

CRANFIELD UNIVERSITY

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**Recirculation in a full scale Rotating Biological Contactor for
Nitrogen Removal**

School of Water Science

MSc Thesis

CRANFIELD UNIVERSITY
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**Recirculation in a full scale Rotating Biological Contactor for
Nitrogen Removal**

Supervisor: E Cartmell

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for the degree of Master of Science

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Abstract

The effect of an internal recirculation on the total nitrogen removal efficiency in a full scale Rotating Biological Contactor (RBC). The study consists of two trials using two RBC units in parallel, with one acting as a control and the other with a recycle system installed.

Trial 1 was to recycle nitrate rich effluent from the humus tank back to the septic tank at the front of the unit, where denitrification occurs using the raw wastewater as a carbon source. TN removal had improved from 25% to 74% when the recycle ratio (R) was increased from 0 to 2. There is no noticeable effect on BOD₅ concentration in the effluent as R increases, maintaining a steady 96% removal rate. The effluent had shown a slight increase in turbidity as R increase.

Trial 2 was to recycle from the biozone to the septic tank. An overall reduction in removal efficiencies in the test unit have shown that recycling directly from the biozone could not achieve a better performance. Recycling from the biozone had also induced simultaneous nitrification and denitrification in the septic tank, resulting in a 50% reduction in BOD₅ and TN prior entering the biozone.

Acknowledgements

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Finally, I would like to thank all the Severn Trent Water site technicians for their help on site.

Executive Summary

Nitrogen rich effluent discharged from treatment works can cause eutrophication and damages to the environment. In order to achieve a future consent for small works with capacity of less than 10,000 population equivalent, the reliability of nitrogen removal in Rotating Biological Contactor (RBC) is being investigated.

The study consists of two trials, with one recycling from the humus tank to the septic tank, and the other recycling directly from the biozone to the septic tank. Different recycle ratios had been completed for both settings.

Results had shown recycling from the humus tank had provided higher nitrogen removal efficiency, while the quality of the final effluent deteriorated with increasing recycle ratio.

In this study, it is shown that by recycling from the humus tank at a recycle ratio 2, the unit performance is best. While increasing the recycle ratio beyond this value, further reduction in nitrogen is expected.

Recirculation within the RBC unit is a simple and economically viable option for nitrogen removal. But it is essential to identify the best operating conditions while maintaining a relatively low concentration of suspended solids and BOD.

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2 Introduction

Although there are currently no total nitrogen (TN) removal standards for small works in the UK, but experience have shown the discharge of nutrients rich effluents can result in eutrophication, in which caused a deterioration of water quality and damages to the local habitats.

The Urban Wastewater Treatment Directive (UWWTD) have outlined the appropriate level of treatment required for discharges from more sensitive areas (>10,000pe) to less sensitive areas (<2,000pe). A TN consent was set to 15 mg/l for works with 10,000 – 100,000pe and 10mg/l for >100,000pe under the UWWTD. With legislations like the Habitats Directive and the Water Framework Directive, which are aimed to maintain a balance and diverse ecosystem and an improved performance of the works, an even tighter consent is foresee to be a strong probability. The trend towards a change in TN consent, especially for sensitive areas, was considered inevitable.

At present, most of the RBC units in the UK operate aerobically to achieve BOD removal. Nitrification is commonly found to occur coincide with BOD removal, while denitrification involves an addition anoxic step. Denitrification can be achieve prior (Pre-denitrification), after (Post-denitrification) or simultaneously (Simultaneous Nitrification and Denitrification) with nitrification. Studies on post-denitrification (Murphy et al., 1977) had indicated an external carbon source is required for the removal of nitrate, while pre-denitrification obtain the carbon from the influence wastewater.

Denitrification can be achieved in RBC systems by completely submerging the RBC unit in the water. Methanol is commonly used as an external carbon source for the process. Although an 84% nitrogen removal can be achieved with this arrangement, the addition of

methanol will increase both the cost and maintenance of the process. Therefore, an interest is expressed in finding a more cost effective and reliable solution.

3 Aims and objectives

The aim of this project is to investigate the feasibility of achieving a reliable nitrogen removal method by recirculation within the RBC unit.

The objectives are:

- To assess current performance and investigate nitrogen removal rate at different recycle ratio.
- The effect of internal recirculation on final BOD and suspended solids concentrations.
- Differences between recycling directly from the biozone and from the humus tank.

4 Literature review

4.1 Nitrogen removal

4.1.1 Characteristics of wastewater

Nitrogen in municipal wastewater comes in many different forms. The main sources are (1) biological degradable nitrogen decayed from animals and plants, (2) sodium nitrate where used extensively in agriculture land as a fertilizer, and (3) atmospheric nitrogen where nitrogen (N_2) in the atmosphere is converted to other forms of nitrogen compounds via a naturally occurring process (Metcalf & Eddy et al., 2003). At different oxidation state, nitrogen is present in different forms. The definitions of various terms used for different nitrogen species is shown in Table 1-1.

Table 1-1 Definitions of various terms used for different nitrogen species. (Metcalf & Eddy et al., 2003)

Form of nitrogen	Abbreviation	Definition
Ammonia gas	NH_3	NH_3
Ammonium ion	NH_4^+	NH_4^+
Total ammonia nitrogen	TAN	$NH_3 + NH_4^+$
Nitrite	NO_2^-	NO_2^-
Nitrate	NO_3^-	NO_3^-
Total inorganic nitrogen	TIN	$NH_3 + NH_4^+ + NO_2^- + NO_3^-$
Total Kjeldahl nitrogen	TKN	Organic N + $NH_3 + NH_4^+$
Organic nitrogen	Organic N	$TKN - (NH_3 + NH_4^+)$
Total nitrogen	TN	Organic N + $NH_3 + NH_4^+ + NO_2^- + NO_3^-$

The majority of the nitrogen in raw sewage exists as organic nitrogen and ammonia, with a small quantity of nitrite and nitrate found

naturally. The strength of the wastewater can be concluded using organic nitrogen and ammonia into Table 1-2 as shown below.

Table 1-2 Nitrogen content of municipal wastewater (mg N/l). (Sedlak, 1991)

Nitrogen form	Type of Sewage		
	Strong	Medium	Weak
Organic	35	15	8
Ammonia	50	25	12
Total	85	40	20

4.1.2 Mechanism of N removal

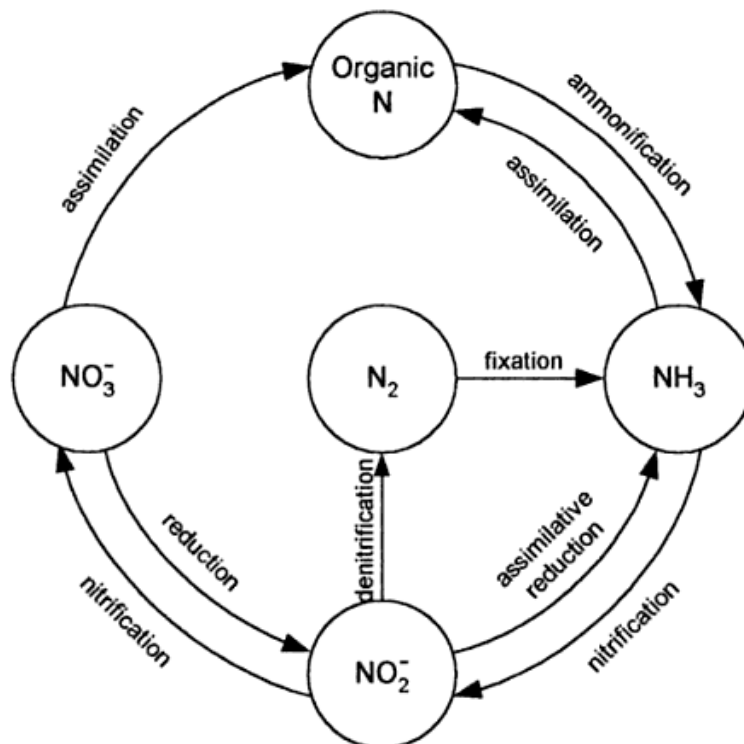


Figure 1-1 The nitrogen cycle. (Grady et al. 1999)

Nitrogen can be removed from the water in a number of ways. It can be converted from ammonia (NH_4^+) to nitrogen gas (N_2) either by

oxidation with a powerful oxidant (Cl_2), or by biological nitrification and denitrification. Nitrogen can also be uptake by plants as a nutrient source for growth or stripped out by raising the pH. Other techniques like ion exchange and the membrane technology can also be used to remove nitrogen from the water. A list of the N removal process is shown in Table 1-3 below.

Table 1-3 Nitrogen removal and conversion process. (Water Environment Federation. Municipal Subcommittee, 1998)

Initial species	Ultimate species	Process
Organic N	Ammonium, NH_4^+ -N	Ammonification
		Biological conversion of organic nitrogen to ammonia
Ammonium, NH_4^+ -N	Nitrate, NO_3^- -N	Biological nitrification
	Ammonia gas, $\text{NH}_3(\text{g})$	Stripping
	Organic nitrogen	Biological uptake during bacterial growth
	Nitrogen gas, $\text{N}_2(\text{g})$	Breakpoint chlorination
	Resin	Ion exchange will exchange ammonia for another cation
Nitrate, NO_3^- -N	Nitrogen gas, $\text{N}_2(\text{g})$	Biological denitrification
	Resin	Ion exchange will exchange nitrate for another anion

4.1.3 Process options

The selection of process depends on the required effluent quality. Biological N removal, being the most effective as well as economically viable options in most cases, is the most commonly used method for nitrogen removal in modern day wastewater

treatment. Physical and chemical processes have been introduced in the past but the high costs associated with the technologies have limited the uses of these processes.

