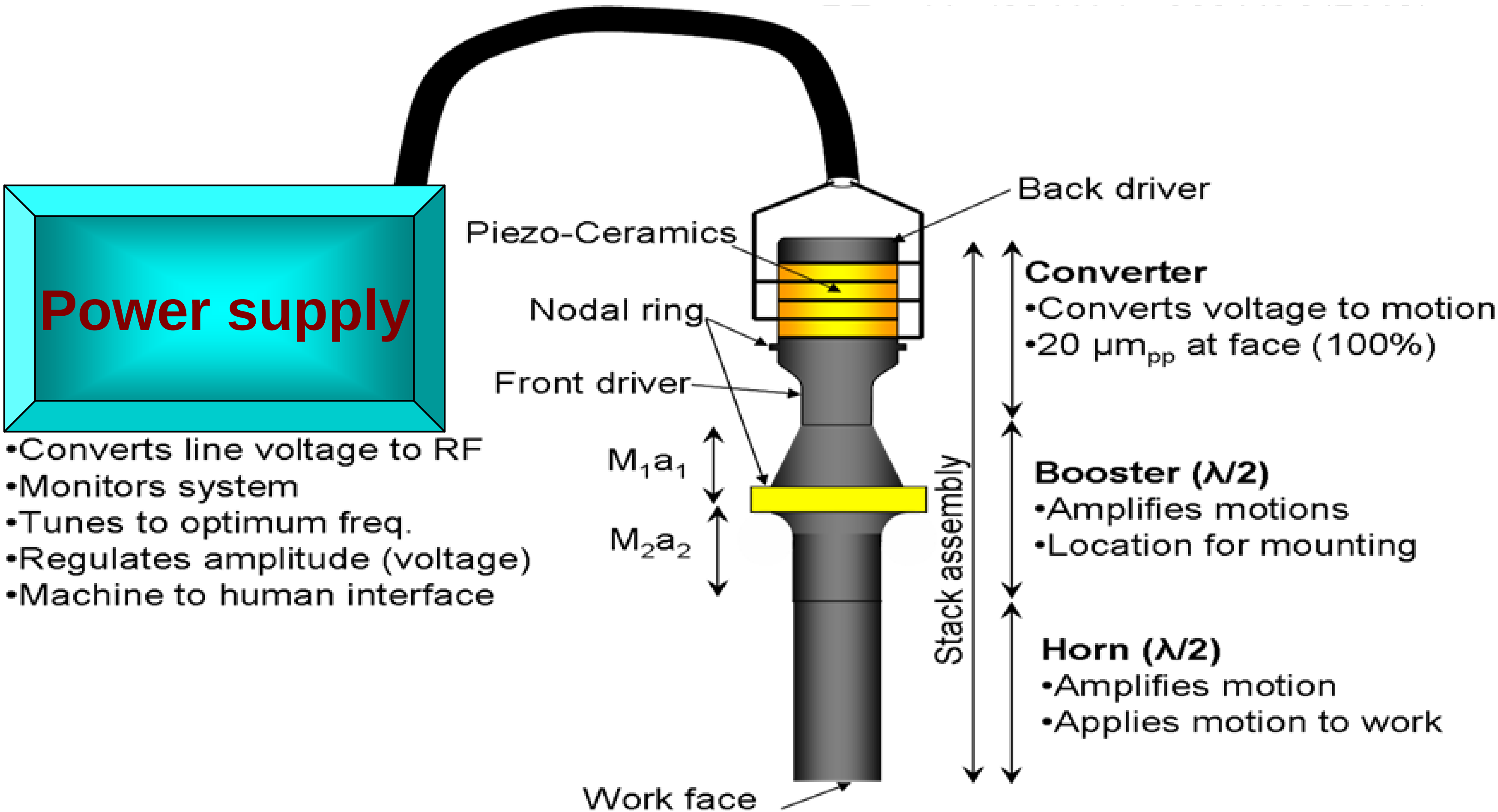
Sludge pretreatment

1. Mechanical: Ultrasound, Homogenizer, stirred ball mills
2. Thermal: Thermal hydrolysis (autoclave or steam heating)
3. Chemical: Use of enzymes or ozone
   Alkaline/Acid hydrolysis
4. Biological: Thermophilic condition

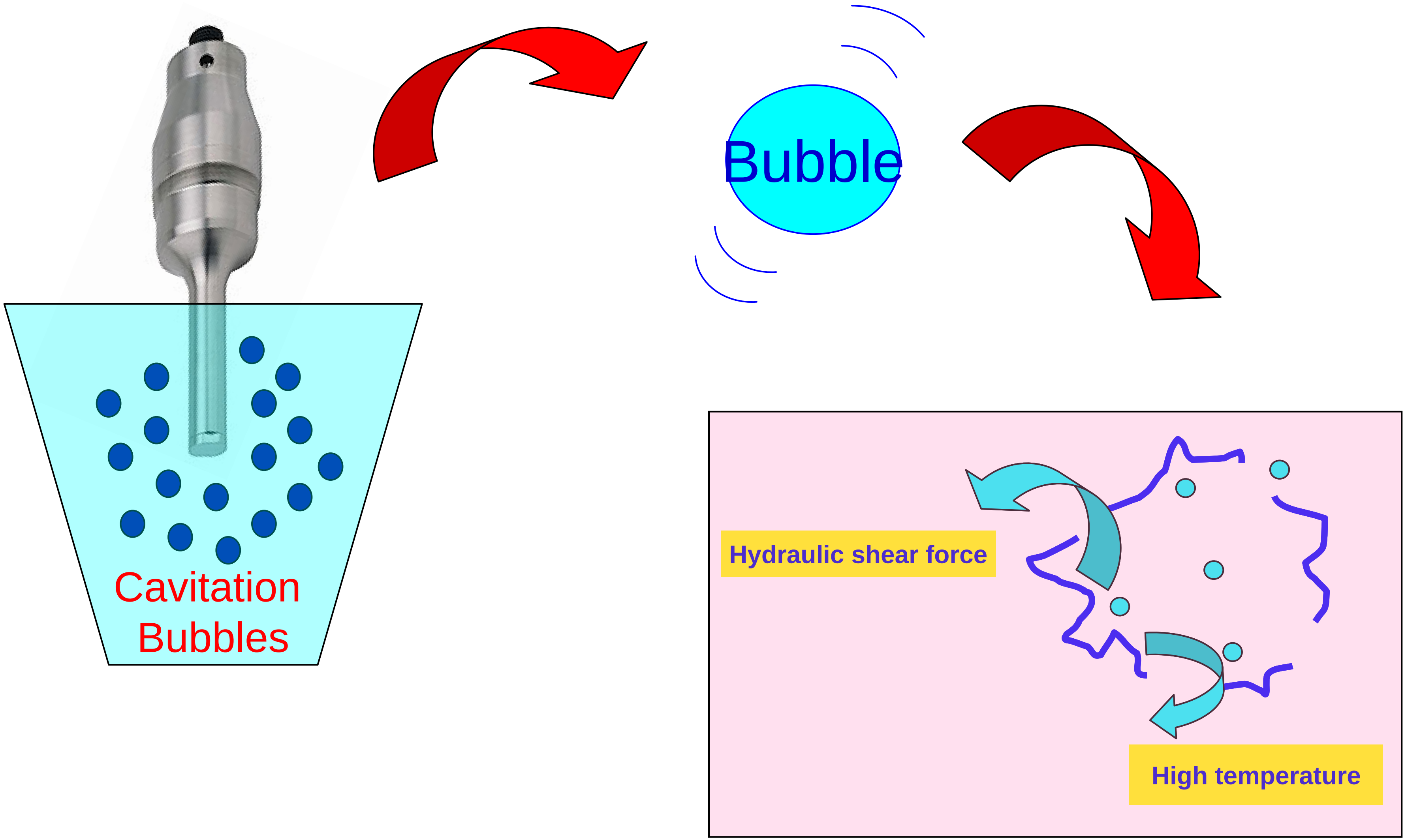
Advantages of Ultrasonic

- Non generate of secondary toxic compounds
- Compact design
- No chemical adding
- Can break down recalcitrant compound

