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นางสาวภริตา พิมพันธุ์

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ROCK-BED FILTRATION PERFORMANCE EVALUATION USING DOMESTIC WASTEWATER

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ภริตา พิมพันธุ์ : การประเมินประสิทธิภาพชั้นหินกรองในการบำบัดน้ำเสียชุมชน
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การวิจัยครั้งนี้ เป็นการทดลองศักยภาพของชั้นหินกรองในการกำจัดมลพิษออกจากน้ำและน้ำเสีย โดยมีวัตถุประสงค์เพื่อประเมินประสิทธิภาพ และศึกษาสภาพการดำเนินงานที่เหมาะสมของระบบชั้นหินกรอง ระบบชั้นหินกรองที่ใช้ทดลองประกอบด้วย ถังปฏิกิริยารูปสี่เหลี่ยม 2 ถัง ภายในบรรจุหินกรองขนาดเส้นผ่าศูนย์กลาง 2-4 เซนติเมตร ในถังปฏิกิริยาที่ 1 และ 5-7 เซนติเมตร ในถังปฏิกิริยาที่ 2 ถังทั้งสองติดตั้งระบบเติมอากาศ 3 ทาง และ 6 ทาง โดยทำการทดลองในสภาวะที่แตกต่างกัน 3 ช่วงเวลา คือ ระยะเวลาเก็บกัก 6, 9 และ 12 ชั่วโมง

ผลการทดลองพบว่า ตลอดการทดลอง ระบบชั้นหินกรองมีประสิทธิภาพสูงในการกำจัดมลสารอยู่ในช่วง 60-90 % และยังแสดงให้เห็นถึงกลไกสำคัญในกระบวนการนี้คือ การตกตะกอนของมลสาร ในการทดลองช่วงที่ 3 ปรากฏว่า การกำจัดบีโอดีทั้งหมดมีค่าประมาณ 81-82 % ซึ่งแสดงให้เห็นว่า การใช้ชั้นหินกรองชีวภาพในการกำจัดมลพิษนั้นต้องอาศัยเวลานาน จึงจะมีประสิทธิภาพในการกำจัดดี และเมื่อระยะเวลาเก็บกักนานขึ้นจะทำให้ประสิทธิภาพในการกำจัดมลพิษสูงขึ้นด้วยยกเว้นการกำจัดสารละลายซีโอดี โดยประสิทธิภาพในการกำจัดมลพิษจะมีค่ามากที่สุดในช่วง 6-9 ชั่วโมง หลังจากนั้นจะมีค่าเพิ่มขึ้นเพียงเล็กน้อยในช่วง 9-12 ชั่วโมง จึงอาจสรุปได้ว่า ระยะเวลาเก็บกักที่เหมาะสมในการกำจัดมลพิษคือ 9 ชั่วโมง เมื่อเปรียบเทียบผลของการกำจัดมลสารของหินกรองพบว่า หินกรองขนาดเล็กมีประสิทธิภาพดีกว่าหินกรองขนาดใหญ่ประมาณ 8 % แต่หินกรองขนาดเล็กจะมีประสิทธิภาพในการกำจัดมลสารดีกว่าในช่วงเริ่มต้น และจะลดลงหลังจากผ่านช่วงอุดตัน ระบบการเติมอากาศมีผลต่อประสิทธิภาพในการกำจัดมลสาร ประมาณ 8-9 % สำหรับการทดลองช่วงที่ 2 ซึ่งใช้ระบบเติมอากาศ 3 ทางในช่วงแรก และระบบเติมอากาศ 6 ทางในช่วงหลัง พบว่าค่าเฉลี่ยในการกำจัดบีโอดีทั้งหมดประมาณ 46 % และ 76 % ตามลำดับ ชี้ให้เห็นว่า ระบบเติมอากาศ 6 ทางมีประสิทธิภาพมากกว่า และช่วยให้ฟิล์มชีวภาพมีประสิทธิภาพในการกำจัดบีโอดีทั้งหมดมากขึ้นด้วย นอกจากนี้ค่าความพรุนของทั้ง 2 ถังปฏิกิริยามีค่าลดลงจาก 47-48 % เป็น 42-43 % ในช่วง 5 ½ เดือน โดยค่าความพรุนของถังปฏิกิริยาที่ 1 มากกว่าถังปฏิกิริยาที่ 2 เล็กน้อย

สาขาวิชาวิศวกรรมสิ่งแวดล้อม ลายมือชื่อนักศึกษา____________________________
ปีการศึกษา 2544 ลายมือชื่ออาจารย์ที่ปรึกษา______________________

PARITA PIMPAN : ROCK-BED FILTRATION PERFORMANCE EVALUATION USING DOMESTIC WASTEWATER THESIS ADVISOR : DR.RANJNA JINDAL, 123 PP.

This study was conducted to investigate the potential of rock-bed filtration method to accomplish removal of pollutants from water/wastewater. The purpose of this investigation was to evaluate the process efficiency, optimum design parameters, and most appropriate operating conditions. Experimental setup consisted of two rectangular reactor units (named RBF I and RBF II), filter media (with equivalent diameters of 2-4 cm and 5-7 cm), aeration system (3 and 6 air diffusers). The experiments were divided into 3 runs with different operating conditions.

The results of this research showed that the maximum removal efficiency was found for particulate matter (SS and VSS), ranging 60-90 % throughout the experimental period. This implied that the main removal mechanism was sedimentation of the particulate matter. In case of T-BOD, removal was not significant at the beginning but reached up to 81-82 % during the third run. This means that for effective biofilm performance, longer operation is required. An increase in HRT increased the removal efficiency in all cases except S-COD. However, maximum increase in removal efficiency was observed between 6 h and 9 h and then only a nominal increase for 9 h < HRT < 12 h. Thus, the optimum HRT seems to be 9 h. The effect of rock size was observed as about 8 % increase in particulates removal for smaller rocks compared to the bigger ones. Smaller rocks showed a bit better particulate removal initially but the removal decreased later due to clogging. The aeration had some effect on SS and VSS removal (8-9 % improvement). The average percent removal of T-BOD during the second run with 3 air diffusers in the first half period and with 6 air diffusers during the second half one, were 46 % and 76 %, respectively. More aeration (6 diffusers) helped microorganisms in attached biofilm to remove more T-BOD. Porosity in both reactors reduced from about 47-48 % to 42-43 % over a period of 5 ½ months. The porosity reduction in RBF I was only slightly higher than RBF II.

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List of Abbreviations

Abbreviation	Description	Unit
A	Reactor surface area	m^2
C_1	Particulate organic matter (POM)	g COD/m^3
C_2	Inert suspended solids (ISS)	g/m^3
C_3	Dissolved oxygen (DO)	g/m^3
C_4	Dissolved organic matter (DOM)	g COD/m^3
C_5	Ammonium nitrogen (NH_4^+-N)	g N/m^3
C_s	Dissolved oxygen (DO) saturation value	g/m^3
DO	Dissolved oxygen	mg/L
d_1	Sedimentation coefficient for POM	day^{-1}
d_2	Sedimentation coefficient for ISS	day^{-1}
h	Height of the reactor	m
HRT	Hydraulic retention time	h
H	Effective height of the reactor	m
h_1	Water levels before water removed in the reactor	m
h_2	Water levels after water removed in the reactor	m
K_L	Gas mass transfer rate coefficient for surface reaeration	m/day
K_1	Half saturation coefficients for oxic decomposition of DOM	g/m^3
K_2	Half saturation coefficients for nitrification	g/m^3
K_3	Half saturation coefficients for nitrification	g/m^3

Abbreviation	Description	Unit
l	Length of the reactor	m
NH_3-N	Ammonia nitrogen	mg/L
P_1	Reaeration rate	g O_2/m^3-day
P_2	Sedimentation rate of particulate organic matter (POM)	g COD/ m^3-day
P_3	Sedimentation rate of inert suspended solid (ISS)	g/m^3-day
P_4	Reaction rate of oxic decomposition of DOM	g/m^3-day
P_5	Rate of nitrification	g N/m^3-day
Q	Flow rate	m^3/h
r_1	Reaction rate coefficient for oxic decomposition of DOM	day^{-1}
r_2	Reaction rate coefficient for nitrification	g N/m^3-day
SS	Suspended solids	mg/L
S-COD	Filtrate chemical oxygen demand	mg/L
T-BOD	Total biological oxygen demand	mg/L
T-COD	Total chemical oxygen demand	mg/L
V	Volume of water in the reactor	m^3
VSS	Volatile suspended solids	mg/L
V_1	Volume of water removed in the reactor	m^3
V_2	Volume of water and rocks in the reactor	m^3
w	Width of the reactor	m
$\in$	Porosity of the rock-bed	
θ	Hydraulic retention time	h

CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Water is considered to be the most important factor for life in our biosphere. It is essential for all living things including humans. At the same time, water is a carrier of many lethal diseases and pollutants distributed to human communities. At present there are problems of drought and scarcity of natural water sources for consumption and utilization. This is because there are limited resources and these limited resources are facing a variety of pollution situations therefore they cannot be used as before. An environmentalist's role comes in for the second of above measures; that is: (a) polluted waters must be treated before they are discharged into the rivers and other water bodies, and (b) water quality in the contaminated sources should be improved in one way or another. At present there are mainly two popular concepts of the treatment of polluted water: 1) outlet treatment, e.g., sewage treatment, and 2) inlet treatment, e.g., water treatment. Both types of above mentioned treatment processes are essential for water resources' protection, safe water usage and reduction of the pollutants in wastewater effluents.

Thus, a new concept for environmental conservation is emerging by using natural treatment systems taking advantage of the self-purification capacity of the water bodies. Main purpose of such treatment methods is to remove suspended solids and organic carbon from moderately polluted water bodies. This study deals with one such method using rock-bed filtration process, which can accomplish removal of pollutants from water/wastewater.

1.2 Rock-bed Filtration Process

Rock-bed filtration (RBF) is a combination of physical and biological processes (sedimentation and biological decomposition of living organisms). This process aims at the enhancement of the self-purification capacity of the water bodies by promoting the natural reactions occurring there. Target pollutants are mainly organics:particulate & dissolved. If dissolved oxygen concentration (DO) is sufficient some nitrification can be expected. Also denitrification will occur in the bottom parts of the sediments. Thus, this process can improve water quality in water bodies by reducing suspended solids (SS), BOD_5, NH_3-N and total nitrogen (T-N). What makes this process beneficial is the low cost of the treatment due to the low operation and maintenance requirements.

In its most basic form, the rock-bed system consists of a rectangular tank filled with rocks as shown in Figure 1-1. Polluted water enters from one side of the rectangular tank, passes through the rock-bed and comes out from the other end. Inside the tank, some natural physico-chemical and biological reactions take place, which cause the self-purification of the water. Technically, it is a combination of physical and biological processes, e.g., sedimentation, filtration and biodegradation of pollutants by the microorganisms. During the process, the suspended solids could be removed through rock-bed media by sedimentation and filtration process while colloidal solids and portion of soluble organic materials are removed by the biofilm coated on the rock surface. Biodegradation occurs by attached growth metabolism of microorganism. The solids will settle down on the bottom of the reactor containing a portion of suspended organisms and detachments. These will still take a long time to be digested by the aerobic, anoxic, anaerobic decomposition and later the nitrogen will be removed by biological nitrification and denitrification.

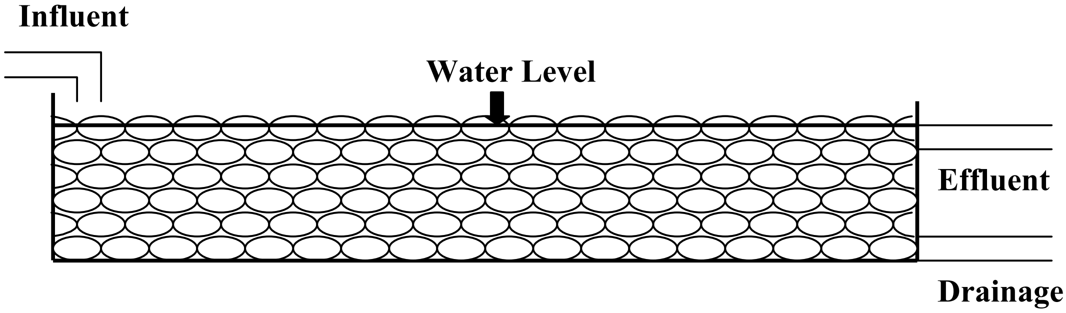


Figure 1-1. Conceptual diagram of rock-bed reactor.

Physical phenomenon of sedimentation causes the suspended solid to settle down at the bottom of the tank. During the course of their downward journey, inert as well as organic particulate matter gets attached to the surface of the rock. Also, the biofilm developed on the media surface (rocks) causes the removal of dissolved organic matter from the influent water. Thus, the effluent that comes out from the other end of the rock-bed reactor channel becomes clear in terms of the pollutant concentration. As the time passes, the thickness of the layer of the settled sediments increases. Therefore, sludge removal after a long-term operation will be required. Rocks are used for two purposes: one is to enhance the attached growth bacterial activity and the other is to promote sedimentation by reducing the sedimentation height.

1.4 Research Objectives

The objectives of this study were to conduct the following investigations:

1. To evaluate the performance of the rock-bed filtration process for wastewater treatment.
2. To obtain optimum design and operating conditions for the rock-bed filtration process.

1.5 Scope of Research

The study was carried out as following:

1. Setting two pilot-scale rock-bed filtration units.
2. Analysis of influent and effluent characteristics for the following parameters:
    a) Dissolved Oxygen (DO)
    b) Suspended Solids (SS)
    c) Volatile Suspended Solids (VSS)
    d) Total Biological Oxygen Demand (T-BOD)
    e) Total Chemical Oxygen Demand (T-COD)
    f) Filtrate Chemical Oxygen Demand (S-COD)
    g) Ammonia Nitrogen (NH_3-N)
3. Assessment of rock-bed filtration process performance by removal efficiency evaluation.
4. Determination of rock-bed porosity reduction.
5. Determination of optimum design and operating conditions.

CHAPTER II
LITERATURE REVIEW

2.1 Self-Purification

Natural self-purification in surface waters is a very important phenomenon. It is the ability to treat itself by natural process in water resource after it gets contaminated. Self-purification means the partial or complete restoration, by natural processes of a stream's pristine condition following the introduction of foreign matter sufficient in quality and quantity to cause a measurable change in physical, chemical, and/or biological characteristics of the stream. River self-purification systems, organic matter is assimilated by a number of processes including sedimentation which is enhanced by mechanical and biological flocculation, chemical oxidation, and the death of enteric and pathogenic microorganisms by exposure to sunlight. The most important process is biochemical oxidation; i.e., the aerobic break down of organic matter by microorganisms (Gray, 1989).

The self-purification in natural water systems is a complex process. Chemical processes convert iron and phosphate into solid forms, and the physical process of sedimentation removes it from suspension. Biological reactions convert the organic to biological solids and other end products that are degraded over a period of time (Peavy et al, 1985). Microorganisms play a very important role in biological degradation during self-purification processes. Mainly, there are two types of the microorganism responsible for biological degradation: 1) suspended-growth organisms in water, 2) attached to the surfaces of the objects in water. The water related micro-biomass might become visible to the naked eye. Depending on the morphology and the flow condition in the reactor, either the surface growths or the free-swimming organisms may contribute to the largest proportion of the self-purification capacity. However, overall quantity of biomass in relation to the volume of water involved is so low that the self-purification effect proceeds very slowly over a period of several years (Mudrack and Kunst, 1986).

2.2 Purification Mechanism

Natural water purification systems are capable of removing pollutants. The self-purification of natural systems includes physical, chemical, and biological processes. The speed and completeness with which these processes occur depend on many variables that are system specific. Hydraulic characteristics such as turbidity, flow volume, flow rate, flow pattern; physical and chemical characteristics of water and sediments as well as bottom and bank material; sunlight, temperature are the variables that have influence on the self-purification process rate (Peavy et al, 1985). However, by carefully controlling the system variables, the rate at which the process occurs is maximized and the time required for purification is minimized. Reactions may thus be carried out to completion in engineered purification systems in a fraction of the time and space required for the similar efficiencies in natural water system.

2.2.1 Physical Process

Sedimentation

Sedimentation is used to the removal of suspended and colloidal particles from water and wastewater through gravity settling by the Stoke's Law principle. It is normally carried out in large basins or tanks in which the flow is dispersed uniformly to minimize turbulence that often keeps particles in natural water systems. The common criteria for sizing settling basins are: detention time, overflow rate, weir loading, and with rectangular tank-horizontal velocity (Hammer, 1986).

Sedimentation can be of two types: a) plain sedimentation and b) chemically assisted sedimentation. A plain sedimentation basin serves the purpose of reducing turbidity and removing suspended matter. It can be applied as an appropriate pretreatment for slow sand filters to treat chemically dosed waters. Plain sedimentation is quite effective in tropical countries because higher temperatures improve the sedimentation process by lowering the viscosity of water. It can be used as a pretreatment process for both; rapid and slow sand filtration plants. However, in the latter case, its use is limited to the situation where it is possible to reduce the raw water turbidity to 30 NTU or less to avoid too frequent clogging of the sand bed. The efficiency of plain sedimentation, measured by turbidity reduction, largely depends on the size of the suspended particles and they're settling rate, and would serve no practical purpose for the removal of material smaller than 0.01 mm (Okun and Schulz, 1986). The economic and technical feasibility of achieving allowable settling time using plain sedimentation may be determined by settling tests on raw water.

2.2.2 Biological Processes

Natural watercourses contain many dissolved minerals and gases that interact chemically with one another in complex and varied ways. Oxidation-reduction, dissolution-precipitation and other chemical conversions may alternately aid or obstruct self-purification processes of natural water systems. Most of the chemical reactions involved in self-purification processes are biologically mediated; i.e., being biochemical in strictly speaking sense (Peavy et al, 1985).

1) Attached Growth System-Biofilm Theory

Self-purification process in natural system is the attached growth type microorganisms that are normally responsible for the greatest removal. The suspended growth type microorganisms are comparably less important in self-purification process (Gray, 1989).

Sirinathakumar and Amritrajah (1983) compared important of suspended microbial population to the biofilm community in river self-purification systems. They also determined the kinetics of organic carbon uptake rate by river biofilms by using an artificial stream channel. The microorganisms such as bacteria and algae can attach to the streambed or can be suspended in the overlying water. Studies have show that immersed surfaces typically have a much larger number of attached bacteria than the water flowing over them. One reason for this may be that the adhesion at the streambed provides the organisms with a stationary location exposed to a continuous supply of nutrients and also protect them against different stresses in the environment.

Heijnen et al (1992) studied the effect of particle properties and hydraulic retention time on the biofilm formation in a biofilm airlift suspension reactor. The result showed that small and rough particles contributed the biofilm formation well. Low hydraulic retention time benefited the formation of biofilm.

At higher retention time, the suspended biomass was washed out slowly. Consequently, the suspended biomass consumed more substrate compared to lower retention time.

2) Submerged Fixed-film Bioreactors

Aerobic treatment processes are extensively used for the removal organics from wastewater as well as polluted surface waters. In particular, fixed-film biological processes have gained more attention recently.

Hammoda and Abed-el-bary (1987) developed a multi-stage fixed-film reactor in which stationary submerged biofilm is attached to ceramic tiles under diffused aeration, tracer studies revealed that the reactor's regime was described by a CSTR-in-series model. Reactor performance at 20°C was examined using sucrose wastewater. The reactor demonstrated the capability of achieving 97 % soluble COD removals at low loadings and exhibited efficient and stable performance at high hydraulic and organic loadings.

Christensen et al (1989) conducted experimental studies to investigate the close interrelationship between biofilm kinetics and structural changes caused by the kinetics. Based on the results of their study, they concluded that the traditional modeling of wastewater treatment processes in biofilm reactors based on substrate removal kinetics alone will fail in many cases, due to the inevitable changes in the biofilm structures not taken into consideration. Therefore, design rules for substrate removal in biofilms used for wastewater treatment must include correlation between the removal kinetics and the structure and development of the biological film.

Nakamura et al (1989) carried out some experimental studies with biofilm reactors to investigate the substrate affinity of the attached growth microorganisms under low nutrient conditions. Microorganisms known to live and carry out metabolic reactions in low concentrations are called oligotrophs. Oligotrophic microorganisms, mainly bacteria, are living in soil, marine and fresh water. However, only a limited number of studies have been conducted on fresh water oligotrophs as compared with marine and soil oligotrophs. They concluded from their investigations that the growth characteristics of attached oligotrophs were very similar to those of suspended oligotrophs. The dominant bacterium in oligotrophic biofilm was Pseudomonas. And, under a certain organic loading, the K_{sa} value can be decreased by using the media having a larger surface area.

Takasaki et al (1990) through the results of their experimental investigations, demonstrated that the submerged biofilm process is a promising method for polluted raw water pretreatment. This was also felt and confirmed by several other studies in Japan during the early 1980s. This process is thought to be more economic and safer compared to other physicochemical treatment systems. A significant difference in using the submerged biofilm process in raw water treatment compared to biological processes for wastewater treatment is the influent water quality. The BOD of most influent raw waters in Japan is generally below 10 mg/L. Microbial films grow naturally on the submerged carriers during operation of the system in a similar manner as the microbial biofilms found in many aquatic habitats.

Several pilot and full-scale experiments using submerged biofilm process, conducted in Japan in recent years, were aimed at reduction in ammonium nitrogen, organic carbon, phytoplankton, odor, and taste from the raw water. Although these experiments have been carried out to demonstrate the feasibility of this process, comprehensive data on plant performance have not been presented. Each process has had a different configuration, operating conditions and influent water quality.

In their experiments, Takasaki et al (1990) investigated the reactors' performance and factors affecting treatment efficiency using water from four different lakes. Submerged carriers of the "honeycomb tube" type were used in the experiments. Influent BOD was generally below 10 mg/L and NH_4-N concentration was below 0.4 mg/L. In general, good removal efficiency in term of BOD, COD and NH_4-N was observed. The efficiency of removal of NH_4-N was about 80 % under complete mixing condition and when the raw water quality did not fluctuate rapidly. Under the adverse conditions of the low temperatures during winter and spring, the removal of NH_4-N was 60-80 %. The critical NH_4-N concentration was observed to be approximately 0.01 to 0.2 mg/L. Overall treatment performance was superior in the systems, which had the carriers not likely to become clogged very fast.

Gantzer et al (1991) conducted some experimental study to demonstrate that long-term change in water velocity affected the amount of biofilm biomass associated with a sand-free cobble streambed. They stated that the application of biofilm kinetic models to stream water quality modeling is complicated, because mass transport to and biomass accumulation of streambed biofilms are affected by water velocity. In general, it is expected that increasing water velocity improves mass transport within the deeper portion of a streambed and thereby allows a greater long-term accumulation of biofilm biomass. The results of their experiments implied that the rate of biodegradable contaminant removal in shallow biofilm-dominated streams is a function of both the present water velocity and historical water velocities.

2.3 Rock-bed Filtration

Rock-bed filtration is quite different as compared to other type filtration. It is in fact a modified biofilter. In this process, raw water is passed through a reactor basin filled with rocks. During the course of journey to the other end of the reactor, sedimentation and filtration remove suspended solids by rock media. Colloidal solids and a portion of the soluble organic material are coated on the rock's surfaces as fixed films and biodegradation reaction occur by attached growth metabolism of microorganisms. Solids settle down to the bottom of the reactor and contain a portion of suspended organisms as well as detachments from the rock' surfaces. There, these take still long time to be digested by the aerobic, anoxic, and anaerobic decompositions and then nitrification and denitrification remove the nitrogen.

A pilot-scale experiment was started in Inagawa river basin, Japan, the rock bed filtration method was used to treat the effluent of sewage treatment plant; 1980. The dimensions of the rock bed reactors were l × w × h : 20 × 2 × 2 m. Average diameters of the rocks were 15 cm for first 5 m length, 10 cm for next 5 m, and 5 cm for the rest of 10 m length. Average initial porosity of rocks was 50 %. Three different HRTs (4 h, 6 h and 10 h) were used during different experimental periods. Even though the influent water had very low concentrations (as 8.05 mg SS/L, 16.9 mg COD/L and 7.47 mg BOD/L, etc.), it had a good removal efficiency in terms of SS (77 %) and BOD (52 %).

In 1984, two pilot plants for RBF were constructed to treat moderately polluted wastewater (5.4 mg SS/L, 16.9 mg COD/L, 18.8 mg BOD/L and so on) in Inagawa basin, Japan. The dimension was 20 × 2 × 2 m (l × w × h) for a non-aeration system (RBF I) and 30 × 2 × 2 m for aeration system (RBF II). The diameters of rock media were 20-25 cm varied along the length also. The results of 3 years operation showed that sediment decomposition rate were 54.2-70.5 % and 72.3-88.8 % in term of SS and VSS, respectively. Removal efficiencies of both RBF were related to the length of reactors. Reduction of porosity for RBF I was 3.1 % per year and 3.8 % per year for RBF II (Inagawa, 1984).

Hosokawa et al (1992) carried out large-scale experiments in model channels filled with a porous bed of crushed stones. The purpose of the research was to test the process for coastal water purification along the Japanese waterfronts in inner bays. Salinity in coastal waters strongly affects biological activities and ecological diversity. Moreover, coastal waters have lower organic and SS concentrations and much larger volumes to deal with. Therefore, it is difficult to apply the conventional wastewater treatment techniques directly to improve the coastal water quality. Natural coast has its own purification capacity through filtration at sandy beach and bio assimilation of detritus by shells. It is thus advantageous to utilize such biological activities for water clarification without any additional reagents. Porous beds coated with natural biofilm are one of the promising techniques. However, the applicability and efficiency of SS and organic removal of this process are still not very well known, especially for coastal water.

In the above mentioned study carried out over 5 month of experimental period, effects of sedimentation and biological oxidation were observed for different hydraulic retention times (HRT:1-5 hours) and different sized stones used as media (mean diameter : 10-100 mm). The results showed removal of 50-60 %SS and 10-20 %TOC for 1 h HRT. Clogging and transportation of stocked humus was also observed. The removal efficiency was higher with longer HRT and smaller stone size.

Hozalski et al (1992) conducted an experimental study to evaluate the use of biofiltration for removal of natural organic matter to achieve biologically stable drinking water. Major objective of their research was to examine that how the differences in the source and composition of the natural organic matter relate to the biodegradability of it and how it influences the effectiveness of biofiltration. The overall goal of their study was also to evaluate the influence of microbial activity during biofiltration on post treatment processes e.g., ozonation.

Soe (1993) carried out a pilot-scale study with two RBF reactors, each containing different size and shape of rock media. The RBF method was applied to moderately polluted wastewater at Asian Institute of Technology (AIT), Thailand. Influent was a mixture of tap water and domestic wastewater, and horizontal flow was applied into the reactor at BOD loading rate between 18-22 g BOD/m^2-day. The RBFs were operated 4 months for experimental period and constant detention time (4 h) under aeration and non-aeration system. The results showed that the aeration system was more efficient for the removal of SS, VSS and S-COD compare to non-aeration system. The removal efficiencies of SS, VSS, BOD and S-BOD in half broken bricks were higher than the whole bricks for non-aeration system. In the case of aeration system, the removal efficiency of SS, VSS, COD and S-COD for half broken bricks were higher than the whole bricks. The removal efficiencies of those parameters were completely related to the length of reactor. However, there was no significant difference in reduction after 3 m length up to the effluents of reactor. The percent porosity reduction and sediment decomposition of half broken bricks were higher than whole bricks during months operation.