4.1.3.1 Biological N removal

Biological N removal involved two processes, nitrification and denitrification. Nitrification described the process of conversion of ammonium NH_4^+ to nitrite NO_2^- , and then to nitrate NO_3^- through microbiology like Nitrosomonas and Nitrobacter. Denitrification is the conversion of nitrate NO_3^- to nitrogen gas N_2 . The details of these processes will be discussed later.

4.1.3.1.1 Suspended growth process

A typical suspended growth process is the activated sludge (AS) process. The activated sludge process was preceded by Dr. Angus Smith back in the early 1880s, during an investigation of the relationship of aeration and oxidation of organic matter in wastewater.(Metcalf & Eddy et al., 2003) In an activated sludge process, microorganisms under aeration conditions are kept in suspension for the removal of organic matters in the wastewater. The mixture will then go through a clarification process, usually a sedimentation tank, and the sludge will be partly recycled back to the reactor in order to maintain the process. Nitrification in an AS process often occurs in conjunction with BOD removal in the aerobic zone. Denitrification can be found in either a separate stage anaerobic process or a single stage combined process with nitrification and carbon oxidation.

4.1.3.1.2 Attached growth process

In an attached growth process, microorganisms are attached to a supporting media, which can be rock or plastic. Trickling filters and rotating biological contactors are common attached growth

processes. The wastewater is then distributed through the media where BOD removal occurs. Heterotrophic bacteria, which are responsible for the removal of BOD, typically outgrow the nitrifying bacteria. Therefore nitrification often occurs where the BOD loading decreases, for example, the lower end of a trickling filter and the back end of an RBC unit. (Water Environment Federation. Municipal Subcommittee, 1998) Denitrification can be achieved in a completely submerged system with sufficient supplies of carbonaceous materials.

4.1.3.2 Chemical and Physical N removal

4.1.3.2.1 Breakpoint chlorination

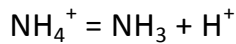
Chlorine is a powerful oxidant; it is commonly used in the disinfection process in water treatment. When sufficient amount of chlorine is added to wastewater, ammonia is oxidized to nitrogen gas. A simplified overall reaction can be expressed as follow:



From the equation above, the calculated amount of chlorine required to oxidize ammonia to nitrogen gas is 7.6 mg Cl₂ / mg NH₄⁺ - N. (Water Environment Federation. Municipal Subcommittee, 1998) Since only 95 to 99 percent of the ammonia are converted to nitrogen gas, other nitrogen species like nitrate (NO₃⁻) and nitrogen trichloride (NCl₃) are being produced as a by-product of the process. In practical, around 10 mg of Cl₂ are required to oxidize 1mg of NH₄⁺ - N.

4.1.3.2.2 Air stripping

The air stripping method for N removal is based on the equilibrium of ammonium ion and ammonia-N shown below:



The equilibrium has a pKa value of 9.5. As the pH in the water raises, the equilibrium shifts to the right and more $\text{NH}_3(\text{g})$ is produced. Given a large enough air : water ratio, ammonia can then be stripped from the water. A typical value is $1600 \text{ m}^3 \text{ air}/\text{m}^3 \text{ water}$. (Water Environment Federation. Municipal Subcommittee, 1998) The major problems encountered with the process are failing in cold weather; decrease in temperature reduces the efficiency. Scale formation with pH adjustment using lime and potential air pollution problems.

4.2 Biological N removal

Biological nitrogen removal involves two processes, nitrification and denitrification. It can be employed separately or in conjunction with BOD removal in a wastewater treatment plant. The three major approaches are shown in Figure 1-2 below.

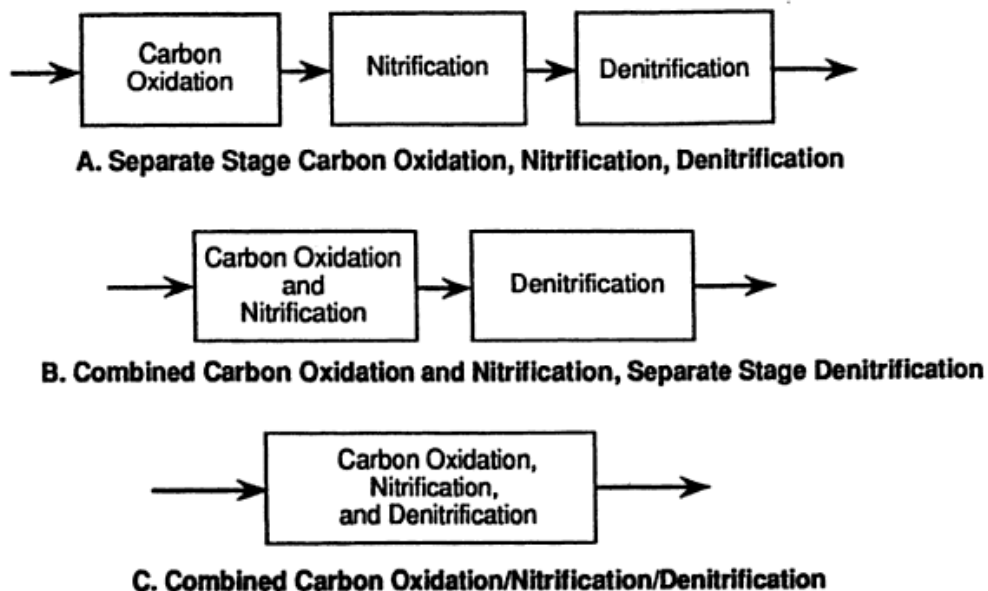


Figure 1-2 Three biological nitrogen removal approaches. (Sedlak, 1991)

The first approach is a separate stage process, where all three processes take place in three different tanks, independent to each others. The second option includes a combined carbon oxidation and nitrification process, followed by a separate stage denitrification process. The third approach is referred as a single-sludge denitrification process where all three processes are combined and occurs simultaneously in one single tank.

4.2.1 Nitrification

Nitrification is a natural occurring process commonly found in both soils and water environments. The process was discovered by Winogradsky in the late nineteen century. It is a very important process in the natural nitrogen cycle. In biological wastewater treatment, nitrification can be found in both suspended growth and attached growth processes.

Nitrification is an aerobic process and often occurs nearer to the end of a RBC unit. The reason being heterotrophic bacteria, which are responsible for BOD removal, often outgrow the bacteria responsible for nitrification at the front of the unit where the BOD concentration is much higher. Two different groups of aerobic autotrophic bacteria, Nitrosomonas and Nitrobacter, are responsible for the two stages of the process, ammonia oxidation and nitrite oxidation respectively.

4.2.1.1 Ammonia oxidation

The first stage of the process is ammonia oxidation, the oxidation of ammonia NH_3 to nitrite NO_2^- . Ammonia-oxidizing bacteria (AOB) like Nitrosomonas are responsible for the process. The stoichiometry of the reaction is as follow:



Municipal Subcommittee, 1998)

From the stoichiometry equation above, we can calculate the oxygen consumption for the reaction, which is 1.5 mole O_2 / mole ammonium-N, equivalent to 3.43g O_2 / g ammonium-N.

4.2.1.2 Nitrite oxidation

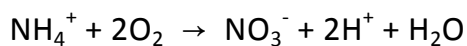
Nitrite oxidation is the second stage of the nitrification process. Nitrite NO_2^- is oxidized to nitrate NO_3^- by nitrite-oxidizing bacteria (NOB) like Nitrobacter. The reaction is as follow:

$NO_2^- + 0.5O_2 \rightarrow NO_3^-$ (Water Environment Federation. Municipal Subcommittee, 1998)

Nitrite is used as an electron donor by the nitrite-oxidizing bacteria and oxygen is acting as the final electron acceptor. The oxidation of nitrite has a much lower growth yield compared with the oxidation of ammonia, having a free energy yield of $-74 \text{ kJ}\cdot\text{mole}^{-1}$ and $-275 \text{ kJ}\cdot\text{mole}^{-1}$ respectively. (Cervantes, 2009)

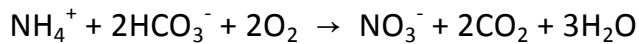
4.2.1.3 Overall oxidation reaction

The overall oxidation reaction can be summarised as follow:



The total oxygen consumption for the overall complete oxidation reaction is calculated to be 4.57 g O_2 / g N, with 3.43 g O_2 / g ammonium-N for ammonia oxidation and 1.14 g O_2 / g nitrite-N for nitrite oxidation. (Metcalf & Eddy et al., 2003)

The reaction given above can be rewritten as follow:



It can be calculated that 7.14 g of alkalinity as CaCO₃ is required per g of ammonia nitrogen oxidized. (Metcalf & Eddy et al., 2003)

4.2.1.4 Factors affecting nitrification

As of all biological processes, nitrification is influenced by a lot of environmental factors such as temperature, pH, oxygen concentration and inhibiting compounds. These factors can restrain the growth rate of the nitrifying bacteria, hence the nitrification rate. NOB is considered more sensitive to changes in its surroundings compared to AOB. The fluctuation of conditions will have a greater effect on the nitrite oxidation rate and consequently a build up of nitrite in the water.