Configuration of Ultrasonic

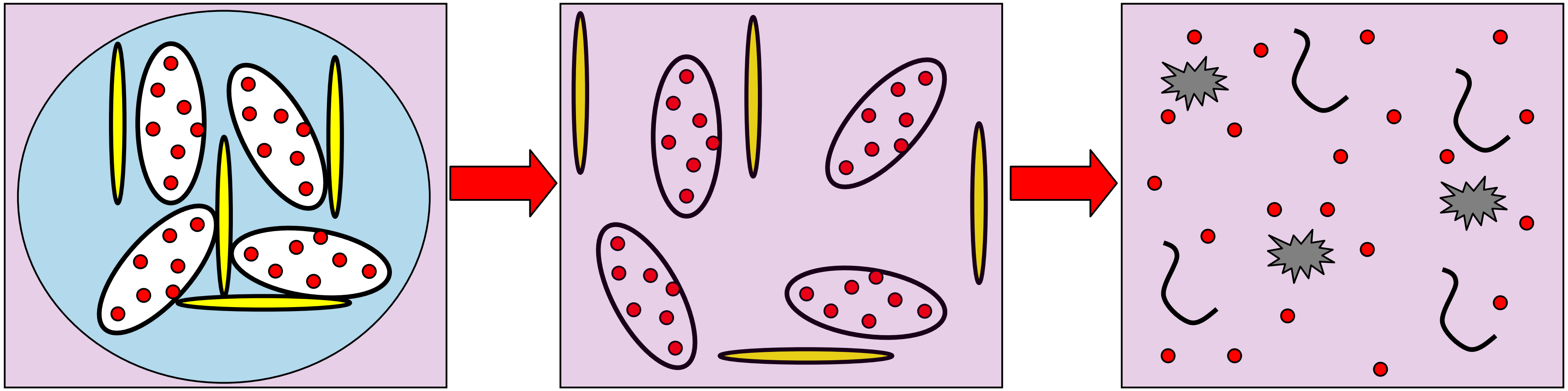


Mechanism of Ultrasonic Pretreatment



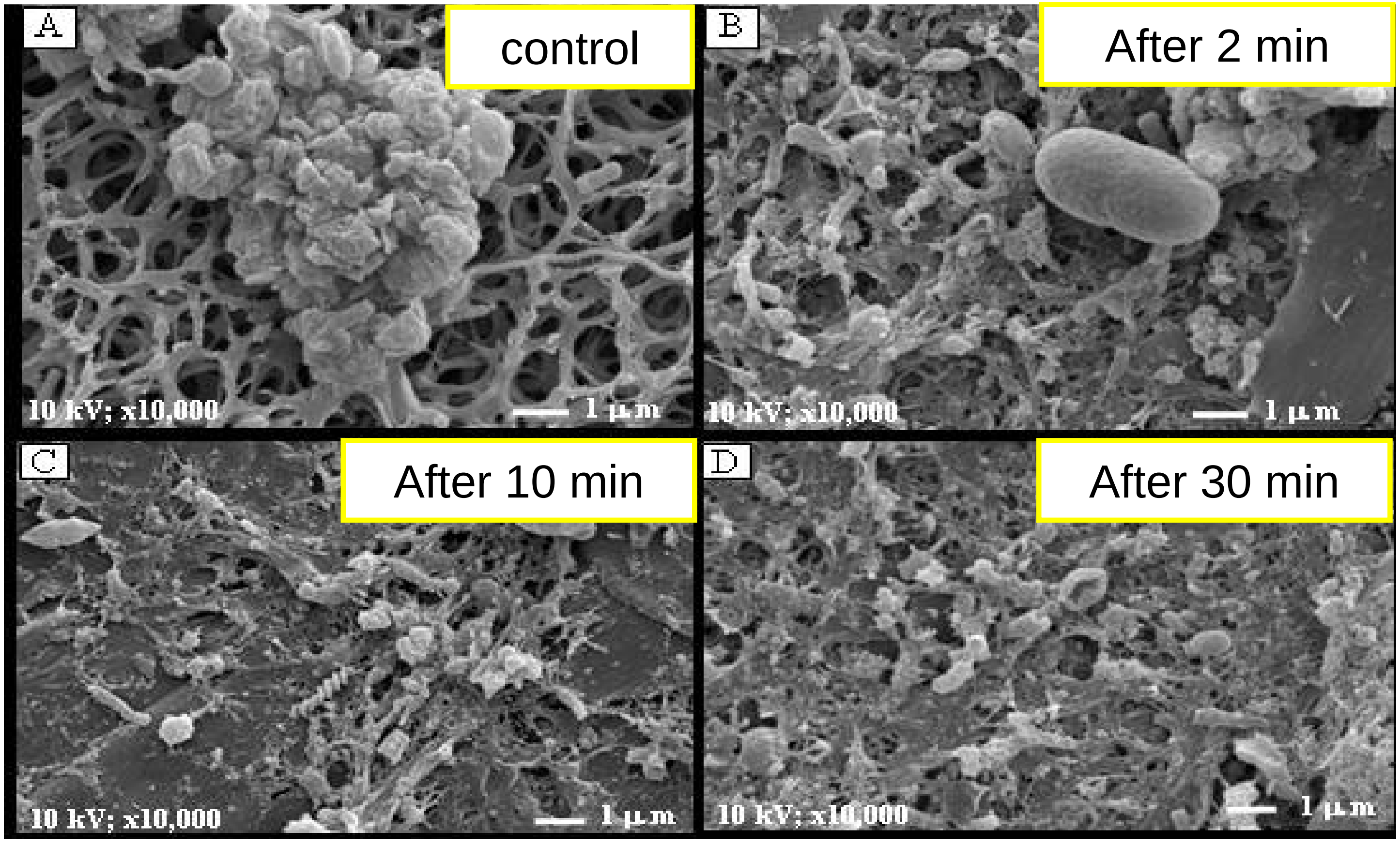
Phenomenon of Cavitations

- Hydro mechanical shear force
- Sonochemical reactions
  - Generation of hydroxyl radical



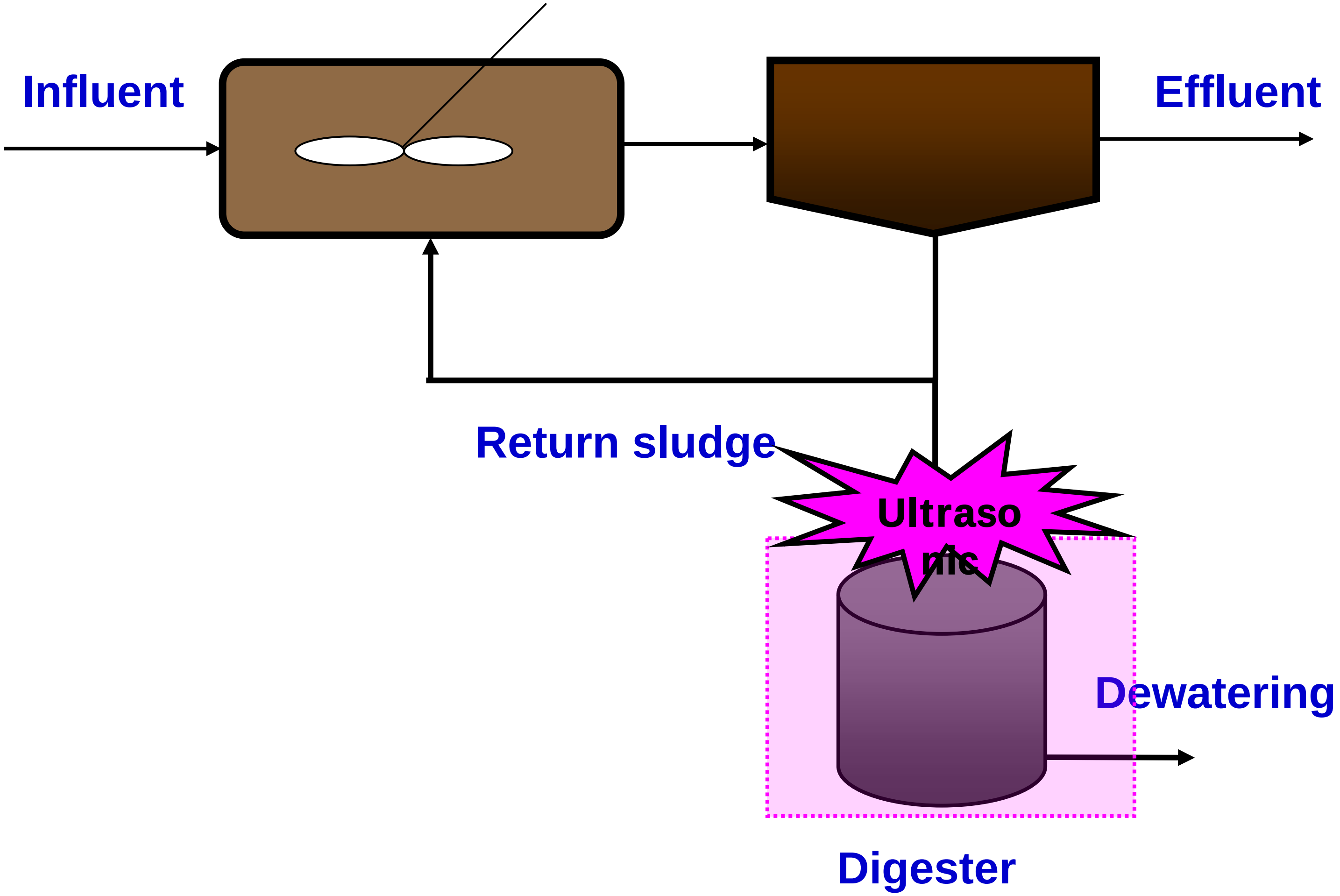
Sludge floc **Floc disintegration** **Floc broken down & release intracellular substance**