Muangphan (1994) carried out another pilot-scale study with the same RBF reactors at AIT. Influent wastewater was a mixture of AIT sewage and tap water (1:1) for achievement of moderately polluted water. The high performance of the RBFs was observed at first-half portion of the RBFs' length and then the pollutants were removed gradually. At the OLRs of 20-70 g BOD/m^2-day, RBFs' length of 2-3 m can be applied for higher overall removal efficiency. The reactor, which contained the rocks, had better effluent quality than that of the reactor containing half broken bricks, especially with respect to SS and VSS removal under the same operating conditions. The difference in aerator location has not much effect on overall pollutant removal. The percent removal of SS, VSS, T-COD, S-COD, T-BOD and S-BOD in the aeration pattern 2 (at 0.5 and 2.0 m) was the highest. It would be suggested to install aerators not only in the influent, but also in the middle of reactor. The different HRT or OLR has a significant effect on pollutant removal. Under the same operating conditions, the longer HRT of 8 hours had the highest removal efficiency as compared to the operation at 2-hour HRT. The main mechanisms of pollutant removal in RBF in this study are considered to be that of sedimentation and adsorption.

Jindal (1995) conducted pilot-plant experiments at a site along a canal in Bangkok to evaluate the application of the RBF method for on-site water treatment and to observe the performance of the system under different operating condition. Two rectangular reactor units, 5.04 m long, 0.5 m wide and 0.75 m deep. Three different rock sizes with approximate equivalent diameters 10 cm, 15 cm and 20 cm were used as filter media. A diffuser network was installed at the bottom along the length of each reactor to provide aeration. Maximum removal efficiency was found for SS, while it was low for S-COD. This implied that main reaction mechanism was the sedimentation of particulate matter and biodegradability of canal water was poor. An increase in HRT increased the removal efficiency in all cases but NO_3^--N. However, a distinct increase in removal efficiency was observed for HRT between 6 h and 9 h, except in case of T-BOD. It appeared that combined rock sizes resulted in about 10 % improvement on the effluent particulate matter removal. Improved DO levels at mid-way along the reactor length were helpful in achieving nitrification reaction. However, NO_3^--N concentration increased in effluent during the runs in which NH_4^+-N concentration reduced, implying that denitrification did not occur.

The overall porosity in both reactors reduced from about 64 % to 48 % over a period of 14 months. The results showed that there was high decomposition of the organics in sediments ranging from 60 % to 70 % from the start of experiment. However, the organics constituted the main part of the sediments and thus decomposition of organics only led to an overall reduction in sediments of 15-25 %. The solid content in the sediments was observed to be increase during the operation. Therefore it was expected that during the prolonged operations, the increment in sediment height might reduce due to the combined effect of decomposition of organic and the increase in the solid content in the sediments. The performance of the pilot-scale rock-bed filtration system revealed it to be an effective water treatment method for the removal of suspended solids and organic carbon from moderately polluted waters.

2.4 Mathematical Equations of Rock-bed Filtration Processes

The mathematical equations for various physical and biological processes are given as below (Jindal, 1995).

2.4.1 Physical Processes

1) Reaeration (Air-Water Gas Transfer)

The rate of oxygen transfer at air-water surface is very important in natural purification processes in streams. This rate can be evaluated by the expression of the oxygen balance in streams as shown below:

$$P_1 = \frac{K_L (C_S - C_3)}{H} \tag{2-1}$$

Where, P_1 = reaeration rate (g O_2/m^3-day)

K_L = gas transfer rate constant (m/day)

C_S = dissolved oxygen (DO) saturation value (g/m^3)

C_3 = influent (DO) concentration (g/m^3)

H = effective height of the tank (m)

2) Sedimentation of Particulate Organic Matter (POM)

As water flows over the rocks' surface in the rock-bed system, suspended matter is removed in part by sedimentation, which is enhanced by low flow velocities and shallow depths; and in part by filtration through the living vegetation and vegetative litter. Initially, the bacteria do not oxidize the particulate organic matter (POM), because it is a slowly biodegradable material. Therefore, first it would be entrapped in the sediments and then be hydrolyzed by bacteria. Process rate of sedimentation is a first order reaction as shown in Equation (2-2) below:

$$P_2 = d_1 C_1 \tag{2-2}$$

Where, P_2 = sedimentation rate of particulate organic matter, (g COD/m^3-day)

d_1 = sedimentation coefficient for POM (day^{-1})

C_1 = influent concentration of POM (g COD/m^3)

3) Sedimentation of Inert Suspended Solids (ISS)

Bacteria do not oxidize the inert suspended solids (ISS) because it is a non-biodegradable material. Therefore, it simply settles down to the sediment zone. Process rate is also a first order equation as shown below:

$$P_3 = d_2 C_2 \tag{2-3}$$

Where, P_3 = sedimentation rate of inorganic suspended solids, (g COD/m^3-day)

d_2 = sedimentation coefficient for ISS (day^{-1})

C_2 = influent concentration of ISS (g COD/m^3)

2.4.2 Biological Processes

1) Oxic Decomposition of Dissolved Organic Matter (DOM)

Dissolved organic matter (DOM) is first oxidized by heterotrophic bacteria in oxic conditions and produces end products: NH_4^+ and alkalinity. The reaction rate is given by Monod type equation as shown below:

$$\text{Org. Matter} + O_2 + H_2O \xrightarrow{\text{Bacteria}} CO_2 + NH_4^+ + OH^- \tag{2-4}$$

$$P_4 \quad = \quad r_1 \frac{C_3}{(K_1 + C_3)} C_4 \tag{2-5}$$

Where, P_4 = reaction rate of oxic decomposition of DOM (g/m^3-day)

r_1 = biological reaction coefficient (day^{-1})

K_1 = half saturation coefficient (g/m^3)

C_3 = concentration of dissolved oxygen (g/m^3)

C_4 = concentration of dissolved organic matter (g COD/m^3)

Reaction mechanism can be represented in Figure 2-1 below:

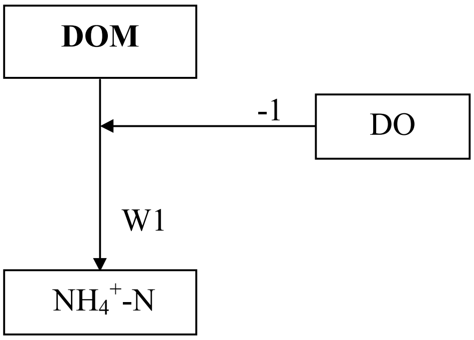


Figure 2-1. Oxic decomposition of dissolved organic matter (DOM).

Where, W1 is the N/COD ratio in DOM and for present study it was observed to be 0.124 (pilot-plant experiments).

2) Nitrification

This is an oxidation reaction of NH_4^+-N by nitrifying bacteria represented by the general equation as below:

$$NH_4^+ + O_2 \longrightarrow NO_X^- \qquad (2\text{-}6)$$

This process actually consists of two steps. In first reaction, ammonia is oxidized to the intermediate product – nitrite by the ***Nitrosomonas*** sp. And then nitrite is converted to nitrate by another kind of bacteria – ***Nitrobacter*** sp. In the second step. The two stoichiometric reactions are shown below:

$$NH_4^+ + 1.5\ O_2 \xrightarrow{\textit{Nitrosomonas}} NO_2^- + H_2 + 2\ H^+ \qquad (2\text{-}7)$$

$$NO_2^- + 0.5\ O_2 \xrightarrow{\textit{Nitrobacter}} NO_3^- \qquad (2\text{-}8)$$

Overall reaction can be written as shown below:

$$NH_4^+ + 2\ O_2 \longrightarrow NO_3^- + H_2O + 2\ H^+ \qquad (2\text{-}9)$$

Thus oxidation of 1 g ammonia nitrogen to convert it to nitrate, requires (2×32)/14 = 4.6 g of oxygen. As any organic nitrogen associated with the influent must be convert to ammonia by heterotrophs before it can be oxidized by autotrophs, a double saturation function is used to express the dependency of the autotrophic specific growth rate upon the concentrations of ammonia nitrogen and oxygen. Reaction rate is given by the equation below:

$$P_5 = r_2 \frac{C_3}{(K_2 + C_3)} \frac{C_5}{(K_3 + C_5)} \qquad (2\text{-}10)$$

Where, P_5 = rate of nitrification (g N/m^3-day)

r_2 = nitrification rate coefficient (g N/m^3-day)

C_5 = concentration of NH_4-N (g N/m^3)

K_2, K_3 = half saturation coefficients (g O_2/m^3 , g N/m^3)

Reaction mechanism can be represented in Figure 2-2 below:

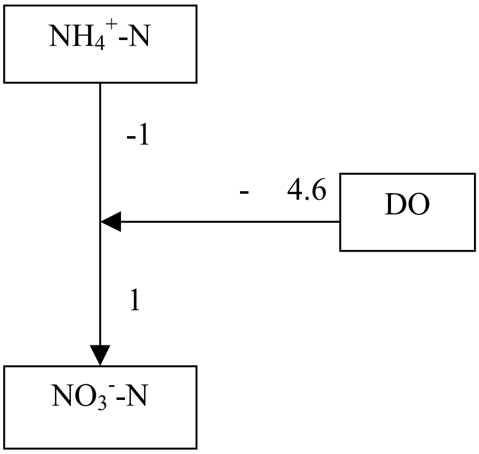


Figure 2-2. Nitrification.

CHAPTER III

METHODOLOGY

3.1 Experimental Setup

Pilot-scale rock-bed filtration units were constructed at the wastewater treatment pond-system site near Suranaree University of Technology (SUT) dairy farm as shown in Figure 3-1. Experimental setup consisted of two reactor units, one head tank unit, three storage tanks, filter media, and aeration system. The schematic layout of the setup is shown in Figure 3-2. Figures 3-3 and 3-4 show pilot-scale rock-bed filtration units. The relevant design details of the setup are given below.

3.1.1 Reactor units

Two reactor units with the dimensions ($l \times w \times h = 3.0 \times 0.5 \times 0.5$ m) were made of concrete with the wall thickness of 0.1 m. In each reactor, the influent was fed from one end, and the effluent was discharged through a pipe installed at the other end. Both reactors had run under ambient conditions and with constant water depth of 0.38 m. The effective volume of each reactor was 0.57 m^3 (3.0 m long, 0.5 m wide and 0.38 m high). Two reactors were named as RBF I and RBF II, respectively.

3.1.2 Head Tank

Three interconnected tanks were used for water storage in the head tank unit as shown in Figure 3-5. The volume of each storage tank was 200 L and of head tank was 100 L. First, a water pump fed the wastewater to the top of first storage tank with a level controller. The wastewater passed through the second and third storage tanks via two connecting pipes. Subsequently, the wastewater from the third storage tank flowed to the head tank (constant level) from which it reached to the inlet portions of the two rock-bed reactors.

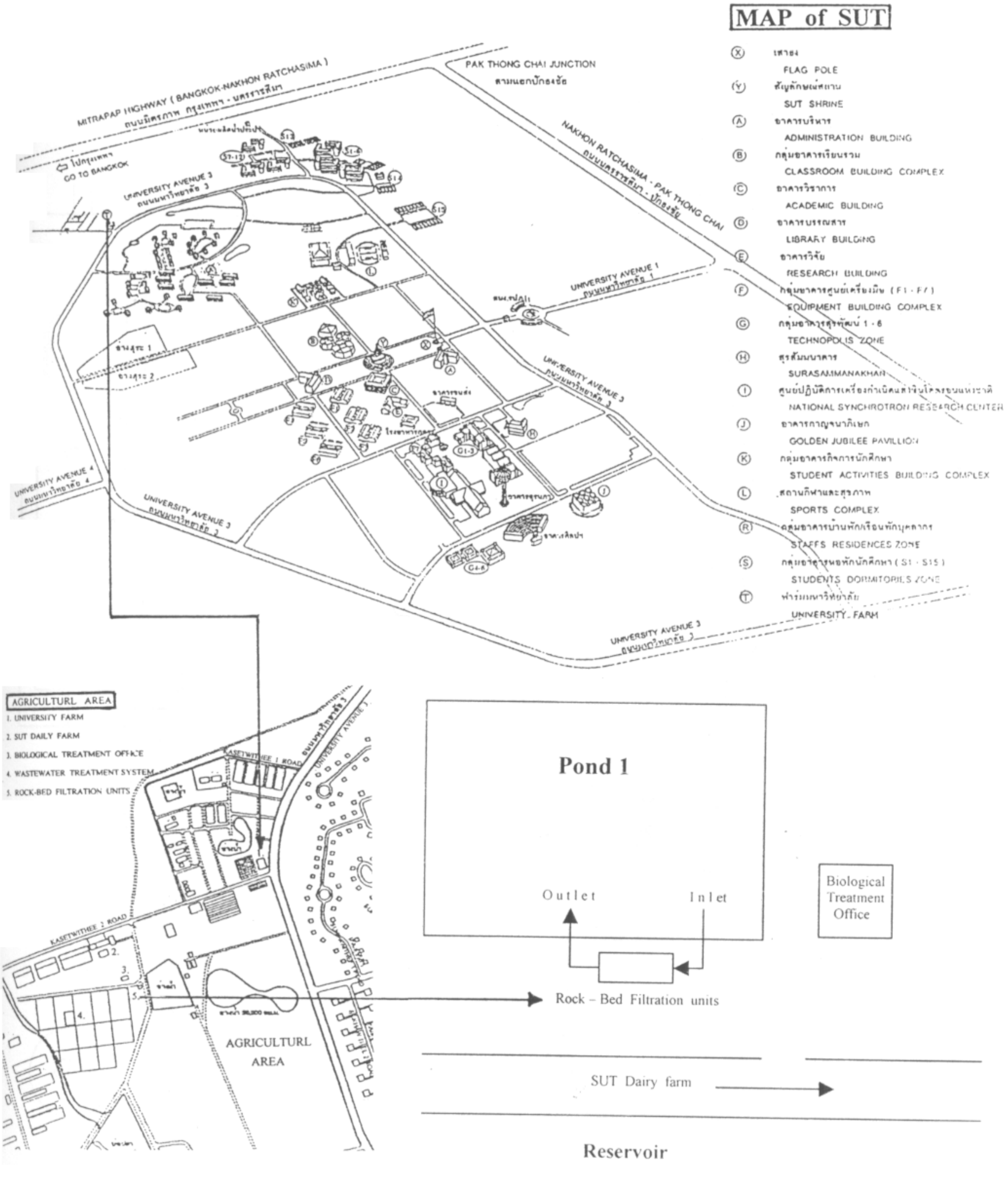


Figure 3-1. Pilot-scale rock-bed filtration units near pond 1 of SUT Biological Treatment System.

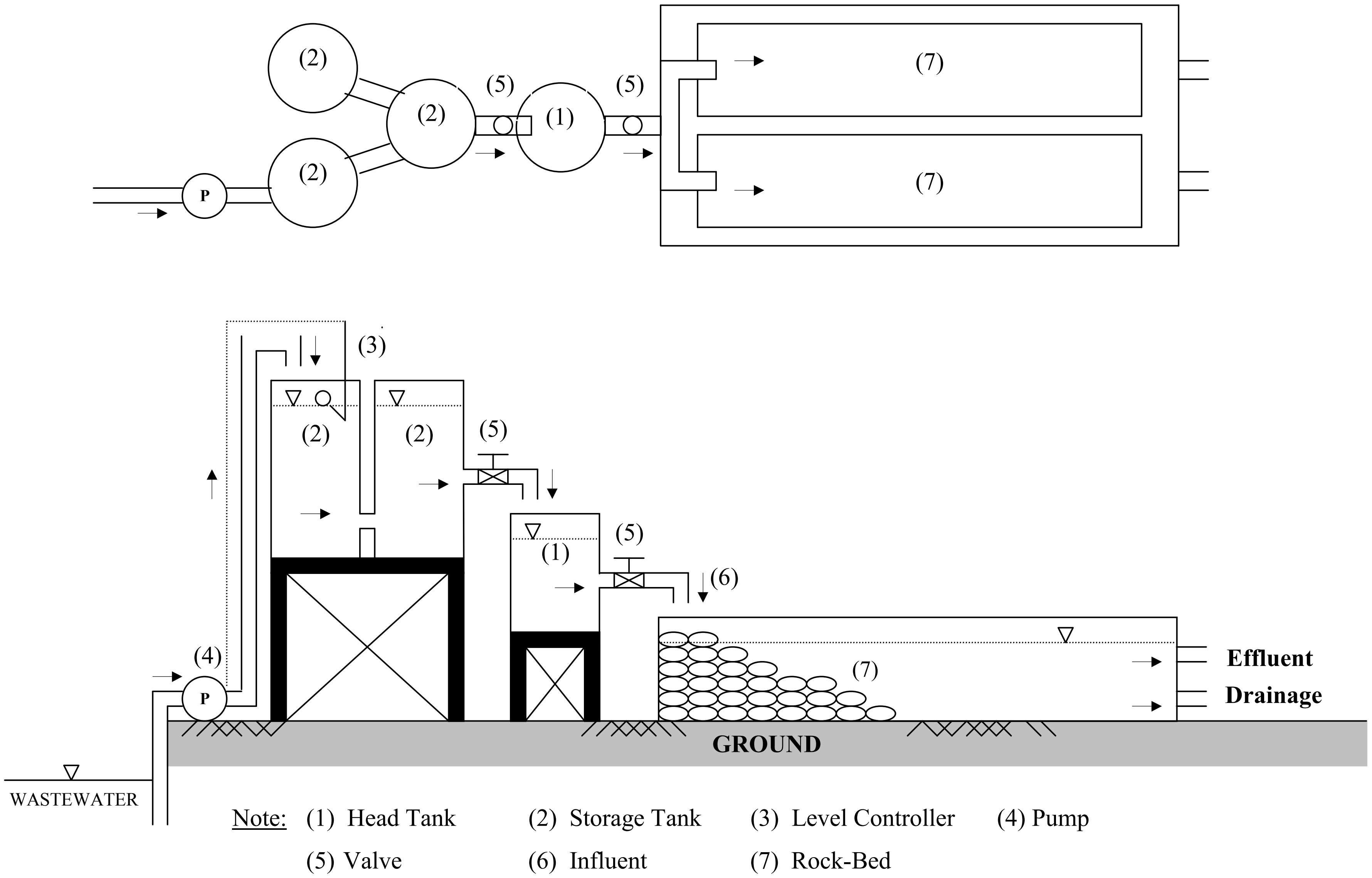


Figure 3-2. Schematic layout of the pilot-scale rock-bed filtration units.

Figure 3-3. Front view of pilot-scale rock-bed filtration units.

Figure 3-4. Side view of pilot-scale rock-bed filtration units.

Figure 3-5. Head tank unit.

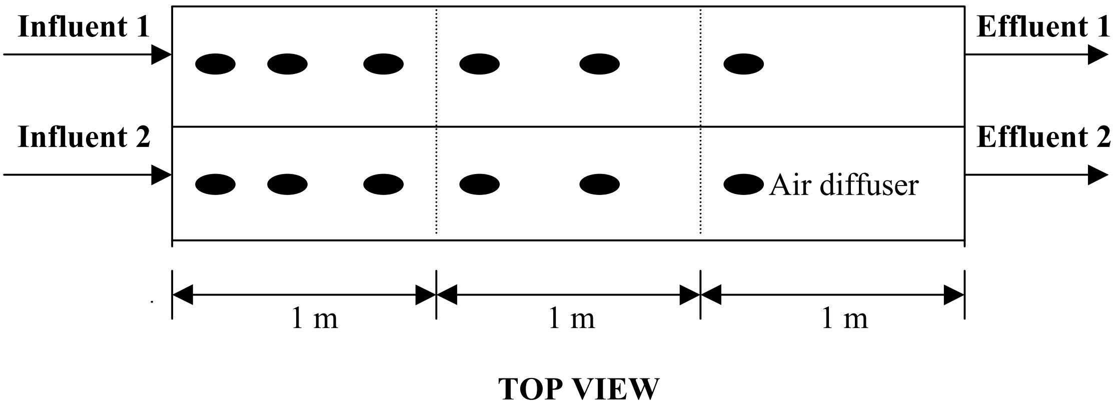
3.1.3 Filter Media

For each reactor, two different rock-sizes, represented by small and big, with approximate equivalent diameters of 2.0-4.0 cm and 5.0-7.0 cm, respectively were used filter media as shown in Figure 3-6.

Figure 3-6. Two sizes of the filter media.

3.1.4 Aeration System

The aeration in each reactor unit was provided through 6 air diffusers, the type that is used in fish tank. The diffusers were installed at the bottom of each reactor at 0.15, 0.4, 0.8, 1.2, 1.7 and 2.2 m, respectively from the influent end as shown in Figure 3-7.



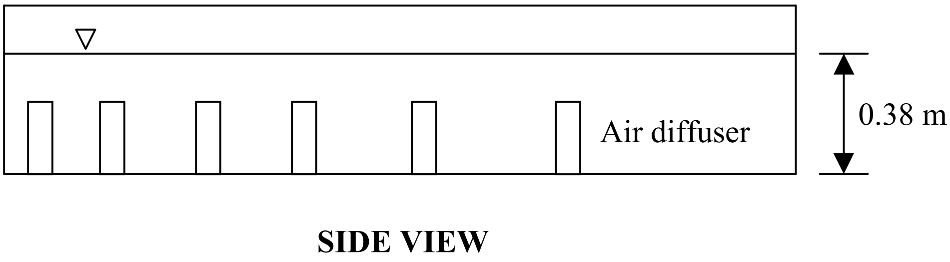


Figure 3-7. Schematic diagram of aeration arrangement.

3.2 Pilot-scale RBF units Installation

Pilot-scale rock-bed filtration units was constructed at wastewater treatment pond-system site of SUT. The site was prepared by sand filling and compacting. Two reactors were built by reinforced concrete during January 6-10, 2000. Electrical system, water pump and level controller were also installed. During January 11-12, 2000, rocks were transported to the site by truck.

3.3 Preliminary Tests

After pilot-scale experimental setup was installed, preliminary observations were made for flow rate, water level, temperature, and microorganism growth for about one week. Also initial porosity measurements were carried out for the rock-beds in two RBF units.

Porosity Measurement

Initial porosity measurement was made on 19 January 2000. After filling the reactor units with rock media, the initial porosity was measured by recording the water levels after some regular time intervals while removing known volumes of water from the reactors. The porosity of the rock media was obtained by the following equation:

$$\in \quad = \quad \frac{V_1}{V_2} \times 100\ (\%) \qquad (3\text{-}1)$$

Where, $\in$ = porosity of the rock media

V_1 = volume of water removed in the reactor (m^3)

V_2 = volume of water and rocks in the reactor (m^3)

V_2 = $l \times w \times (h_1\text{-}h_2)$ (m^3)

h_1 = water levels before water removed in the reactor (m)

h_2 = water levels after water removed in the reactor (m)

Porosity was measured again at the end of experimental run.

3.4 Experimental Plan – Operating Conditions

Total experimental duration (January 15 – June 29, 2000) was divided into 3 experimental periods (represents by R1, R2 and R3) with different operating conditions (rock size, influent flow rate, retention time, aeration, etc.). Table 3-1 summarizes the plan of all experimental operating conditions.

3.5 Sampling points and Frequency

During the experiments, wastewater samples were collected regularly from the influent and effluent in each reactor. Flow rate and temperature were measured twice a day. DO, pH, SS, VSS, T-COD, S-COD and NH_3-N were measured 3 times per week. T-BOD was analyzed 2 times per week. The samples were analyzed in the Environmental Engineering Laboratory, SUT.

Table 3-1. Plan of experimental operating conditions.

Date / Month	Experiment Condition		Run Number	Rock Size (cm)	Retention Time (h)	Aeration Condition
January 20 – March 11	R1	RBF I	R11-6	2 – 4	6	6 air diffusers
(52 days)		RBF II	R12-6	5 – 7	6	6 air diffusers
March 14 – April 13	R2-I	RBF I	R21-3	2 – 4	9	3 air diffusers
(31 days)		RBF II	R22-3	5 – 7	9	3 air diffusers
April 20 – May 24	R2-II	RBR I	R21-6	2 – 4	9	6 air diffusers
(35 days)		RBF II	R22-6	5 – 7	9	6 air diffusers
May 31 – June 29	R3	RBF I	R31-6	2 – 4	12	6 air diffusers
(30 days)		RBF II	R32-6	5 – 7	12	6 air diffusers

3.6 Analytical Methods

The following parameters were analyzed in accordance with the "Standard Methods" (1995) with respective methods as specified in the parenthesis:

1. Temperature (thermometer)
2. pH (portable digital pH meter)
3. DO (portable digital DO meter)
4. BOD (Azid modification method, 5-Day BOD Test)
5. COD (Dichromate Reflux Method)
6. SS (Filtration Method using GF/C filter paper drying at 103 °C)
7. VSS (Filtration Method using GF/C filter paper igniting at 550 °C)
8. NH_3-N (Titrimetric Method)

CHAPTER IV
RESULTS AND DISCUSSION

4.1 General

Pilot-scale experiments with the two rock-bed filtration units were conducted according to the experimental plan as in Table 3-1 over a period of 162 days. Figure 4-1 shows the variation in influent and effluent flow rate and water level during the experimental period. The influent and effluent flow rates during all the experimental runs were nearly constant. The range of water level in the reactors varied between 35-37 cm at inlet and outlet. The variation in influent and effluent in pH and temperature during the experimental period is shown in Figure 4-2. The pH values can affect the microorganism growth rate. During the experimental period, pH values of influent were between 8.0-8.5 with the average of 8.15. This wastewater was suitable for most of bacteria since the optimum pH value for bacterial generation is slightly on the alkaline side (Wilkinson, 1975). The temperature is very important parameter because biological reaction rates and DO concentration depend on temperature. The temperature during various runs varied between 25-32ºC, and the variation was not too wide. The average temperatures were 30°C and 28°C for influent and effluent, respectively.

4.2 Influent Quality

Figure 4-3 shows weekly variations in suspended solids, volatile suspended solids and ammonia in influent and effluent, respectively. SS and VSS in influent were 30-70 mg/L and 25-45 mg/L, respectively during the month of March 2000 and again during mid April–May 2000; but were 10-30 mg/L and 10-25 mg/L, respectively for the rest of the period. Ammonia concentrations were 0-6 mg/L throughout the experimental period. The variations in influent and effluent total COD (T-COD), filtrate COD (S-COD), and total BOD (T-BOD) are shown in Figure 4-4. Total COD, filtrate COD, and total BOD were in the range of 50-120 mg/L, 25-60 mg/L, and 15-40 mg/L, respectively during the first two runs, and decreased to 30-50 mg/L, 15-25 mg/L, and 5-15 mg/L, respectively during the third run.