4.2.1.4.1 Temperature

Nitrification can be achieved in temperature ranging from 4 to 50°C, the optimum temperature is between 30 to 36°C. (Water Environment Federation. Municipal Subcommittee, 1998) The relationship between the growth rate of nitrifying bacteria and temperature can be expressed by the van't Hoff-Arrhenius equation:

$$\mu = \mu_{20} \cdot \theta^{T-20}$$

Where μ = the rate coefficient (d^{-1}), μ_{20} = the value of μ at 20°C (d^{-1}), θ = temperature coefficient (dimensionless), T = temperature (°C). (Cervantes, 2009) The equation has shown a general relation that the rate coefficient is directly proportional to the temperature.

4.2.1.4.2 pH

Optimum nitrification occurs under neutral to moderately alkaline

conditions (pH 7.5 to 8.0)(Gieseke et al., 2006) Nitrification rate decreases with decreasing pH, with the nitrification rate approaching zero at pH below 6 or above 10.(Water Environment Federation. Municipal Subcommittee, 1998)

Although nitrification have been found occurring in acidic conditions where autotrophic bacteria acting as the main nitrifying agents in most acid soils(De Boer and Kowalchuk, 2001), alkalinity is often added in wastewater treatment plant to maintain a pH of 7.0 to 7.2 for reasonable nitrification rates.(Metcalf & Eddy et al., 2003)

4.2.1.4.3 Oxygen concentration

Nitrification rates are affected by the dissolved oxygen (DO) concentration in the wastewater. Experimental results have shown that Nitrobacter are more vulnerable than Nitrosomonas at low DO concentration (0.2 to 0.5 mgL⁻¹), with K (m) values of 1-15 and 22-166 μM O₂ for nitrite oxidation and ammonia oxidation respectively.(Laanbroek and Gerards, 1993) This in turn leads to incomplete nitrification and nitrite accumulations in the process.

It should be noted that since nitrifying bacteria often affixed to the media in a thick layer in attached growth processes, DO concentration measured does not always represent the true value of the available oxygen for nitrification.

4.2.1.4.4 Inhibiting compounds

Nitrification can be affected by a wide range of organic and inorganic compounds. Studies have shown the sensitivity of Nitrosomonas to toxic compounds is significantly greater (one order of magnitude) than the sensitivities of aerobic heterotrophs and methanogens. (Blum and Speece, 1991) Compounds that are toxic include solvent organic chemicals, amines, proteins, tannins, phenolic compounds,

alcohols, cyanates, ethers, carbamates and benzene. (Metcalf & Eddy et al., 2003) Nitrification can also be inhibited by other compounds like metals (Cu, Ni, Cr, Zn, Co) (Cervantes, 2009), un-ionized ammonia (NH₃) and un-ionized nitrous acid (HNO₂). (Anthonisen et al., 1976)

Since the nitrifying bacteria have a very low growth rate, minimum inhibition could have a considerable effect on the overall nitrification rate.

With inhibiting compounds presence in the water, nitrifying bacteria may continue to grow and some nitrification may still occur. But in some cases, the toxicity may be sufficient to kill the nitrifying bacteria. (Metcalf & Eddy et al., 2003)

4.2.2 Denitrification

Denitrification described the conversion of nitrate NO₃⁻ to nitrogen gas which can be release into the atmosphere safely. The process is often intergraded with conventional wastewater treatment plant to prevent eutrophication or when disposing into a nitrogen sensitive area. It is a very cost effective solution compare to other nitrogen removal technique like breakpoint chlorination and air stripping.

Denitrification can be complete by a wide range of microorganisms. Most of these microorganisms are facultative, meaning the capability to change metabolic pathways (aerobic and anaerobic). Aerobic respiration occurs when oxygen is available, with the oxygen acting as an electron acceptor. Anoxic respiration occurs in opposite where no oxygen is available, and nitrite and nitrate are used as the terminal electron acceptor. In biological denitrification, oxygen must be excluded since microorganisms are in favour of aerobic respirations rather than anoxic respirations.

4.2.2.1 Assimilation and dissimilation

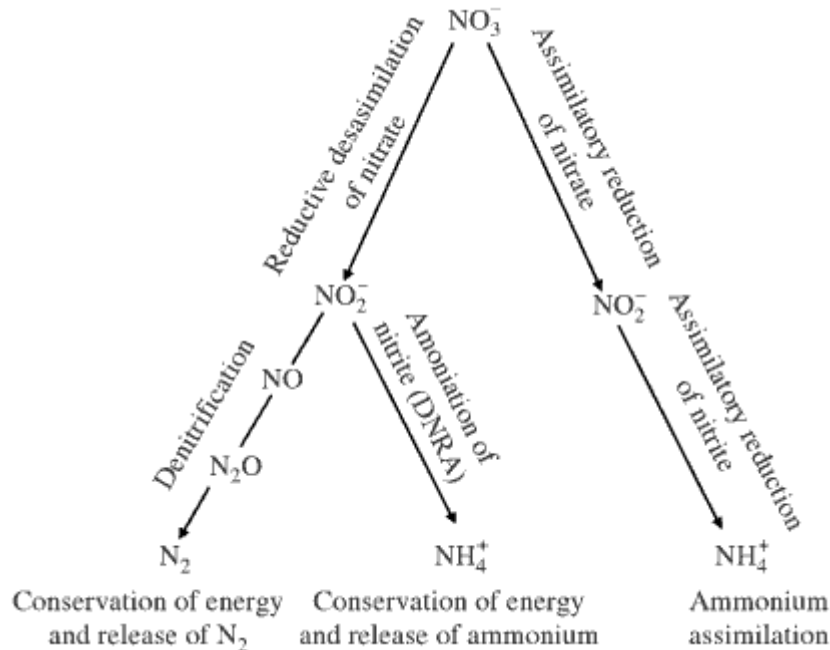


Figure 1-3 Nitrate assimilative and dissimilative pathways (Cervantes, 2009)

Nitrate in general can be removed in two different pathways, assimilation and dissimilation. In assimilation, nitrate is reduced to ammonia for biomass synthesis where there is no $\text{NH}_4\text{-N}$ available and is independent of DO concentration. (Metcalf & Eddy et al., 2003) Dissimilation nitrate reduction uses nitrate or nitrite as an electron acceptor to oxidize a number of organic and inorganic electron donors (Metcalf & Eddy et al., 2003), generating energy as part of the respiratory metabolism and releases nitrogen gas in the process. (Cervantes, 2009)

4.2.2.2 Stoichiometry

In biological denitrification, the following steps are involved in the reduction of nitrate to nitrogen gas:

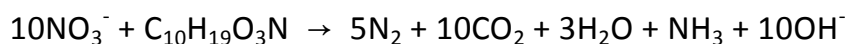


Nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and nitrogen gas (N_2) are reduced in each step by a particular nitrate reductase enzyme accordingly, and it helps to transfer hydrogen and electrons to nitrate as a terminal electron acceptor. (Metcalf & Eddy et al., 2003)

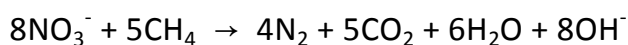
Gayle *et al* (1989) have found that at least 14 different types of bacteria contain denitrifying species, which includes Bacillus, Pseudomonas, Methanomonas, Paracoccus, Spirillum, and Thiobacillus. Some of these bacteria are heterotrophic and a few of them are autotrophic, but they all require a carbon source for cell synthesis in the denitrification process.

Carbon can be obtained from either biodegradable soluble COD (bsCOD) which already exists in the wastewater, bsCOD produced during endogenous decay (methane, CH_4), or an external sources such as methanol and acetate. (Metcalf & Eddy et al., 2003) The stoichiometry equations of the different electron donors are shown below:

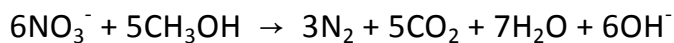
Biodegradable organic matter in wastewater ($\text{C}_{10}\text{H}_{19}\text{O}_3\text{N}$):



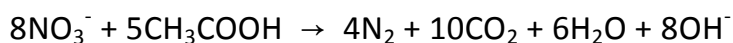
Methane (CH_4):



Methanol (CH_3OH):



Acetate (CH_3COOH):



(Water Environment Federation. Municipal Subcommittee, 1998)

The calculated oxygen equivalent of nitrate and nitrite is 2.86 g O₂ / g NO₃-N and 1.71 g O₂ / g NO₂-N respectively, and alkalinity production is equal to 3.57 g CaCO₂ / g NO₃⁻ reduced.(Metcalf & Eddy et al., 2003)