Ultrasonic Disintegration SEM Observation

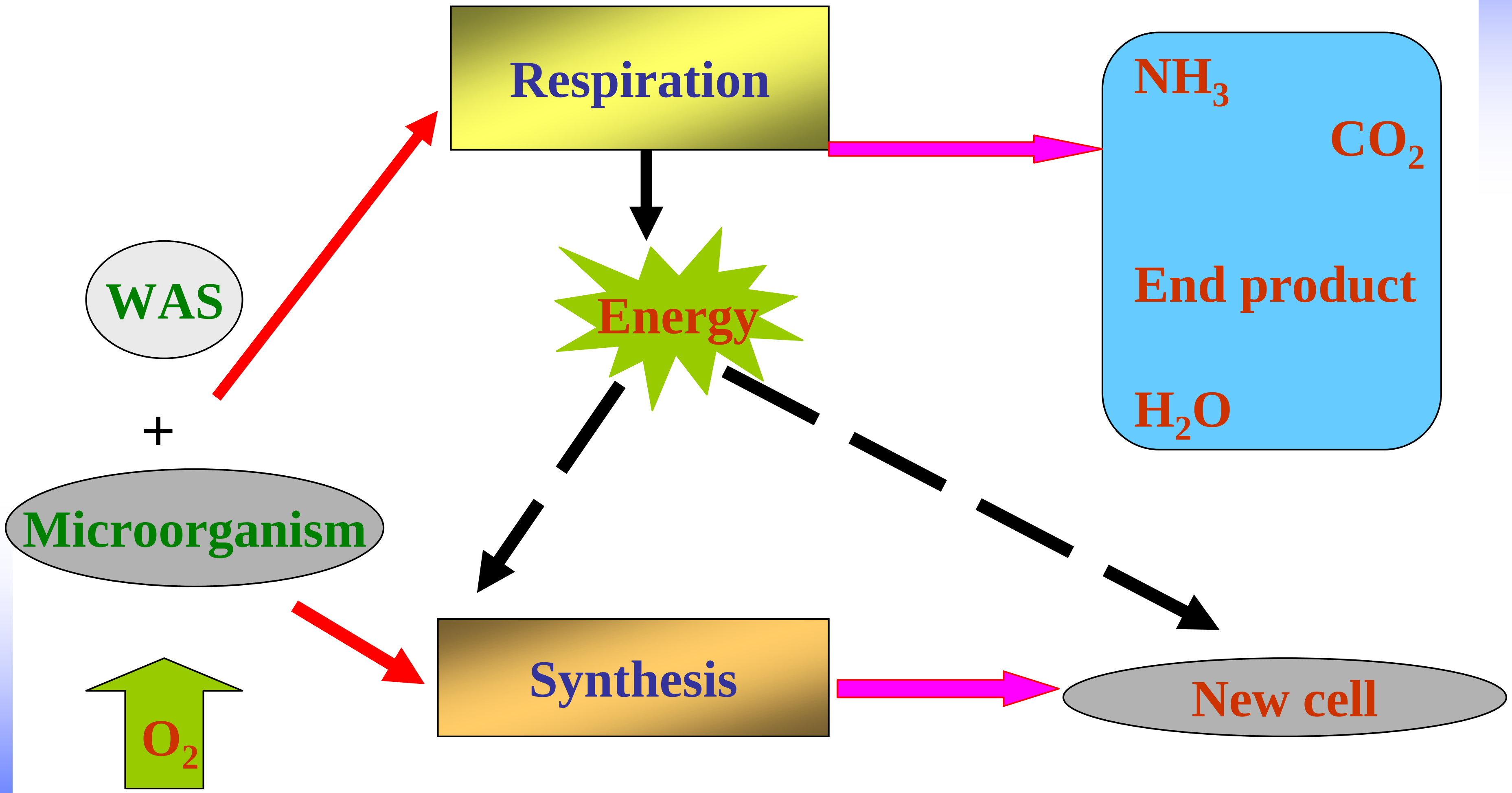


(Khanal et al, 2007)

Aerobic Digestion of WAS



Aerobic Pathway



Objectives

- **1. To optimize sonication conditions with maximize WAS disintegration.**
- **2. To examine the aerobic digestibility at different solids retention time of 10 days and 20 days.**
- **3. To evaluate the quality of digested sludge with ultrasonic pretreatment.**

Scopes of the Study

- Evaluate the efficiency of sludge disintegration

SCOD
Microscopic examination

- Evaluate the efficiency of aerobic digestion

DOC, VS,TS, SOUR
NH_3,NO_3
CST

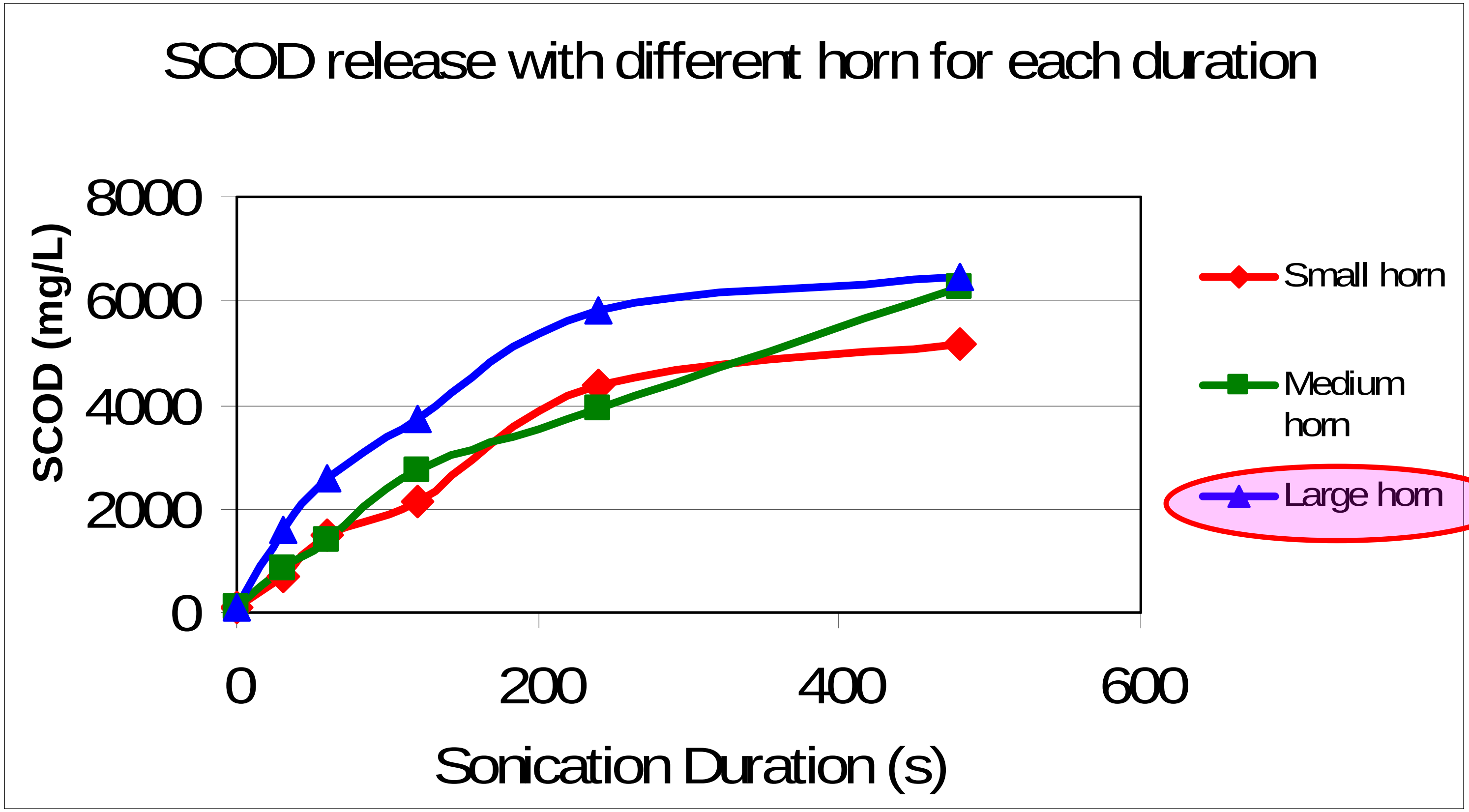
- Evaluate the quality of biosolids

TKN
Total phosphorus
Pathogen count

Sonication optimization

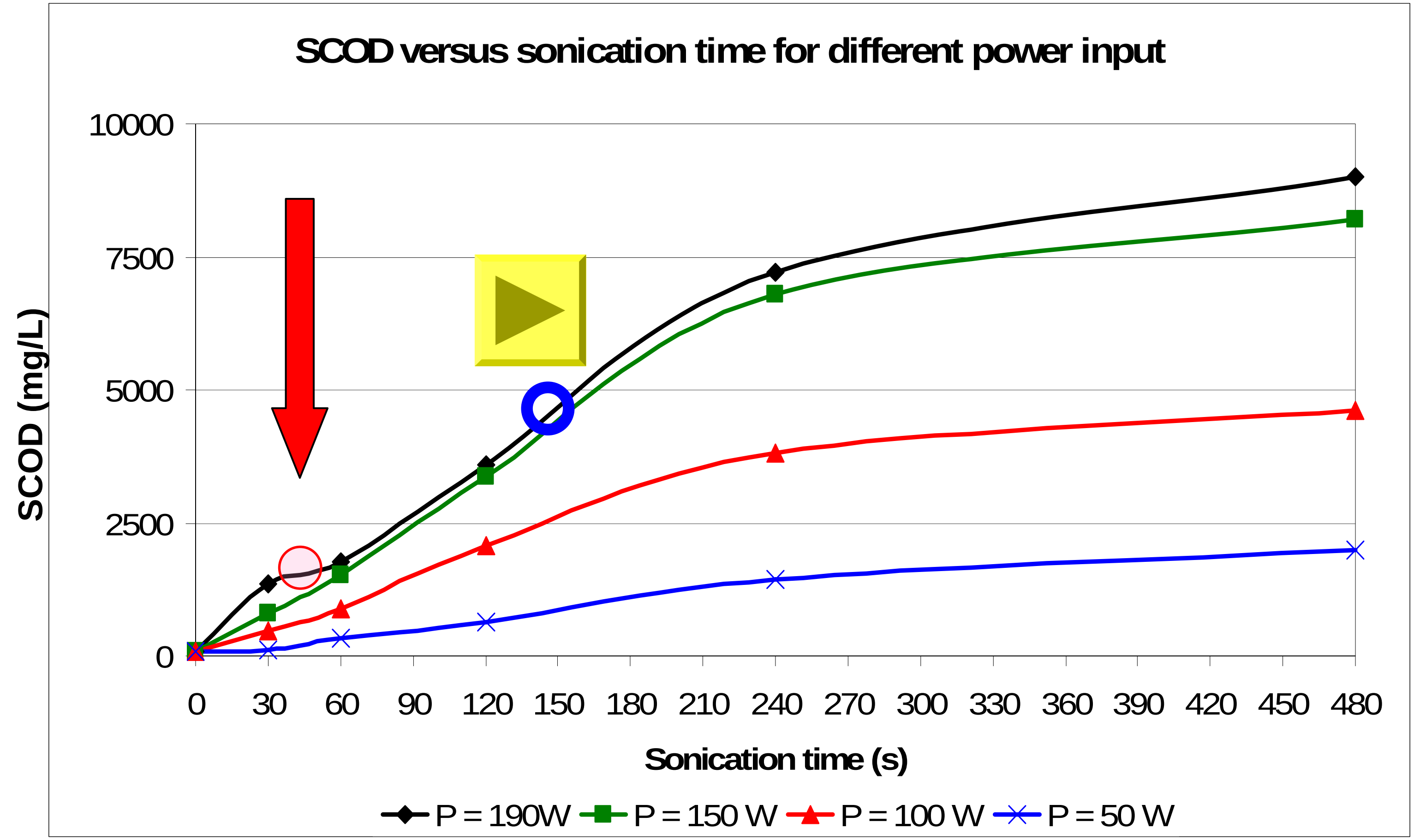
- WAS at 3% TS was sonicated at 190W with
  - Small, medium, large horn
  - Different duration of 30s, 60s, 120s, 240s and 480s
- Each conditions were determine the efficiency
- by SCOD and microscopic examination