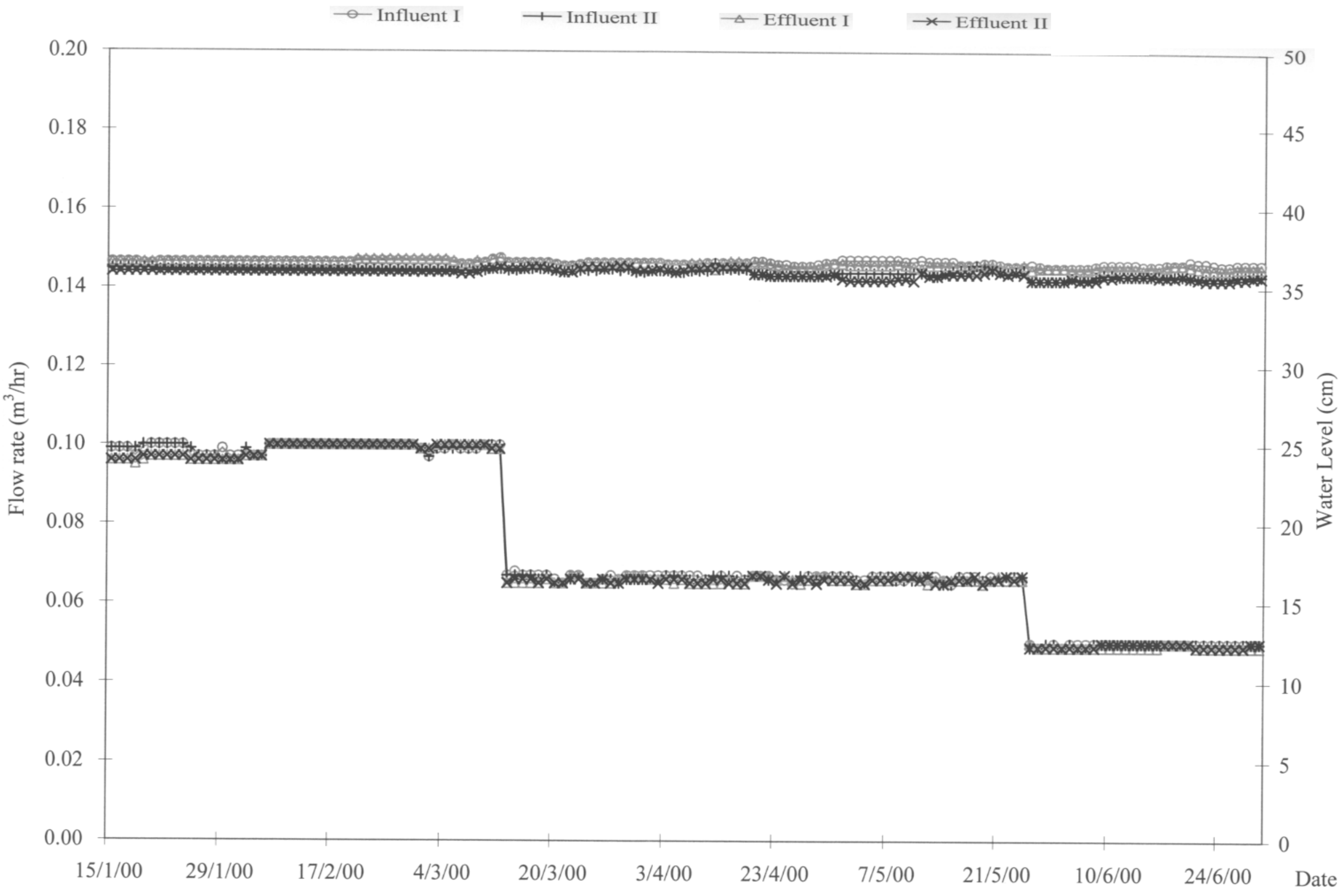


Figure 4-1. Flow rate and Water Level.

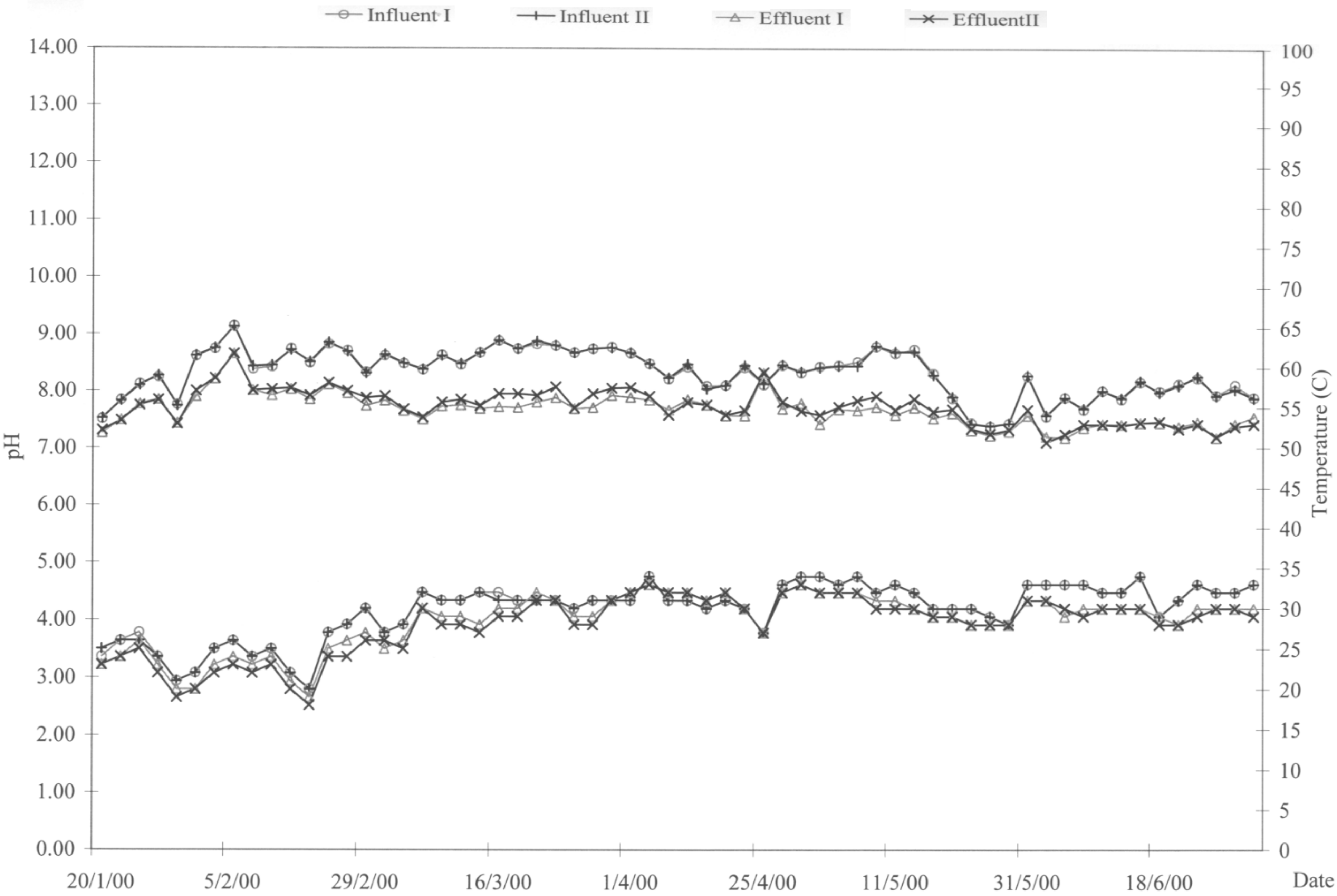


Figure 4-2. pH and Temperature.

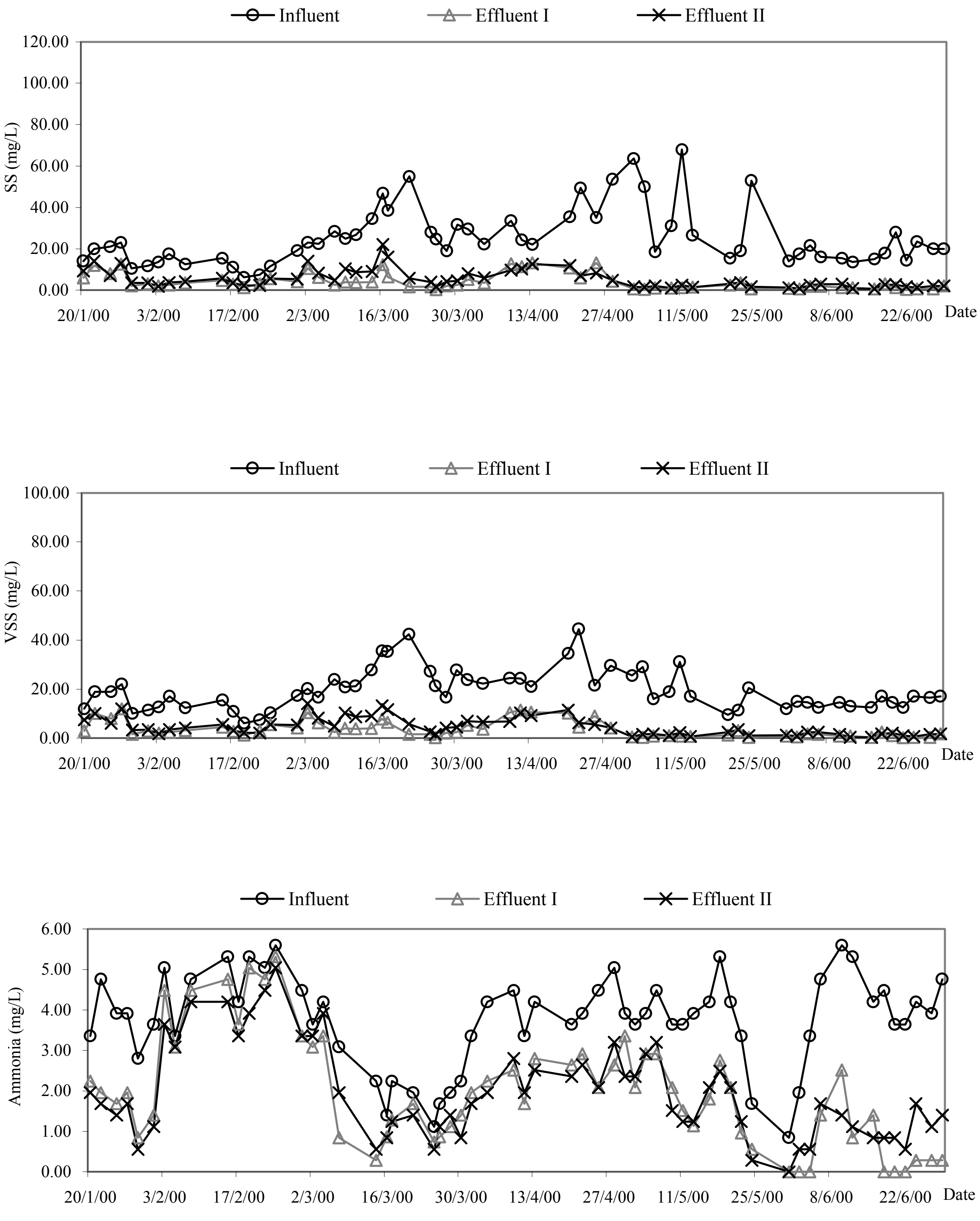


Figure 4-3. Variation in influent and effluent SS, VSS and NH_3-N concentrations.

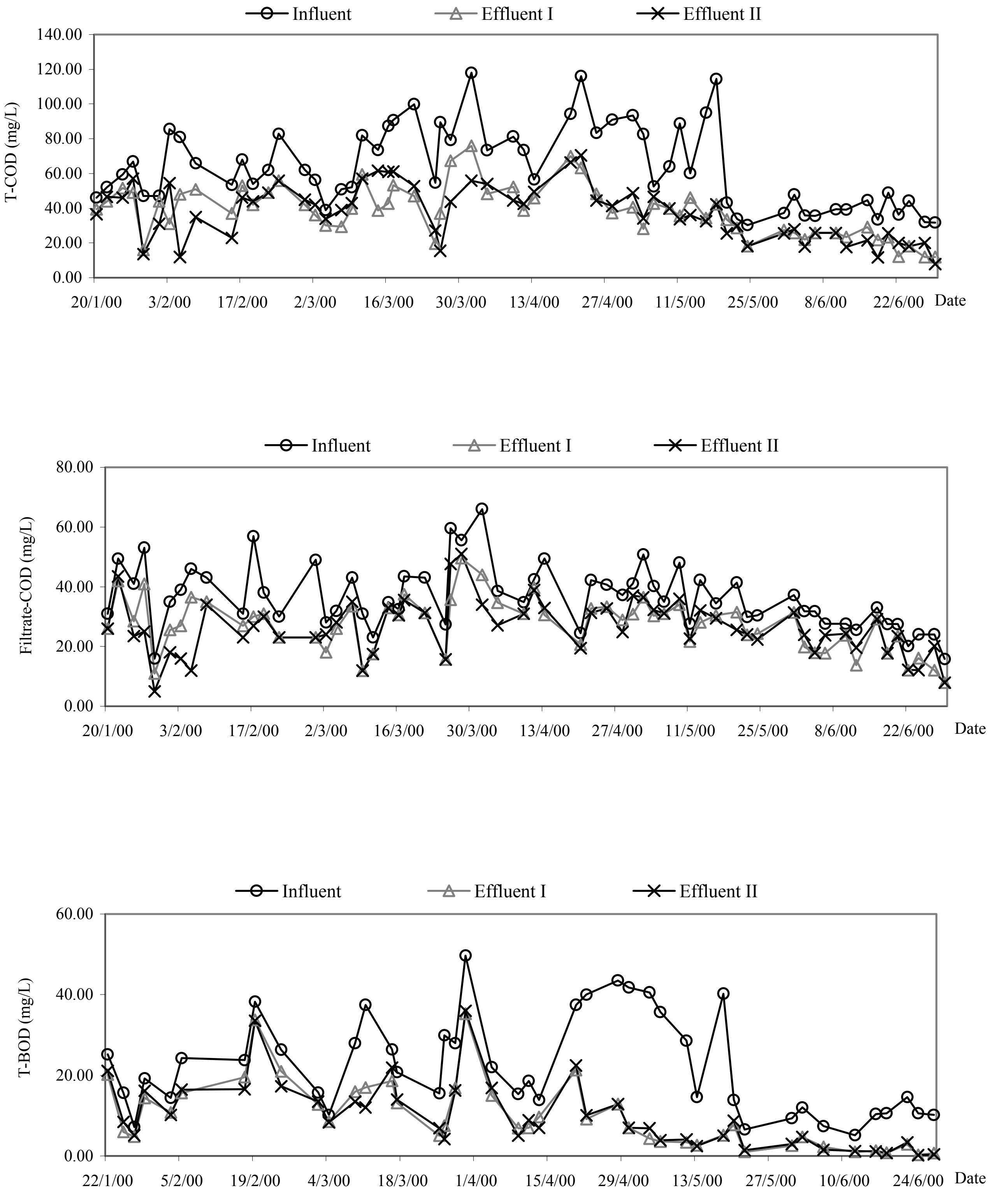


Figure 4-4. Variation in influent and effluent T-COD, S-COD, and T-BOD concentrations.

4.3 Removal Efficiencies

The range and average percent removal efficiencies of RBF I and RBF II can be seen in Table 4-1.

Table 4-1. Removal efficiencies of parameters.

Run Number	SS		VSS		T-COD		S-COD		T-BOD	
	Range %	Avg. %	Range %	Avg. %	Range %	Avg. %	Range %	Avg. %	Range %	Avg. %
R11	40-92	70.3	45-90	69.9	13-66	31.2	13-61	27.9	12-62	26.0
R12	30-87	62.3	31-86	61.2	11-85	32.1	12-74	36.9	12-46	25.3
R21	62-99	89.2	58-99	87.7	16-66	42.7	11-33	21.8	43-90	76.3
R22	66-97	88.4	67-98	85.9	11-66	42.7	10-38	22.3	37-89	73.9
R31	83-97	93.1	85-98	93.3	26-67	45.1	12-50	33.0	61-97	81.5
R32	82-96	89.9	81-97	90.5	28-75	47.8	12-57	31.8	61-98	81.7

Figures 4-5 through 4-9 show removal efficiencies of parameters in each run during the experimental period. As shown in Table 4-1, the maximum average percent removal efficiencies were for SS during the Run III (HRT 12 h) 93.1 % and 89.9 % in RBF I and RBF II, respectively. In case of VSS, the maximum average values were also during the same run for RBF I & RBF II- 93.3 % and 90.5 %, respectively. The range of removal efficiencies for T-COD were 31.2 %-45.1 % and 32.1 %-47.8 % for RBF I and RBF II, respectively. In case of filtrate COD, the range of reduction was 21.8 %-33.0 % for RBF I and 22.3 %-36.9 % for RBF II.

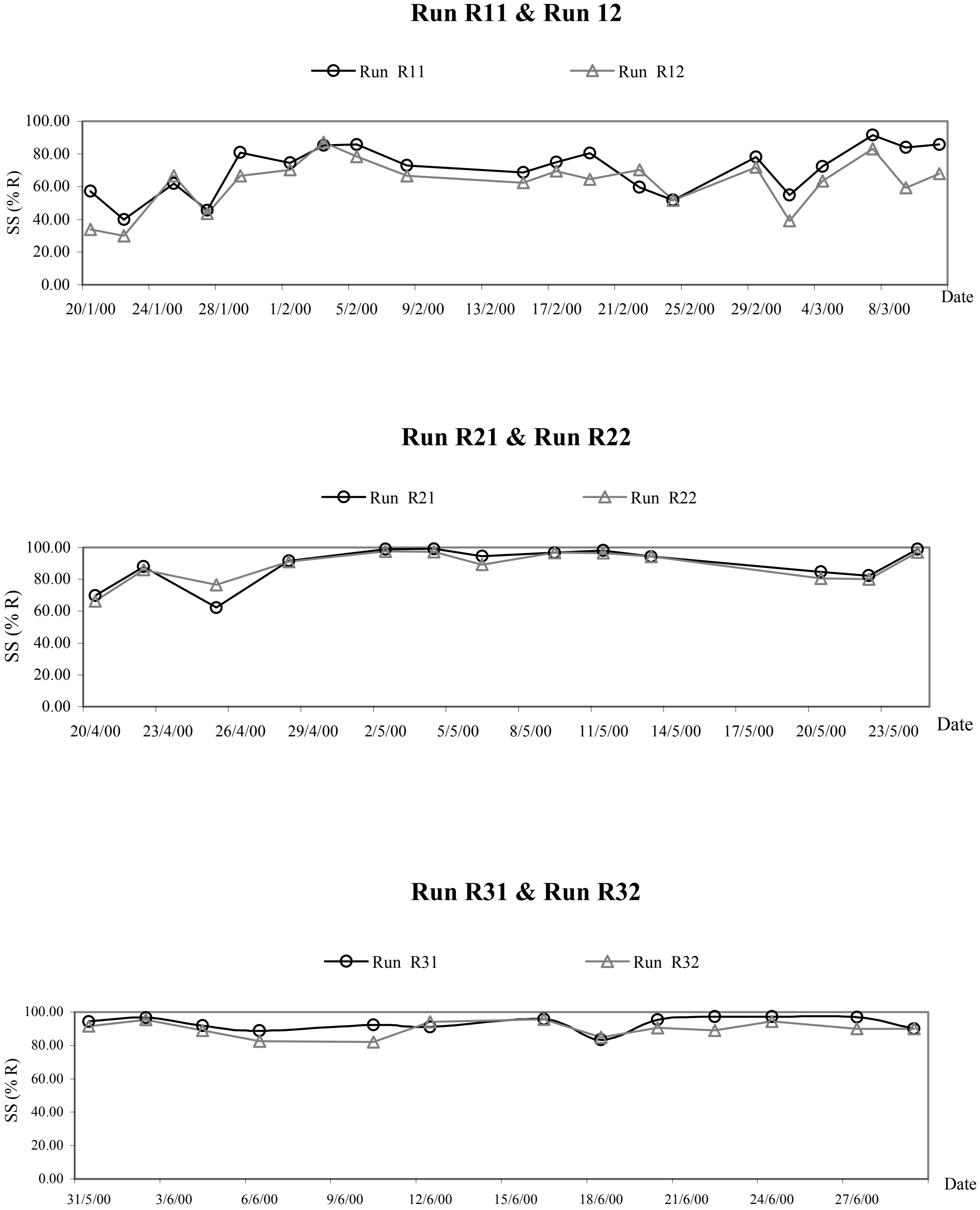
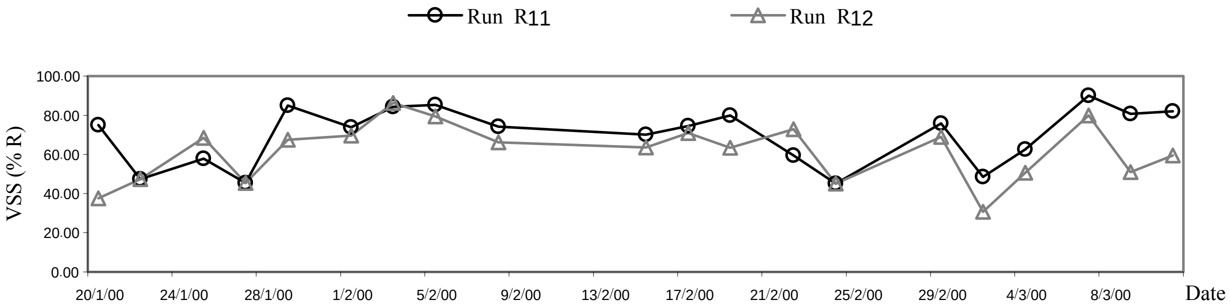
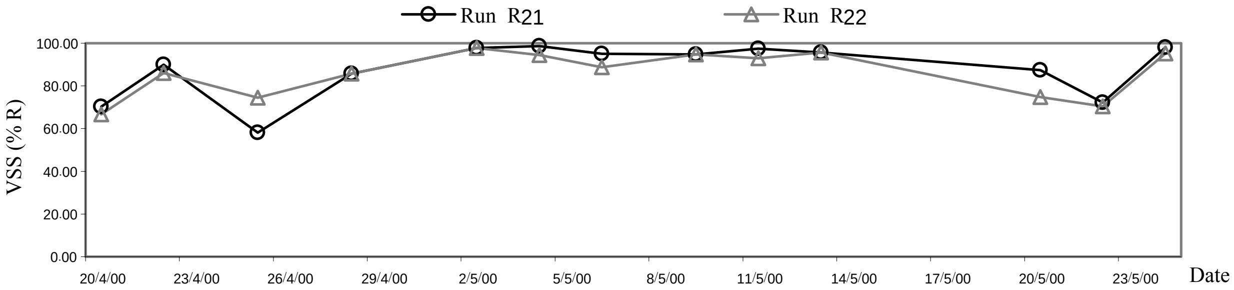


Figure 4-5. Removal efficiency of SS during 3 runs.

Run R11 & Run 12



Run R21 & Run R22



Run R31 & Run R32

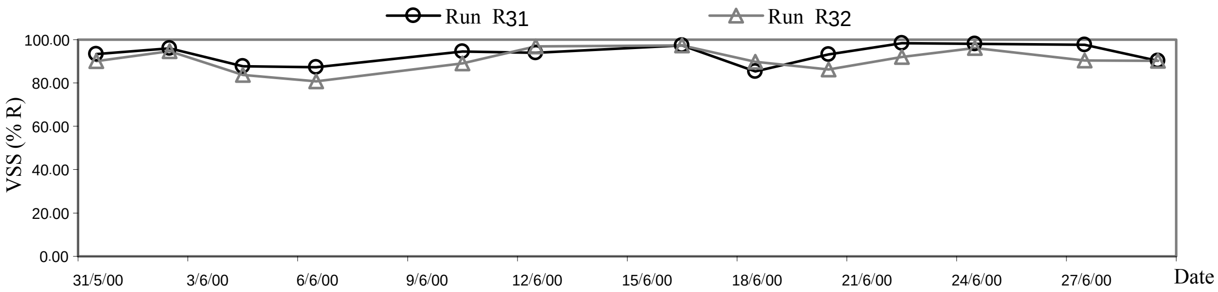
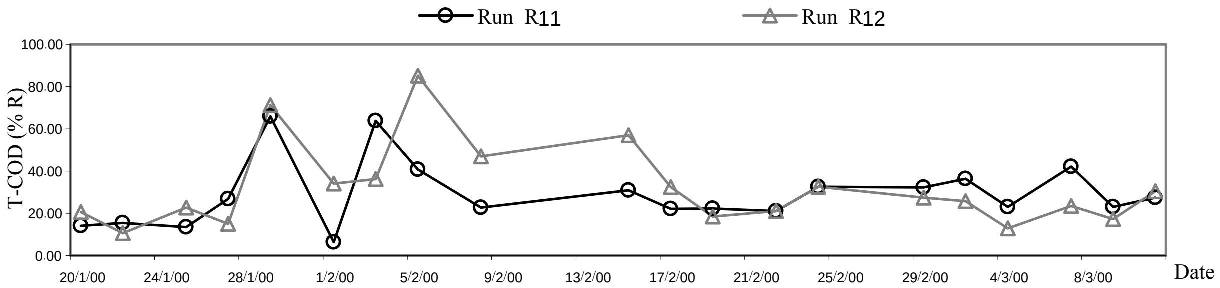
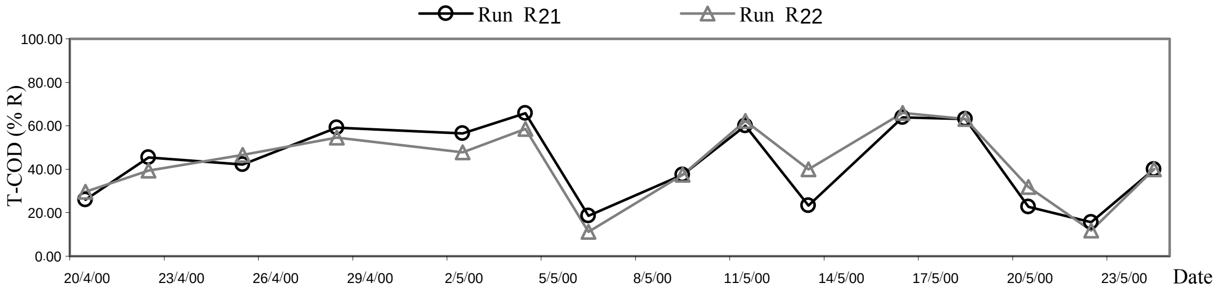


Figure 4-6. Removal efficiency of VSS during 3 runs.

