PERFORMANCE OF SEQUENCING BATCH REACTOR FOR NUTRIENT REMOVAL AS FUNCTIONS OF OPERATING VARIABLES

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ABSTRACT

Sequencing batch reactors were originally used for COD and phosphate removal from wastewaters. Recent regulations over nutrient discharges to natural water systems resulted in modifications in sequential batch reactor (SBR) systems to achieve nitrification, denitrification along with COD and phosphate removal. An SBR treatment system consists of a sequencing operation including the steps of fill, react, settle, decant, and idle in the same reactor. When biological nutrient removal is desired, the steps in the react cycle are adjusted to provide anaerobic, anoxic and aerobic phases in certain number and sequence. Since the same reactor is used for biological oxidation and sedimentation in SBR operations, capital and operating costs are lower than conventional activated sludge processes. Therefore, SBR operations may be more advantageous for treatment of small volume wastewaters in rural areas.

In this respect, this thesis is composed of six main parts investigating different number of steps, different hydraulic retention times (HRT), different sludge ages, different carbon sources, different medium compositions and different specific nutrient loading rates (SNLR) on the biological nutrient removal from a synthetic wastewater.

In the first part of this study, three different operations with different number of steps were used and their nutrient removal performances were compared. Those operations were a three-step operation consisting of anaerobic/ anoxic/ oxic(An/ Ax/ Ox) phases; a four- step operation consisting of anaerobic/ oxic/ anoxic/ oxic (An/ Ox/ Ax/ Ox) phases and a five-step operation consisting of (An/ Ax/ Ox/ Ax/ Ox) phases. Effects of different operations on percent COD, nitrogen (NH_4-N, NO_3-N) and phosphate removal (PO_4-P) performances were investigated. The sludge age was constant at 10 days. The best percent nutrient (nitrogen and phosphate) and percent carbon removals were achieved when the five step operation was used. The highest percent COD, NH_4-N and PO_4-P removals obtained with the five-step operation were 94%, 90 %, and 57 % , respectively.

In the second part of this study, nutrient removal from synthetic wastewater by a five-step sequencing batch operation was studied at different hydraulic retention times (HRT). The nutrient removal process consisted of anaerobic (An), anoxic (Ax), oxic (Ox), anoxic (Ax), oxic (Ox) and settling phases. Sludge age was kept constant at 10 days, while hydraulic retention times (HRT) of each phase was varied. Effects of hydraulic retention time of each phase on percent COD, nitrogen (NH_4-N, NO_3-N) and phosphate (PO_4-P) removals were investigated. Hydraulic retention time of each phase was varied at five different levels and the the most suitable retention time resulting in maximum overall percent nutrient removal was determined. The highest observed percent COD, nitrogen (NH_4-N and NO_3-N) and phosphate (PO_4-P) removals were 96%, 87%, 81% and 90%, respectively which were obtained with An/ Ax/ Ox/ Ax/ Ox phase retention times of 2/ 1/ 4.5/ 1.5/ 1.5 h.

In the third part of the study, nutrient removal was studied at different sludge ages by using a five-step SBR operation at the pre-determined hydraulic retention times. The nutrient removal process consisted of anaerobic, anoxic I, oxic I, anoxic II, oxic II and settling phases. Hydraulic retention times (HRT) of the aforementioned phases were kept constant at 2/1/4.5/1.5/1.5 h. Settling phase was ½ h for all experiments. Sludge age was varied between 5 to 30 days at six different levels. Effects of sludge age on percent COD, nitrogen (NH_4-N, NO_3-N) and phosphate (PO_4-P) removal were investigated and the optimal sludge age resulting in maximum percent nutrient removal was determined. The highest percent COD (94%), NH_4-N (84%) and PO_4-P (70%) removals were obtained at the sludge age of 10 days, although a sludge age of 15 days resulted in slightly lower values. Sludge ages larger than 15 days resulted in lower percent nutrient removals as compared to those obtained at 10 or 15 days of sludge age. Sludge volume index (SVI) was also minimum (55 mL/g) at sludge age of 10 days. Biomass(MLSS) concentration increased with sludge age resulting in MLSS concentration of 3500 mg/L at sludge age of 30 days. On the basis of these results, a sludge age of 10 days was found to be optimal resulting in maximum percent nutrient removals and minimum sludge volume index.