Horn optimization



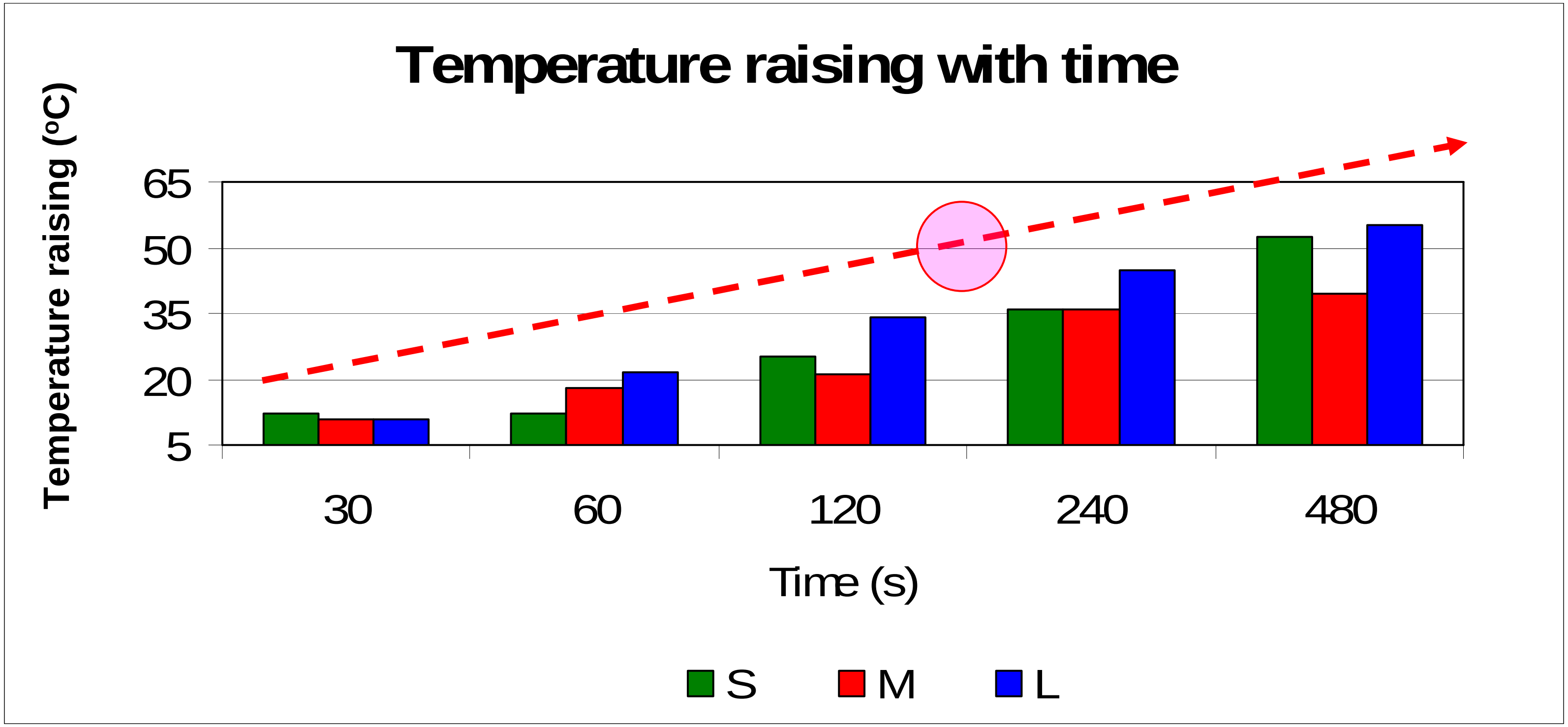
Large can release highest SCOD.

Power Input



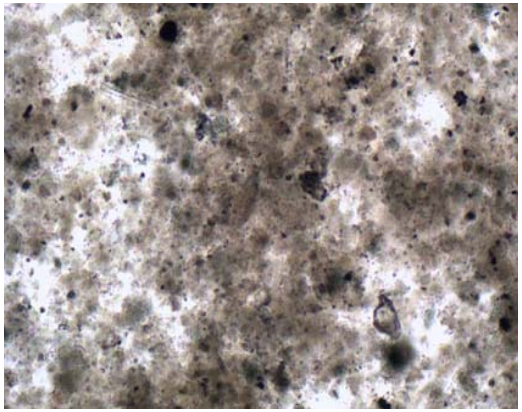
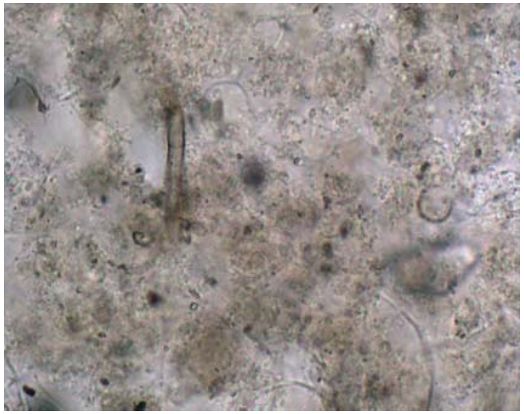
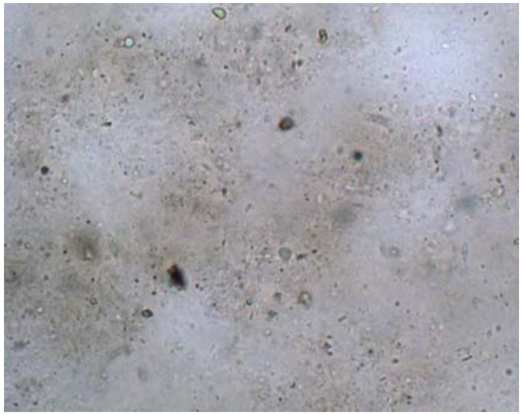
Power input 190 W at sonication time of 150s with the large horn was selected

Temperature Raising

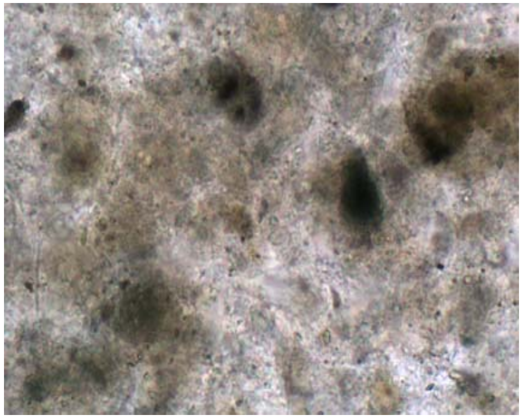
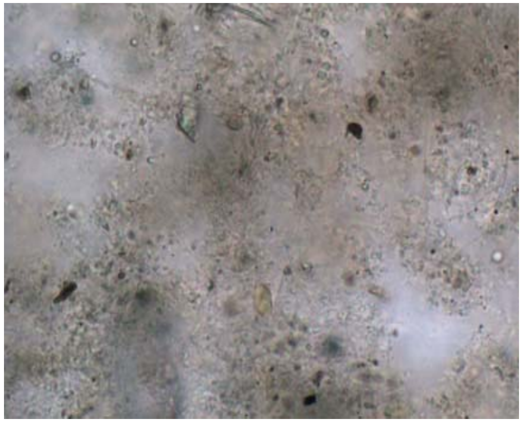
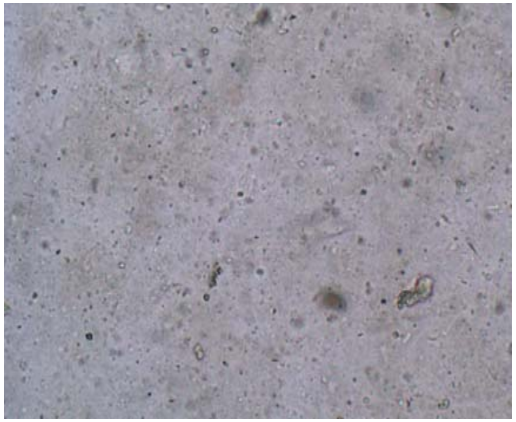