Run R11 & Run 12



Run R21 & Run R22



Run R31 & Run R32

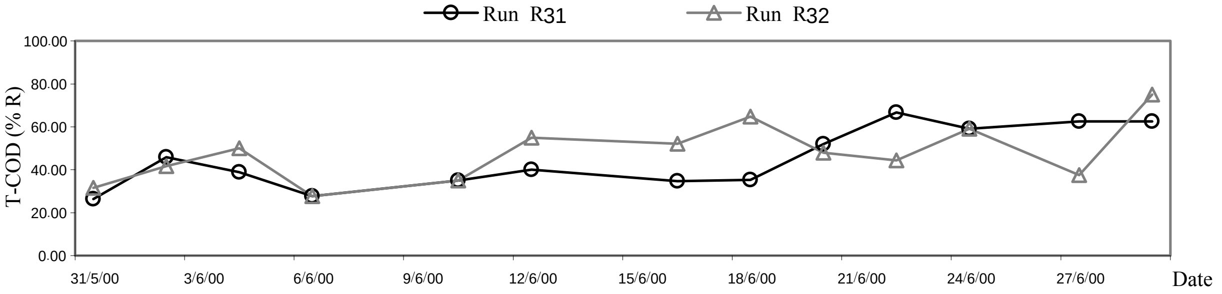
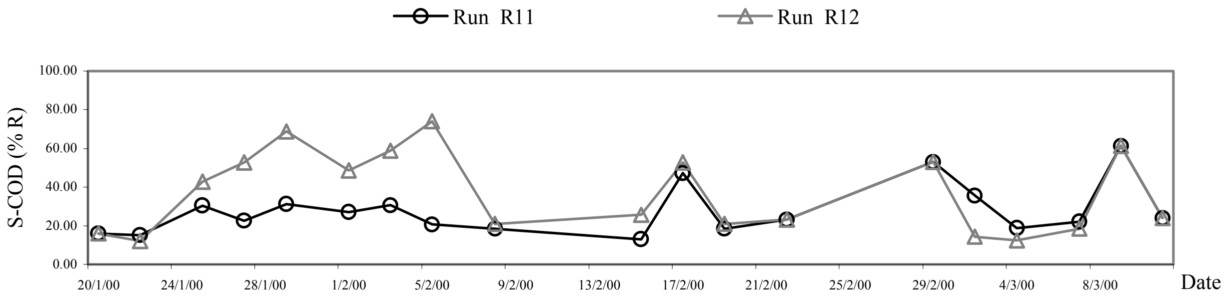
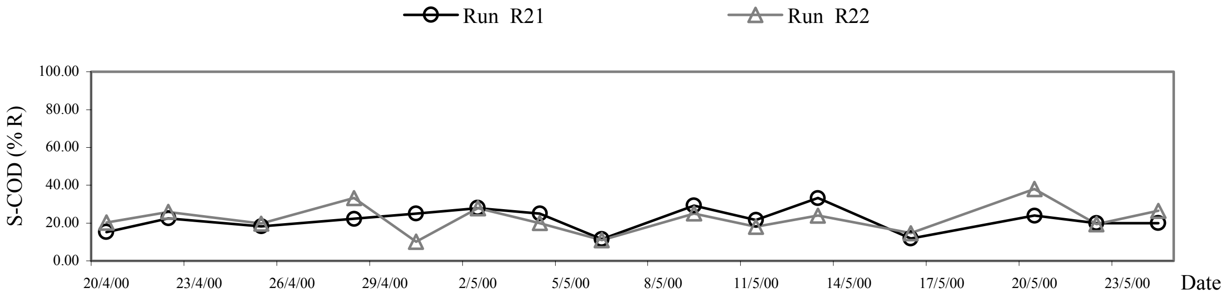


Figure 4-7. Removal efficiency of T-COD during 3 runs.

Run R11 & Run 12



Run R21 & Run R22



Run R31 & Run R32

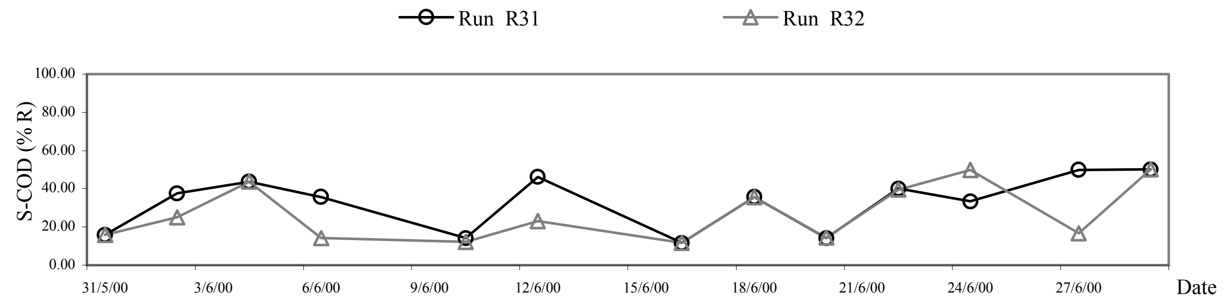
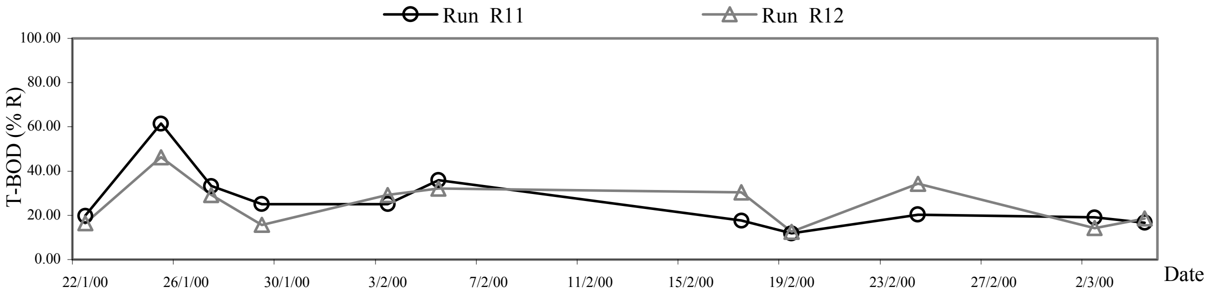
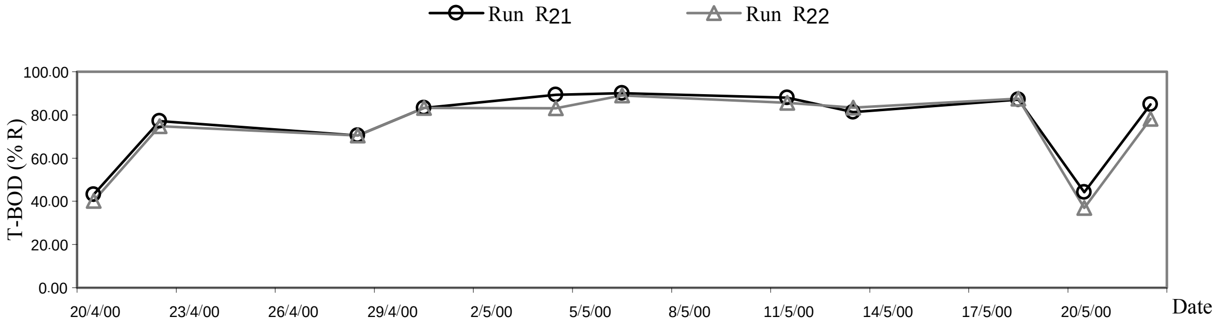


Figure 4-8. Removal efficiency of S-COD during 3 runs.

Run R11 & Run 12



Run R21 & Run R22



Run R31 & Run R32

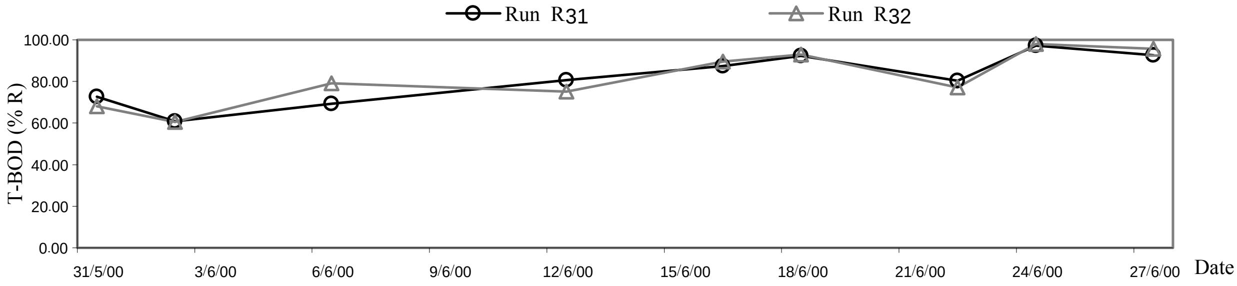


Figure 4-9. Removal efficiency of T-BOD during 3 runs.

In term of suspended solids removal RBF I performed better than RBF II. Same was true for S-COD removal. However, more T-COD removal was found in RBF II on an average basis. In case of T-BOD, both reactors showed similar performance in general and removal ranged between 25-82 %.

From these results, it can be seen that the main reaction mechanism of the RBF method was sedimentation of organic and inorganic particulate matter. The soluble organic removal by the attached biofilm was not so significant in the beginning but reached up to 82 % during the last run. This means that for effective biofilm performance, longer operation is required.

4.4 Effect of Operating Conditions

In view of low values of coefficient of variation, only average values of influent and effluent concentrations over a period of any test run were compared to evaluate the effect of different operating conditions.

4.4.1 Effect of HRT

Effect of HRT on removal efficiencies for various wastewater quality variables (SS, VSS, T-COD, S-COD, T-BOD and NH_3-N) is shown in Figure 4-10. It can be seen from these figures that an increase in HRT increases removal efficiency in general. For SS, VSS, total COD and total BOD, there was maximum increase in removal efficiency for $6 \text{ h} < \text{HRT} < 9 \text{ h}$ and then only a nominal increase for $9 \text{ h} < \text{HRT} < 12 \text{ h}$. In case of NH_3-N, the removal efficiency slightly increased with an increase in HRT from 6 h to 9 h, and after that, a sharp increase occurred for HRT at 12 h. However, for filtrate COD, there was slight decrease in removal efficiency with an increase in HRT from 6 h to 9 h and only a slight increase as the HRT increased from 9 h to 12 h.

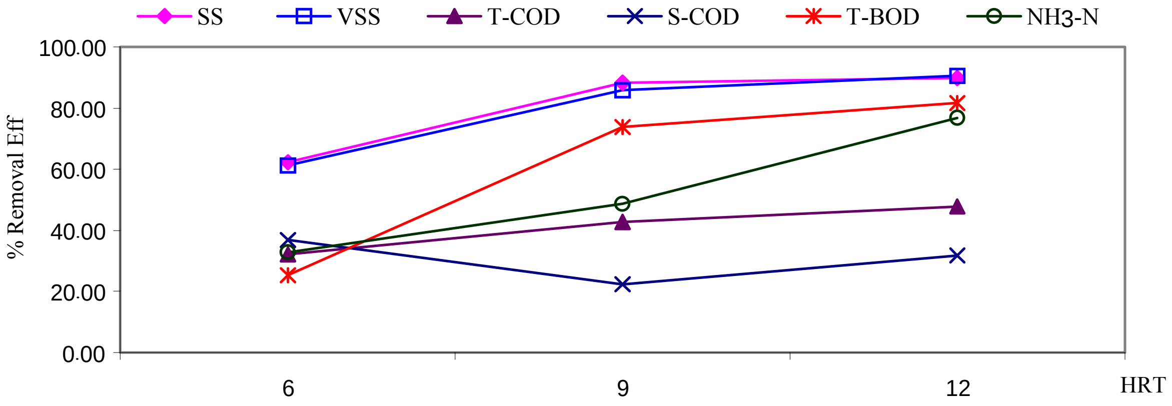


Figure 4-10. Effect of HRT.

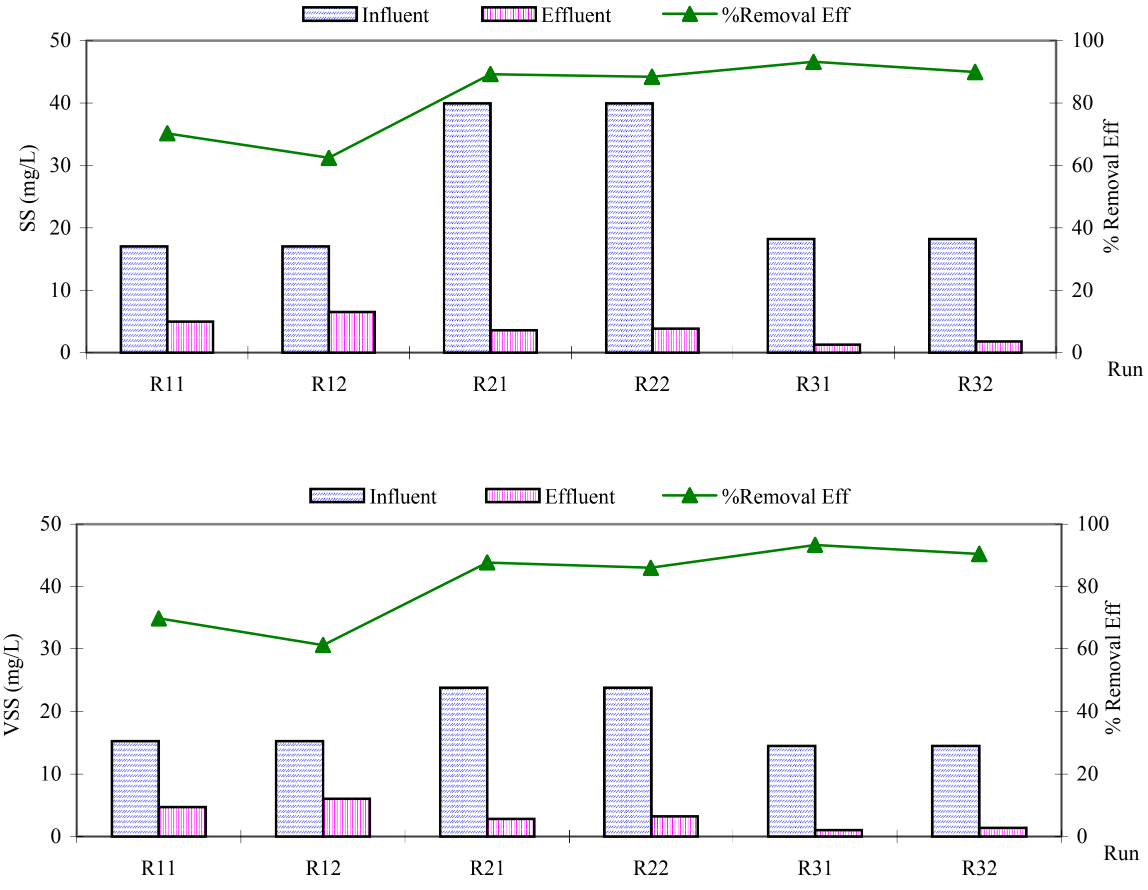


Figure 4-11. Effect of rock size (SS and VSS).

4.4.2 Effect of Rock size

Figures 4-11 and 4-12 show the effect of rock sizes on process performance in terms of SS, VSS, T-COD, S-COD and T-BOD removal. The removal efficiencies of SS and VSS in RBF I (70-93 %) were higher than in RBF II (60-90 %). It could be due to the fact that more media surface was available for smaller rock size (RBF I) which for the biofilm attachment. However, after about 120-125 days from start, the clogging might have occurred in the spaces between small rocks of RBF I causing reduced removal efficiencies and to be almost same as in the reactor, RBF II with bigger rocks.

Therefore, it can be said that for the long run operation of rock-bed filtration process, small rock size may not be beneficial. In fact, in case of using small rocks as media, frequent washing would be required to avoid clogging.

As shown in Figure 4-12, removal of T-COD, S-COD, and T-BOD in RBF I and RBF II were almost similar during the all 3 runs. It can be seen from these results that small rock size had removal efficiencies about 8 % higher in terms of SS and VSS during the initial period of 120-125 days.

4.4.3 Effect of Aeration

For studying the effect of aeration, we divided the Run II (HRT of 9 h) into two parts, the first one month with 3 air diffusers and the later part (1 month) having 6 air diffusers. Figure 4-13 shows the effect of aeration in terms of SS, VSS, and T-BOD removal with 3 and 6 air diffusers, respectively. The removal efficiencies for both SS and VSS were higher for the period with 6 air diffusers than the one with 3 air diffusers. The average percent removal of SS and VSS were 89 %, 88 %, respectively with the 6 air diffusers, and 80 % for each with the 3 air diffusers. Thus, the aeration had some effect on SS and VSS removal (8-9 % improvement). However, these parameters should be mostly removed by sedimentation or physical process in RBF method.

In case of T-BOD, the average percent removal during the second run with 3 air diffusers and with the 6 air diffusers were 46 % and 76 %, respectively. Thus, it may be inferred that more aeration (6 air diffusers) helped microorganisms in attached biofilm to remove more T-BOD.

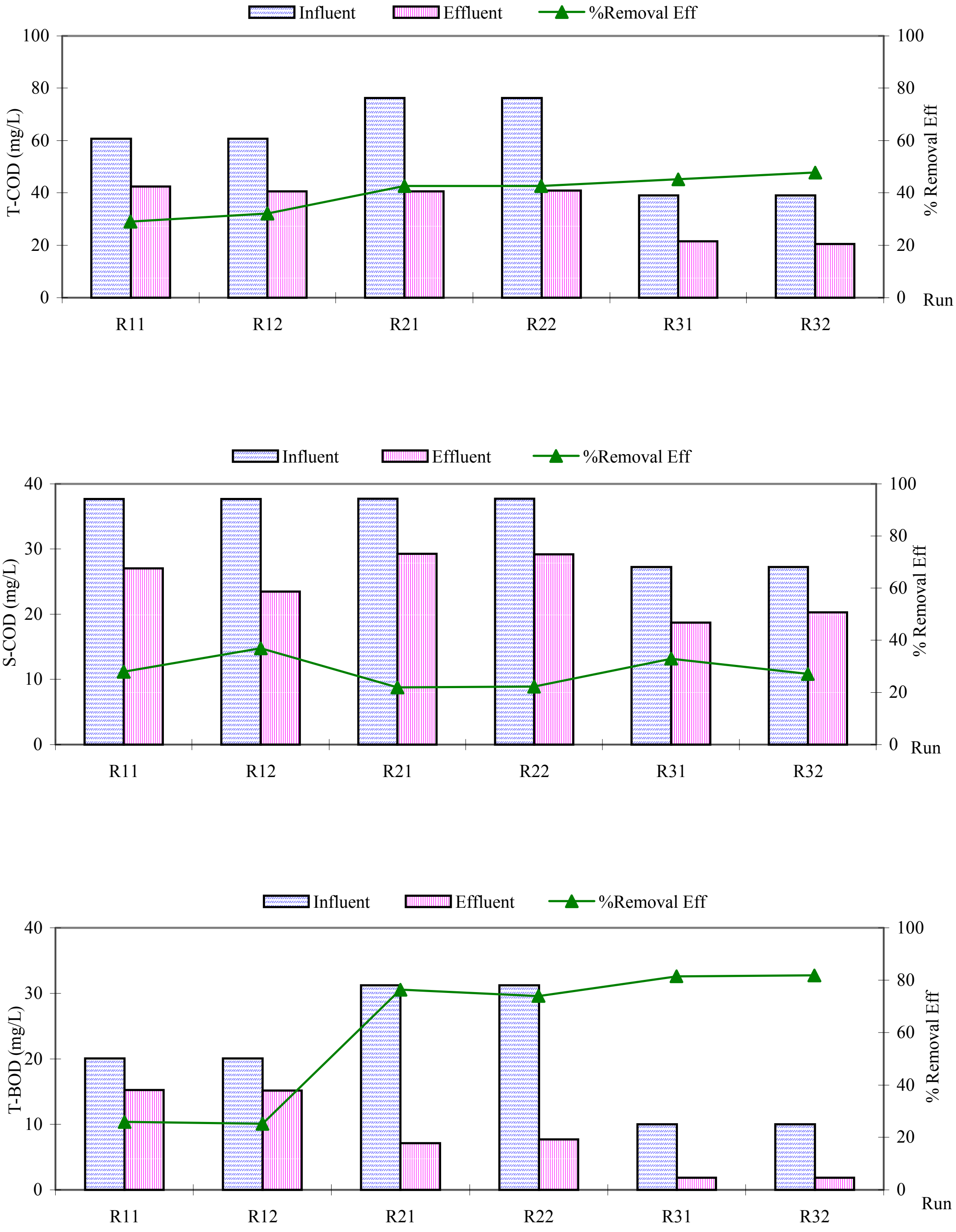


Figure 4-12. Effect of rock size (T-COD, S-COD and T-BOD).

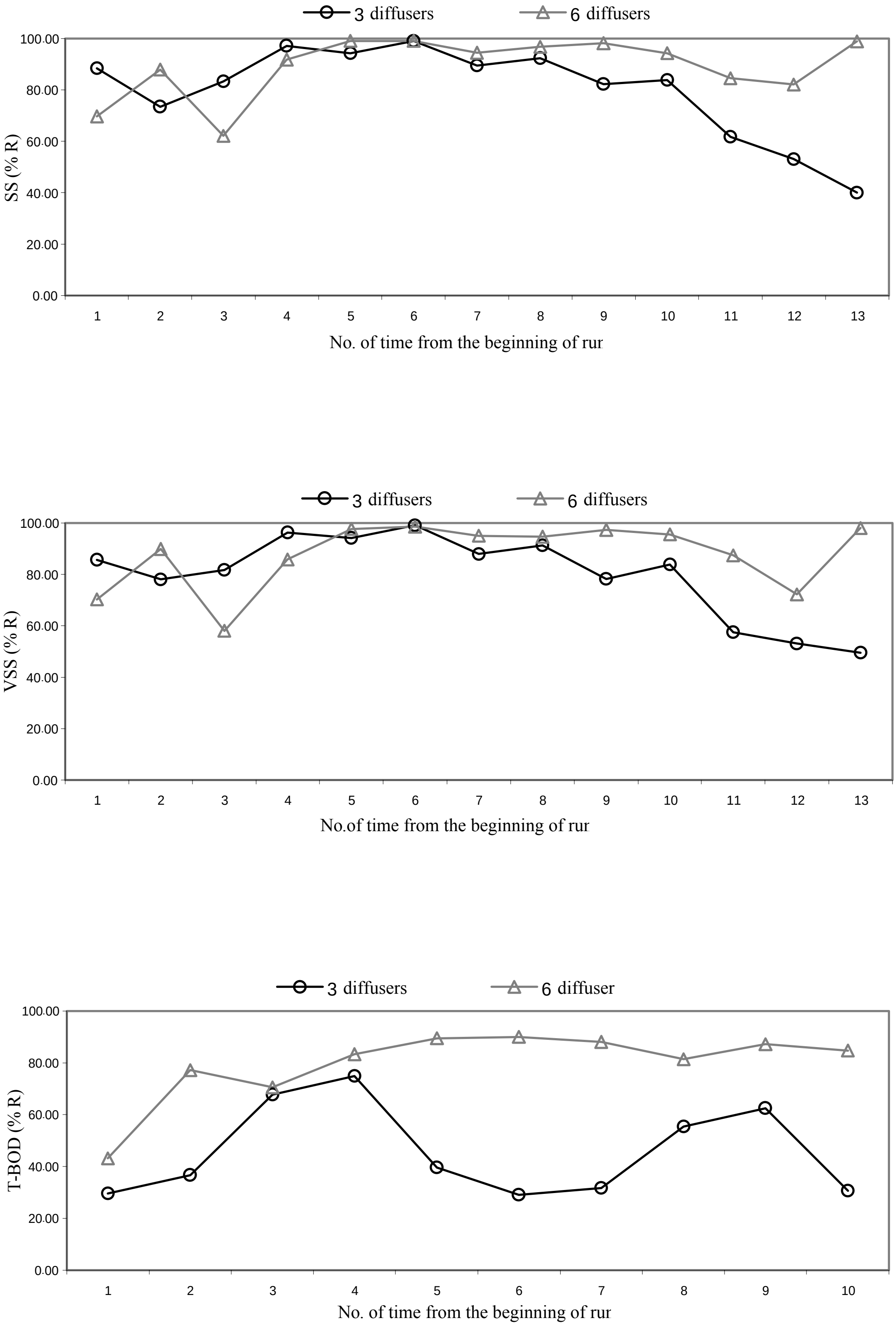


Figure 4-13. Effect of aeration.

4.5 Porosity Change in the two reactors

Porosity change is very important parameter in the RBFs process. The value of porosity depends on the initial porosity, reactor volume, and height of the rock-bed. The porosity reduction occurred due to the sediment and biomass accumulation in the RBFs. Table 4-2 and Figure 4-14 show porosity change in the two reactors during the experimental period of 5 ½ months. Initial overall porosities of the rock-bed in two reactors were 47.1 % for RBF I and 47.6 % for RBF II. After one and a half months of operation (Run I), the porosity in RBF I was reduced to 44.6 % and in RBF II to 45.6 %. At the end of the second run, the porosities were found to be 42.5 % in RBF I and 43.3 % in RBF II. At the end of the last run, the porosities in RBF I and RBF II were 41.9 % and 42.7 %, respectively.

Figure 4-15 shows porosity reduction in RBF I and RBF II during experimental period. It can be seen that the porosity reduction in RBF I was only slightly higher than RBF II. However, if the process was continued for longer period of about 1 year or so, much higher porosity reduction in smaller rock-bed could be expected due to clogging.

Table 4-2. Porosity change and porosity reduction in two reactors.

Number of Reactor	**Porosity (%)**						
	Initial	**End of Run I**	**Reduction (%)**	**End of Run II**	**Reduction (%)**	**End of Run III**	**Reduction (%)**
RBF I (2-4 cm)	47.1	44.6	5.3	42.5	9.8	41.9	11.0
RBF II (5-7 cm)	47.6	45.6	4.2	43.3	9.0	42.7	10.3

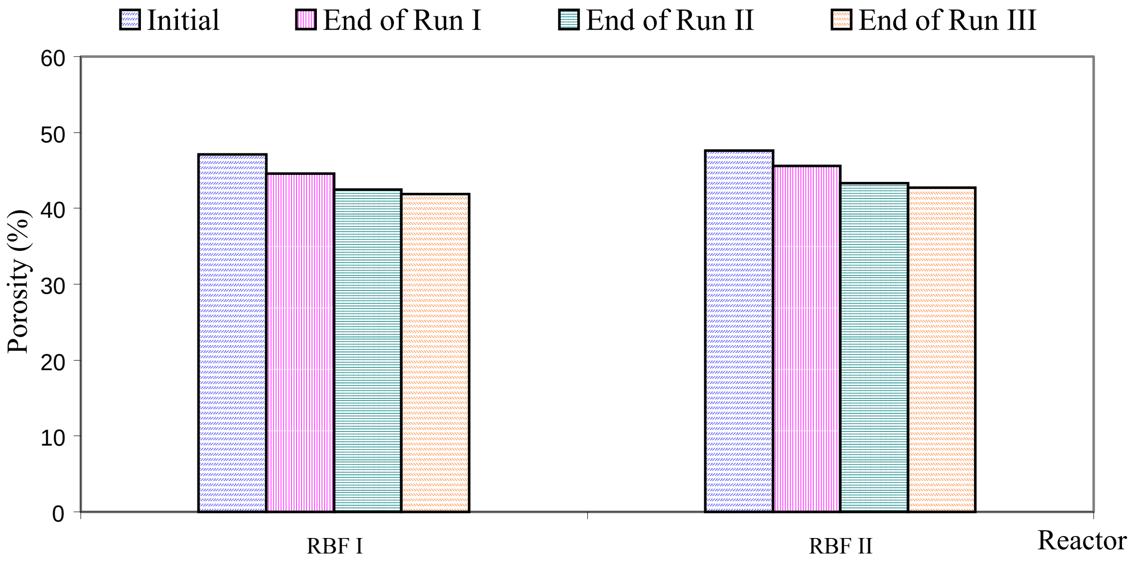


Figure 4-14. Porosity change in two reactors during the experimental period.