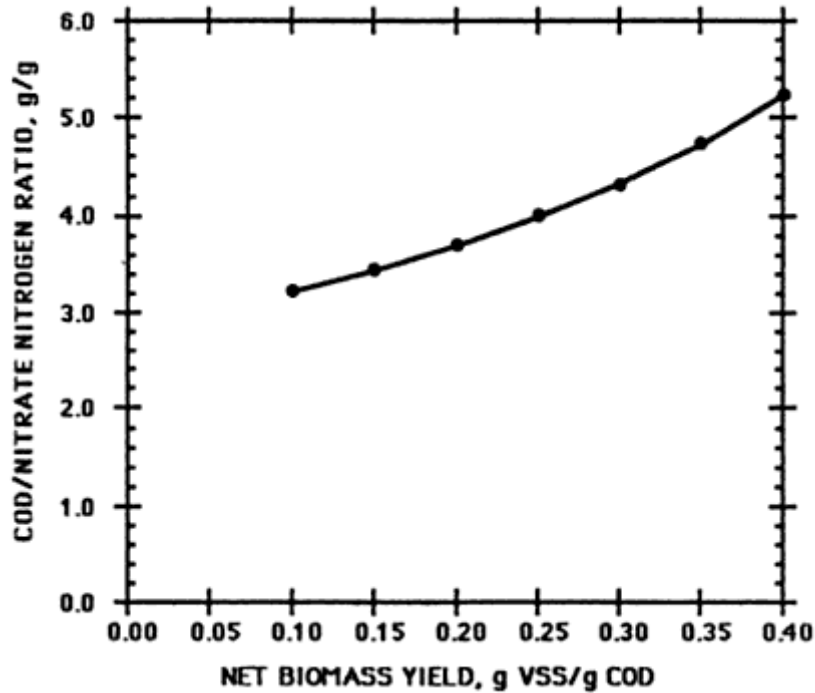


Figure 1-4 Effect of net biomass yield on COD consumed for nitrate reduction. (Barnard et al., 1992)

Figure 1-4 above have shown the relationship between the COD/NO₃-N ratio and the net biomass yield. The COD/N ratio is related to the COD used for the nitrate reduction reactions and to the use of cell synthesis(Barnard et al., 1992). The bsCOD for cell synthesis is equal to 1.42 g O₂ / g volatile suspended solids (VSS) (Metcalf & Eddy et al., 2003). The COD/N ratio for denitrification can be expressed as follow:

$$g \cdot bsCOD / g \cdot NO_3 - N = \frac{2.86}{1 - 1.42Y_n}$$

Where Y_n = net biomass yield, g VSS / g bsCOD
(Metcalf & Eddy et al., 2003)

4.2.2.3 Factors affecting denitrification

4.2.2.3.1 Oxygen and nitrogen oxides

Oxygen and nitrogen oxides are found to be inhibiting factors to the denitrification rate. Oxygen had been found to compete with nitrite reductase for electrons with a saturated DO concentration of 13%, resulting in an accumulation of nitrite in the water, while nitrate reductase are inhibited with a DO concentration of greater than 13%. (Water Environment Federation. Municipal Subcommittee, 1998) NO_2^- and NO_3^- had also been observed to have an inhibitory effect on the denitrifying activities, with 6.2 g NO_3^-/L and 0.27 g NO_2^-/L respectively. (Cervantes, 2009; Vesilind et al., 2003)

4.2.2.3.2 pH and temperature

Denitrifications are reported to take place in a wide range of pH values and temperatures. It had been found that denitrification rate decreases with decreasing pH, with pH value between 6 and 9 being the most efficient. The pH values also have an effect on the final product, with NO being the main product at pH below 5 and N_2 for pH over 7. Temperature is another factor affecting the process, mainly affecting the nitrate consumption rate and the bacteria growth rate. (Cervantes, 2009) In general, a pH between 7 and 8 and temperature between 20 – 35°C is maintained for the denitrifying process.

4.3 Rotating Biological Contactor

4.3.1 Introduction

Rotating Biological Contactors (RBC) are mainly used in small treatment works serving a relatively smaller population. It is often made and delivered as a package plant from the manufacturer. The

main RBC unit consists of a series of plastic media mounted on a shaft, which rotates slowly (at approximately 1 to 2 revolutions a minute) in the tank. The media are partially submerged in the wastewater, typically around 40%, but other configurations of up to 85% submergence have also been found from some manufacturers.

4.3.2 Media

The media is the supporting material for biomass growth, the most important property of a good media is its surface area. The most common media used in the UK are corrugated high-density polyethylene disc which maximise its available surface area. Although manufacturers have tried different types of media in the past, but certain non disc like media have experienced problems like internal clogging as the biomass build up on the media.

Another important aspect of assembling the media is the spacing between the discs. If the discs are too closely placed, a bridging effect may occur, meaning the biomass grown across two discs and reducing the flow and the available surface area. The optimal discs separation varies between 15 to 30 mm, giving an approximate 50 – 80 m² to 450 – 700 m² per meter for 1 meter and 3 meter diameter discs respectively. (Chartered Institution of Water and Environmental Management, 2000)

4.3.3 Organic Loading

The organic loading rate will have to be within the oxygen transfer capability of the system in order to work efficiently (Metcalf & Eddy et al., 2003). According to The British Standard Code of Practice, the organic loadings of the RBC should not exceed 5 g BOD/m² in order to achieve a 20:30 standard. (Chartered Institution of Water and Environmental Management, 2000) High organic loadings enhance biofilm growth and may lead to problems like odours generation, deterioration of effluent quality and the outgrowth of beggiatoa.

Beggiatoa is a sulphur oxidizing bacteria that grows on the outer layer of the biofilm, which prevents sloughing (Metcalf & Eddy et al., 2003). Excessive growth of beggiatoa had been found when the loading limit exceed $0.031 \text{ kg BOD/m}^2 \cdot \text{d}$ (Chartered Institution of Water and Environmental Management, 2000), causing a build up of the biofilm on the discs and possibly damages to the shaft due to the heavy weight of biomass.

5 Paper for publication

Recirculation in a full scale Rotating Biological Contactor for Nitrogen Removal

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Abstract

The effect of an internal recirculation on the total nitrogen removal efficiency in a full scale Rotating Biological Contactor (RBC). The study consists of two trials using two RBC units in parallel, with one acting as a control and the other with a recycle system installed. Trial 1 was to recycle nitrate rich effluent from the humus tank back to the septic tank at the front of the unit, where denitrification occurs using the raw wastewater as a carbon source. TN removal had improved from 25% to 74% when the recycle ratio (R) was increased from 0 to 2. There is no noticeable effect on BOD₅ concentration in the effluent as R increases, maintaining a steady 96% removal rate. The effluent had shown a slight increase in turbidity as R increase. Trial 2 was to recycle from the biozone to the septic tank. An overall reduction in removal efficiencies in the test unit have shown that recycling directly from the biozone could not achieve a better performance. Recycling from the biozone had also induced simultaneous nitrification and denitrification in the septic tank, resulting in a 50% reduction in BOD₅ and TN prior entering the biozone.

Introduction

Nitrogen released from wastewater treatment plant has been proven guilty for eutrophication, causing damages to the watercourse and the environment. Under the current Urban Wastewater Treatment Directive (UWWTD), only treatment works with a capacity of 10,000 population equivalent (pe) plus or when discharging into a nitrogen sensitive area are regulated.

While larger treatment works are carefully regulated, a TN consent of 15mg/l and 10mg/l are required for plants with a capacity of 10,000 – 100,000pe and >100,000pe respectively, smaller works like those using RBCs as the main process for treatment is considered to be a future concern.

In the UK, RBCs are commonly used for BOD removal. Previous studies had found that with an external carbon source, like methanol, 84% nitrogen

removal can be achieved in a RBC system (Murphy et al., 1977). The downside will be an increase in the operating cost and additional maintenance.

While other studies had shown RBC recirculation system were able to achieve satisfying $\text{NH}_3\text{-N}$ removal rate (Ayoub and Saikaly, 2004), there are not a lot of research to prove that good TN removal can be achieved without the addition of an external carbon source.

The aim of this study was to try to determine the accessibility of TN removal with recirculation within the RBC system using the influence wastewater as a carbon source, and also to study the effect on the quality of the water when recycling from different locations.

Material and method

Work site and RBC reactor

The trial was carried out in a small wastewater treatment works located in the Midlands area in the UK. The plant serves a small village with an approximate population of 1700 and has the capacity to treat a dry weather flow (DWF) of $700 \text{ m}^3/\text{d}$. The BOD_5 , SS and NH_3 consent for the final effluents are 20 mg/l, 30 mg/l and 5 mg/l respectively.

The works comprises of 3 RBC units in parallel, a tertiary reedbed and a diversion system at the inlet which divert the flow directly onto the reedbed during storm conditions.

A 5 stages RBC unit with a total surface area of 9578 m^2 is used in this study. The wastewater flows from a splitter box into the septic tank by gravity for primary sedimentations. It then enters the bicone through an orifice located at the front of the unit. The wastewater then flows through the discs, which are 35% submerged and rotates at 1 round per minute (RPM), and exits into

the humus tank. The wastewater then flows over a weir onto the reedbed.

Experimental operating procedures

Week 1 & 2	Initial assessments for plant performance prior to trial
Week 3	Recirculation from humus tank to septic tank at $R = 0.5$
Week 4	Recirculation from humus tank to septic tank at $R = 1$
Week 5	Recirculation from humus tank to septic tank at $R = 1.5$
Week 6	Recirculation from humus tank to septic tank at $R = 2$
Week 7 & 8	Stabilization period (no recirculation)
Week 9 & 10	Recirculation from biozone to septic tank at $R = 1$
Week 11 & 12	Recirculation from biozone to septic tank at $R = 2$

Table 1: Timescales of the complete trial.

Two of the three units on site were used for the experiment, with one being a control unit as a measure of the results. Influent and effluent samples were collected from both the test and control RBC unit without recirculation for 2 weeks for initial assessments.