Temperature raising with sonication duration and horn size

Microscropic Observation

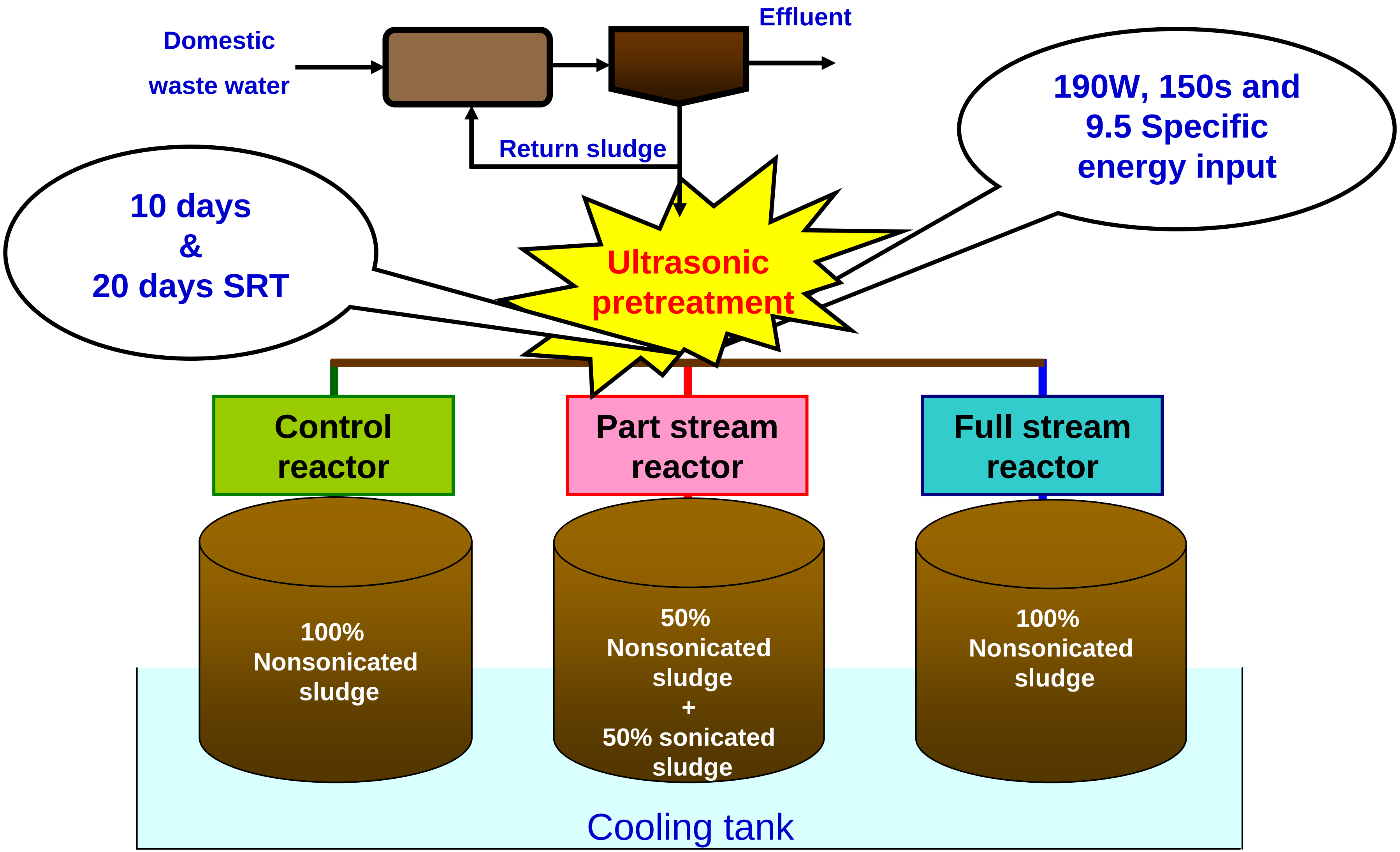




- Control 30 s, 50 w 240 s, 190 w

Control 0.5 w/mL 1.9 w/mL

Experimental set-up

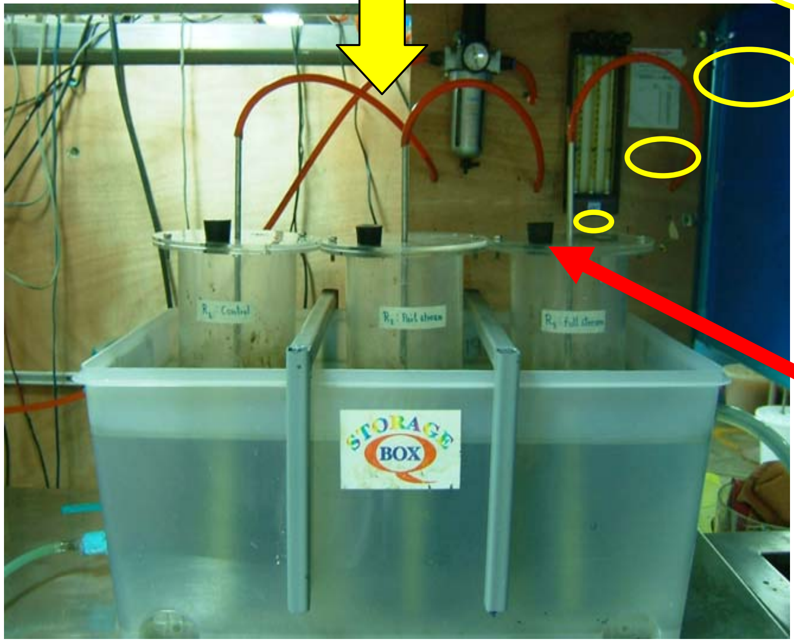


Experimental Set-up

Air compressor
Supply air
continuously 24 hr.

- 25°C
- DO > 1mg/L
- 5.5 mL/min
- pH ~7

- Made up of acrylic
- Total volume 5.8L
- Working volume 3L
- Diameter 14 cm
- High 38 cm
- Semi-batch operation system



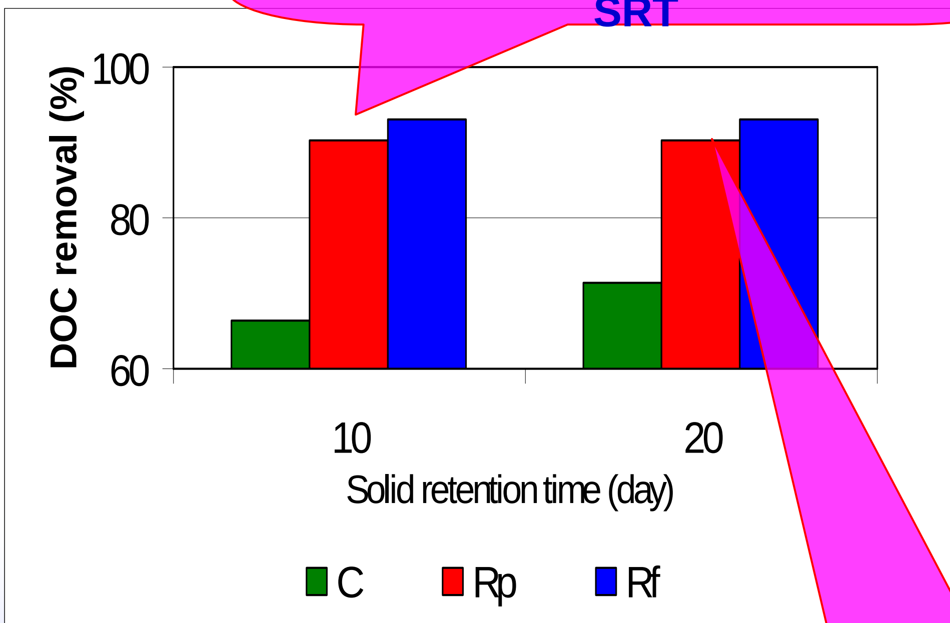
Feeding
&
Withdrawing
every 12h.

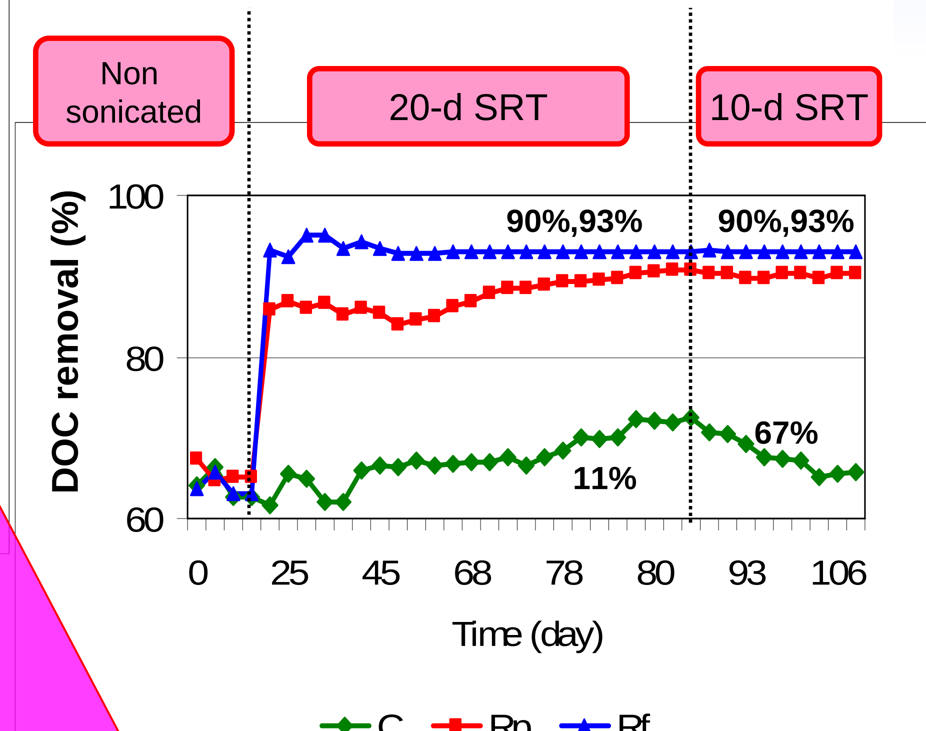
Aerobic Digester Evaluation

- The efficiency of aerobic digester was evaluate by
  - DOC and TS/VS removal efficiency
  - SOUR
  - Ammonification and nitrification rate
  - Capillary suction time