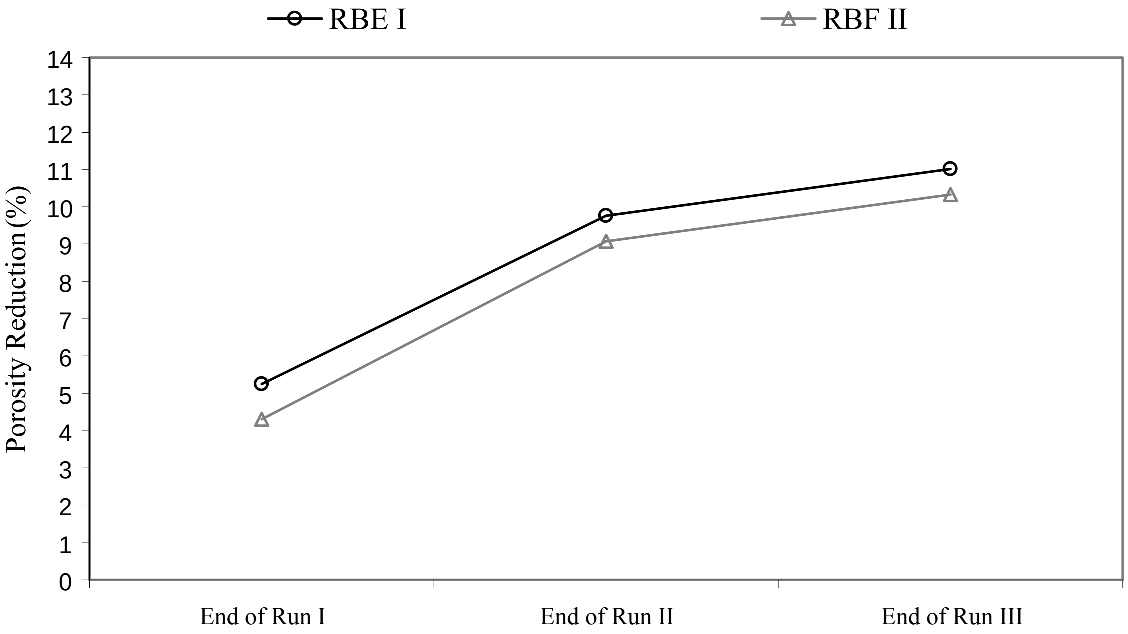


Figure 4-15. Porosity reduction in two reactors.

4.6 Rates of Rock-bed Filtration Processes

The rates of various physical and biological processes were evaluated by using the equations given in Sections 2.4.1 and 2.4.2. Values of various kinetic and stoichiometric coefficients employed for these equations are shown in Table 4-3.

Table 4-3. Values of kinetic and Stoichiometric coefficients.

Parameter	Value	Units	References
d_1	5.4	day^{-1}	Jindal (1995)
d_2	9.2	day^{-1}	Jindal (1995)
r_1	2.4	day^{-1}	Fuji and Somiya (1990)
r_2	30	g N/m^3-day	Jindal (1995)
K_1	0.5	g O_2/m^3	Fuji and Somiya (1990)
K_2	1.0	g O_2/m^3	Jindal (1995)
K_3	1.4	g N/m^3	Fuji and Somiya (1990)
K_L	1.68	m/day	Jindal (1995)

4.6.1 Physical Processes

1) **Reaeration rate**

From Equation (2-1):

$$P_1 = \frac{K_L (C_S - C_3)}{H}$$

Where, P_1 = reaeration rate (g O_2/m^3-day)
K_L = gas transfer rate constant (m/day)
C_S = dissolved oxygen (DO) saturation value (g/m^3)
C_3 = influent (DO) concentration (g/m^3)
H = effective height of the tank (m)

Run I (from Tables B2-1, B3-1 and B10-1), HRT = 6 h, rock level = 40 cm

RBF I, Avg. temp. = 26.0°C , initial porosity = 47.1 %

(C_s = 8.2 g/m^3 at 26.0°C, C_3 = 3.9 g/m^3, H = 0.4 × 0.471 = 0.188 m)

$$P_1 = \frac{1.68 \times (8.2\text{-}3.9)}{0.188} = 38.43 \text{ g } O_2/m^3\text{-day}$$

RBF II, Avg. temp. = 26.0°C, initial porosity = 47.6 %

(C_s = 8.2 g/m^3 at 26.0°C, C_3 = 3.9 g/m^3, H = 0.4 × 0.476 = 0.190 m)

$$P_1 = \frac{1.68 \times (8.2\text{-}3.9)}{0.190} = 38.02 \text{ g } O_2/m^3\text{-day}$$

Run II, HRT = 9 h, rock level = 40 cm

3 diffusers (from Tables B2-2, B3-2 and B10-2)

RBF I, Avg. temp. = 31.2°C, porosity in end of the first run = 44.6 %

(C_s = 7.5 g/m^3 at 31.2°C, C_3 = 4.0 g/m^3, H = 0.4 × 0.446 = 0.178 m)

$$P_1 = \frac{1.68 \times (7.5\text{-}4.0)}{0.178} = 33.03 \text{ g } O_2/m^3\text{-day}$$

RBF II, Avg. temp. = 31.2 °C, porosity in end of the first run = 45.6 %

(C_s = 7.5 g/m^3 at 31.2°C, C_3 = 3.9 g/m^3, H = 0.4 × 0.456 = 0.182 m)

$$P_1 = \frac{1.68 \times (7.5\text{-}3.9)}{0.182} = 33.23 \text{ g } O_2/m^3\text{-day}$$

6 diffusers (from Tables B2-3, B3-3 and B10-2)

RBF I, Avg. temp. = 31.3°C, porosity in end of the first run = 44.6 %

(C_s = 7.5 g/m^3 at 31.3°C, C_3 = 3.0 g/m^3, H = 0.4 × 0.446 = 0.178 m)

$$P_1 = \frac{1.68 \times (7.5\text{-}3.0)}{0.178} = 42.47 \text{ g } O_2/m^3\text{-day}$$

RBF II, Avg. temp. = 31.3°C, porosity in end of the first run = 45.6 %

(C_s = 7.5 g/m^3 at 31.3°C, C_3 = 2.9 g/m^3, H = 0.4 × 0.456 = 0.182 m)

$$P_1 = \frac{1.68 \times (7.5\text{-}2.9)}{0.182} = 42.46 \text{ g } O_2/m^3\text{-day}$$

Run III (from Tables B2-4, B3-4 and B10-3), HRT = 12 h, rock level = 40 cm

RBF I, Avg. temp. = 32.3°C, porosity in end of the second run = 42.5 %

(C_s = 7.4 g/m^3 at 32.3°C, C_3 = 4.7 g/m^3, H = 0.4 × 0.425 = 0.170 m)

$$P_1 = \frac{1.68 \times (7.4\text{-}4.7)}{0.170} = 26.68 \text{ g } O_2/\text{m}^3\text{-day}$$

RBF II, Avg. temp. = 32.3°C, porosity in end of the second run = 43.3 %

(C_s = 7.4 g/m^3 at 32.3°C, C_3 = 4.6 g/m^3, H = 0.4 × 0.433 = 0.173 m)

$$P_1 = \frac{1.68 \times (7.4\text{-}4.6)}{0.173} = 27.19 \text{ g } O_2/\text{m}^3\text{-day}$$

2) Sedimentation rate of POM

From Equation (2-2):

$$P_2 = d_1 C_1$$

Where, P_2 = sedimentation rate of particulate organic matter, (g COD/m^3-day)

d_1 = sedimentation coefficient for POM (day^{-1})

= 5.4 day^{-1}, from Table 4-3

C_1 = influent concentration of POM (g COD/m^3)

= P-COD = (T-COD)-(S-COD)

Run I (from Tables B6-1 and B7-1), HRT = 6 h

Influent of T-COD = 60.7 mg/L, Influent of S-COD = 37.7 mg/L

(C_1 = 60.7-37.7 = 23.0 g COD/m^3)

$$P_2 = 5.4 \times 23.0 = 124.20 \text{ g COD/m}^3\text{-day}$$

Run II, HRT = 9 h

3 diffusers (from Tables B6-2 and B7-2)

Influent of T-COD = 81.5 mg/L, Influent of S-COD = 44.0 mg/L

(C_1 = 81.5-44.0 = 37.5 g COD/m^3)

$$P_2 = 5.4 \times 37.5 = 202.50 \text{ g COD/m}^3\text{-day}$$

6 diffusers (from Tables B6-3 and B7-3)

Influent of T-COD = 76.3 mg/L, Influent of S-COD = 37.7 mg/L

(C_1 = 76.3-37.7 = 38.6 g COD/m^3)

$$P_2 = 5.4 \times 38.6 = 208.44 \text{ g COD/m}^3\text{-day}$$

Run III (from Tables B6-4 and B7-4), HRT = 12 h

Influent of T-COD = 39.0 mg/L, Influent of S-COD = 27.2 mg/L

(C_1 = 39.0-27.2 = 11.8 g COD/m^3)

$$P_2 = 5.4 \times 11.8 = 63.72 \text{ g COD/m}^3\text{-day}$$

3) Sedimentation rate of ISS

From Equation (2-3):

$$P_3 = d_2 C_2$$

Where, P_3 = sedimentation rate of inorganic suspended solids, (g COD/m^3-day)

d_2 = sedimentation coefficient for ISS (day^{-1})

= 9.2 day^{-1}, from Table 4-3

C_2 = influent concentration of ISS (g COD/m^3)

= ISS = (SS)-(VSS)

Run I (from Tables B4-1 and B5-1), HRT = 6 h

Influent of SS = 17.0 mg/L, Influent of VSS = 15.3 mg/L
(C_2 = 17.0-15.3 = 1.7 g COD/m^3)

$$P_3 = 9.2 \times 1.7 = 15.64 \text{ g COD/m}^3\text{-day}$$

Run II, HRT = 9 h

3 diffusers (from Tables B4-2 and B5-2)

Influent of SS = 31.5 mg/L, Influent of VSS = 26.9 mg/L
(C_2 = 31.5-26.9 = 4.6 g COD/m^3)

$$P_3 = 9.2 \times 4.6 = 42.32 \text{ g COD/m}^3\text{-day}$$

6 diffusers (from Tables B4-3 and B5-3)

Influent of SS = 39.9 mg/L, Influent of VSS = 23.8 mg/L
(C_2 = 39.9-23.8 = 16.1 g COD/m^3)

$$P_3 = 9.2 \times 16.1 = 148.12 \text{ g COD/m}^3\text{-day}$$

Run III (from Tables B4-4 and B5-4), HRT = 12 h

Influent of SS = 18.2 mg/L, Influent of VSS = 14.5 mg/L
(C_2 = 18.2-14.5 = 3.7 g COD/m^3)

$$P_3 = 9.2 \times 3.7 = 34.04 \text{ g COD/m}^3\text{-day}$$

4.6.2 Biological Processes

1) Rate of oxic decomposition of DOM

From Equation (2-5):

$$P_4 \quad = \quad r_1 \frac{C_3}{(K_1 + C_3)} C_4$$

Where, P_4 = reaction rate of oxic decomposition of DOM (g/m^3-day)

r_1 = biological reaction coefficient (day^{-1})

= 2.4 day^{-1}, from Table 4-3

K_1 = half saturation coefficients (g/m^3)

= 0.5 g O_2/m^3, from Table 4-3

C_3 = concentration of dissolved oxygen (g/m^3)

C_4 = concentration of dissolved organic matter (g COD/m^3)

Run I (from Tables B3-1 and B7-1), HRT = 6 h

RBF I, (C_3 = 3.9 g/m^3, C_4 = 37.7 g COD/m^3)

$$P_4 \quad = \quad 2.4 \times \frac{3.9}{(0.5+3.9)} \times 37.7 \quad = \quad 80.20 \text{ g/m}^3\text{-day}$$

RBF II, (C_3 = 3.9 g/m^3, C_4 = 37.7 g COD/m^3)

$$P_4 \quad = \quad 2.4 \times \frac{3.9}{(0.5+3.9)} \times 37.7 \quad = \quad 80.20 \text{ g/m}^3\text{-day}$$

Run II, HRT = 9 h

3 diffusers (from Tables B3-2 and B7-2)

RBF I, ($C_3 = 4.0$ g/m^3, $C_4 = 44.0$ g COD/m^3)

$$P_4 = 2.4 \times \frac{4.0}{(0.5+4.0)} \times 44.0 = 93.87 \text{ g/m}^3\text{-day}$$

RBF II, ($C_3 = 3.9$ g/m^3, $C_4 = 44.0$ g COD/m^3)

$$P_4 = 2.4 \times \frac{3.9}{(0.5+3.9)} \times 44.0 = 93.60 \text{ g/m}^3\text{-day}$$

6 diffusers (from Tables B3-3 and B7-3)

RBF I, ($C_3 = 3.0$ g/m^3, $C_4 = 37.7$ g COD/m^3)

$$P_4 = 2.4 \times \frac{3.0}{(0.5+3.0)} \times 37.7 = 77.55 \text{ g/m}^3\text{-day}$$

RBF II, ($C_3 = 2.9$ g/m^3, $C_4 = 37.7$ g COD/m^3)

$$P_4 = 2.4 \times \frac{2.9}{(0.5+2.9)} \times 37.7 = 77.17 \text{ g/m}^3\text{-day}$$

Run III (from Tables B3-4 and B7-4), HRT = 12 h

RBF I, ($C_3 = 4.7$ g/m^3, $C_4 = 27.2$ g COD/m^3)

$$P_4 = 2.4 \times \frac{4.7}{(0.5+4.7)} \times 27.2 = 59.00 \text{ g/m}^3\text{-day}$$

RBF II, ($C_3 = 4.6$ g/m^3, $C_4 = 27.2$ g COD/m^3)

$$P_4 = 2.4 \times \frac{4.6}{(0.5+4.6)} \times 27.2 = 58.88 \text{ g/m}^3\text{-day}$$

2) Rate of nitrification

From Equation (2-10):

$$P_5 \quad = \quad r_2 \frac{C_3}{(K_2 + C_3)} \quad \frac{C_5}{(K_3 + C_5)}$$

Where, P_5 = rate of nitrification (g N/m^3-day)

r_2 = nitrification rate coefficient (g N/m^3-day)

= 30 g N/m^3-day, from Table 4-3

C_3 = concentration of dissolved oxygen (g/m^3)

C_5 = concentration of NH_4-N (g N/m^3)

K_2, K_3 = half saturation coefficients (g O_2/m^3, g N/m^3)

= 1.0 g O_2/m^3, 1.4 g N/m^3, from Table 4-3

Run I (from Tables B3-1 and B9-1), HRT = 6 h

RBF I, (C_3 = 3.9 g/m^3, C_5 = 4.3 g N/m^3)

$$P_5 = 30 \times \frac{3.9}{(1.0+3.9)} \times \frac{4.3}{(1.4+4.3)} = 18.01 \quad \text{g N/m}^3\text{-day}$$

RBF II, (C_3 = 3.9 g/m^3, C_5 = 4.3 g N/m^3)

$$P_5 = 30 \times \frac{3.9}{(1.0+3.9)} \times \frac{4.3}{(1.4+4.3)} = 18.01 \quad \text{g N/m}^3\text{-day}$$

Run II, HRT = 9 h

3 diffusers (from Tables B3-2 and B9-2)

RBF I, (C_3 = 4.0 g/m^3, C_5 = 2.7 g N/m^3)

$$P_5 = 30\times \frac{4.0}{(1.0+4.0)} \times \frac{2.7}{(1.4+2.7)} = 15.80 \quad \text{g N/m}^3\text{-day}$$

RBF II, (C_3 = 3.9 g/m^3, C_5 = 2.7 g N/m^3)

$$P_5 = 30\times \frac{3.9}{(1.0+3.9)} \times \frac{2.7}{(1.4+2.7)} = 15.72 \quad \text{g N/m}^3\text{-day}$$

6 diffusers (from Tables B3-3 and B9-3)

RBF I, (C_3 = 3.0 g/m^3, C_5 = 3.9 g N/m^3)

$$P_5 = 30\times \frac{3.0}{(1.0+3.0)} \times \frac{3.9}{(1.4+3.9)} = 16.56 \quad \text{g N/m}^3\text{-day}$$

RBF II, (C_3 = 2.9 g/m^3, C_5 = 3.9 g N/m^3)

$$P_5 = 30\times \frac{2.9}{(1.0+2.9)} \times \frac{3.9}{(1.4+3.9)} = 16.42 \quad \text{g N/m}^3\text{-day}$$

Run III (from Tables B3-4 and B9-4), HRT = 12 h

RBF I, (C_3 = 4.7 g/m^3, C_5 = 3.9 g N/m^3)

$$P_5 = 30\times \frac{4.7}{(1.0+4.7)} \times \frac{3.9}{(1.4+3.9)} = 18.20 \quad \text{g N/m}^3\text{-day}$$

RBF II, (C_3 = 4.6 g/m^3, C_5 = 3.9 g N/m^3)

$$P_5 = 30\times \frac{4.6}{(1.0+4.6)} \times \frac{3.9}{(1.4+3.9)} = 18.13 \quad \text{g N/m}^3\text{-day}$$

Table 4-4 shows the rates of various rock-bed filtration processes during the experimental period. The rates of reaeration, oxic decomposition of DOM, and nitrification are shown in Figure 4-16. For both reactors, there was a slight increase in the reaeration rate as the HRT increased from 6 h to 9 h and a sharp decrease for 9 h < HRT < 12 h. The rate of oxic decomposition of DOM initially increased with an increase in HRT for 6 h < HRT < 9 h and then decreased with higher HRT (12 h). The rate of nitrification decreased with an increase in HRT from 6 h to 9 h and increased again as the HRT increased from 9 h to 12 h. Figure 4-17 shows the the rates of sedimentation of POM and ISS. For the rates of sedimentation of POM and ISS, there was increase with an increase in HRT from 6 h to 9 h and after that, a sharp decrease for HRT at 12 h.

Table 4-4. The rates of various rock-bed filtration processes.

Processes rate	**HRT = 6 h**		**HRT = 9 h**				**HRT = 12 h**	
			3 diffusers		**6 diffusers**			
	RBF I	**RBF II**	**RBF I**	**RBF II**	**RBF I**	**RBF II**	**RBF I**	**RBF II**
P_1 (g O_2/m^3-day)	38.43	38.02	33.03	33.23	42.47	42.46	26.68	27.19
P_2 (g COD/m^3-day)	124.20	124.20	202.50	202.50	208.44	208.44	63.72	63.72
P_3 (g COD/m^3-day)	15.64	15.64	42.32	42.32	148.12	148.12	34.04	34.04
P_4 (g /m^3-day)	80.20	80.20	93.87	93.60	77.55	77.17	59.00	58.88
P_5 (g N/m^3-day)	18.01	18.01	15.80	15.72	16.56	16.42	18.20	18.13

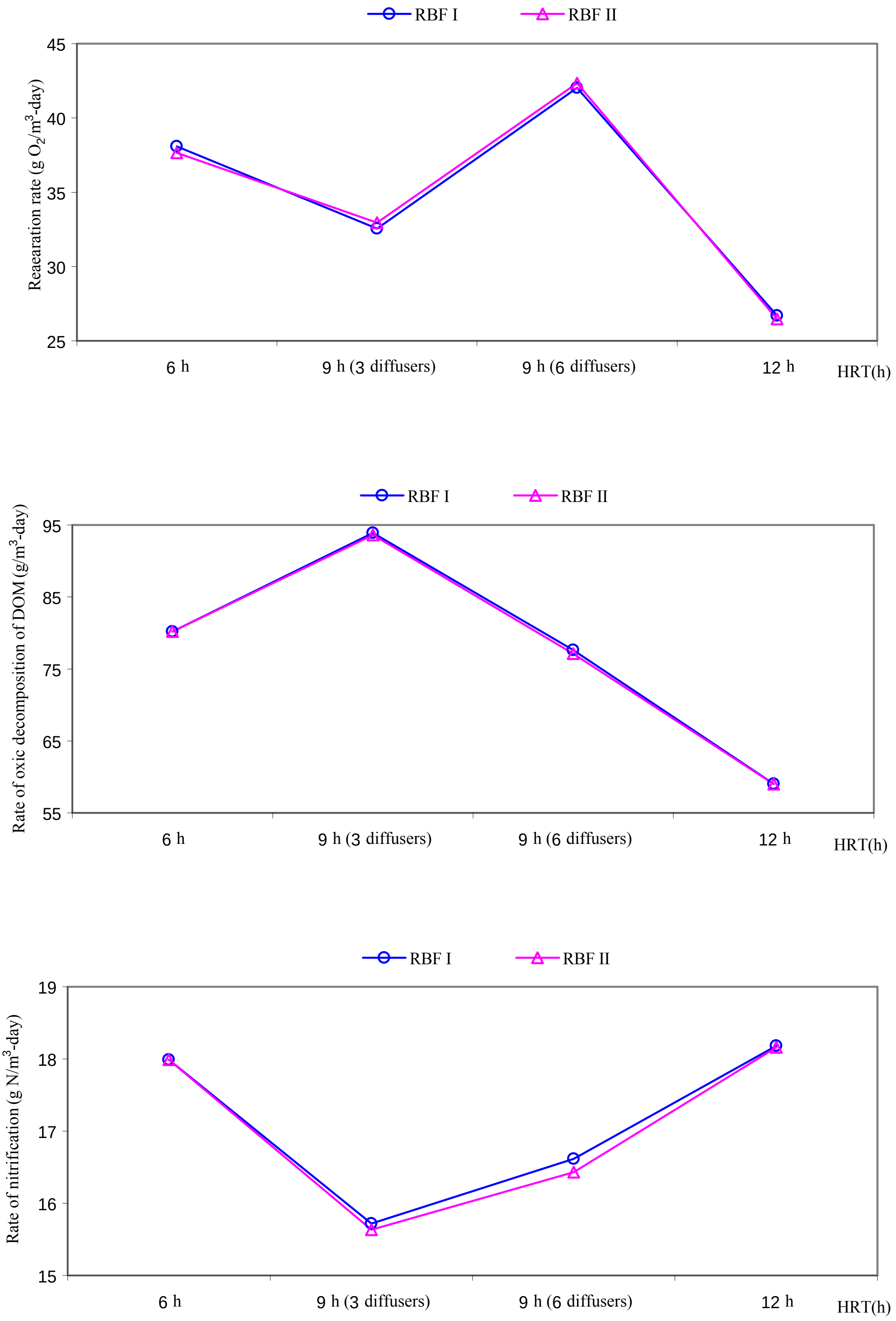
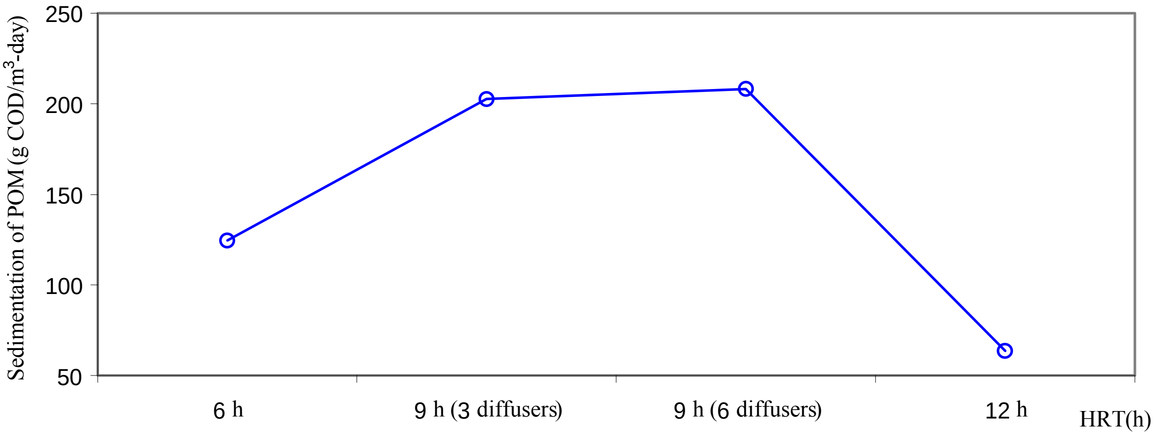


Figure 4-16. The rates of reaeration, oxic decomposition of DOM and nitrification.



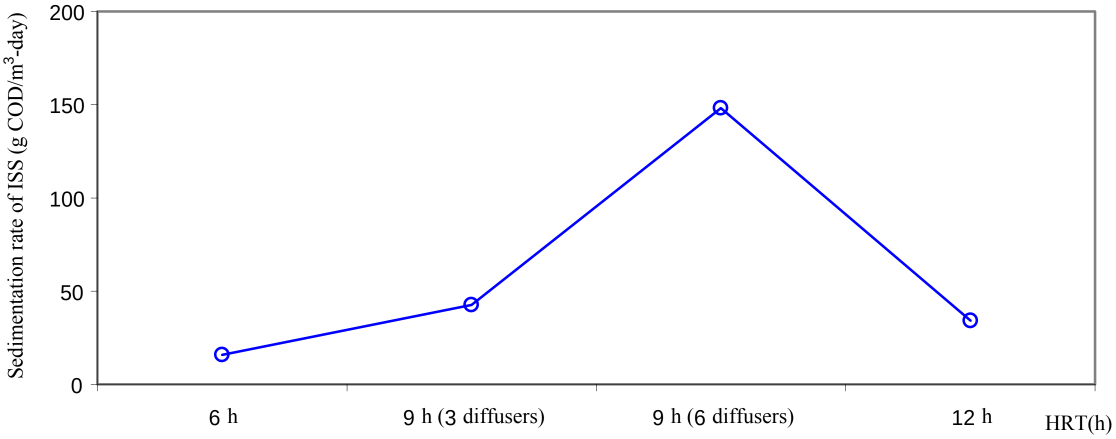


Figure 4-17. The rates of sedimentation of POM and ISS.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The objective of this research was to evaluate the process efficiency, optimum design parameters, and most appropriate operating conditions for the rock-bed filtration method of wastewater treatment. The results from the experiments on pilot-scale rock-bed filtration units, conducted during the 5 ½ months (January–June 2000) are summarized as follows.

The experiments were divided into 3 runs consisting of different operating conditions. Removal efficiency for particulate matter (SS and VSS) was in general high, ranging 60-90 % throughout the experimental period. In case of COD, the removal efficiency for T-COD ranged from 30-50 % but was lower for S-COD. Removal efficiency for T-BOD gradually increased from about 25 % during the first run to 76 % in the later half of the second run, and finally reached up to 82 % during the third run.