In the fourth part of the thesis, a three-step sequencing batch operation was used for nutrient (COD, NH_4-N, PO_4-P) removal from synthetic wastewater by using different carbohydrates and organic acids as carbon sources. The operation consisted of anaerobic, anoxic and oxic (An/ Ax/ Ox) phases with durations of 2/ 1/ 4.5 h. Different carbohydrates glucose, lactose, sucrose, maltose and a mixture of glucose / maltose (50/50) were used as the sole carbon source in the first phase of experiments. Sludge age was kept constant at 10 days. Glucose was found to be the most suitable carbohydrate source with percent COD, NH_4-N and PO_4-P removals of 96%, 99% and 94%, respectively. Nutrient removals obtained with sucrose as the sole carbon source were close to those obtained with glucose. A mixture of glucose and organic acids (50/50) such as acetic, citric, propionic and butyric acid were used as carbon source in the second phase of the experiments. Percent COD, NH_4-N and PO_4-P removals were 93%, 97% and 96%, respectively when a mixture of glucose and acetic acid (50/50) was used. Glucose-citric acid (50/50) combination also resulted in comparable nutrient removals. Changing the ratio of glucose / acetic acid in the mixture did not improve the nutrient removal performance.

In the fifth part of this study, nutrient removal from synthetic wastewater was studied as a function of nutrient medium composition using a five-step sequencing batch reactor (SBR). The nutrient removal process was consisted of anaerobic, anoxic, oxic, anoxic, oxic phases with hydraulic retention times (HRT) of 2/ 1/ 4.5/ 1.5/ 1.5 h. Sludge age and settling phase were 10 days and ½ hour, respectively in all experiments. Initial chemical oxygen demand (COD) concentration was constant at 1200 mg/L. COD/N and COD/P ratios in the nutrient medium were considered as independent variables. Box-Wilson statistical experiment design was used to determine the effects of independent variables on percent COD, NH_4-N, PO_4-P removals. The results were correlated by a response function and the coefficients were determined by regression analysis. The COD/N/ P ratio resulting in maximum percent COD, NH_4-N and PO_4-P removals was determined to be 100 / 2 / 0.54 resulting in 95% COD, 94% NH_4-N and 99% PO_4-P removals.

In the last part of this study, nutrient removal from a synthetic wastewater by a five-step SBR operation was studied at different specific nutrient loading rates (SNLR). The operation consisted of anaerobic (An), anoxic (Ax), oxic (Ox), anoxic (An) and oxic (Ox) phases with hydraulic retention times (HRT) of 2 / 1 / 4.5 / 1.5 / 1.5 h, respectively with a 45 minutes settling phase. Initial COD concentration was varied between 600 to 4800 mg/L at eight different levels with constant COD / N / P ratio of 100 / 3.33 / 0.7. Effects of specific nutrient loading rates (SNLR) on percent COD, NH_4-N and PO_4-P removal were investigated. Percent nutrient removals decreased and effluent nutrient levels increased with increasing nutrient loading rates. The highest percent COD (99%), NH_4-N (99%) and PO_4-P (97%) removals were obtained with the initial COD concentration of 600 mg/L at COD loading rate of nearly 40 mg COD/g biomass.h. However, the sludge volume index (SVI) decreased with increasing COD loading rate resulting minimum SVI of 46 mL/g at COD loading rate of nearly 86 mg COD/g biomass.h. Biomass concentration increased with increasing specific nutrient loading rate resulting in biomass concentration of 3.84 g/L at COD loading rate of 86 mg COD/g biomass.h.

In summary, nutrient removal from a synthetic wastewater was extensively studied and a five-step SBR operation with 10 days sludge age was found to be the most suitable among the others tested. The effects of hydraulic retention times of each step, wastewater composition and the nutrient loading rates on the system performance were investigated and the optimum operational values were determined.