DOC Removal Efficiency

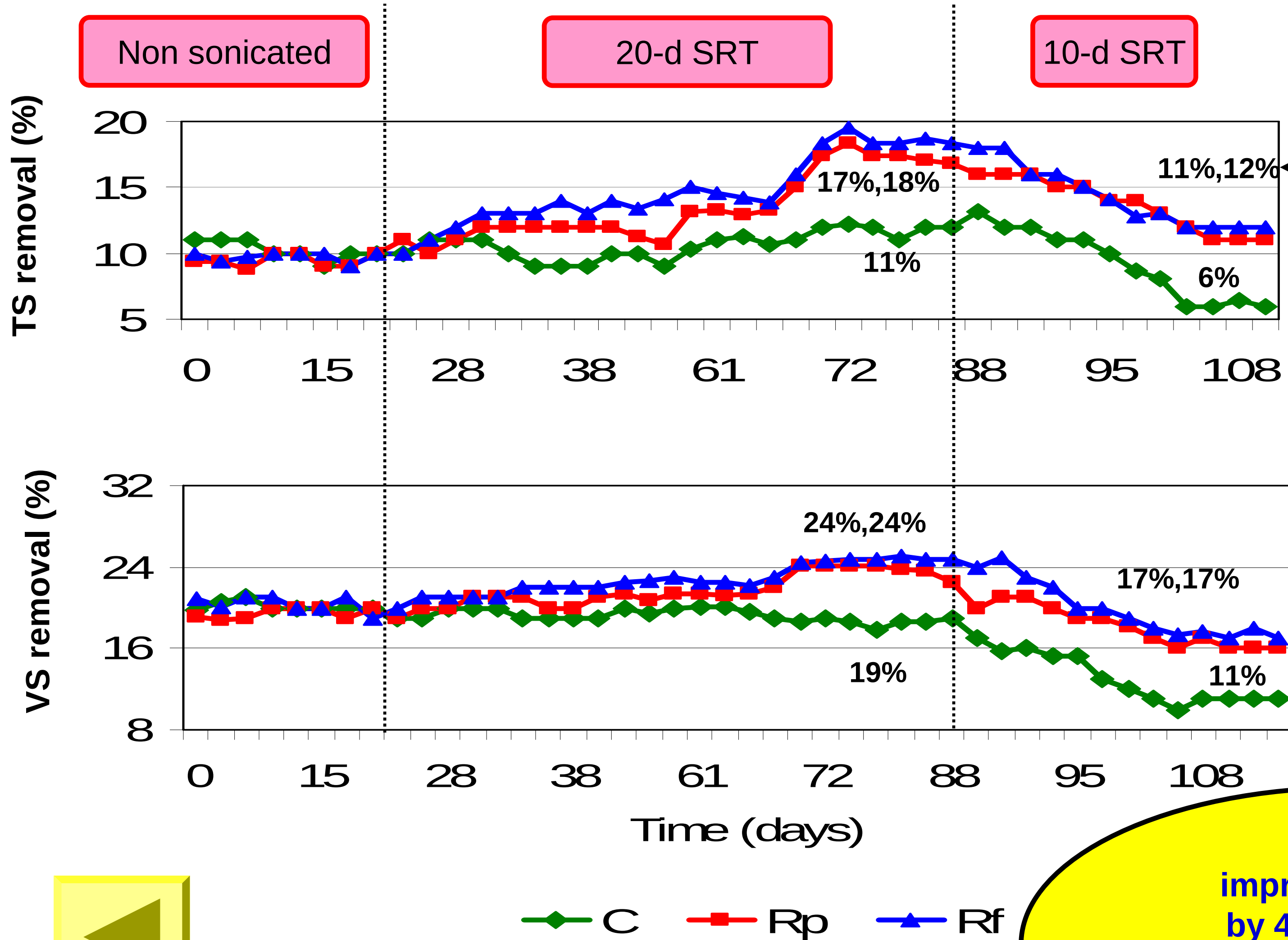
DOC removal rate of Rp & Rf were improved higher than control reactor by 26% and 28% at 10-d SRT





DOC removal rate of Rp & Rf were improved higher than control reactor by 20% and 23% at 20-d SRT

TS/VS Removal Efficiency

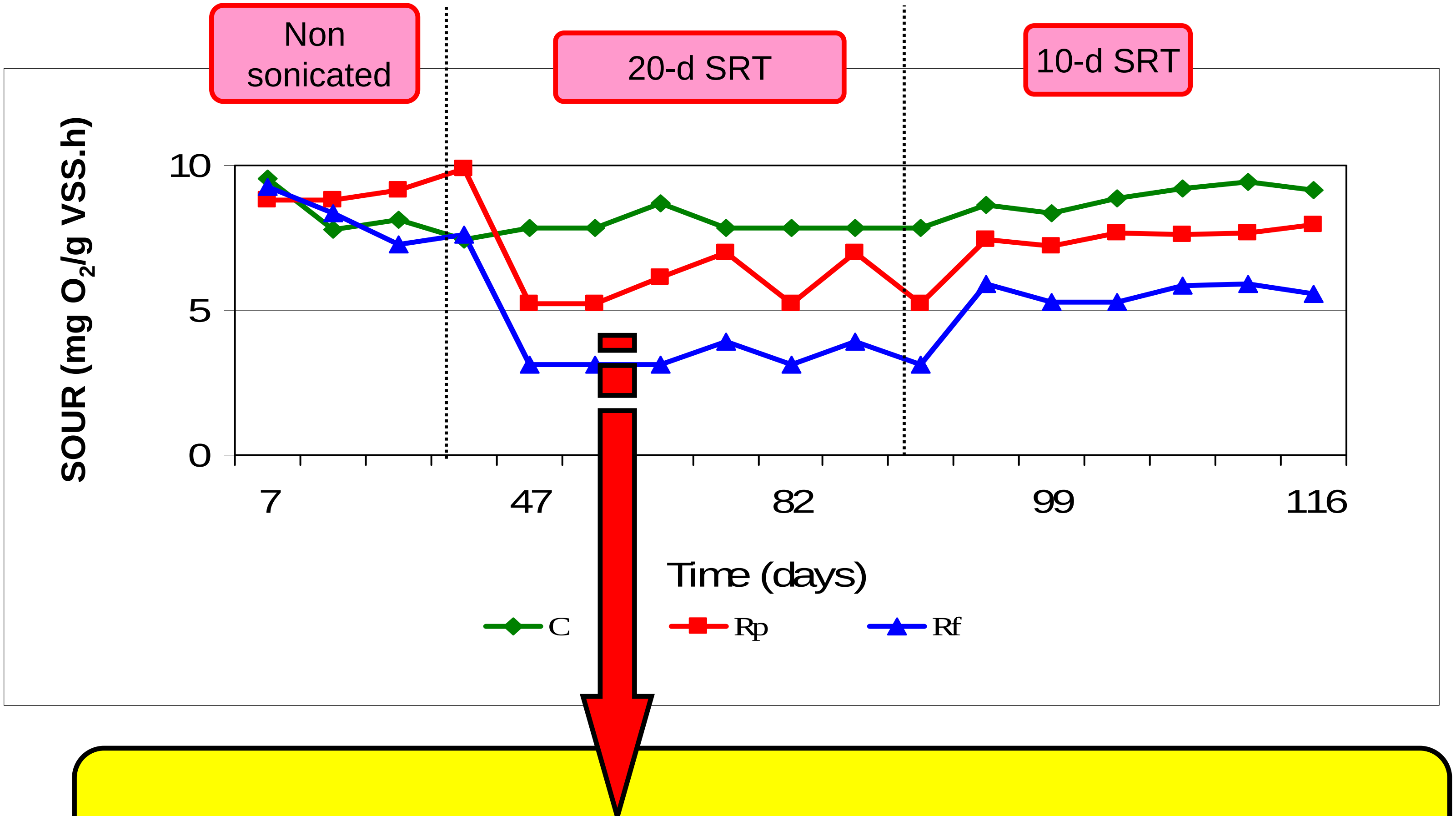


TS removal rate were higher by 46% and 50% at 10-d SRT.

While the values only 32% and 36% for 20-d SRT

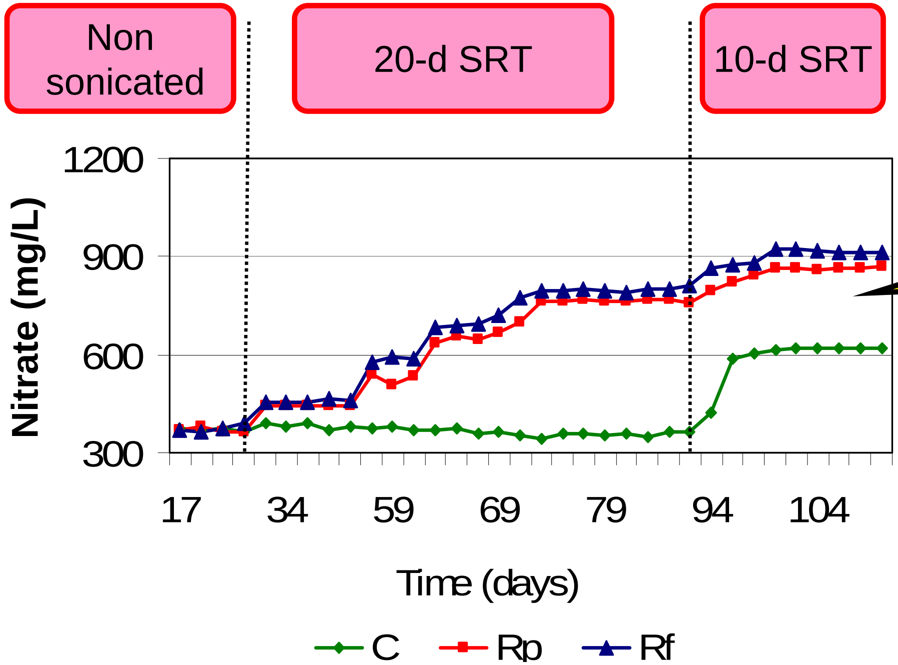
VS improved higher by 46% and 50% at 10-d SRT.
While the values only 32% and 36% for 20-d SRT

Specific Oxygen Uptake Rate (SOUR)