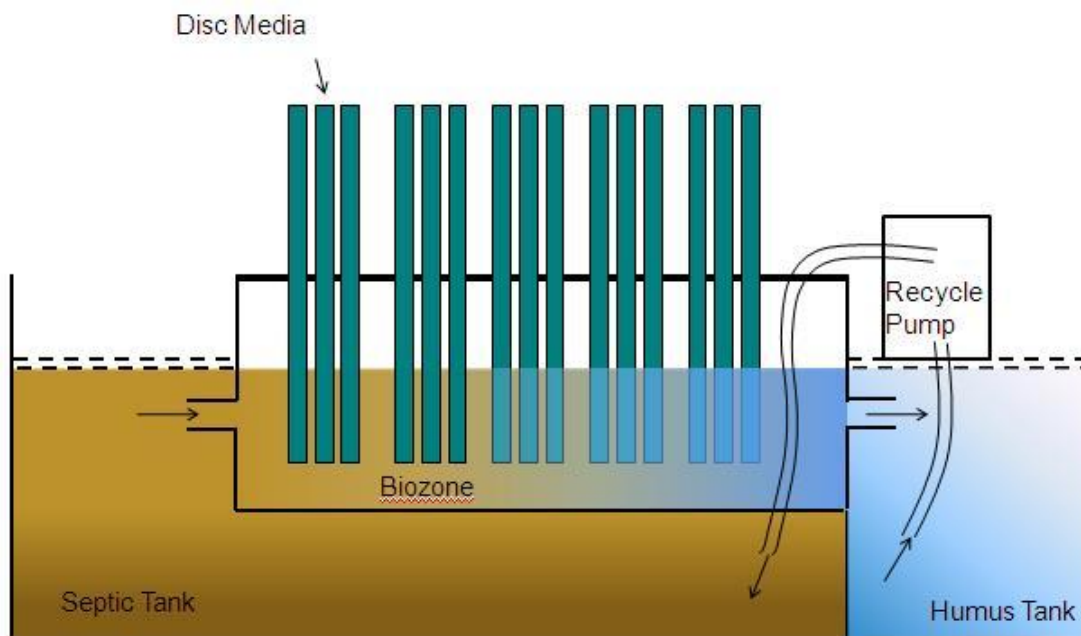


Figure 1: Recirculation from humus tank to septic tank.

A submersible pump was installed in the humus tank for the recirculation to

the septic tank. The speed of the pump was manually altered by a control panel located on the rail inside the RBC unit. The recirculation flow rate was calibrated by measuring the time required to fill a 40 l tank.

Recirculation from the humus tank started after the initial assessment period and samples were taken for 4 weeks at recycle ratio (R) 0.5, 1, 1.5 and 2 respectively. The plant was continued being sampled and allowed to stabilize for two weeks with no recirculation.

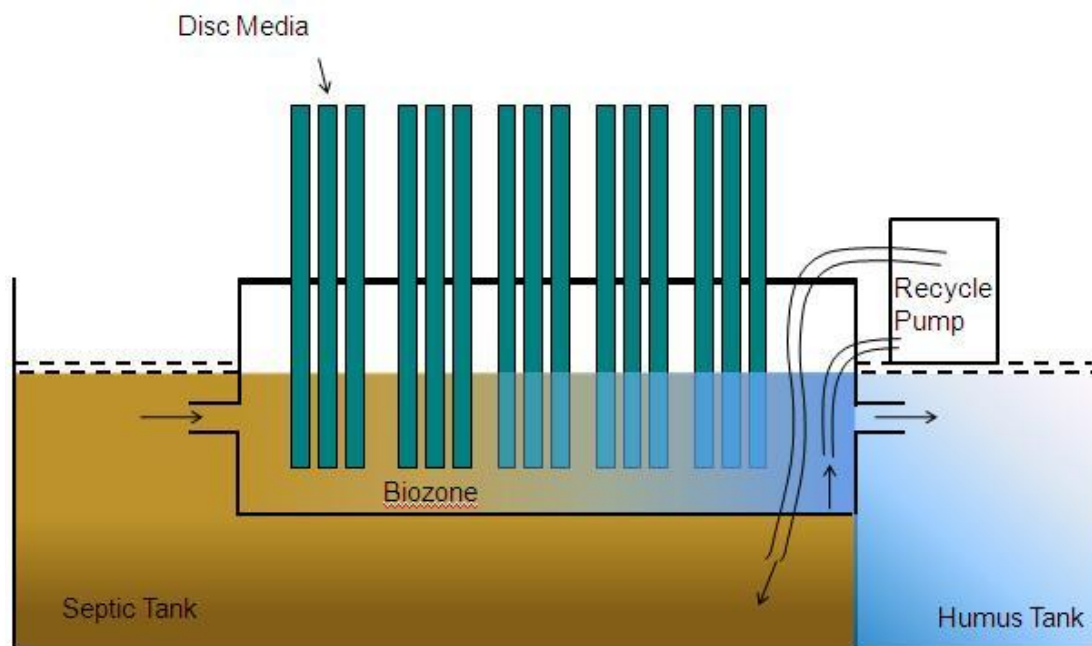


Figure 2: Recirculation from biozone to septic tank.

A second suction pump was set up in the RBC unit for the recirculation from the biozone to the septic tank. The pump was controlled and calibrated using the same method as the first submersible pump. Samples were collected for a further 4 weeks, with R increasing from 1 to 2 after two weeks.

Sampling procedures

Influent samples were collected near the biozone inlet in the septic tank where spot samples were taken twice a week using an automatic sampling machine. Effluent samples were collected at the humus tank 3 times a week where composite samples were taken at 15 minutes interval for 24 hours.

All the samples collected were sent to a NAMAS (National Accreditation of Measurement and Sampling) accredited laboratory for analysis on the same day. NH₃, TON, SS, BOD₅ and pH were tested for all samples.

Analytical methods

pH: $\text{pH} = -\text{Log}_{10} [\text{H}^+]$, the pH of the sample was measured directly using a pH probe which has been previously calibrated with a predetermined solution. (Severn Trent Laboratory, WAS039-MS)

BOD₅: 5 day Biochemical Oxygen Demand (BOD₅) is defined as the oxygen uptake for the biochemical oxidation in the sample at 20°C over a 5 days period. The sample was mixed and diluted with de-ionized water and placed in the dark at 20°C for 5 days. The dissolved oxygen (DO) level was measured prior and after the test to calculate the BOD₅ level. Allythiourea(ATU) was used to minimise the effect of nitrification during the test. (Severn Trent Laboratory, WAS001-MS)

Suspended Solids (SS): A representative sample with a known volume was taken and filtered through a pre-treated, pre-weighted glass fibre filter paper. The sample was then dried in an oven at 105±5°C and weighted to determine the amount of SS in the sample. (Severn Trent Laboratory, WAS006-MS)

Total Oxidized Nitrogen (TON): the TON of the sample was determined by reducing nitrate ions (NO₃⁻) to nitrite (NO₂⁻) using the reducing agent, hydrazine (N₂H₄), with cupric ions (Cu²⁺) acting as a catalyst. The total nitrite solution was then reacted with sulphanilamide and N-1-Naphthylenediamine dihydrochloride under acidic conditions, generating a pink solution. It was then measured by a spectrophotometer at 540nm. (Severn Trent Laboratory, WAS036-MS)

Ammonia: Hypochlorite ions generated from the reagent, sodium dichlorocyanurate, were reacted with ammonia in the sample to form

monochloramine. The solution then reacts with salicylate at pH 10.5 with sodium nitroprusside to form a blue iodophenol compound. It was then measured by a spectrophotometer at 660nm. (Severn Trent Laboratory, WAS036-MS)

Results

Influences pH, BOD₅, SS, Ammoniacal N, and Total oxidised N concentrations had been tested for both RBC units. A relatively consistent pH with value between 7.1 to 8.2 has been observed throughout the trial period. Ammoniacal N had been taken as TN in the influences since low concentrations of TON were neglected. A comparison of the BOD₅, SS and TN concentration over time for the two units can be seen in Figure 1, Figure 2 and Figure3 respectively.

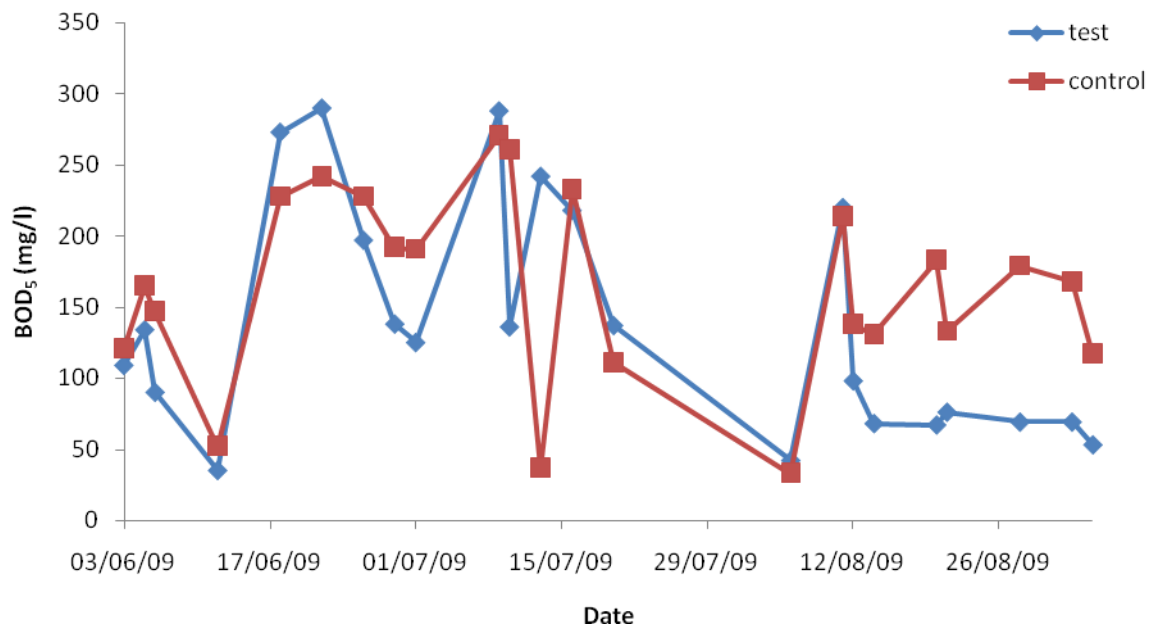


Figure 3: A comparison of the influent BOD₅ concentration for the test and control unit.