ÖZET

Ardışık zamanlı kesikli reaktörler (AZKR) atıksulardan öncelikle KOİ ve fosfat giderimi için kullanılmışlardır. Doğal su sistemlerine yapılan nutrient deşarjlarındaki son düzenlemelerle KOİ ve fosfat giderimi yanında nitrifikasyon ve denitrifikasyon ile azot giderimi de zorunlu kılınmıştır. Ardışık zamanlı kesikli reaktörde arıtma, aynı reaktör içerisinde doldurma, reaksiyon, çökeltim, boşaltma ve dinlendirme basamaklarını içeren ardışık işletmeyi içerir. Biyolojik nutrient giderimi istenildiğinde, reaksiyon çevrimindeki basamaklar belli sayı ve sırada anaerobik, anoksik ve oksik fazlar sağlanarak gerçekleştirilir. Ardışık zamanlı kesikli işletmelerde biyolojik oksidasyon ve çökeltme için aynı reaktör kullanıldığından, yatırım ve işletme masrafları klasik aktif çamur sistemlerine göre daha düşüktür. Bu nedenle, ardışık zamanlı kesikli reaktör işletmeler kırsal alanlardaki küçük hacimli atıksuların arıtılması için daha avantajlı olabilir.

Bu tez çalışması, AZKR'de biyolojik nutrient giderimi üzerine farklı basamak sayılarının, farklı hidrolik alıkonma süreleri (HAS), farklı çamur yaşları (ÇY), farklı karbon kaynakları, farklı atıksu kompozisyonu ve farklı özgül nutrient yükleme hızlarının (ÖNYH) etkilerini araştıran altı ana bölümden oluşmaktadır.

Birinci bölümde üç, dört ve beş basamak içeren üç farklı işletme kullanılarak, biyolojik nutrient giderme performansları karşılaştırılmıştır. Bu işletmeler sırasıyla üç basamaklı, anaerobik/ anoksik/ oksik (An/ Ax/ Ox) işletme; dört basamaklı, anaerobik/ anoksik/ oksik/ anoksik (An/ Ax/ Ox/ An) işletme ve beş basamaklı, anaerobik/ anoksik/ oksik/ anoksik/ oksik (An/ Ax/ Ox/ An/ Ox) işletmelerdir. İşletme basamaklarının, KOİ, azot (NH_4-N, NO_3-N) ve fosfat giderme (PO_4-P) verimleri üzerine etkileri incelenmiştir. KOİ, azot ve fosfatın biyolojik giderimi 10 günlük çamur yaşında gerçekleştirilmiştir. En iyi nutrient (azot ve fosfat) ve karbon giderim verimleri beş basamaklı işletme (An/ Ax/ Ox/ Ax/ Ox) kullanılarak elde edilmiştir. Beş basamaklı işletmede KOİ, NH_4-N ve PO_4-P giderim verimleri sırasıyla %94, % 90 ve % 57 olarak bulunmuştur.

Çalışmanın ikinci kısmında, ardışık kesikli işletme ile sentetik atıksudan nutrient giderimi farklı hidrolik alıkonma sürelerinde (HAS) incelenmiştir. Bu aşamada beş basamaklı işletme kullanılmış çamur yaşı (ÇY) 10 günde sabit tutularak, her basamağın hidrolik alıkonma süreleri değiştirilmiştir. KOİ, azot (NH_4-N, NO_3-N) ve fosfat (PO_4-P) giderme verimleri üzerinde her fazın hidrolik alıkonma sürelerinin etkileri araştırılmıştır. Her fazın hidrolik alıkonma süresi beş farklı seviyede değiştirilmiş ve maksimum nutrient giderme verimiyle sonuçlanan en uygun alıkonma süresi bulunmuştur. Gözlenen en yüksek KOİ, azot (NH_4-N ve NO_3-N) ve fosfat (PO_4-P) giderme verimleri sırasıyla 96%, 87%, 81% ve 90% olup An/ Ax/ Ox/ Ax/ Ox fazları için 2/ 1/ 4.5/ 1.5/ 1.5 saatlik alıkonma sürelerinde elde edilmiştir.