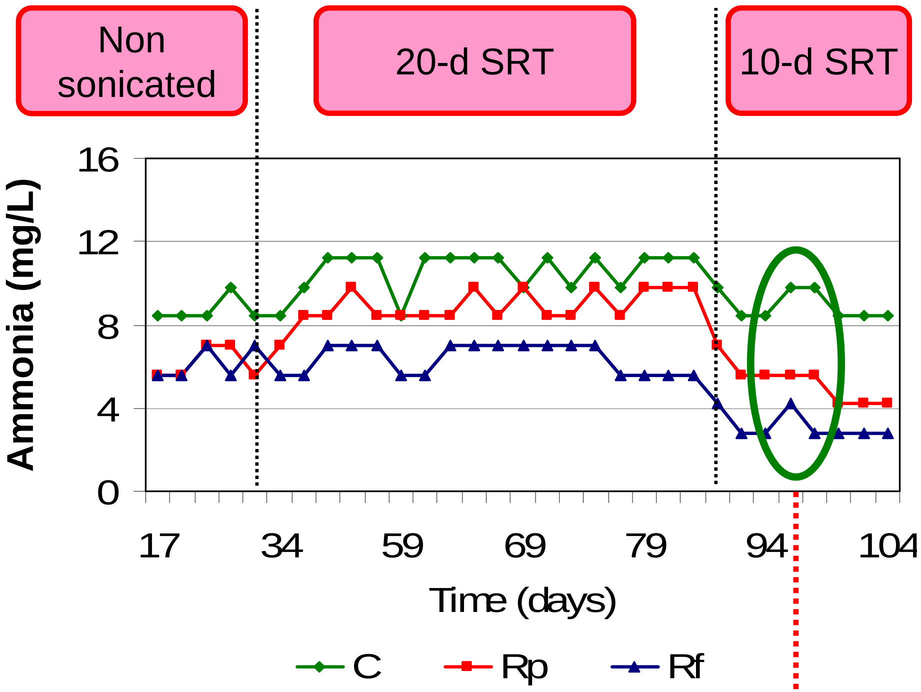


Active cell was destroyed more at 20-d SRT. Then SOUR decreased.

Ammonification & Nitrification

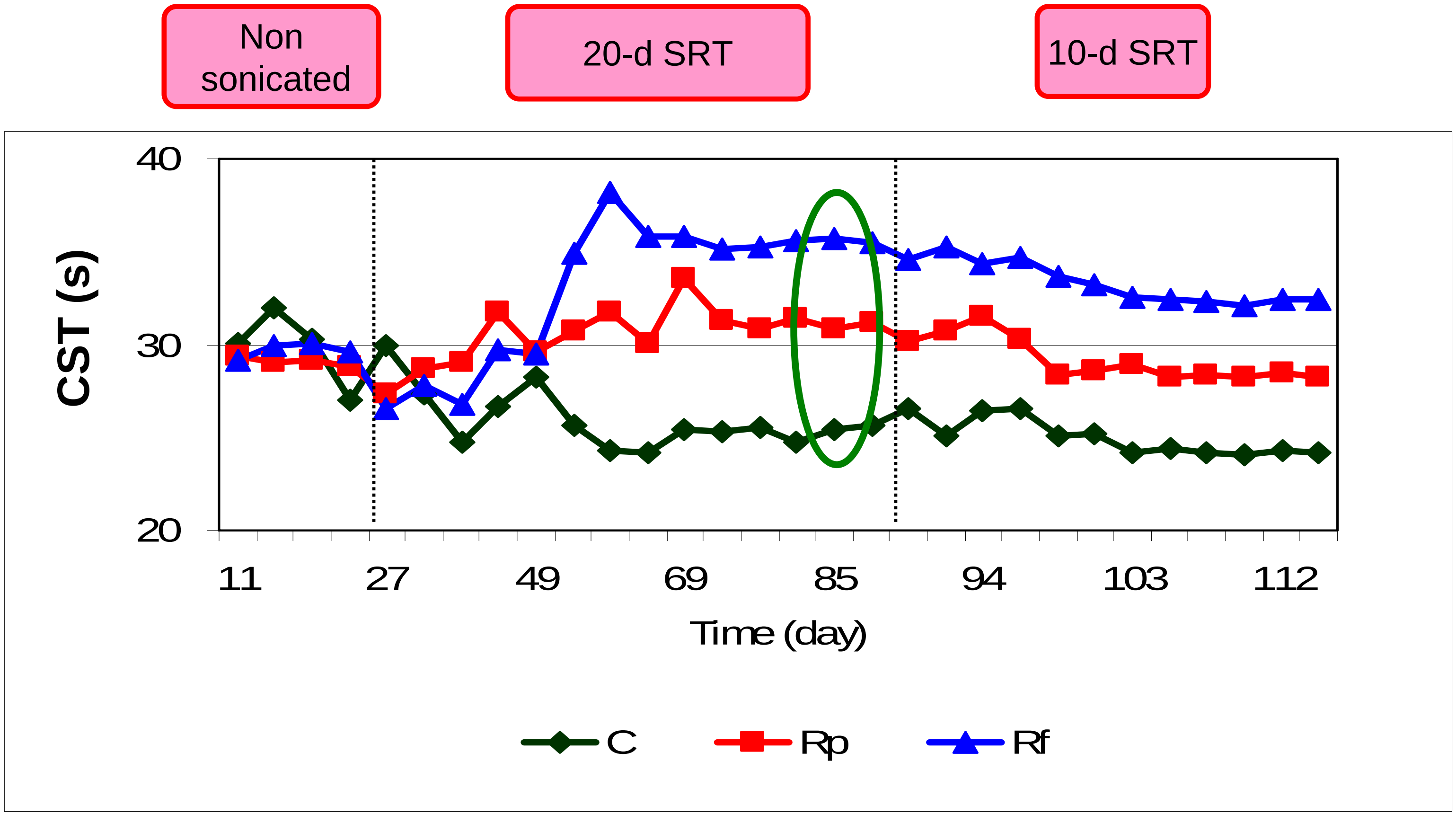


Nitrification was higher at 10-d SRT.



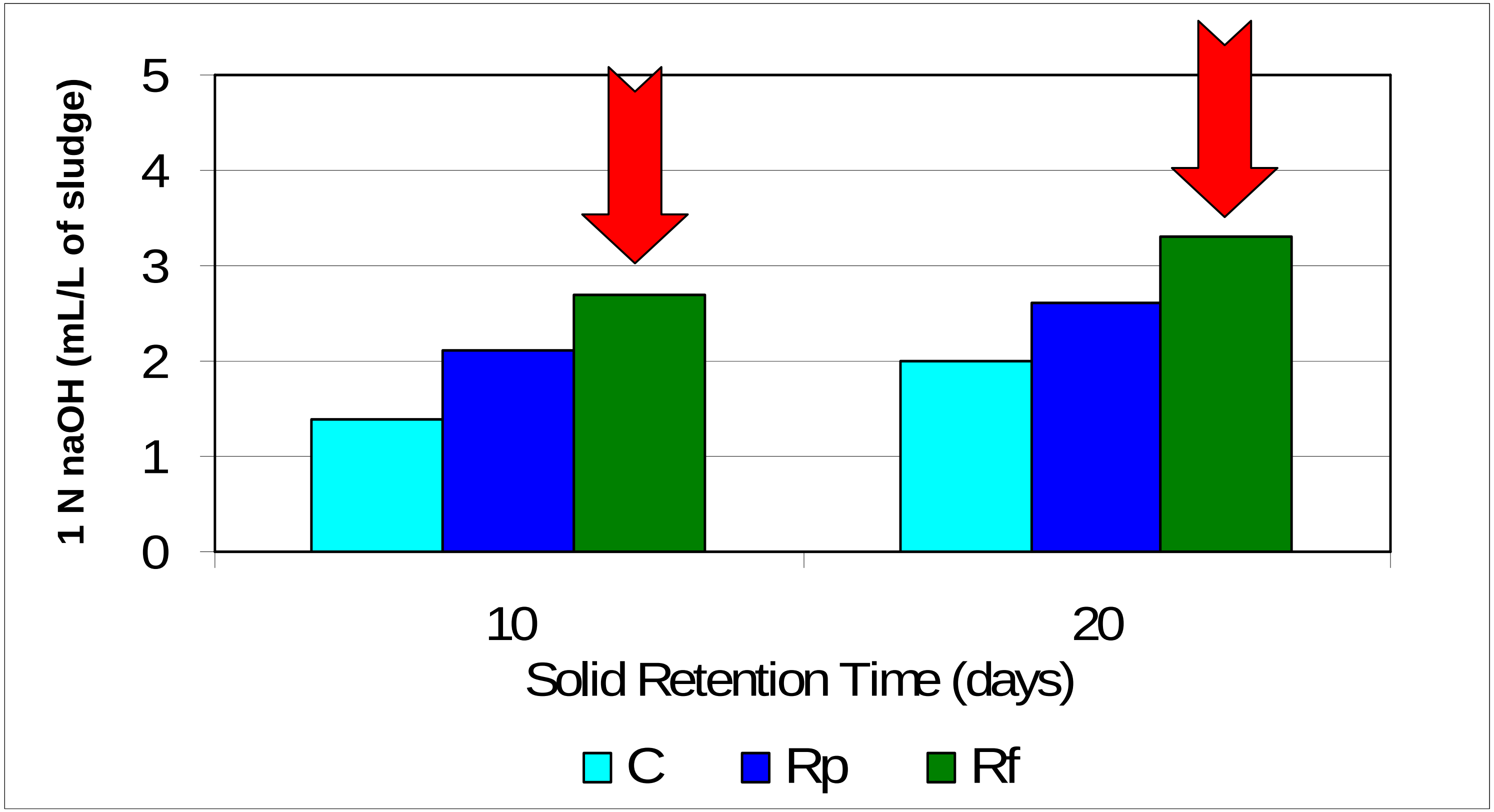
Ammonification occure higher at 10-d SRT.