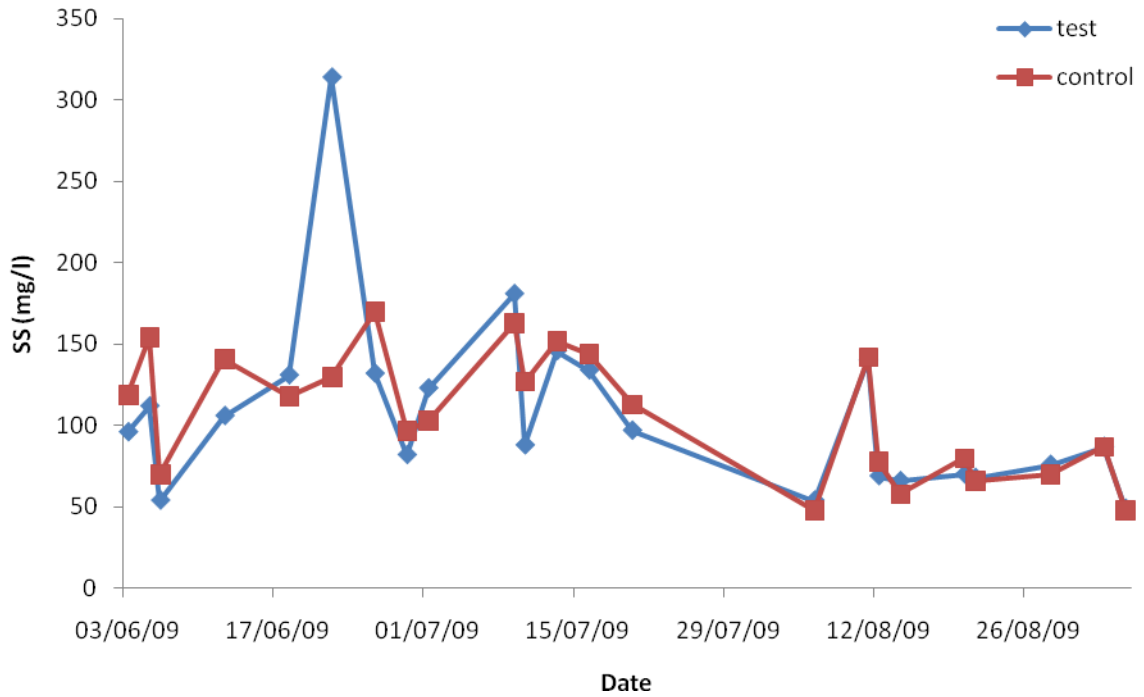


Figure 4: A comparison of the influent SS concentration for the test and control unit.

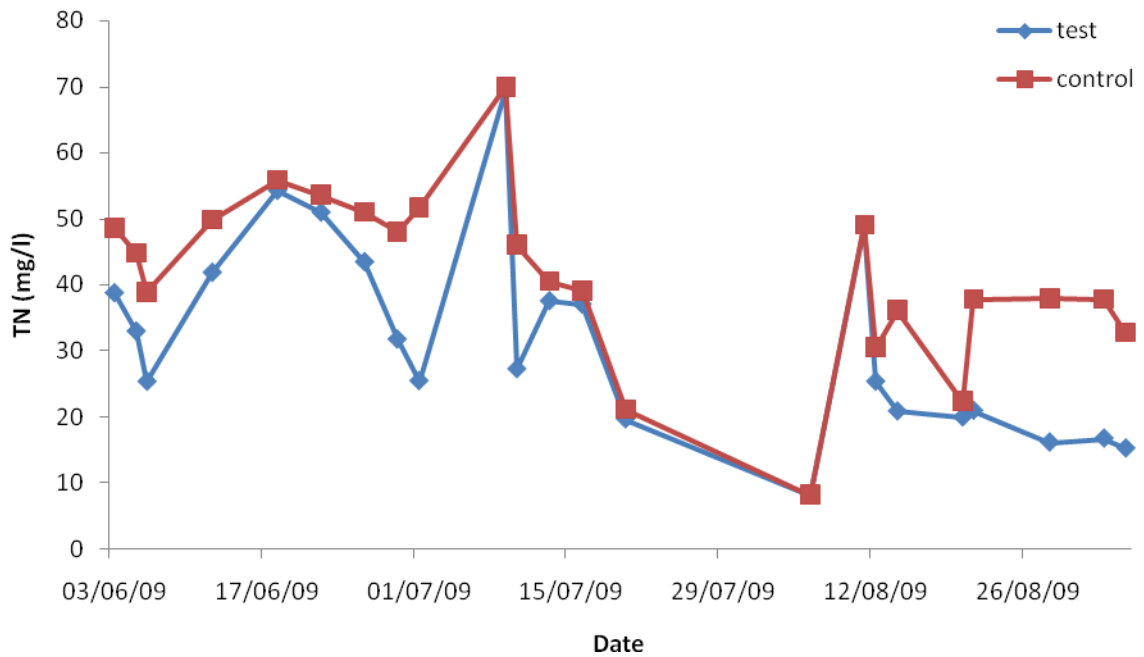


Figure 5: A comparison of the influent TN concentration for the test and control unit.

During trial 1 (from 03/06/09 to 12/08/09), BOD₅ concentration has shown some variations over the 6 weeks period. The most significant being a BOD₅ concentration of 37 mg/l was recorded on 13/07/09 for the control unit (Figure 4). Suspended solids concentration was significantly higher for the

test unit (314mg/l) on 22/06/09 compare to the control unit (130mg/l) (Figure 4). The test unit have shown a lower TN concentration in general during trial 1, with nearly 50% less than the control unit on 01/07/09 (Figure 5).

The influence wastewater samples have shown a similar characteristic for both units in trial 1 (from 03/06/09 to 12/08/09).

During trial 2 (12/08/09 onwards), the BOD₅ and TN concentration for the test unit are approximately 50% less than the control unit (Figure 3 and 5), whereas the SS have shown no noticeable difference.

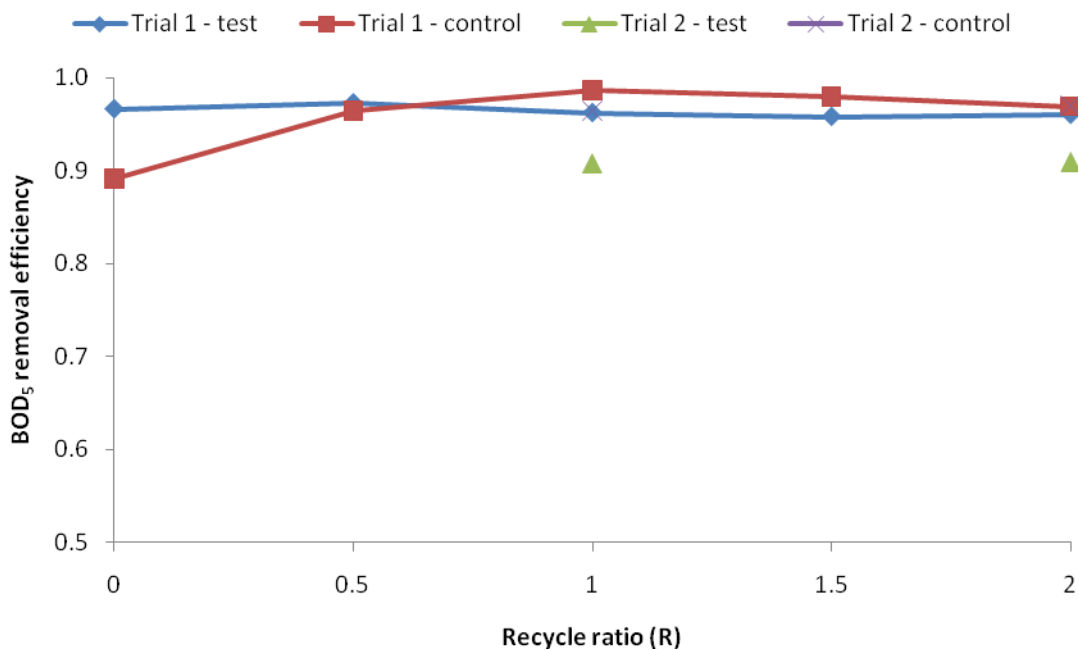


Figure 6: A comparison of the effluent BOD₅ concentration for the test and control unit.