An increase in HRT (6 h, 9 h and 12 h) increased removal efficiency of various wastewater quality parameters in general. For SS, VSS, T-COD, T- BOD and NH_3-N, there was maximum increase in removal efficiency for 6 h < HRT< 9 h and then only a nominal increase for 9 h < HRT< 12 h. However, for filtrate COD, there was slight decrease in removal efficiency with an increase in HRT from 6 h to 9 h and only a slight increase as the HRT increased from 9 h to 12 h. The effect of rock size on process performance was only observed as about 8 % increase in particulates removal for smaller rocks compared to the bigger ones. However, for T-COD, S-COD, and T-BOD, the rock size did not have significant effect on removal efficiency. The aeration had some effect on SS and VSS removal (8-9 % improvement). However, these parameters should be mostly removed by sedimentation or physical process in RBF method. In case of T-BOD, the average percent removal during the second run with 3 air diffusers and with the 6 air diffusers were 46 % and 76 %, respectively. Thus, it may be inferred that more aeration (6 air diffusers) helped microorganisms in attached biofilm to remove more T-BOD.

Porosity reduction occurred due to the sediment and biomass accumulation in the RBFs. The porosity of rock-beds was reduced by approximately 11 % over 5 ½ months operation. However, if the process was continued for longer period of about 1 year or so, much higher porosity reduction in smaller rock-bed could be expected due to clogging.

For both reactors, there was a slight increase in the reaeration rate as the HRT increased from 6 h to 9 h and a sharp decrease for 9 h < HRT < 12 h. The rates of oxic decomposition of DOM, sedimentation of POM and ISS, there was increase with an increase in HRT from 6 h to 9 h and after that, a sharp decrease for HRT at 12 h. The rate of nitrification decreased with an increase in HRT from 6 h to 9 h and increased again as the HRT increased from 9 h to 12 h.

5.2 Conclusions

Based on the experimental results and the analysis of variance (ANOVA) results (Appendix C) of this study, following conclusions can be made:

1. The main reaction mechanism in the treatment process of rock-bed filtration process is sedimentation of suspended solids.
2. Soluble organic matter may be removed by the attached biofilm after an adequate time of operation has passed.
3. Smaller rocks show a bit better particulate removal initially but the removal decreases later due to clogging.
4. T-BOD removal is proportionally related to time. That is, the longer time, the higher removal efficiency. This is because biofilm requires long period of time to develop for efficient removal of dissolved organic matter (DOM).
5. For SS, VSS, T-COD, T- BOD and NH_3-N, there was maximum increase in removal efficiency for 6 h < HRT< 9 h and then only a nominal increase for 9 h < HRT < 12 h. Thus, the optimum HRT seems to be 9 h.
6. Increased aeration improved T-BOD removal significantly (from 46 % to 76 % during the second run with 3 air diffusers and 6 air diffusers, respectively). More aeration (6 air diffusers) helped microorganisms in attached biofilm to remove more T-BOD.

Based on the above results and discussion, the optimum operating conditions for RBF process can be summarized in Table 5-1 below:

Table 5-1. Recommended optimum operation conditions.

Parameter	Value
Rock size	5-7 cm
HRT	9 h
Aeration	504 x 10^{-3} m^3 air/m^3 water-h

Based on the past experiences as well as results of this study, the range of influent concentrations for adequate performance of the rock-bed filtration process are shown in Table 5-2.

Table 5-2. Range of influent concentrations of the RBF process.

Parameter	Range
SS	40-70 mg/L
T-COD	40-70 mg/L
T-BOD	20-40 mg/L
NH_3-N	1-10 mg/L

5.3 Recommendations

The following work is recommended for future research:

1. Different conditions of water/wastewater influent to RBF process, for example, from ponds, reservoir, river, and/or water with high sludge content, etc. should be investigated.
2. Study for the appropriate time for washing and cleaning, and life cycle of rock-bed filtration process for a media size must be evaluated.
3. Analysis of the other parameters such as nitrate nitrogen, total phosphate, coliform bacteria and E.coli, etc. should be done.
4. Other alternate media such as different size of rocks, bits of ceramic tiles, crushed bricks, broken concrete pieces or molded concrete, etc. should also be evaluated for RBF process.

APPENDIX A

Flow rate and Porosity reduction

A1. Flow rate.

$$Q = \frac{\forall}{\theta}$$

Where, Q = Flow rate (m^3/h)

$\forall$ = Volume of the reactor (m^3)

= $3\ \text{m} \times 0.5\ \text{m} \times 0.5\ \text{m}$ = $0.6\ \text{m}^3$

θ = Retention time (h)

HRT = 6 h

$$Q = \frac{0.6\ \text{m}^3}{6\ \text{h}}$$

$= 0.1\ \text{m}^3/\text{h}$

$= (0.1\ \text{m}^3/\text{h})\times(1\ \text{h}/3600\text{s})\times(1000\text{L}/1\ \text{m}^3)$

$= 1\ \text{L}/36\text{s}$

$= (0.1\ \text{m}^3/\text{h})\times(24\ \text{h/day})\times(1000\text{L}/1\ \text{m}^3)$

$= 2400\ \text{L/day}$

HRT = 9 h

$$Q = \frac{0.6\ \text{m}^3}{9\ \text{h}}$$

$= 0.067\ \text{m}^3/\text{h}$

$= 1\ \text{L}/54\text{s}$

$= 1600\ \text{L/day}$

HRT = 12 h

$$Q = \frac{0.6\ \text{m}^3}{12\ \text{h}}$$

$= 0.05\ \text{m}^3/\text{h}$

$= 1\ \text{L}/72\text{s}$

$= 1200\ \text{L/day}$

A2. Porosity Reduction.

$$\text{Porosity Reduction (\%)} = \frac{(\text{Initial} - \text{End of RUN}) \times 100\ \%}{\text{Initial}}$$

End of Run I

$$\text{Porosity Reduction in RBF I} = \frac{(47.1 - 44.6) \times 100\ \%}{47.1}$$

$$= 5.3\ \%$$

$$\text{Porosity Reduction in RBF II} = \frac{(47.6 - 45.6) \times 100\ \%}{47.6}$$

$$= 4.2\ \%$$

End of Run II

$$\text{Porosity Reduction in RBF I} = \frac{(47.1 - 42.5) \times 100\ \%}{47.1}$$

$$= 9.8\ \%$$

$$\text{Porosity Reduction in RBF II} = \frac{(47.6 - 43.3) \times 100\ \%}{47.6}$$

$$= 9.0\ \%$$

End of Run III

$$\text{Porosity Reduction in RBF I} = \frac{(47.1 - 41.9) \times 100\ \%}{47.1}$$

$$= 11.0\ \%$$

$$\text{Porosity Reduction in RBF II} = \frac{(47.6 - 42.7) \times 100\ \%}{47.6}$$

$$= 10.3\ \%$$

APPENDIX B

Results of Pilot-scale Experiments

Table B1-1. pH of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**		**Run R12-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
20/1/00	7.51	7.26	7.52	7.31
22/1/00	7.84	7.49	7.83	7.48
25/1/00	8.12	7.77	8.10	7.75
27/1/00	8.24	7.85	8.27	7.84
29/1/00	7.76	7.43	7.74	7.42
1/2/00	8.61	7.90	8.62	8.00
3/2/00	8.74	8.21	8.75	8.22
5/2/00	9.14	8.65	9.13	8.65
8/2/00	8.38	8.01	8.43	8.01
15/2/00	8.42	7.92	8.45	8.03
17/2/00	8.74	8.03	8.72	8.05
19/2/00	8.49	7.85	8.51	7.92
22/2/00	8.82	8.11	8.85	8.14
24/2/00	8.71	7.96	8.69	8.00
29/2/00	8.33	7.74	8.31	7.88
2/3/00	8.62	7.83	8.64	7.91
4/3/00	8.48	7.65	8.49	7.68
7/3/00	8.37	7.50	8.38	7.54
9/3/00	8.63	7.73	8.62	7.80
11/3/00	8.46	7.75	8.48	7.85
Average	**8.42**	**7.83**	**8.43**	**7.87**
SD	**0.39**	**0.31**	**0.39**	**0.30**
Coeff. of variations	**4.63**	**3.96**	**4.63**	**3.81**

Table B1-2. pH of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**		**Run R22-3**	
	Influent	**Effluent**	**Influent**	**Effluent**
14/3/00	8.67	7.69	8.67	7.74
16/3/00	8.88	7.72	8.89	7.95
17/3/00	8.74	7.71	8.74	7.95
21/3/00	8.82	7.80	8.87	7.92
25/3/00	8.79	7.88	8.80	8.07
26/3/00	8.67	7.69	8.67	7.70
28/3/00	8.74	7.71	8.74	7.95
30/3/00	8.77	7.92	8.76	8.05
1/4/00	8.66	7.89	8.67	8.06
4/4/00	8.48	7.84	8.48	7.91
9/4/00	8.21	7.67	8.23	7.58
11/4/00	8.42	7.85	8.47	7.80
13/4/00	8.09	7.76	8.04	7.76
Average	**8.61**	**7.78**	**8.62**	**7.88**
SD	**0.24**	**0.09**	**0.25**	**0.15**
Coeff. of variations	**2.79**	**1.16**	**2.90**	**1.90**

Table B1-3. pH of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**		**Run R22-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
20/4/00	8.10	7.57	8.10	7.58
22/4/00	8.41	7.57	8.45	7.66
25/4/00	8.11	8.32	8.13	8.33
28/4/00	8.45	7.69	8.46	7.81
30/4/00	8.32	7.79	8.34	7.65
2/5/00	8.43	7.42	8.41	7.58
4/5/00	8.45	7.68	8.44	7.72
6/5/00	8.51	7.66	8.44	7.83
9/5/00	8.78	7.72	8.79	7.91
11/5/00	8.66	7.58	8.69	7.67
13/5/00	8.73	7.71	8.69	7.86
16/5/00	8.31	7.52	8.28	7.64
18/5/00	7.87	7.61	7.90	7.68
20/5/00	7.44	7.31	7.42	7.34
22/5/00	7.38	7.22	7.39	7.25
24/5/00	7.43	7.29	7.43	7.32
Average	**8.21**	**7.60**	**8.21**	**7.68**
SD	**0.46**	**0.25**	**0.45**	**0.26**
Coeff. of variations	**5.60**	**3.29**	**5.48**	**3.39**

Table B1-4. pH of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**		**Run R32-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
31/5/00	8.25	7.57	8.27	7.67
2/6/00	7.55	7.20	7.57	7.10
4/6/00	7.88	7.18	7.88	7.24
6/6/00	7.67	7.35	7.69	7.41
10/6/00	8.00	7.42	8.00	7.41
12/6/00	7.85	7.41	7.87	7.39
16/6/00	8.15	7.44	8.17	7.44
18/6/00	7.99	7.44	7.97	7.46
20/6/00	8.12	7.37	8.09	7.33
22/6/00	8.22	7.45	8.25	7.41
24/6/00	7.92	7.18	7.91	7.19
27/6/00	8.10	7.42	8.02	7.37
29/6/00	7.88	7.54	7.87	7.41
Average	**7.97**	**7.38**	**7.97**	**7.37**
SD	**0.21**	**0.13**	**0.20**	**0.14**
Coeff. of variations	**2.63**	**1.76**	**2.51**	**1.90**

Table B2-1. Temperature of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**		**Run R12-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
20/1/00	24	23	25	23
22/1/00	26	24	26	24
25/1/00	27	26	26	25
27/1/00	24	23	24	22
29/1/00	21	20	21	19
1/2/00	22	20	22	20
3/2/00	25	23	25	22
5/2/00	26	24	26	23
8/2/00	24	23	24	22
15/2/00	25	24	25	23
17/2/00	22	21	22	20
19/2/00	20	19	20	18
22/2/00	27	25	27	24
24/2/00	28	26	28	24
29/2/00	30	27	30	26
2/3/00	27	25	27	26
4/3/00	28	26	28	25
7/3/00	32	30	32	30
9/3/00	31	29	31	28
11/3/00	31	29	31	28
Average	**26.0**	**24.4**	**26.0**	**23.6**
SD	**3.4**	**3.0**	**3.4**	**3.1**
Coeff. of variations	**13.1**	**12.3**	**13.1**	**13.1**

Table B2-2. Temperature of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**		**Run R22-3**	
	Influent	**Effluent**	**Influent**	**Effluent**
14/3/00	32	28	32	27
16/3/00	32	30	31	29
17/3/00	31	30	31	29
21/3/00	31	32	31	31
25/3/00	31	31	31	31
26/3/00	30	29	30	28
28/3/00	31	29	31	28
30/3/00	31	31	31	31
1/4/00	31	32	31	32
4/4/00	34	33	34	33
9/4/00	31	32	31	32
11/4/00	31	32	31	32
13/4/00	30	31	30	31
Average	**31.2**	**30.8**	**31.2**	**30.3**
SD	**1.0**	**1.5**	**1.0**	**1.9**
Coeff. of variations	**3.2**	**4.9**	**3.2**	**6.3**

Table B2-3. Temperature of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**		**Run R22-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
20/4/00	31	32	31	32
22/4/00	30	30	30	30
25/4/00	27	27	27	27
28/4/00	33	32	33	32
30/4/00	34	33	34	33
2/5/00	34	32	34	32
4/5/00	33	32	33	32
6/5/00	34	32	34	32
9/5/00	32	31	32	30
11/5/00	33	31	33	30
13/5/00	32	30	32	30
16/5/00	30	29	30	29
18/5/00	30	29	30	29
20/5/00	30	28	30	28
22/5/00	29	28	29	28
24/5/00	28	28	28	28
Average	**31.3**	**30.3**	**31.3**	**30.1**
SD	**2.2**	**1.9**	**2.2**	**1.9**
Coeff. of variations	**7.0**	**6.3**	**7.0**	**6.3**

Table B2-4. Temperature of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**		**Run R32-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
31/5/00	33	31	33	31
2/6/00	33	31	33	31
4/6/00	33	29	33	30
6/6/00	33	30	33	29
10/6/00	32	30	32	30
12/6/00	32	30	32	30
16/6/00	34	30	34	30
18/6/00	29	29	29	28
20/6/00	31	28	31	28
22/6/00	33	30	33	29
24/6/00	32	30	32	30
27/6/00	32	30	32	30
29/6/00	33	30	33	29
Average	**32.3**	**29.8**	**32.3**	**29.6**
SD	**1.3**	**0.8**	**1.3**	**1.0**
Coeff. of variations	**4.0**	**2.7**	**4.0**	**3.4**

Table B3-1. DO of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**		**Run R12-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
20/1/00	2.4	3.0	2.5	3.2
22/1/00	2.1	2.3	2.5	2.6
25/1/00	4.8	1.8	4.8	1.9
27/1/00	4.9	1.6	5.0	1.8
29/1/00	3.2	1.4	3.3	1.4
1/2/00	4.4	1.4	4.4	1.4
3/2/00	3.0	1.3	3.0	1.5
5/2/00	4.5	1.9	4.4	2.1
8/2/00	2.5	1.5	2.5	1.5
15/2/00	4.9	1.6	5.0	1.8
17/2/00	3.4	1.4	3.4	1.5
19/2/00	2.6	1.3	2.4	1.3
22/2/00	3.0	1.5	2.6	1.3
24/2/00	5.4	1.4	5.3	1.2
29/2/00	5.6	1.6	5.6	1.3
2/3/00	3.2	1.1	3.0	1.2
4/3/00	3.8	1.4	3.7	1.3
7/3/00	5.0	1.3	5.2	1.7
9/3/00	5.2	1.1	5.1	1.2
11/3/00	4.6	1.1	4.8	1.3
Average	**3.9**	**1.6**	**3.9**	**1.6**
SD	**1.1**	**0.4**	**1.1**	**0.5**
Coeff. of variations	**28.2**	**25.0**	**28.2**	**31.3**

Table B3-2. DO of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**		**Run R22-3**	
	Influent	**Effluent**	**Influent**	**Effluent**
14/3/00	5.0	1.0	5.3	1.0
16/3/00	4.8	1.1	4.6	1.2
17/3/00	4.7	1.2	4.6	1.2
21/3/00	5.0	0.9	5.0	1.2
25/3/00	4.5	1.3	4.2	1.3
26/3/00	4.0	0.7	3.9	1.0
28/3/00	3.8	1.2	3.6	1.2
30/3/00	4.2	1.5	4.2	1.0
1/4/00	4.2	1.5	4.0	1.2
4/4/00	3.7	1.1	3.8	1.4
9/4/00	3.2	1.4	2.8	1.4
11/4/00	2.0	1.4	1.8	1.6
13/4/00	3.1	1.9	3.0	2.0
Average	**4.0**	**1.2**	**3.9**	**1.3**
SD	**0.9**	**0.3**	**1.0**	**0.3**
Coeff. of variations	**22.5**	**25.0**	**25.6**	**23.1**

Table B3-3. DO of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**		**Run R22-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
20/4/00	3.3	1.0	2.6	1.0
22/4/00	2.8	0.9	2.8	0.8
25/4/00	3.2	0.8	3.2	0.9
28/4/00	2.8	0.9	2.8	1.2
30/4/00	3.4	1.2	3.3	1.4
2/5/00	2.7	0.9	2.8	1.0
4/5/00	2.6	1.3	2.7	1.3
6/5/00	3.1	1.0	3.4	1.3
9/5/00	3.1	0.9	2.8	1.2
11/5/00	2.3	1.2	2.4	1.3
13/5/00	3.0	1.0	2.8	1.3
16/5/00	2.6	1.0	2.4	1.1
18/5/00	3.1	1.0	3.0	1.2
20/5/00	3.6	1.2	3.2	1.4
22/5/00	3.3	1.1	3.0	1.4
24/5/00	3.2	1.3	2.8	1.4
Average	**3.0**	**1.0**	**2.9**	**1.2**
SD	**0.3**	**0.2**	**0.3**	**0.2**
Coeff. of variations	**10.0**	**20.0**	**10.3**	**16.7**

Table B3-4. DO of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**		**Run R32-6**	
	Influent	**Effluent**	**Influent**	**Effluent**
31/5/00	4.6	1.8	4.5	1.4
2/6/00	3.6	1.5	3.1	1.6
4/6/00	4.1	2.0	4.2	1.8
6/6/00	3.4	1.0	3.6	1.6
10/6/00	4.8	1.3	4.8	1.6
12/6/00	5.0	1.2	5.2	1.5
16/6/00	5.2	0.9	5.1	1.7
18/6/00	4.8	1.0	4.8	1.1
20/6/00	5.0	1.0	5.0	0.9
22/6/00	5.2	1.4	5.2	1.4
24/6/00	5.4	1.2	5.4	1.5
27/6/00	4.8	1.1	4.8	1.6
29/6/00	4.8	1.8	4.6	1.4
Average	**4.7**	**1.3**	**4.6**	**1.5**
SD	**0.6**	**0.4**	**0.7**	**0.2**
Coeff. of variations	**12.8**	**30.8**	**15.2**	**13.3**

Table B4-1. SS of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**			**Run R12-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/1/00	14.0	6.0	57.1	14.0	9.3	33.9
22/1/00	20.0	12.0	40.0	20.0	14.0	30.0
25/1/00	21.0	8.0	61.9	21.0	7.0	66.7
27/1/00	23.0	12.5	45.7	23.0	13.0	43.5
29/1/00	10.5	2.0	81.0	10.5	3.5	66.7
1/2/00	11.8	3.0	74.5	11.8	3.5	70.2
3/2/00	13.5	2.0	85.2	13.5	1.8	87.0
5/2/00	17.5	2.5	85.7	17.5	3.8	78.6
8/2/00	12.6	3.4	73.0	12.6	4.2	66.7
15/2/00	15.4	4.8	68.8	15.4	5.8	62.3
17/2/00	11.2	2.8	75.0	11.2	3.4	69.6
19/2/00	6.2	1.2	80.6	6.2	2.2	64.5
22/2/00	7.4	3.0	59.5	7.4	2.2	70.3
24/2/00	11.6	5.6	51.7	11.6	5.6	51.7
29/2/00	19.2	4.2	78.1	19.2	5.4	71.9
2/3/00	23.0	10.4	54.8	23.0	14.0	39.1
4/3/00	22.4	6.2	72.3	22.4	8.2	63.4
7/3/00	28.4	2.4	91.5	28.4	4.8	83.1
9/3/00	25.0	4.0	84.0	25.0	10.2	59.2
11/3/00	26.8	3.8	85.8	26.8	8.6	67.9
Average	**17.0**	**5.0**	**70.3**	**17.0**	**6.5**	**62.3**
SD	**6.5**	**3.3**	**14.8**	**6.5**	**3.9**	**15.5**
Coeff. of variations	**38.2**	**66.0**	**21.1**	**38.2**	**60.0**	**24.9**

Table B4-2. SS of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**			**Run R22-3**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
14/3/00	34.6	4.0	88.4	34.6	9.0	74.0
16/3/00	46.8	12.4	73.5	46.8	14.0	70.1
17/3/00	38.4	6.4	83.3	38.4	7.0	81.8
21/3/00	55.0	1.6	97.1	55.0	5.8	89.5
25/3/00	28.0	1.6	94.3	28.0	4.0	85.7
26/3/00	24.7	0.2	99.2	24.7	1.6	93.5
28/3/00	19.0	2.0	89.5	19.0	4.2	77.9
30/3/00	31.7	2.4	92.4	31.7	4.6	85.5
1/4/00	29.4	5.2	82.3	29.4	8.0	72.8
4/4/00	22.3	3.6	83.9	22.3	6.0	73.1
9/4/00	33.5	12.8	61.8	33.5	9.6	71.3
11/4/00	24.3	11.4	53.1	24.3	10.2	58.0
13/4/00	22.0	13.2	40.0	22.0	12.6	42.7
Average	**31.5**	**5.9**	**79.9**	**31.5**	**7.4**	**75.1**
SD	**10.4**	**4.8**	**18.1**	**10.4**	**3.6**	**13.6**
Coeff. of variations	**33.0**	**81.4**	**22.7**	**33.0**	**48.6**	**18.1**

Table B4-3. SS of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**			**Run R22-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/4/00	35.5	10.8	69.7	35.5	12.0	66.2
22/4/00	49.5	6.0	87.9	49.5	7.0	85.9
25/4/00	35.0	13.3	62.1	35.0	8.3	76.4
28/4/00	53.5	4.4	91.8	53.5	4.8	91.0
2/5/00	63.5	0.6	99.1	63.5	1.6	97.5
4/5/00	50.0	0.4	99.2	50.0	1.4	97.2
6/5/00	18.5	1.0	94.6	18.5	2.0	89.2
9/5/00	31.0	1.0	96.8	31.0	1.0	96.8
11/5/00	68.0	1.2	98.2	68.0	2.4	96.5
13/5/00	26.5	1.5	94.3	26.5	1.5	94.3
20/5/00	15.5	2.4	84.5	15.5	3.0	80.7
22/5/00	19.0	3.4	82.1	19.0	3.8	80.0
24/5/00	53.0	0.6	98.9	53.0	1.6	97.0
Average	**39.9**	**3.6**	**89.2**	**39.9**	**3.9**	**88.4**
SD	**17.3**	**4.1**	**11.8**	**17.5**	**3.3**	**9.9**
Coeff. of variations	**43.4**	**113.9**	**13.2**	**43.9**	**84.6**	**11.2**

Table B4-4. SS of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**			**Run R32-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
31/5/00	14.0	0.8	94.3	14.0	1.2	91.4
2/6/00	17.5	0.6	96.6	17.5	0.8	95.4
4/6/00	21.7	1.8	91.7	21.7	2.4	88.9
6/6/00	16.0	1.8	88.8	16.0	2.8	82.5
10/6/00	15.5	1.2	92.3	15.5	2.8	81.9
12/6/00	13.5	1.2	91.1	13.5	0.8	94.1
16/6/00	15.0	0.7	95.5	15.0	0.7	95.5
18/6/00	18.0	3.0	83.3	18.0	2.8	84.7
20/6/00	28.0	1.3	95.3	28.0	2.7	90.5
22/6/00	14.5	0.4	97.2	14.5	1.6	89.0
24/6/00	23.5	0.7	97.2	23.5	1.3	94.3
27/6/00	20.0	0.6	97.0	20.0	2.0	90.0
29/6/00	20.0	2.0	90.0	20.0	2.0	90.0
Average	**18.2**	**1.2**	**93.1**	**18.2**	**1.8**	**89.9**
SD	**4.3**	**0.8**	**4.1**	**4.3**	**0.8**	**4.6**
Coeff. of variations	**23.6**	**66.7**	**4.4**	**23.6**	**44.4**	**5.1**

Table B5-1. VSS of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**			**Run R12-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/1/00	12.0	3.0	75.0	12.0	7.5	37.5
22/1/00	19.0	10.0	47.4	19.0	10.0	47.4
25/1/00	19.0	8.0	57.9	19.0	6.0	68.4
27/1/00	22.0	12.0	45.5	22.0	12.0	45.5
29/1/00	10.0	1.5	85.0	10.0	3.3	67.5
1/2/00	11.5	3.0	73.9	11.5	3.5	69.6
3/2/00	12.8	2.0	84.3	12.8	1.8	86.3
5/2/00	17.0	2.5	85.3	17.0	3.5	79.4
8/2/00	12.4	3.2	74.3	12.4	4.2	66.1
15/2/00	15.4	4.6	70.2	15.4	5.6	63.6
17/2/00	11.0	2.8	74.6	11.0	3.2	70.9
19/2/00	6.0	1.2	80.0	6.0	2.2	63.3
22/2/00	7.4	3.0	59.5	7.4	2.0	73.0
24/2/00	10.2	5.6	45.1	10.2	5.6	45.1
29/2/00	17.4	4.2	75.9	17.4	5.4	69.0
2/3/00	20.2	10.4	48.5	20.2	14.0	30.7
4/3/00	16.6	6.2	62.7	16.6	8.2	50.6
7/3/00	24.0	2.4	90.0	24.0	4.8	80.0
9/3/00	20.8	4.0	80.8	20.8	10.2	51.0
11/3/00	21.2	3.8	82.1	21.2	8.6	59.4
Average	**15.3**	**4.7**	**69.9**	**15.3**	**6.1**	**61.2**
SD	**5.2**	**3.1**	**14.6**	**5.2**	**3.5**	**14.9**
Coeff. of variations	**34.0**	**66.0**	**20.9**	**34.0**	**57.4**	**24.3**

Table B5-2. VSS of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**			**Run R22-3**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
14/3/00	27.8	4.0	85.6	27.8	9.0	67.6
16/3/00	35.6	7.8	78.1	35.6	13.8	61.2
17/3/00	35.2	6.4	81.8	35.2	7.0	80.1
21/3/00	42.3	1.6	96.2	42.3	5.8	86.3
25/3/00	27.3	1.6	94.1	27.3	2.6	90.5
26/3/00	21.3	0.2	99.1	21.3	1.6	92.5
28/3/00	16.6	2.0	88.0	16.6	4.2	74.7
30/3/00	27.7	2.4	91.3	27.7	4.6	83.4
1/4/00	23.8	5.2	78.2	23.8	7.0	70.6
4/4/00	22.3	3.6	83.9	22.3	6.6	70.4
9/4/00	24.5	10.4	57.6	24.5	6.7	72.7
11/4/00	24.3	11.4	53.1	24.3	10.2	58.0
13/4/00	21.0	10.6	49.5	21.0	9.2	56.2
Average	**26.9**	**5.2**	**79.7**	**26.9**	**6.8**	**74.2**
SD	**7.1**	**3.8**	**16.4**	**7.1**	**3.3**	**11.9**
Coeff. of variations	**26.4**	**73.1**	**20.6**	**26.4**	**48.5**	**16.0**

Table B5-3. VSS of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**			**Run R22-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/4/00	34.5	10.3	70.3	34.5	11.5	66.7
22/4/00	44.5	4.5	89.9	44.5	6.3	86.0
25/4/00	21.5	9.0	58.1	21.5	5.5	74.4
28/4/00	29.5	4.2	85.8	29.5	4.2	85.8
2/5/00	25.5	0.6	97.7	25.5	0.6	97.7
4/5/00	29.0	0.4	98.6	29.0	1.6	94.5
6/5/00	16.0	0.8	95.0	16.0	1.8	88.8
9/5/00	19.0	1.0	94.7	19.0	1.0	94.7
11/5/00	31.0	0.8	97.4	31.0	2.2	92.9
13/5/00	17.0	0.8	95.6	17.0	0.8	95.6
20/5/00	9.5	1.2	87.4	9.5	2.4	74.7
22/5/00	11.5	3.2	72.2	11.5	3.4	70.4
24/5/00	20.5	0.4	98.1	20.5	1.0	95.1
Average	**23.8**	**2.9**	**87.7**	**23.8**	**3.3**	**86.0**
SD	**9.8**	**3.3**	**13.0**	**9.8**	**3.1**	**10.8**
Coeff. of variations	**41.2**	**113.8**	**14.8**	**41.2**	**93.9**	**12.6**

Table B5-4. VSS of Runs R31-6 and R32-6.