Üçüncü bölümdeki çalışmalarda ardışık kesikli işletme ile sentetik atıksudan nutrient giderme verimi üzerine çamur yaşının (ÇY) etkileri incelenmiştir. Kullanılan nutrient giderme prosesi beş basamaklı olup anaerobik, anoksik I, oksik I, anoksik II, oksik II ve çökeltme fazlarını içermektedir. Bahsedilen fazların hidrolik alıkonma süreleri (HAS) 2/ 1/ 4.5/ 1.5/ 1.5 saatlerde sabit tutulmuştur. Çökeltme fazı tüm deneylerde ½ saattir. Çamur yaşı 5 ile 30 gün arasında altı farklı seviyede değiştirilmiştir. KOİ, azot (NH_4-N, NO_3-N) ve fosfat (PO_4-P) giderimi üzerinde çamur yaşının etkisi araştırılmış ve maksimum nutrient giderme verimiyle sonuçlanan optimum çamur yaşı deneysel olarak bulunmuştur. En yüksek KOİ (%94), NH_4-N (%84) ve PO_4-P (%70) giderme verimleri 10 günlük çamur yaşında elde edilmiştir. 15 günlük çamur yaşlarından daha büyük çamur yaşlarında, 10 günlük ya da 15 günlük çamur yaşlarına göre daha düşük nutrient giderme verimleri elde edilmiştir. On günlük çamur yaşında, minimum çamur hacim indeksi 55 mL/g' dır. Biomass (MLSS) konsantrasyonu 30 günlük çamur yaşında 3500 mg/L olup çamur yaşıyla yükselmiştir. Bu sonuçlara göre, 10 günlük çamur yaşı maksimum

nutrient giderme verimleri ve minimum çamur hacim indeksi veren en uygun çamur yaşı olarak bulunmuştur.

Çalışmanın dördüncü kısmında, üç basamaklı ardışık kesikli işletme ile sentetik atıksudan nutrient (KOİ, NH_4-N, PO_4-P) giderimi için farklı karbonhidrat ve organik asit bileşikleri karbon kaynağı olarak kullanılmıştır. Anaerobik, anoksik ve oksik (An/ Anok/ Ok) fazlardaki alıkonma süreleri 2/ 1/ 4.5 saat olarak ayarlanmıştır. Karbonhidrat kaynağı olarak glukoz, laktoz, sukroz, maltoz ve glukoz / maltoz (50/50) karışımı kullanılmış ve çamur yaşı 10 günde sabit tutulmuştur. Glukoz kullanıldığında KOİ, NH_4-N ve PO_4-P giderme verimleri sırasıyla %96, %99 ve %94 olmuş ve glukozun en uygun karbonhidrat kaynağı olduğu bulunmuştur. Sakkaroz kullanıldığında elde edilen nutrient giderme verimleri glukozla elde edilen değerlere yakın bulunmuştur. Deneylerin ikinci kısmında, glukozla organik asitler, (asetik , sitrik, propiyonik ve butirik asitler) 50/50 oranında karıştırılarak sistemin nutrient giderme performansı incelenmiştir. Glukoz ve asetik asit 50/50 oranında karıştırıldığında KOİ, NH_4-N ve PO_4-P giderme verimleri sırasıyla %93, %97 ve %96 olarak bulunmuştur. Glukoz-sitrik asit (50/50) karışımı da karşılaştırılabilir nutrient giderme verimleriyle sonuçlanmıştır. Farklı glukoz / asetik asit oranlarında sistemin nutrient giderme performansı daha düşük olmuştur.

Çalışmanın beşinci kısmında, sentetik atıksudan nutrient giderimi beş basamaklı ardışık kesikli reaktörde nutrient ortamı kompozisyonunun bir fonksiyonu olarak incelenmiştir. Nutrient giderme prosesi anaerobik, anoksik, oksik, anoksik, oksik fazları içermiştir. Adı geçen fazların hidrolik alıkonma süreleri (HAS) sırasıyla 2/ 1/ 4.5/ 1.5/ 1.5 saatlerde sabit tutulmuştur. Tüm deneylerde çamur yaşı (ÇY) ve çökeltme süresi sırasıyla 10 gün ve ½ saatte sabit tutulmuştur. Başlangıç kimyasal oksijen ihtiyacı (KOİ) 1200 mg/L' de sabit tutularak nutrient ortamında KOİ / N ve KOİ / P oranları bağımsız değişkenler olarak dikkate alınmıştır. Box-Wilson istatistiksel deney tasarımı kullanılarak KOİ, NH_4-N, PO_4-P giderme verimleri üzerine bağımsız değişkenlerin etkileri incelenmiştir. Sonuçlar bir cevap fonksiyonu ile doğrulanarak gerekli katsayılar regresyon analizi ile hesap edilmiştir. Maksimum

KOİ, NH_4-N ve PO_4-P giderme verimleri, KOI / N / P oranının 100 / 2 / 0.54 olduğu durumda %95 KOI, %94 NH_4-N ve %99 PO_4-P giderimi olarak elde edilmiştir.