During trial 1, the test unit has maintained a relatively stable BOD₅ removal rate at around 96% removal as the recycle ratio increased gradually from 0.5 to 2. The control unit has shown a poorer performance achieving only around 90% removal at the start, but rose to a relatively steady rate with an average of 97.5% removal for the rest of the trial.

During trial 2, as there are no changes made to the control unit, it had maintain around a 97% removal rate very similar on the whole comparing with the result in trial 1. Where the wastewater was recirculated directly

from the biozone to the septic tank in the test unit, BOD₅ removal had again maintained a relatively consistent but lower rate regardless of the recycle ratio. The BOD₅ removal rate had dropped from 96% in trial 1 to around 91% removal in trial 2.

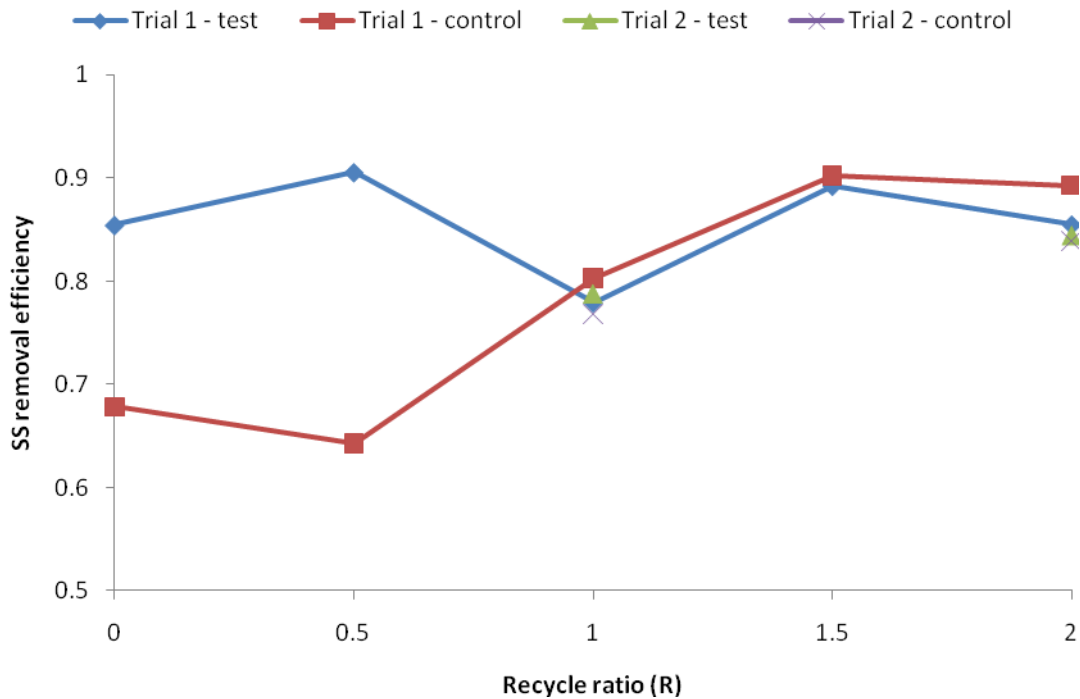


Figure 7: A comparison of the effluent SS concentration for the test and control unit.

During trial 1, the control unit had an increased SS removal efficiency from around 65% to 90% removal. At the same period, the test unit had shown more fluctuated removal rate ranging from 78% to 91% removal. As the test unit had shown a better performances when $R = 0$ and $R = 0.5$, the more similar results, compare to the control unit, shown on the graph as the recycle ratio increases can be considered a decrease in performance for SS removal efficiency in the test unit.

During trial 2, both unit have shown very similar results with around 77% removal at $R = 1$ and 84% at $R = 2$. There is also no clear evident showing any differences between recycling from the humus tank and the biozone as the test unit achieves a very similar removal rate in both cases.

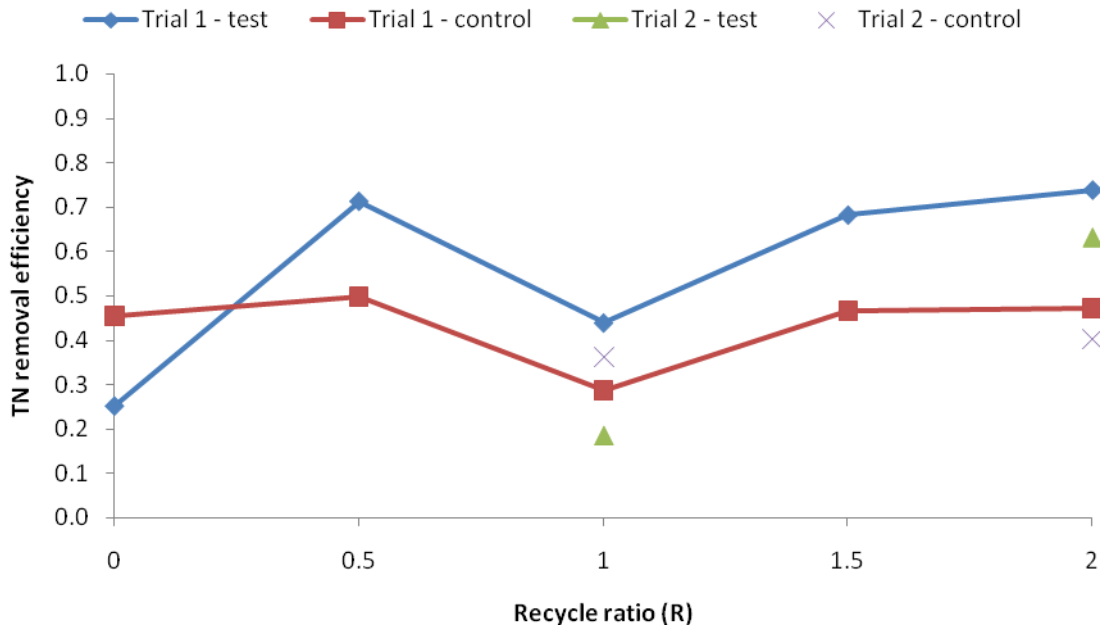


Figure 8: A comparison of the effluent TN concentration for the test and control unit.

During trial 1, the test unit have shown an increase in TN removal rate in general as the recycle ratio increases, with only 25% TN removal when there are no recirculation and rose to 73% with $R = 2$. Meanwhile the control unit has shown a more consistent rate at around 44% removal.

During trial 2, the control unit have once again shown some very consistent results (with an average of around 38% removal) comparing to trial 1 (average 44% removal). While the test unit had also shown an increase in TN removal efficiency as the recycle ratio increases (rose from 19% to 63% removal), it was not able to achieve the removal rate shown in trial 1 at $R = 1$ and $R = 2$ (44% removal and 74% removal respectively).

BOD ₅	Trial 1		Trial 2	
	Trial 1 - test	Trial 1 - control	Trial2 - test	Trial 2 - control
R				
0	0.97	0.89		
0.5	0.97	0.96		
1	0.96	0.99	0.91	0.96
1.5	0.96	0.98		
2	0.96	0.97	0.91	0.97

Table 2: A comparison of the BOD₅ removal efficiency.

SS	Trial 1		Trial 2	
	Trial 1 - test	Trial 1 - control	Trial2 - test	Trial 2 - control
0	0.85	0.68		
0.5	0.91	0.64		
1	0.78	0.80	0.79	0.77
1.5	0.89	0.90		
2	0.85	0.89	0.84	0.84

Table 3: A comparison of the SS removal efficiency.

TN	Trial 1		Trial 2	
	Trial 1 - test	Trial 1 - control	Trial2 - test	Trial 2 - control
0	0.25	0.45		
0.5	0.71	0.50		
1	0.44	0.29	0.19	0.36
1.5	0.68	0.47		
2	0.74	0.47	0.63	0.40

Table 4: A comparison of the TN removal efficiency.

Discussion

The influent wastewater had shown relatively similar characteristics for both RBC units in trial 1 as seen in Figure 3, Figure 4 and Figure 5. While the results had also shown a clear reduction in BOD₅ and TN level in the influent samples for the RBC unit during trial 2, which suggested that simultaneous nitrification and denitrification occurred in the septic tank.

Ammonia N being reduced as a result of nitrification while BOD₅ was used as a carbon source for denitrification. Both the BOD₅ and Ammonia N prior entering the biozone in the test unit had been reduced by nearly 50% compare to the control unit in the same period (Figure 3 and Figure 5). Although the results from trial 2 had followed the same trend as trial 1, it had also suggested an overall decrease in the removal efficiency for the three parameters tested.

It should be note that both units had been desludged on 23/06/09 and 24/06/09, just before recycling at $R = 1$ in trial 1. Although no data had been collected during the time but it is thought to have an adverse effect on the plant performance, primarily on the results at $R = 1$ in trial 1 for both units. It should also be emphasized that while we had no control on the maintenance of the plant, outside factors such as power cuts and pump failures, which results in no recirculation in the middle of a trial and diverting all the flow to one RBC unit, had greatly affected the consistency of the results.

Conclusion

TN removal efficiency increases with the recycle ratio, in the expense of an increase in SS in the effluent. Internal recirculation in RBC unit had proven to be a cheap and reliable way to achieve TN removal.

Recirculation directly from the biozone results in simultaneous nitrification and denitrification in the septic tank, causes a drop in BOD_5 and TN concentration prior entering the biozone.