D/M/Y	Run R31-6			Run R32-6		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
31/5/00	12.0	0.8	93.3	12.0	1.2	90.0
2/6/00	15.0	0.6	96.0	15.0	0.8	94.7
4/6/00	14.7	1.8	87.7	14.7	2.4	83.6
6/6/00	12.5	1.6	87.2	12.5	2.4	80.8
10/6/00	14.5	0.8	94.5	14.5	1.6	89.0
12/6/00	13.0	0.8	93.9	13.0	0.4	96.9
16/6/00	12.5	0.3	97.4	12.5	0.3	97.4
18/6/00	17.0	2.5	85.3	17.0	1.8	89.7
20/6/00	14.5	1.0	93.1	14.5	2.0	86.2
22/6/00	12.5	0.2	98.4	12.5	1.0	92.0
24/6/00	17.0	0.3	98.1	17.0	0.7	96.1
27/6/00	16.5	0.4	97.6	16.5	1.6	90.3
29/6/00	17.0	1.7	90.2	17.0	1.7	90.2
Average	**14.5**	**1.0**	**93.3**	**14.5**	**1.4**	**90.5**
SD	**1.9**	**0.7**	**4.4**	**1.9**	**0.7**	**5.0**
Coeff. of variations	**13.1**	**70.0**	**4.7**	**13.1**	**50.0**	**5.5**

Table B6-1. T-COD of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**			**Run R12-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/1/00	46.0	39.5	14.1	46.0	36.5	20.7
22/1/00	52.0	44.0	15.4	52.0	46.5	10.6
25/1/00	59.5	51.5	13.5	59.5	46.0	22.7
27/1/00	67.0	49.0	26.9	67.0	57.0	14.9
29/1/00	47.0	16.0	66.0	47.0	13.5	71.3
1/2/00	47.0	24.0	48.9	47.0	31.0	34.0
3/2/00	85.5	31.0	63.7	85.5	54.5	36.3
5/2/00	81.0	48.0	40.7	81.0	12.0	85.2
8/2/00	66.0	51.0	22.7	66.0	35.0	47.0
15/2/00	53.5	37.0	30.8	53.5	23.0	57.0
17/2/00	68.0	53.0	22.1	68.0	46.0	32.4
19/2/00	54.0	42.0	22.2	54.0	44.0	18.5
22/2/00	62.0	49.0	21.0	62.0	49.0	21.0
24/2/00	83.0	56.0	32.5	83.0	56.0	32.5
29/2/00	62.0	42.0	32.3	62.0	45.0	27.4
2/3/00	56.5	36.0	36.3	56.5	42.0	25.7
4/3/00	39.0	30.0	23.1	39.0	34.0	12.8
7/3/00	51.0	29.5	42.2	51.0	39.0	23.5
9/3/00	52.0	40.0	23.1	52.0	43.0	17.3
11/3/00	82.0	59.5	27.4	82.0	57.0	30.5
Average	**60.7**	**41.4**	**31.2**	**60.7**	**40.5**	**32.1**
SD	**13.6**	**11.3**	**14.8**	**13.6**	**13.0**	**19.5**
Coeff. of variations	**22.4**	**27.3**	**47.4**	**22.4**	**32.1**	**60.7**

Table B6-2. T-COD of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**			**Run R22-3**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
14/3/00	73.6	38.8	47.4	73.6	61.6	16.4
16/3/00	87.4	42.7	51.2	87.4	61.0	30.2
17/3/00	90.9	53.4	41.3	90.9	61.3	32.6
21/3/00	99.8	47.0	52.9	99.8	52.8	47.1
25/3/00	54.7	19.5	64.3	54.7	27.3	50.0
26/3/00	89.5	37.0	58.7	89.5	15.6	82.6
28/3/00	79.4	67.5	15.0	79.4	43.6	45.0
1/4/00	118.0	76.0	35.6	118.0	56.0	52.5
4/4/00	73.4	48.3	34.2	73.4	54.1	26.3
9/4/00	81.2	52.2	35.7	81.2	44.5	45.2
11/4/00	73.5	38.7	47.4	73.5	42.6	42.1
13/4/00	56.5	45.9	18.8	56.5	49.5	12.5
Average	**81.5**	**47.2**	**41.9**	**81.5**	**47.5**	**40.2**
SD	**17.6**	**14.6**	**14.9**	**17.6**	**14.1**	**18.7**
Coeff. of variations	**21.6**	**30.9**	**35.6**	**21.6**	**29.7**	**46.5**

Table B6-3. T-COD of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**			**Run R22-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/4/00	94.4	69.9	25.9	94.4	66.4	29.6
22/4/00	116.2	63.4	45.5	116.2	70.4	39.4
25/4/00	83.3	48.2	42.2	83.3	44.4	46.7
28/4/00	90.9	37.2	59.1	90.9	41.3	54.6
2/5/00	93.5	40.7	56.5	93.5	48.8	47.8
4/5/00	82.7	28.2	65.9	82.7	34.3	58.5
6/5/00	52.5	42.8	18.5	52.5	46.7	11.1
9/5/00	64.0	40.0	37.5	64.0	40.0	37.5
11/5/00	88.9	35.6	60.0	88.9	33.6	62.2
13/5/00	60.2	46.2	23.3	60.2	36.2	40.0
16/5/00	95.1	34.4	63.8	95.1	32.4	66.0
18/5/00	114.5	42.2	63.2	114.5	42.2	63.2
20/5/00	43.3	33.5	22.7	43.3	29.5	31.8
22/5/00	33.9	28.6	15.6	33.9	29.9	11.8
24/5/00	30.4	18.2	40.0	30.4	18.2	40.0
Average	**76.3**	**40.6**	**42.7**	**76.3**	**41.0**	**42.6**
SD	**27.3**	**13.1**	**18.1**	**27.3**	**13.6**	**17.1**
Coeff. of variations	**35.8**	**32.3**	**42.4**	**35.8**	**33.2**	**40.1**

Table B6-4. T-COD of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**			**Run R32-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
31/5/00	37.3	27.5	26.3	37.3	25.5	31.6
2/6/00	47.8	25.9	45.8	47.8	27.9	41.7
4/6/00	35.9	21.9	38.9	35.9	17.9	50.0
6/6/00	35.6	25.7	27.8	35.6	25.7	27.8
10/6/00	39.5	25.7	35.0	39.5	25.7	35.0
12/6/00	39.2	23.5	40.0	39.2	17.7	55.0
16/6/00	44.8	29.2	34.8	44.8	21.4	52.2
18/6/00	33.5	21.7	35.3	33.5	11.8	64.7
20/6/00	49.0	23.5	52.0	49.0	25.5	48.0
22/6/00	36.3	12.1	66.7	36.3	20.2	44.4
24/6/00	44.2	18.1	59.1	44.2	18.1	59.1
27/6/00	32.1	12.1	62.5	32.1	20.1	37.5
29/6/00	31.8	11.9	62.5	31.8	7.9	75.0
Average	**39.0**	**21.4**	**45.1**	**39.0**	**20.4**	**47.8**
SD	**5.8**	**6.1**	**14.0**	**5.8**	**5.9**	**13.6**
Coeff. of variations	**14.9**	**28.5**	**31.0**	**14.9**	**28.9**	**28.5**

Table B7-1. S-COD of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**			**Run R12-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/1/00	31.0	26.0	16.1	31.0	26.0	16.1
22/1/00	49.5	42.0	15.2	49.5	43.5	12.1
25/1/00	41.0	28.5	30.5	41.0	23.5	42.7
27/1/00	53.0	41.0	22.6	53.0	25.0	52.8
29/1/00	16.0	11.0	31.3	16.0	5.0	68.8
1/2/00	35.0	25.5	27.1	35.0	18.0	48.6
3/2/00	39.0	27.0	30.8	39.0	16.0	59.0
5/2/00	46.0	36.5	20.7	46.0	12.0	73.9
8/2/00	43.0	35.0	18.6	43.0	34.0	20.9
15/2/00	31.0	27.0	12.9	31.0	23.0	25.8
17/2/00	57.0	30.0	47.4	57.0	27.0	52.6
19/2/00	38.0	31.0	18.4	38.0	30.0	21.1
22/2/00	30.0	23.0	23.3	30.0	23.0	23.3
29/2/00	49.0	23.0	53.1	49.0	23.0	53.1
2/3/00	28.0	18.0	35.7	28.0	24.0	14.3
4/3/00	32.0	26.0	18.8	32.0	28.0	12.5
7/3/00	43.0	33.5	22.1	43.0	35.0	18.6
9/3/00	31.0	12.0	61.3	31.0	12.0	61.3
11/3/00	23.0	17.5	23.9	23.0	17.5	23.9
Average	**37.7**	**27.0**	**27.9**	**37.7**	**23.5**	**36.9**
SD	**10.6**	**8.6**	**13.2**	**10.6**	**9.0**	**20.9**
Coeff. of variations	**28.1**	**31.9**	**47.3**	**28.1**	**38.3**	**56.6**

Table B7-2. S-COD of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**			**Run R22-3**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
14/3/00	34.9	32.9	5.7	34.9	33.0	5.6
16/3/00	32.5	30.5	6.2	32.5	30.5	6.3
17/3/00	43.5	37.6	13.6	43.5	35.6	18.2
21/3/00	43.1	31.3	27.3	43.1	31.3	27.3
25/3/00	27.3	15.6	42.9	27.4	15.6	42.9
26/3/00	59.5	35.7	40.0	59.5	47.6	20.0
28/3/00	55.6	49.6	10.7	55.6	51.0	8.2
1/4/00	66.0	44.0	33.3	66.0	34.0	48.5
4/4/00	38.6	34.8	10.0	38.6	27.0	30.0
9/4/00	34.8	31.0	11.1	34.8	31.0	11.1
11/4/00	42.6	39.7	6.8	42.6	38.9	8.7
13/4/00	49.5	30.6	38.1	49.5	32.9	33.6
Average	**44.0**	**34.4**	**20.5**	**44.0**	**34.0**	**21.7**
SD	**11.7**	**8.4**	**14.6**	**11.7**	**9.1**	**14.7**
Coeff. of variation	**26.6**	**24.4**	**71.2**	**26.6**	**26.8**	**67.7**

Table B7-3. S-COD of Runs R21-6 and R22-6.

D/M/Y	**Run R21-6**			**Run R22-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/4/00	24.5	20.7	15.3	24.5	19.5	20.4
22/4/00	42.3	32.7	22.5	42.3	31.3	26.0
25/4/00	40.7	33.3	18.2	40.7	32.7	19.6
28/4/00	37.2	28.9	22.2	37.2	24.8	33.3
30/4/00	41.2	30.9	25.0	41.2	37.0	10.0
2/5/00	50.8	36.6	28.0	50.8	36.6	28.0
4/5/00	40.3	30.2	25.0	40.3	32.3	20.0
6/5/00	35.0	31.0	11.4	35.0	31.1	11.1
9/5/00	48.0	34.0	29.2	48.0	36.0	25.0
11/5/00	27.7	21.7	21.7	27.7	22.7	18.0
13/5/00	42.2	28.1	33.3	42.2	32.1	23.8
16/5/00	34.4	30.4	11.8	34.4	29.4	14.6
20/5/00	41.3	31.5	23.8	41.3	25.6	38.1
22/5/00	29.9	23.9	20.0	29.9	24.1	19.4
24/5/00	30.4	24.3	20.0	30.4	22.3	26.4
Average	**37.7**	**29.2**	**21.8**	**37.7**	**29.1**	**22.3**
SD	**7.4**	**4.7**	**6.1**	**7.4**	**5.6**	**7.7**
Coeff. of variations	**19.6**	**16.1**	**28.0**	**19.6**	**19.2**	**34.5**

Table B7-4. S-COD of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**			**Run R32-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
31/5/00	37.3	31.4	15.8	37.3	25.5	31.6
2/6/00	31.9	19.9	37.5	31.9	23.9	25.0
4/6/00	31.9	17.9	43.8	31.9	17.9	43.8
6/6/00	27.7	17.8	35.7	27.7	23.7	14.3
10/6/00	27.7	23.7	14.3	27.7	24.3	12.3
12/6/00	25.5	13.7	46.2	25.5	19.6	23.1
16/6/00	33.1	29.2	11.8	33.1	21.4	35.3
18/6/00	27.6	17.7	35.7	27.6	11.8	57.2
20/6/00	27.5	23.5	14.3	27.5	23.5	14.4
22/6/00	20.2	12.1	40.0	20.2	12.2	39.7
24/6/00	24.1	16.1	33.3	24.1	12.0	50.0
27/6/00	24.1	12.1	50.0	24.1	20.1	16.7
29/6/00	15.9	7.9	50.0	15.9	7.9	50.0
Average	**27.2**	**18.7**	**33.0**	**27.2**	**18.8**	**31.8**
SD	**5.6**	**6.8**	**14.1**	**5.6**	**5.9**	**15.5**
Coeff. of variartions	**20.6**	**36.4**	**42.7**	**20.6**	**31.4**	**48.7**

Table B8-1. T-BOD of Runs R11-6 and R12-6.

D/M/Y	Run R11-6			Run R12-6		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
22/1/00	25.2	20.2	19.8	25.2	21.1	16.3
25/1/00	15.6	6.0	61.5	15.6	8.4	46.2
27/1/00	7.2	4.8	33.3	7.2	5.1	29.2
29/1/00	19.2	14.4	25.0	19.2	16.2	15.6
3/2/00	14.4	10.8	25.0	14.4	10.2	29.2
5/2/00	24.3	15.6	35.8	24.3	16.5	32.1
17/2/00	23.8	19.6	17.7	23.8	16.6	30.3
19/2/00	38.3	33.8	11.8	38.3	33.5	12.4
24/2/00	26.3	21.0	20.2	26.3	17.3	34.2
2/3/00	15.8	12.8	19.1	15.8	13.5	14.3
4/3/00	10.2	8.5	16.7	10.2	8.3	18.6
Average	**20.0**	**15.2**	**26.0**	**20.0**	**15.2**	**25.3**
SD	**8.7**	**8.3**	**13.8**	**8.7**	**7.8**	**10.6**
Coeff. of variations	**43.5**	**54.6**	**53.1**	**43.5**	**51.3**	**41.9**

Table B8-2. T-BOD of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**			**Run R22-3**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
16/3/00	26.5	18.6	29.7	26.5	21.9	17.5
17/3/00	20.8	13.1	36.8	20.8	14.0	32.5
25/3/00	15.5	5.0	67.7	15.5	6.9	55.7
26/3/00	30.0	7.5	75.0	30.0	4.3	85.8
28/3/00	28.0	16.9	39.7	28.0	16.3	42.0
30/3/00	49.8	35.3	29.2	49.8	36.0	27.6
4/4/00	22.0	15.0	31.8	22.0	16.9	23.3
9/4/00	15.4	6.9	55.4	15.4	5.0	67.4
11/4/00	18.6	7.0	62.4	18.6	8.9	52.4
13/4/00	13.9	9.6	30.6	13.9	7.0	49.4
Average	**24.0**	**13.5**	**45.8**	**24.0**	**13.7**	**45.4**
SD	**10.6**	**9.0**	**17.6**	**10.6**	**9.8**	**21.2**
Coeff. of variations	**44.2**	**66.7**	**38.4**	**44.2**	**71.5**	**46.7**

Table B8-3. T-BOD of Runs R21-6 and R22-6.

D/M/Y	Run R21-6			Run R22-6		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/4/00	37.5	21.3	43.2	37.5	22.4	40.2
22/4/00	40.1	9.1	77.2	40.1	10.1	74.8
28/4/00	43.6	12.8	70.6	43.6	12.8	70.6
30/4/00	41.8	7.0	83.3	41.8	7.0	83.2
4/5/00	40.5	4.3	89.4	40.5	6.9	83.1
6/5/00	35.7	3.6	90.0	35.7	3.9	89.1
11/5/00	28.6	3.4	88.0	28.6	4.1	85.6
13/5/00	14.6	2.7	81.3	14.6	2.4	83.4
18/5/00	40.2	5.2	87.2	40.2	5.0	87.5
20/5/00	13.9	7.7	44.3	13.9	8.7	37.0
22/5/00	6.6	1.0	84.8	6.6	1.4	78.2
Average	**31.2**	**7.1**	**76.3**	**31.2**	**7.7**	**73.9**
SD	**13.3**	**5.8**	**17.1**	**13.3**	**5.9**	**18.3**
Coeff. of variations	**42.6**	**81.7**	**22.4**	**42.6**	**76.6**	**24.8**

Table B8-4. T-BOD of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**			**Run R32-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
31/5/00	9.4	2.6	72.6	9.4	3.0	68.0
2/6/00	12.0	4.7	60.8	12.0	4.8	60.5
6/6/00	7.4	2.3	69.3	7.4	1.5	79.1
12/6/00	5.1	1.0	80.6	5.1	1.3	75.1
16/6/00	10.4	1.3	87.4	10.4	1.1	89.5
18/6/00	10.7	0.8	92.3	10.7	0.8	93.0
22/6/00	14.6	2.9	80.3	14.6	3.4	77.1
24/6/00	10.6	0.3	97.2	10.6	0.2	97.9
27/6/00	10.2	0.8	92.7	10.2	0.5	95.6
Average	**10.1**	**1.9**	**81.5**	**10.1**	**1.8**	**81.7**
SD	**2.7**	**1.4**	**12.2**	**2.7**	**1.5**	**13.0**
Coeff. of variations	**26.7**	**73.7**	**15.0**	**26.7**	**83.3**	**15.9**

Table B9-1. Ammonia of Runs R11-6 and R12-6.

D/M/Y	**Run R11-6**			**Run R12-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/1/00	3.4	2.2	33.3	3.4	2.0	41.7
22/1/00	4.8	2.0	58.8	4.8	1.7	64.7
25/1/00	3.9	1.7	57.1	3.9	1.4	64.3
27/1/00	3.9	2.0	50.0	3.9	1.7	57.1
29/1/00	2.8	0.8	70.0	2.8	0.6	80.0
1/2/00	3.6	1.4	61.5	3.6	1.1	69.2
3/2/00	5.0	4.5	11.1	5.0	3.6	27.8
5/2/00	3.4	3.1	8.3	3.4	3.1	8.3
8/2/00	4.8	4.5	5.9	4.8	4.2	11.8
15/2/00	5.3	4.8	10.5	5.3	4.2	21.1
17/2/00	4.2	3.6	13.3	4.2	3.4	20.0
19/2/00	5.3	5.0	5.3	5.3	3.9	26.3
22/2/00	5.0	4.8	5.6	5.0	4.5	11.1
24/2/00	5.6	5.3	5.0	5.6	5.0	10.0
29/2/00	4.5	3.4	25.0	4.5	3.4	25.0
2/3/00	3.6	3.1	15.4	3.6	3.4	7.7
4/3/00	4.2	3.4	20.0	4.2	3.9	6.7
7/3/00	3.1	0.8	72.7	3.1	2.0	36.4
Average	**4.3**	**3.1**	**29.4**	**4.3**	**2.9**	**32.7**
SD	**0.8**	**1.5**	**25.0**	**0.8**	**1.3**	**24.3**
Coeff. of variations	**18.6**	**48.4**	**85.0**	**18.6**	**44.8**	**74.3**

Table B9-2. Ammonia of Runs R21-3 and R22-3.

D/M/Y	**Run R21-3**			**Run R22-3**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
14/3/00	2.2	0.3	87.5	2.2	0.6	75.0
16/3/00	1.4	0.9	38.6	1.4	0.8	40.0
17/3/00	2.2	1.3	42.9	2.2	1.2	44.6
21/3/00	2.0	1.7	14.3	2.0	1.4	28.6
25/3/00	1.1	0.7	33.9	1.1	0.6	50.0
26/3/00	1.7	0.9	48.8	1.7	1.1	33.3
28/3/00	2.0	1.1	42.9	2.0	1.4	28.6
30/3/00	2.2	1.4	37.5	2.2	0.8	62.5
1/4/00	3.4	2.0	41.7	3.4	1.7	50.0
4/4/00	4.2	2.2	46.7	4.2	2.0	53.3
9/4/00	4.5	2.5	43.8	4.5	2.8	37.5
11/4/00	3.4	1.7	50.0	3.4	2.0	41.7
13/4/00	4.2	2.8	33.3	4.2	2.5	40.0
Average	**2.7**	**1.5**	**43.2**	**2.7**	**1.5**	**45.0**
SD	**1.1**	**0.7**	**16.2**	**1.1**	**0.7**	**13.3**
Coeff. of variations	**40.7**	**46.7**	**37.5**	**40.7**	**46.7**	**29.6**

Table B9-3. Ammonia of Runs R21-6 and R22-6.

D/M/Y	Run R21-6			Run R22-6		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
20/4/00	3.6	2.6	27.5	3.6	2.4	35.2
22/4/00	3.9	2.9	25.5	3.9	2.6	32.7
25/4/00	4.5	2.1	53.6	4.5	2.1	53.6
28/4/00	5.0	2.6	47.6	5.0	3.2	36.5
30/4/00	3.9	3.4	14.3	3.9	2.4	39.8
2/5/00	3.6	2.1	42.9	3.6	2.4	35.2
4/5/00	3.9	2.9	25.5	3.9	2.9	25.5
6/5/00	4.5	3.0	34.8	4.5	3.2	28.6
9/5/00	3.6	2.1	42.9	3.6	1.5	58.2
11/5/00	3.6	1.5	58.2	3.6	1.2	65.9
13/5/00	3.9	1.1	70.9	3.9	1.2	68.4
16/5/00	4.2	1.8	57.1	4.2	2.1	50.5
18/5/00	5.3	2.8	48.1	5.3	2.5	53.4
20/5/00	4.2	2.1	50.5	4.2	2.1	50.5
22/5/00	3.4	1.0	71.4	3.4	1.2	63.1
24/5/00	1.7	0.6	66.7	1.7	0.3	83.3
Average	**3.9**	**2.2**	**46.1**	**3.9**	**2.1**	**48.8**
SD	**0.8**	**0.8**	**17.1**	**0.8**	**0.8**	**16.4**
Coeff. of variations	**20.5**	**36.4**	**37.1**	**20.5**	**38.1**	**33.6**

Table B9-4. Ammonia of Runs R31-6 and R32-6.

D/M/Y	**Run R31-6**			**Run R32-6**		
	Influent	**Effluent**	**% R**	**Influent**	**Effluent**	**% R**
31/5/00	0.8	0.0	100.0	0.8	0.0	100.0
2/6/00	2.0	0.0	100.0	2.0	0.6	71.4
4/6/00	3.4	0.0	100.0	3.4	0.6	83.3
6/6/00	4.8	1.4	70.6	4.8	1.7	64.7
10/6/00	5.6	2.5	55.0	5.6	1.4	75.0
12/6/00	5.3	0.8	84.2	5.3	1.1	79.0
16/6/00	4.2	1.4	66.7	4.2	0.8	80.0
18/6/00	4.5	0.0	100.0	4.5	0.8	81.3
20/6/00	3.6	0.0	100.0	3.6	0.8	76.9
22/6/00	3.6	0.0	100.0	3.6	0.6	84.6
24/6/00	4.2	0.3	93.3	4.2	1.7	60.0
27/6/00	3.9	0.3	92.9	3.9	1.1	71.4
29/6/00	4.8	0.3	94.1	4.8	1.4	70.6
Average	**3.9**	**0.5**	**89.0**	**3.9**	**1.0**	**76.8**
SD	**1.3**	**0.8**	**15.3**	**1.3**	**0.5**	**10.0**
Coeff. of variations	**33.3**	**160.0**	**17.2**	**33.3**	**50.0**	**13.0**

Table B10-1. Porosity of Initial.

RBF I (2-4cm)

NO.	Water level			h (cm)	Vol of Water (V1)	Vol of Water & rocks (V2)	Porosity (%)
	1	2	Average				
1	40.0	40.0	40.0	8.5	60.0	127.5	47.1
2	31.5	31.5	31.5	8.5	60.0	127.5	47.1
3	23.0	23.0	23.0	8.3	60.0	124.5	48.2
4	14.7	14.7	14.7	8.7	60.0	130.5	46.0
5	6.0	6.0	6.0	6.0	42.4	90.0	47.1
							47.1

RBF II (5-7cm)

NO.	Water level			h (cm)	Vol of Water (V1)	Vol of Water & rocks (V2)	Porosity (%)
	1	2	Average				
1	40.0	40.2	40.1	8.6	60.0	129.0	46.5
2	31.4	31.6	31.5	8.2	60.0	123.0	48.8
3	23.2	23.4	23.3	8.3	60.0	124.5	48.2
4	14.9	15.1	15.0	8.5	60.0	127.5	47.1
5	6.4	6.6	6.5	6.5	46.4	97.5	47.6
							47.6

Table B10-2. Porosity in End of Run I.

RBF I (2-4cm)

NO.	Water level			h (cm)	Vol of Water	Vol of Water & rocks	Porosity
	1	2	Average		(V1)	(V2)	(%)
1	40.0	40.0	40.0	8.8	60.0	132.0	45.5
2	31.2	31.2	31.2	9.0	60.0	135.0	44.4
3	22.2	22.2	22.2	8.9	60.0	133.5	44.9
4	13.3	13.3	13.3	6.0	40.0	90.0	44.4
5	7.3	7.3	7.3	7.3	47.9	109.5	43.7
							44.6

RBF II (5-7cm)

NO.	Water level			h (cm)	Vol of Water	Vol of Water & rocks	Porosity
	1	2	Average		(V1)	(V2)	(%)
1	40.2	40.0	40.1	8.9	60.0	133.5	44.9
2	31.3	31.1	31.2	8.7	60.0	130.5	46.0
3	22.6	22.4	22.5	9.0	60.0	135.0	44.4
4	13.6	13.4	13.5	5.7	40.0	84.8	47.2
5	7.9	7.8	7.9	7.9	53.4	117.8	45.4
							45.6

Table B10-3. Porosity in End of Run II.