Çalışmanın son kısmında, ardışık zamanlı kesikli işletme (AZKR) ile sentetik atıksudan nutrient giderimi farklı özgül nutrient yükleme hızlarında (ÖNYH) incelenmiştir. Ardışık zamanlı kesikli reaktörde (AZKR) nutrient giderimi beş basamaklı, anaerobik (An), anoksik (Anok), oksik (Ok), anoksik (Anok) ve oksik (Ok) fazları içeren prosesle gerçekleştirilmiş ve hidrolik alıkonma süreleri (HAS) sırasıyla 2/ 1/ 4.5/ 1.5/ 1.5 saatlerde sabit tutulmuştur. Tüm deneylerde, çökeltim süresi 45 dakikada sabit tutulmuştur. Başlangıç KOİ konsantrasyonu 600 ile 4800 mg/L arasında sekiz farklı seviyede değiştirilmiş KOİ / N / P oranı 100 / 3.33 / 0.7' de sabit tutulmuştur. Nutrient giderme verimleri artan nutrient yükleme hızlarıyla azalmış ve çıkış nutrient değerleri buna karşılık artmıştır. En yüksek KOİ (%99), NH_4-N (%99) ve PO_4-P (%97) giderme verimleri başlangıç KOİ konsantrasyonunun 600 mg/L ve KOİ yükleme hızı yaklaşık 40 mg KOİ/ g biomass.saat olduğunda elde edilmiştir. Ancak, çamur hacim indeksi (ÇHİ), yaklaşık 86 mg KOİ/g biomass.saat KOİ yükleme hızında, minimum 46 mL/g olarak bulunmuş ve ÇHİ, artan KOİ yükleme hızıyla azalmıştır. Biyokütle konsantrasyonu, 86 mg KOİ/g biomass.saat KOİ yükleme hızında 3.84 g/L olarak bulunmuş ve artan özgül nutrient yükleme hızıyla yükselmiştir.

Özetle, sentetik atıksudan nutrient giderimi ardışık zamanlı kesikli reaktör kullanılarak ayrıntılı olarak incelenmiş; beş basamaklı işletme ve 10 günlük çamur yaşı en yüksek nutrient giderimi sağlayan en uygun işletme koşulları olarak bulunmuştur. Her basamağın hidrolik alıkonma süreleri, giriş atık suyun bileşimi ve özgül nutrient yükleme hızlarının nutrient giderim performansı üzerine etkileri incelenmiş ve nutrient gideriminin en yüksek olduğu şartlar bulunmuştur.

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CHAPTER ONE

INTRODUCTION

1.1. INTRODUCTION

There are several reasons, or benefits, for utilizing biological nutrient removal (BNR) processes for the treatment of wastewaters which may be classified as environmental, economical, and operational benefits. The most important of these is the control of eutrophication in the effluent receiving water, which is an environmental benefit. Historically, treatment requirements were determined by the need to protect the oxygen resources of the receiving water, and this was accomplished primarily through the removal of degradable solids and dissolved organics from the wastewater before discharge. In more recent years, considerable emphasis has been placed on also reducing the quantities of nutrients discharged. Excess nitrogen and phosphorus in effluent wastewaters stimulate growth of algae and other photosynthetic life, which lead to accelerated eutrophication, excessive loss of oxygen resources, and undesirable changes in aquatic populations.

Biological nutrient removal (BNR) processes provide a methodology for the removal of nitrogen and phosphorus from point sources which are both environmentally and economically superior to other options. The utilization of biological nutrient removal (BNR) processes for the treatment of wastewaters is potentially more economical than conventional activated sludge treatment or methods that incorporate chemical or physicochemical processes. The principal mainstream biological nutrient removal (BNR) processes are described in Table 1.1.

An activated sludge system must include one or more unaerated zones and be a single sludge system in order to accomplish BNR. Single sludge system means that each train contains only one secondary clarifier and settled biomass must recycle through all zones. This is essential for selection of the types of bacteria and biochemical processes desired. Phosphorus removal can be maximized by placing the anaerobic zone first so that the phosphorus-removing bacteria have the first opportunity to utilize the organic substrate, thus giving them a competitive edge over those bacteria which cannot utilize or store substrate under anaerobic conditions. Likewise, nitrogen removal can be maximized by placing the anoxic zone first. Phosphorus removal is still possible if the anaerobic zone is placed after an anoxic zone, but only if readily available organics are still present in solution in substantial quantity. Nitrogen removal is less sensitive to the types of organics available, so the anaerobic zone is usually placed first and the anoxic zone follows. However, it is impossible to operate a nutrient removal sequencing batch reactor (SBR) without going through the anoxic phase before the anaerobic phase, if the system is accomplishing nitrification.