The trial had shown recycling from the humus tank is able to achieve a better performance than recycling from the biozone, with a removal efficiency of 74% and 63 % at $R = 2$ respectively.

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7 Appendix

RBC1 - influance test

		pH	Ammoniacal Nitroacen as N	Nitroacen. Total Oxidised as N	Suspended Solids	BOD + ATU (5 day)	
SP1	2009/6/3	7.5	38.7	<0.3	96	109	
SP3	2009/6/5	7.8	32.9	<0.3	112	134	<= current assessment
SP5	2009/6/6	7.6	25.3	<0.3	54	90	
SP7	2009/6/12	7.9	41.8	<0.3	106	35	
SP9	2009/6/18	8.1	54.2	<0.3	131	273	<= recycle ratio = 0.5
SP11	2009/6/22	7.3	50.9	<0.3	314	290	
SP13	2009/6/26	7.5	43.4	<0.3	132	197	<= recycle ratio = 1
SP15	2009/6/29	7.3	31.7	<0.3	82	138	
SP17	2009/7/1	7.5	25.4	<0.3	123	125	<= recycle ratio = 1.5
SP19	2009/7/9	7.1	69.3	<0.3	181	288	
SP21	2009/7/10	7.4	27.2	<0.3	88	136	<= recycle ratio = 2
SP23	2009/7/13	7.2	37.5	<0.3	146	242	
SP25	2009/7/16	7.1	37	<0.3	134	218	<= stablization
SP27	2009/7/20	8	19.6	<0.3	97	137	
SP29	2009/8/6	7.4	8.1	<0.3	54	42	
SP31	2009/8/11	7.1	48.8	<0.3	140	220	<= recycle ratio = 1
SP33	2009/8/12	7.1	25.3	<0.3	69	98	
SP35	2009/8/14	7.3	20.8	<0.3	66	68	
SP37	2009/8/20	7.2	19.9	<0.3	70	67	
SP39	2009/8/21	7.2	20.9	0.7	68	76	<= recycle ratio = 2
SP41	2009/8/28	7.2	16.1	<0.3	76	69	
SP43	2009/9/2	7	16.7	<0.3	87	69	
SP45	2009/9/4	7.9	15.2	<0.3	49	53	

RBC2 - influence controlled

		pH	Ammoniacal Nitroacen as N	Nitroacen. Total Oxidised as N	Suspended Solids	BOD + ATU (5 day)	
SP2	2009/6/3	7.7	48.6	<0.3	119	121	
SP4	2009/6/5	7.9	44.8	<0.3	154	165	<= current assessment
SP6	2009/6/6	7.3	38.9	<0.3	70	147	
SP8	2009/6/12	8.1	49.8	<0.3	141	52	
SP10	2009/6/18	8.2	55.9	<0.3	118	228	<= recycle ratio = 0.5
SP12	2009/6/22	7.7	53.6	<0.3	130	242	
SP14	2009/6/26	7.4	51	<0.3	170	228	<= recycle ratio = 1
SP16	2009/6/29	7.2	48	<0.3	97	192	
SP18	2009/7/1	7.5	51.7	<0.3	103	191	<= recycle ratio = 1.5
SP20	2009/7/9	7.1	70	<0.3	163	271	
SP22	2009/7/10	7.3	46	<0.3	127	261	<= recycle ratio = 2
SP24	2009/7/13	7.2	40.5	<0.3	152	37	
SP26	2009/7/16	7.2	39.1	<0.3	144	233	<= stablization
SP28	2009/7/20	7.9	21.1	<0.3	113	111	
SP30	2009/8/6	7.4	8.1	<0.3	48	33	
SP32	2009/8/11	7.1	49.1	<0.3	142	214	
SP34	2009/8/12	7.1	30.5	<0.3	78	138	<= recycle ratio = 1
SP36	2009/8/14	7.3	36.1	<0.3	58	131	
SP38	2009/8/20	7.2	22.3	<0.3	80	183	
SP40	2009/8/21	7.2	37.8	<0.3	66	133	
SP42	2009/8/28	7.3	37.9	<0.3	70	179	<= recycle ratio = 2
SP44	2009/9/2	7.3	37.8	<0.3	87	168	
SP46	2009/9/4	7.9	32.7	<0.3	48	117	

RBC1 - Effluence test

		pH	Ammoniacal Nitrogen as N	Nitrogen, Total Oxidised as N	Suspended Solids	BOD + ATU (5 day)	
C1	2009/6/3	7.4	<0.3	28.7	9	3	<= current assessment
C3	2009/6/5	7.7	2.1	29.1	15	3	
C5	2009/6/6	7.4	4	17.9	2	3	
C7	2009/6/10	7.5	<0.3	24.9	10	3	
C9	2009/6/12	7.6	<0.3	26.9	25	3	<= recycle ratio = 0.5
C11	2009/6/15	7.6	<0.3	27.7	15	2	
C13	2009/6/18	8	<0.3	16.8	22	9	<= recycle ratio = 1
C15	2009/6/19	8.1	<0.3	12.8	23	7	
C17	2009/6/22	7.5	0.7	15.8	18	7	
C19	2009/6/26	7.4	3	21.9	28	12	<= recycle ratio = 1.5
C21	2009/6/29	7	<0.3	23.3	19	3	
C23	2009/6/30	7.1	<0.3	18	24	4	<= recycle ratio = 2
C25	2009/7/1	7.2	<0.3	16.4	21	8	
C27	2009/7/2	7.2	<0.3	14.6	20	14	
C29	2009/7/9	7.3	<0.3	14.3	8	4	
C33	2009/7/10	7.4	0.9	10.8	28	12	<= stablization
C35	2009/7/13	7.6	0.7	6.2	6	3	
C37	2009/7/16	7.2	42.7	<0.3	76	188	
C39	2009/7/17	7.3	18.3	<0.3	52	62	
C41	2009/7/20	8.1	6	2.6	17	14	
C43	2009/8/6	7.6	1.7	7.4	38	12	
C45	2009/8/7	8.2	<0.3	10.8	8	4	
C47	2009/8/11	7.4	8	6.3	41	31	

C49	2009/8/12	7.4	<0.3	18.6	18	8
C51	2009/8/13	7.6	<0.3	16.9	5	8
C53	2009/8/14	7.5	<0.3	17.4	9	4
C55	2009/8/20	7.4	0.4	19.4	17	12
C57	2009/8/21	7.5	<0.3	19.5	20	6
C59	2009/8/24	7.3	<0.3	29.3	19	5
C61	2009/8/27	7.3	<0.3	20.2	13	4
C63	2009/8/28	7.3	2.6	15.3	9	5
C65	2009/9/2	7.2	<0.3	11.6	26	11
C67	2009/9/3	7.6	0.6	8.1	5	6
C69	2009/9/4	8	<0.3	11.2	2	3

<= recycle ratio = 1
<= recycle ratio = 2

RBC2 - Effluence controlled

		pH	Ammoniacal Nitrogen as N	Nitrogen, Total Oxidised as N	Suspended Solids	BOD + ATU (5 day)	
C2	2009/6/3	7.2	1	29	24	5	<= current assessment
C4	2009/6/5	7.5	1.4	30.2	27	10	
C6	2009/6/6	7.4	2.2	16.6	42	12	
C8	2009/6/10	7.1	1.4	25.2	41	10	
C10	2009/6/12	7.3	3.2	20	56	20	<= recycle ratio = 0.5
C12	2009/6/15	7.2	1.3	28	35	16	
C14	2009/6/18	7.9	2.7	22.5	71	2	<= recycle ratio = 1
C16	2009/6/19	7.9	<0.3	30.7	29	12	
C18	2009/6/22	7.4	1.4	29.1	33	11	
C20	2009/6/26	7.1	0.5	35.4	39	<1	<= recycle ratio = 1.5
C22	2009/6/29	6.8	<0.3	35.6	21	3	
C24	2009/6/30	6.9	<0.3	34.8	19	4	<= recycle ratio = 2
C26	2009/7/1	7.1	<0.3	35.7	11	6	
C28	2009/7/2	7.1	<0.3	35.6	20	5	
C30	2009/7/9	7.4	<0.3	26.1	8	3	<= stablization
C34	2009/7/10	7.3	<0.3	27.2	20	6	
C36	2009/7/13	7.4	1.7	18.5	10	3	
C38	2009/7/16	7.1	0.5	24.8	20	8	
C40	2009/7/17	7.3	0.7	23.2	16	9	
C42	2009/7/20	8	<0.3	12.1	19	4	
C44	2009/8/6	7.4	<0.3	12.6	17	1	
C46	2009/8/7	8.4	<0.3	11.7	15	3	
C48	2009/8/11	7.2	<0.3	25.2	18	4	

C50	2009/8/12	7.3	1.7	23.7	29	6
C52	2009/8/13	7.5	<0.3	20.8	5	5
C54	2009/8/14	7.5	<0.3	24	8	1
C56	2009/8/20	7.3	0.7	25.4	26	7
C58	2009/8/21	7.2	<0.3	31.5	7	3
C60	2009/8/24	7.1	<0.3	29.3	23	9
C62	2009/8/27	7.2	0.8	26	22	6
C64	2009/8/28	7.1	<0.3	25.1	13	4
C66	2009/9/2	7.1	<0.3	25.7	15	8
C68	2009/9/3	7.5	<0.3	14.3	3	3
C70	2009/9/4	8.1	<0.3	16.5	2	2

<= recycle ratio = 1
<= recycle ratio = 2