RBF I (2-4cm)

NO.	Water level			h (cm)	Vol of Water	Vol of Water & rocks	Porosity
	1	2	Average		(V1)	(V2)	(%)
1	40.3	40.0	40.2	9.0	60.0	135.0	44.4
2	31.3	31.0	31.2	9.5	60.0	142.5	42.1
3	21.8	21.5	21.7	9.6	60.0	144.0	41.7
4	12.2	11.9	12.1	4.9	30.0	73.5	40.8
5	7.3	7.0	7.2	7.2	46.5	107.3	43.4
							42.5

RBF II (5-7cm)

NO.	Water level			h (cm)	Vol of Water	Vol of Water & rocks	Porosity
	1	2	Average		(V1)	(V2)	(%)
1	40.1	40.0	40.1	9.3	60.0	139.5	43.0
2	30.8	30.7	30.8	8.8	60.0	132.0	45.5
3	22.0	21.9	22.0	9.2	60.0	138.0	43.5
4	12.8	12.7	12.8	4.7	30.0	70.5	42.6
5	8.1	8.0	8.1	8.1	50.8	120.8	42.1
							43.3

Table B10-4. Porosity in End of Run III.

RBF I (2-4cm)

NO.	**Water level**			**h (cm)**	**Vol of Water**	**Vol of Water & rocks**	**Porosity**
	1	**2**	**Average**		**(V1)**	**(V2)**	**(%)**
1	40.2	40.0	40.1	9.5	60.0	142.5	42.1
2	30.7	30.5	30.6	9.3	60.0	139.5	43.0
3	21.4	21.2	21.3	9.6	60.0	144.0	41.7
4	11.8	11.6	11.7	6.5	40.0	97.5	41.0
5	5.3	5.1	5.2	5.2	32.5	78.0	41.7
							41.9

RBF II (5-7cm)

NO.	**Water level**			**h (cm)**	**Vol of Water**	**Vol of Water & rocks**	**Porosity**
	1	**2**	**Average**		**(V1)**	**(V2)**	**(%)**
1	40.3	40.0	40.2	9	60.0	135.0	44.4
2	31.3	31.0	31.2	9.5	60.0	142.5	42.1
3	21.8	21.5	21.7	9.3	60.0	139.5	43.0
4	12.5	12.2	12.4	6.5	40.0	97.5	41.0
5	6.0	5.7	5.9	5.85	37.7	87.8	43.0
							42.7

APPENDIX C

Analysis of variance (ANOVA) results

Table C1-1. Effect of HRT on process performance (RBF I)

Oneway

Descriptives

		N	Mean	Std. Deviation	Std. Error	fidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
SS	6 h	20	70.3145	14.7743	3.3036	63.3999	77.2291	40.00	91.55
	9 h	13	89.1708	11.8233	3.2792	82.0260	96.3155	62.14	99.20
	12 h	13	93.0900	4.1168	1.1418	90.6023	95.5777	83.33	97.24
	Total	46	82.0800	15.6533	2.3080	77.4315	86.7285	40.00	99.20
VSS	6 h	20	69.8760	14.5936	3.2632	63.0460	76.7060	45.10	90.00
	9 h	13	87.7454	12.9476	3.5910	79.9212	95.5695	58.14	98.62
	12 h	13	93.2738	4.4217	1.2264	90.6018	95.9458	85.29	98.40
	Total	46	81.5385	15.8495	2.3369	76.8318	86.2452	45.10	98.62
T-COD	6 h	20	31.2430	14.8391	3.3181	24.2981	38.1879	13.45	65.96
	9 h	15	42.6507	18.0763	4.6673	32.6403	52.6610	15.64	65.85
	12 h	13	45.1269	13.9542	3.8702	36.6945	53.5594	26.32	66.67
	Total	48	38.5681	16.6167	2.3984	33.7431	43.3931	13.45	66.67
S-COD	6 h	19	27.8763	13.2323	3.0357	21.4985	34.2541	12.90	61.29
	9 h	15	21.8300	6.1014	1.5754	18.4512	25.2088	11.42	33.33
	12 h	13	32.9438	14.1371	3.9209	24.4009	41.4868	11.76	50.00
	Total	47	27.3483	12.2831	1.7917	23.7418	30.9548	11.42	61.29
T-BOD	6 h	11	25.9809	13.7654	4.1504	16.7332	35.2287	11.76	61.54
	9 h	11	76.2936	17.0916	5.1533	64.8113	87.7760	43.16	90.04
	12 h	9	81.4633	12.1603	4.0534	72.1161	90.8106	60.77	97.24
	Total	31	59.9416	29.3233	5.2666	49.1857	70.6975	11.76	97.24
Ammonia	6 h	18	29.3856	25.0063	5.8940	16.9502	41.8209	5.00	72.73
	9 h	16	46.0944	17.1007	4.2752	36.9821	55.2067	14.29	71.43
	12 h	13	88.9831	15.2817	4.2384	79.7484	98.2177	55.00	100.00
	Total	47	51.5581	31.4000	4.5802	42.3387	60.7775	5.00	100.00

Table C1-2. Effect of HRT on process performance (RBF I)

Oneway

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
SS	Between Groups	4998.028	2	2499.014	17.826	0.000
	Within Groups	6028.195	43	140.191		
	Total	11026.223	45			
VSS	Between Groups	5011.447	2	2505.724	17.122	0.000
	Within Groups	6292.785	43	146.344		
	Total	11304.232	45			
T-COD	Between Groups	1882.388	2	941.194	3.817	0.029
	Within Groups	11094.980	45	246.555		
	Total	12977.369	47			
S-COD	Between Groups	869.104	2	434.552	3.149	0.053
	Within Groups	6071.165	44	137.981		
	Total	6940.268	46			
T-BOD	Between Groups	19796.559	2	9898.279	46.199	0.000
	Within Groups	5999.097	28	214.253		
	Total	25795.656	30			
Ammonia	Between Groups	27535.003	2	13767.502	33.995	0.000
	Within Groups	17819.227	44	404.982		
	Total	45354.230	46			

Table C1-3. Effect of HRT on process performance (RBF I)

Multiple Comparisons (Tukey HSD)

Dependent Variable	(I) HRT	(J) HRT	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
SS	6 h	9 h	-18.8563	4.2182	0.000	-29.096	-8.617
		12 h	-22.7755	4.2182	0.000	-33.015	-12.536
	9 h	6 h	18.8563	4.2182	0.000	8.617	29.096
		12 h	-3.9192	4.6441	0.678	-15.193	7.354
	12 h	6 h	22.7755	4.2182	0.000	12.536	33.015
		9 h	3.9192	4.6441	0.678	-7.354	15.193
VSS	6 h	9 h	-17.8694	4.3098	0.000	-28.331	-7.408
		12 h	-23.3978	4.3098	0.000	-33.860	-12.936
	9 h	6 h	17.8694	4.3098	0.000	7.408	28.331
		12 h	-5.5285	4.7449	0.480	-17.047	5.990
	12 h	6 h	23.3978	4.3098	0.000	12.936	33.860
		9 h	5.5285	4.7449	0.480	-5.990	17.047
T-COD	6 h	9 h	-11.4077	5.3633	0.096	-24.406	1.591
		12 h	-13.8839	5.5941	0.044	-27.442	-0.326
	9 h	6 h	11.4077	5.3633	0.096	-1.591	24.406
		12 h	-2.4763	5.9500	0.909	-16.897	11.944
	12 h	6 h	13.8839	5.5941	0.044	0.326	27.442
		9 h	2.4763	5.9500	0.909	-11.944	16.897
S-COD	6 h	9 h	6.0463	4.0572	0.305	-3.794	15.887
		12 h	-5.0675	4.2280	0.460	-15.323	5.188
	9 h	6 h	-6.0463	4.0572	0.305	-15.887	3.794
		12 h	-11.1138	4.4511	0.042	-21.910	-0.318
	12 h	6 h	5.0675	4.2280	0.460	-5.188	15.323
		9 h	11.1138	4.4511	0.042	0.318	21.910
T-BOD	6 h	9 h	-50.3127	6.2414	0.000	-65.756	-34.869
		12 h	-55.4824	6.5790	0.000	-71.761	-39.204
	9 h	6 h	50.3127	6.2414	0.000	34.869	65.756
		12 h	-5.1697	6.5790	0.715	-21.449	11.109
	12 h	6 h	55.4824	6.5790	0.000	39.204	71.761
		9 h	5.1697	6.5790	0.715	-11.109	21.449
Ammonia	6 h	9 h	-16.7088	6.9145	0.051	-33.480	0.062
		12 h	-59.5975	7.3247	0.000	-77.364	-41.832
	9 h	6 h	16.7088	6.9145	0.051	-0.062	33.480
		12 h	-42.8887	7.5142	0.000	-61.114	-24.663
	12 h	6 h	59.5975	7.3247	0.000	41.832	77.364
		9 h	42.8887	7.5142	0.000	24.663	61.114

The mean difference is significant at the .05 level.

Table C2-1. Effect of HRT on process performance (RBF II)

Oneway

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
SS	6 h	20	62.3170	15.4524	3.4553	55.0850	69.5490	30.00	87.04
	9 h	13	88.3538	9.9359	2.7557	82.3496	94.3581	66.20	97.48
	12 h	13	89.8700	4.5536	1.2629	87.1183	92.6217	81.94	95.53
	Total	46	77.4620	17.7021	2.6100	72.2051	82.7188	30.00	97.48
VSS	6 h	20	61.2110	14.8941	3.3304	54.2403	68.1817	30.69	86.27
	9 h	13	85.9392	10.7676	2.9864	79.4324	92.4460	66.67	97.65
	12 h	13	90.5246	5.0144	1.3907	87.4944	93.5548	80.80	97.36
	Total	46	76.4837	17.8252	2.6282	71.1903	81.7771	30.69	97.65
T-COD	6 h	20	32.0600	19.5101	4.3626	22.9290	41.1910	10.58	85.19
	9 h	15	42.6760	17.0517	4.4027	33.2331	52.1189	11.11	65.96
	12 h	13	47.8415	13.5761	3.7653	39.6376	56.0455	27.78	75.00
	Total	48	39.6517	18.2631	2.6361	34.3486	44.9547	10.58	85.19
S-COD	6 h	19	36.9137	20.9060	4.7962	26.8373	46.9901	12.12	73.91
	9 h	15	22.2580	7.6674	1.9797	18.0119	26.5041	10.00	38.10
	12 h	13	31.7885	15.4502	4.2851	22.4520	41.1249	12.28	57.18
	Total	47	30.8187	17.0498	2.4870	25.8127	35.8247	10.00	73.91
T-BOD	6 h	11	25.3000	10.5907	3.1932	18.1850	32.4150	12.42	46.15
	9 h	11	73.8709	18.2989	5.5173	61.5775	86.1643	36.97	89.12
	12 h	9	81.7433	12.9956	4.3319	71.7541	91.7326	60.54	97.91
	Total	31	58.9216	29.0984	5.2262	48.2482	69.5950	12.42	97.91
Ammonia	6 h	18	32.7283	24.2821	5.7233	20.6531	44.8035	6.67	80.00
	9 h	16	48.7650	16.3877	4.0969	40.0326	57.4974	25.51	83.33
	12 h	13	76.8100	10.0061	2.7752	70.7634	82.8566	60.00	100.00
	Total	47	50.3804	25.5311	3.7241	42.8842	57.8767	6.67	100.00

Table C2-2. Effect of HRT on process performance (RBF II)

Oneway

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
SS	Between Groups	8131.101	2	4065.550	29.282	0.000
	Within Groups	5970.270	43	138.843		
	Total	14101.371	45			
VSS	Between Groups	8390.314	2	4195.157	30.534	0.000
	Within Groups	5907.885	43	137.393		
	Total	14298.199	45			
T-COD	Between Groups	2161.829	2	1080.914	3.599	0.035
	Within Groups	13514.654	45	300.326		
	Total	15676.483	47			
S-COD	Between Groups	1817.337	2	908.669	3.460	0.040
	Within Groups	11554.656	44	262.606		
	Total	13371.993	46			
T-BOD	Between Groups	19580.316	2	9790.158	47.091	0.000
	Within Groups	5821.220	28	207.901		
	Total	25401.536	30			
Ammonia	Between Groups	14731.279	2	7365.640	21.247	0.000
	Within Groups	15253.337	44	346.667		
	Total	29984.616	46			

Table C2-3. Effect of HRT on process performance (RBF II)

Multiple Comparisons (Tukey HSD)

Dependent Variable	(I) HRT	(J) HRT	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
SS	6 h	9 h	-26.0368	4.1979	0.000	-36.227	-15.847
		12 h	-27.5530	4.1979	0.000	-37.743	-17.363
	9 h	6 h	26.0368	4.1979	0.000	15.847	36.227
		12 h	-1.5162	4.6217	0.942	-12.735	9.703
	12 h	6 h	27.5530	4.1979	0.000	17.363	37.743
		9 h	1.5162	4.6217	0.942	-9.703	12.735
VSS	6 h	9 h	-24.7282	4.1759	0.000	-34.865	-14.591
		12 h	-29.3136	4.1759	0.000	-39.450	-19.177
	9 h	6 h	24.7282	4.1759	0.000	14.591	34.865
		12 h	-4.5854	4.5975	0.583	-15.746	6.575
	12 h	6 h	29.3136	4.1759	0.000	19.177	39.450
		9 h	4.5854	4.5975	0.583	-6.575	15.746
T-COD	6 h	9 h	-10.6160	5.9193	0.183	-24.962	3.730
		12 h	-15.7815	6.1740	0.037	-30.745	-0.818
	9 h	6 h	10.6160	5.9193	0.183	-3.730	24.962
		12 h	-5.1655	6.5669	0.713	-21.081	10.750
	12 h	6 h	15.7815	6.1740	0.037	0.818	30.745
		9 h	5.1655	6.5669	0.713	-10.750	21.081
S-COD	6 h	9 h	14.6557	5.5972	0.032	1.080	28.232
		12 h	5.1252	5.8328	0.656	-9.022	19.273
	9 h	6 h	-14.6557	5.5972	0.032	-28.232	-1.080
		12 h	-9.5305	6.1406	0.277	-24.425	5.364
	12 h	6 h	-5.1252	5.8328	0.656	-19.273	9.022
		9 h	9.5305	6.1406	0.277	-5.364	24.425
T-BOD	6 h	9 h	-48.5709	6.1482	0.000	-63.784	-33.358
		12 h	-56.4433	6.4808	0.000	-72.479	-40.408
	9 h	6 h	48.5709	6.1482	0.000	33.358	63.784
		12 h	-7.8724	6.4808	0.455	-23.908	8.163
	12 h	6 h	56.4433	6.4808	0.000	40.408	72.479
		9 h	7.8724	6.4808	0.455	-8.163	23.908
Ammonia	6 h	9 h	-16.0367	6.3973	0.041	-31.553	-0.520
		12 h	-44.0817	6.7769	0.000	-60.519	-27.645
	9 h	6 h	16.0367	6.3973	0.041	0.520	31.553
		12 h	-28.0450	6.9522	0.001	-44.908	-11.183
	12 h	6 h	44.0817	6.7769	0.000	27.645	60.519
		9 h	28.0450	6.9522	0.001	11.183	44.908

The mean difference is significant at the .05 level.

Table C3-1. Effect of rock size on process performance (HRT = 6 h)

T-Test

Group Statistics

	Reactor	N	Mean	Std. Deviation	Std. Error Mean
SS	RBF I	20	70.3145	14.7743	3.3036
	RBF II	20	62.3170	15.4524	3.4553
VSS	RBF I	20	69.8760	14.5936	3.2632
	RBF II	20	61.2110	14.8941	3.3304
T-COD	RBF I	20	31.2430	14.8391	3.3181
	RBF II	20	32.0600	19.5101	4.3626
S-COD	RBF I	19	27.8763	13.2323	3.0357
	RBF II	19	36.9137	20.9060	4.7962
T-BOD	RBF I	11	25.9809	13.7654	4.1504
	RBF II	11	25.3000	10.5907	3.1932
Ammonia	RBF I	18	29.3856	25.0063	5.8940
	RBF II	18	32.7283	24.2821	5.7233

Table C3-2. Effect of rock-size on process performance (HRT = 6 h)

T-Test

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SS	Equal variances assumed	0.056	0.814	1.673	38	0.103	7.9975	4.7805	-1.6801	17.6751
	Equal variances not assumed			1.673	37.924	0.103	7.9975	4.7805	-1.6807	17.6757
VSS	Equal variances assumed	0.000	0.996	1.858	38	0.071	8.6650	4.6627	-0.7741	18.1041
	Equal variances not assumed			1.858	37.984	0.071	8.6650	4.6627	-0.7742	18.1042
T-COD	Equal variances assumed	0.533	0.470	-0.149	38	0.882	-0.8170	5.4811	-11.9129	10.2789
	Equal variances not assumed			-0.149	35.471	0.882	-0.8170	5.4811	-11.9389	10.3049
S-COD	Equal variances assumed	12.249	0.001	-1.592	36	0.120	-9.0374	5.6762	-20.5491	2.4744
	Equal variances not assumed			-1.592	30.428	0.122	-9.0374	5.6762	-20.6228	2.5481
T-BOD	Equal variances assumed	0.039	0.846	0.130	20	0.898	0.6809	5.2367	-10.2426	11.6044
	Equal variances not assumed			0.130	18.767	0.898	0.6809	5.2367	-10.2888	11.6506
Ammonia	Equal variances assumed	0.158	0.694	-0.407	34	0.687	-3.3428	8.2156	-20.0389	13.3534
	Equal variances not assumed			-0.407	33.971	0.687	-3.3428	8.2156	-20.0395	13.3539

Table C4-1. Effect of rock size on process performance (HRT = 9 h)

T-Test

Group Statistics

	Reactor	N	Mean	Std. Deviation	Std. Error Mean
SS	RBF I	13	89.1708	11.8233	3.2792
	RBF II	13	88.3538	9.9359	2.7557
VSS	RBF I	13	87.7454	12.9476	3.5910
	RBF II	13	85.9392	10.7676	2.9864
T-COD	RBF I	15	42.6507	18.0763	4.6673
	RBF II	15	42.6760	17.0517	4.4027
S-COD	RBF I	15	21.8300	6.1014	1.5754
	RBF II	15	22.2580	7.6674	1.9797
T-BOD	RBF I	11	76.2936	17.0916	5.1533
	RBF II	11	73.8709	18.2989	5.5173
Ammonia	RBF I	16	46.0944	17.1007	4.2752
	RBF II	16	48.7650	16.3877	4.0969

Table C4-2. Effect of rock-size on process performance (HRT = 9 h)

T-Test

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SS	Equal variances assumed	0.188	0.668	0.191	24	0.850	0.8169	4.2834	-8.0235	9.6574
	Equal variances not assumed			0.191	23.309	0.850	0.8169	4.2834	-8.0374	9.6713
VSS	Equal variances assumed	0.183	0.672	0.387	24	0.702	1.8062	4.6705	-7.8334	11.4457
	Equal variances not assumed			0.387	23.228	0.702	1.8062	4.6705	-7.8504	11.4627
T-COD	Equal variances assumed	0.354	0.557	-0.004	28	0.997	-0.0253	6.4162	-13.1683	13.1177
	Equal variances not assumed			-0.004	27.905	0.997	-0.0253	6.4162	-13.1703	13.1197
S-COD	Equal variances assumed	0.835	0.369	-0.169	28	0.867	-0.4280	2.5300	-5.6105	4.7545
	Equal variances not assumed			-0.169	26.656	0.867	-0.4280	2.5300	-5.6223	4.7663
T-BOD	Equal variances assumed	0.014	0.909	0.321	20	0.752	2.4227	7.5497	-13.3256	18.1711
	Equal variances not assumed			0.321	19.908	0.752	2.4227	7.5497	-13.3303	18.1758
Ammonia	Equal variances assumed	0.003	0.959	-0.451	30	0.655	-2.6706	5.9213	-14.7635	9.4223
	Equal variances not assumed			-0.451	29.946	0.655	-2.6706	5.9213	-14.7645	9.4232

Table C5-1. Effect of rock size on process performance (HRT = 12 h)

T-Test

Group Statistics

	Reactor	N	Mean	Std. Deviation	Std. Error Mean
SS	RBF I	13	93.0900	4.1168	1.1418
	RBF II	13	89.8700	4.5536	1.2629
VSS	RBF I	13	93.2738	4.4217	1.2264
	RBF II	13	90.5246	5.0144	1.3907
T-COD	RBF I	13	45.1269	13.9542	3.8702
	RBF II	13	47.8415	13.5761	3.7653
S-COD	RBF I	13	32.9438	14.1371	3.9209
	RBF II	13	31.7885	15.4502	4.2851
T-BOD	RBF I	9	81.4633	12.1603	4.0534
	RBF II	9	81.7433	12.9956	4.3319
Ammonia	RBF I	13	88.9831	15.2817	4.2384
	RBF II	13	76.8100	10.0061	2.7752

Table C5-2. Effect of rock-size on process performance (HRT = 12 h)

T-Test

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SS	Equal variances assumed	0.019	0.892	1.891	24	0.071	3.2200	1.7026	-0.2939	6.7339
	Equal variances not assumed			1.891	23.76	0.071	3.2200	1.7026	-0.2958	6.7358
VSS	Equal variances assumed	0.044	0.835	1.483	24	0.151	2.7492	1.8542	-1.0777	6.5761
	Equal variances not assumed			1.483	23.63	0.151	2.7492	1.8542	-1.0809	6.5793
T-COD	Equal variances assumed	0.232	0.634	-0.503	24	0.620	-2.7146	5.3996	-13.8589	8.4297
	Equal variances not assumed			-0.503	23.982	0.620	-2.7146	5.3996	-13.8594	8.4302
S-COD	Equal variances assumed	0.265	0.612	0.199	24	0.844	1.1554	5.8083	-10.8323	13.1431
	Equal variances not assumed			0.199	23.813	0.844	1.1554	5.8083	-10.8373	13.1480
T-BOD	Equal variances assumed	0.156	0.698	-0.047	16	0.963	-0.2800	5.9326	-12.8565	12.2965
	Equal variances not assumed			-0.047	15.93	0.963	-0.2800	5.9326	-12.8610	12.3010
Ammonia	Equal variances assumed	2.771	0.109	2.403	24	0.024	12.1731	5.0661	1.7171	22.6290
	Equal variances not assumed			2.403	20.692	0.026	12.1731	5.0661	1.6279	22.7182

Table C6-1. Effect of aeration on process performance (RBF I)

T-Test

Group Statistics

Aerartion		N	Mean	Std. Deviation	Std. Error Mean
SS	3 air diffusers	13	79.9069	18.0489	5.0059
	6 air diffusers	13	89.1708	11.8233	3.2792
VSS	3 air diffusers	13	79.7231	16.4090	4.5510
	6 air diffusers	13	87.7454	12.9476	3.5910
T-COD	3 air diffusers	12	41.8642	14.9171	4.3062
	6 air diffusers	15	42.6507	18.0763	4.6673
S-COD	3 air diffusers	12	20.4733	14.6361	4.2251
	6 air diffusers	15	21.8300	6.1014	1.5754
T-BOD	3 air diffusers	10	45.8330	17.5813	5.5597
	6 air diffusers	11	76.2936	17.0916	5.1533
Ammonia	3 air diffusers	13	43.2108	16.1456	4.4780
	6 air diffusers	16	46.0944	17.1007	4.2752

Table C6-2. Effect of aeration on process performance (RBF I)

T-Test

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SS	Equal variances assumed	1.924	0.178	-1.548	24	0.135	-9.264	5.9843	-21.6148	3.0872
	Equal variances not assumed			-1.548	20.697	0.137	-9.264	5.9843	-21.7200	3.1923
VSS	Equal variances assumed	0.588	0.451	-1.384	24	0.179	-8.022	5.7972	-19.9871	3.9425
	Equal variances not assumed			-1.384	22.768	0.180	-8.022	5.7972	-20.0214	3.9768
T-COD	Equal variances assumed	1.199	0.284	-0.121	25	0.905	-0.787	6.4910	-14.1551	12.5821
	Equal variances not assumed			-0.124	24.96	0.902	-0.787	6.3503	-13.8663	12.2933
S-COD	Equal variances assumed	26.386	0.000	-0.327	25	0.747	-1.357	4.1552	-9.9144	7.2010
	Equal variances not assumed			-0.301	14.058	0.768	-1.357	4.5092	-11.0243	8.3109
T-BOD	Equal variances assumed	0.433	0.518	-4.024	19	0.001	-30.461	7.5700	-46.3048	-14.6165
	Equal variances not assumed			-4.018	18.691	0.001	-30.461	7.5807	-46.3450	-14.5763
Ammonia	Equal variances assumed	1.071	0.310	-0.463	27	0.647	-2.884	6.2293	-15.6651	9.8979
	Equal variances not assumed			-0.466	26.339	0.645	-2.884	6.1911	-15.6016	9.8344

Table C7-1. Effect of aeration on process performance (RBF II)

T-Test

Group Statistics

	Aeration	N	Mean	Std. Deviation	Std. Error Mean
SS	3 air diffusers	13	75.0679	13.5629	3.7617
	6 air diffusers	13	88.3538	9.9359	2.7557
VSS	3 air diffusers	13	74.1677	11.8761	3.2938
	6 air diffusers	13	85.9392	10.7676	2.9864
T-COD	3 air diffusers	12	40.2167	18.6599	5.3866
	6 air diffusers	15	42.6760	17.0517	4.4027
S-COD	3 air diffusers	12	21.6792	14.7245	4.2506
	6 air diffusers	15	22.2580	7.6674	1.9797
T-BOD	3 air diffusers	10	45.3510	21.2172	6.7095
	6 air diffusers	11	73.8709	18.2989	5.5173
Ammonia	3 air diffusers	13	45.0085	13.2890	3.6857
	6 air diffusers	16	48.7650	16.3877	4.0969

Table C7-2. Effect of aeration on process performance (RBF II)

T-Test

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
SS	Equal variances assumed	0.331	0.571	-2.849	24	0.009	-13.286	4.6631	-22.9100	-3.6618
	Equal variances not assumed			-2.849	22	0.009	-13.286	4.6631	-22.9566	-3.6153
VSS	Equal variances assumed	0.098	0.757	-2.648	24	0.014	-11.772	4.4461	-20.9479	-2.5952
	Equal variances not assumed			-2.648	23.773	0.014	-11.772	4.4461	-20.9525	-2.5906
T-COD	Equal variances assumed	0.013	0.910	-0.357	25	0.724	-2.459	6.8851	-16.6394	11.7208
	Equal variances not assumed			-0.354	22.66	0.727	-2.459	6.9570	-16.8629	11.9443
S-COD	Equal variances assumed	7.765	0.010	-0.132	25	0.896	-0.579	4.3872	-9.6145	8.4568
	Equal variances not assumed			-0.123	15.709	0.903	-0.579	4.6890	-10.5341	9.3764
T-BOD	Equal variances assumed	0.425	0.522	-3.307	19	0.004	-28.520	8.6229	-46.5678	-10.4720
	Equal variances not assumed			-3.283	17.915	0.004	-28.520	8.6866	-46.7761	-10.2637
Ammonia	Equal variances assumed	1.163	0.290	-0.667	27	0.511	-3.757	5.6342	-15.3171	7.8040
	Equal variances not assumed			-0.682	26.999	0.501	-3.757	5.5108	-15.0639	7.5508

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