Capillary Suction Time (CST)



Ultrasonic can not improv the dewaterability of sludge.
However, at 10-d SRT dewaterability of sludge is better than 20-d SRT

Alkalinity adjustment



Sonicated sludge need more alkali dose.
Due to it can produced more ammonification

Biosolids Quality Evaluation

- The quality of biosolids was investigate in term of
  - Pathogen count
  - Total phosphorus
  - TKN

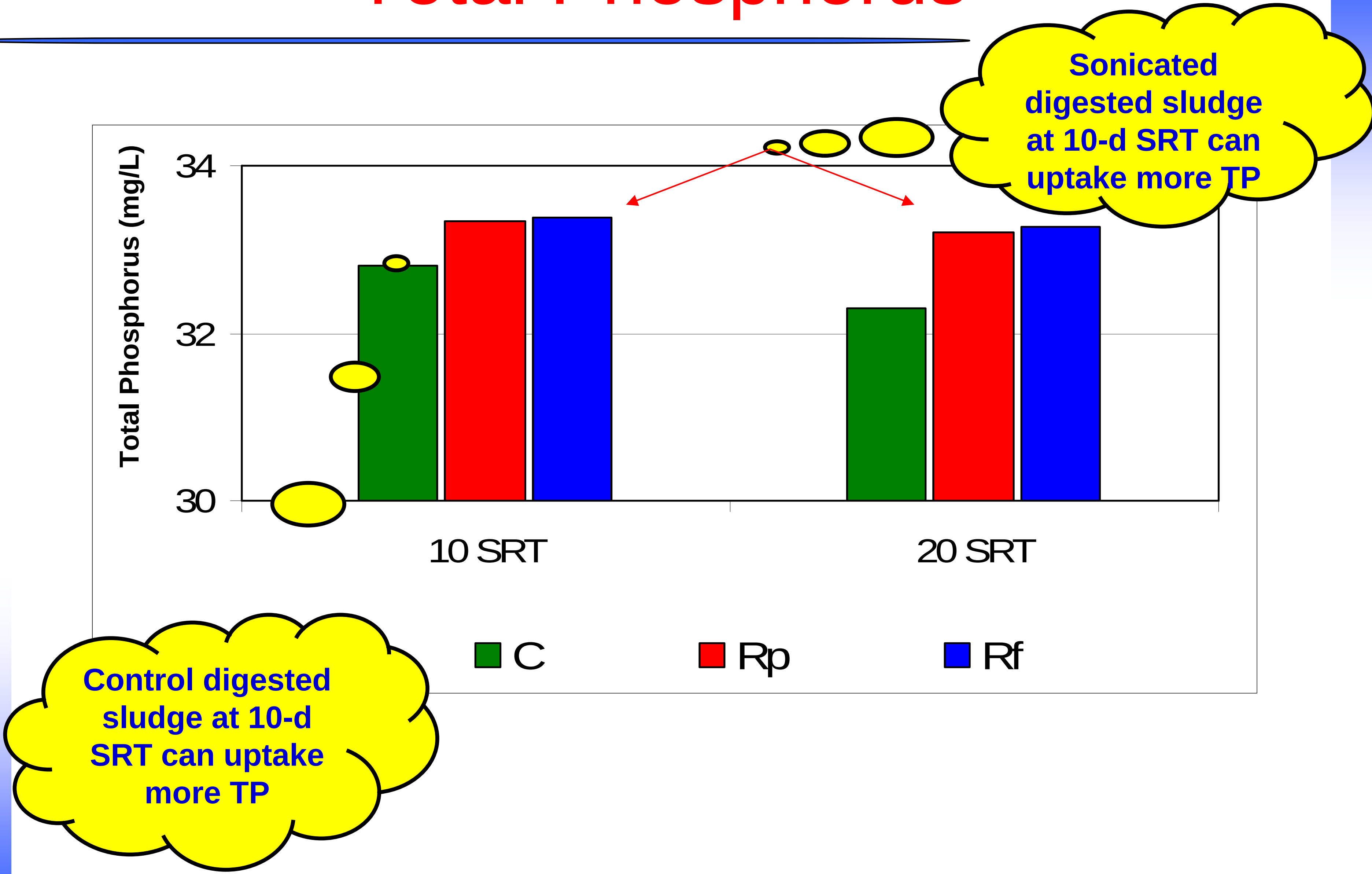
Pathogen Count

Table 1. Pathogen level of digested sludge

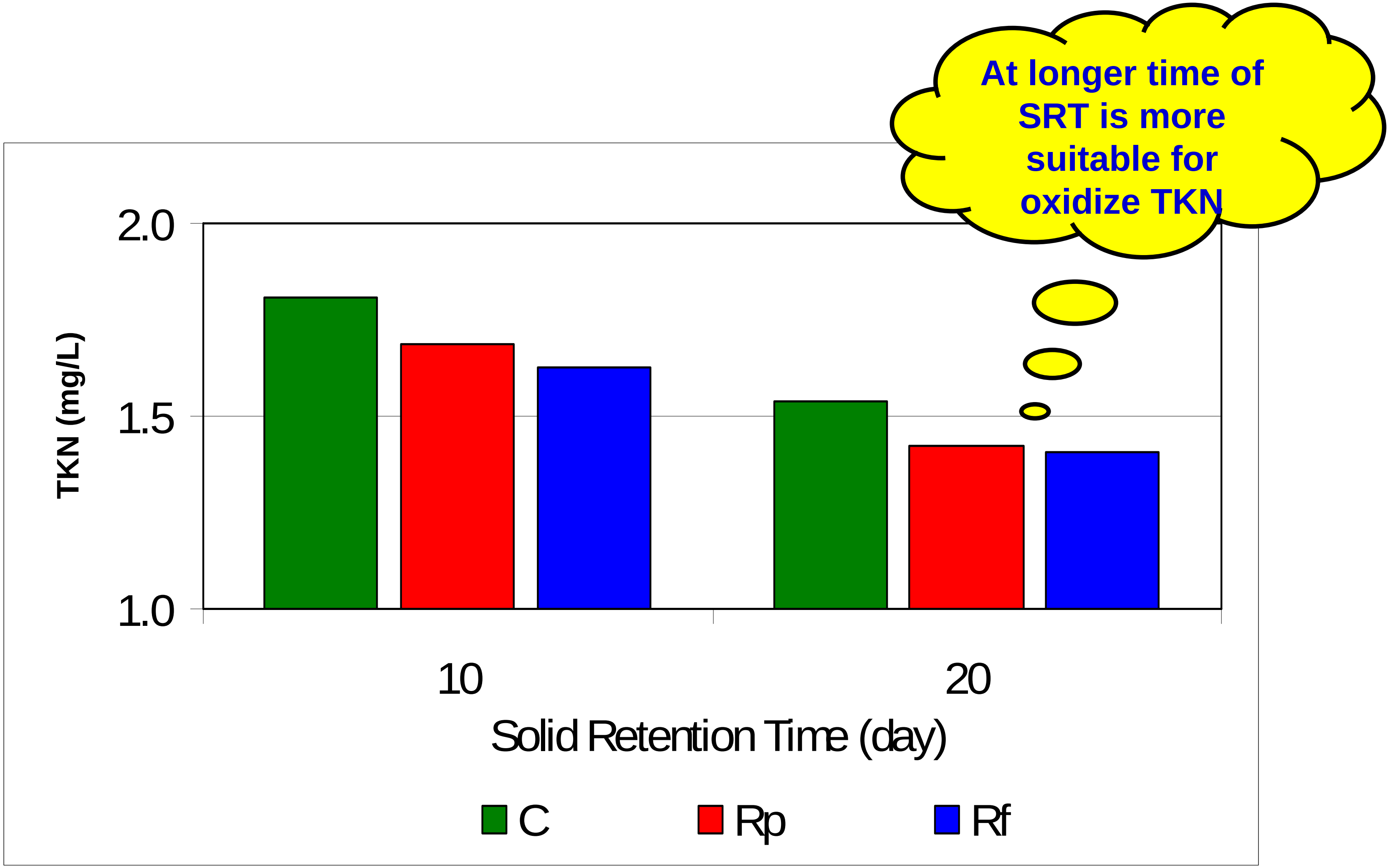
Pathogen type	Pathogen level (by dry weight)		
	C	Rp	Rf
Fecal coliform (MPN/g TS)	$4x10^4$	$1.8x10^4$	$0.47x10^4$
E. coli (MPN/g TS)	$3.3x10^2$	$11x10^2$	$3.2x10^2$
Salmonella sp. (CPU/g TS)	< 100	< 100	< 100

Ultrasonic can not meet the U.S. EPA guide line, class-A Biosolids. (Class-A sludge: the density of fecal coliform less thsn 1,000 MPN/g total)

Total Phosphorus



TKN


At longer time of SRT is more suitable for oxidize TKN
TKN (mg/L)
2.0
1.5
1.0
10
20
Solid Retention Time (day)
C
Rp
Rf

Conclusions

- Large horn is the selected horn which released the highest SCOD with sonication condition of specific energy input 30.4 kJ/kg TS and 480s.
- The sonication condition of this study was selected at sonication time of 150s, ultrasonic density of 1.9 W/mL and specific energy input of 9.5 kJ/kg TS.
- The different between the highest sonication condition and the lowest of sonication condition easily to observe by light microscope.

Conclusions (con't)

- 10-d SRT is better than 20-d SRT for aerobic digestion of sonicated sludge.
- Full stream reactor was showed higher efficiency than part stream reactor.
- Aerobic digestion of sonicated sludge required about 2 times of alkalinity dose compared to control reactor.
- Ultrasonic pretreatment can not improved the dewaterability of digested sludge.

Recommendations

- Cost-benefit analysis need to be conduct to justify the economics of the process in full-scale application
- Energy balance of aerobic digestion system should be investigate.
- Thermophilic aerobic digester is recommended.

Thank you for your attention

Thank you for your attention