The first BNR process configurations were developed in the 1960s. Ludzack and Ettinger (1962) were the first to propose a single sludge nitrification-denitrification process utilizing the biodegradable organics in the influent as the energy source for denitrification. Two reactors in series were used for this purpose which had an anoxic reactor followed by an aerobic reactor. The lack of control of the interchange between the two reactors results in variable performance. Barnard, while developing the Bardenpho process in 1973, proposed an improvement of the Ludzack-Ettinger process by completely separating the anoxic and aerobic reactors, recycling the settled sludge to the anoxic reactor, and providing an additional recycle from the aerobic to the anoxic reactor for the return of nitrates.

Barnard (1973) invented the Bardenpho process by adding a secondary anoxic reactor after the aerobic reactor to increase total denitrification and decrease the effluent total nitrogen (TN). An oxidation ditch can easily be converted to a nitrogen removal system by controlling the amount of air transferred to the mixed liquor. Sequencing batch reactors (SBRs) can be operated for nitrogen removal by adjusting the time periods of the different phases. An SBR treatment cycle consists of a timed sequence which typically includes the following steps: fill, react, settle, decant, empty and idle. When biological nutrient removal (BNR) is desired, the steps in the cycle are adjusted to provide anoxic or anaerobic periods within the standard cycles.

A process configuration for the utilization of biological phosphorus removal (BPR) was first developed by Levin and Shapiro (1965). It was shown that enhanced phosphorus storage by bacteria was possible and an anerobic reactor was included in the system to accomplish phosphorus release. However, the linkage between organic substrate storage and phosphorus release was not understood and the detrimental effects of nitrates in the anaerobic reactor was not known. Consequently, a sidestream anaerobic reactor was used to accomplish phopshorus release from the biomass and the phosphorus from the supernatant was removed using chemical precipitation. This configuration was named as the PhoStrip process and it is still the only sidestream configuration currently in use for biological nutrient removal.

It was observed during the late 1960s that several conventional, plug-flow activated sludge systems, such as the Rilling Road in San Antonio, Texas, the Tuscon, Arizona plant, and the Backwater plant in Baltimore, among others, were accomplishing enhanced phosphorus removal (Vacker et al., 1967; Yall et al., 1970; Milbury, 1971). Barnard reviewed the published information and noted that all of these plants were plug-flow, conventional activated sludge plants operated at high rates to suppress nitrification. He realized the importance of an anaerobic zone to stimulate phosphorus removal and proposed placing an anaerobic step ahead of the aerobic zone so that the influent organics could be used to create anaerobic conditions instead of relying on endogenous respiration as in the PhoStrip process (Barnard, 1975). The resulting configuration, which he called, “Phoredox” process was first applied on a full-scale basis at Germiston, South Africa in 1974. The same configuration was later patented by Air Products and Chemicals, Inc., in the United States under the trademark of “Anaerobic / Oxic”, or A/O process (Spector, 1979).

Barnard (1974, 1975) was the first researcher who first understood the importance of the anaerobic zone, and developed the first mainstream systems accomplishing

BPR by placing an anaerobic reactor in front of an aerobic zone. Barnard identified this process as the Phoredox process. The A/O process is a patented version of Barnard's findings by Air Product and Chemicals, Inc., and the main difference is the use of multiple-staged anaerobic and aerobic reactors. In these processes there is no nitrification, and the anaerobic detention time is 30 min to 1 h to provide the selective condition for biological phosphorus removal. The SRT of the aerobic zone mixed liquor is 2 to 4 d, depending on the temperature.

After pilot-plant and full-scale experimentation, Barnard combined the Phoredox concept with the MLE process at Klerksdorp, South Africa, in 1974. This resulted in the three-stage process called, and trademarked as "Anaerobic/ Anoxic/ Oxic", or A^2/O process which was later patented in the United States by Air Products and Chemicals, Inc. The proprietary A^2 / O process is a modification of the A / O process and provides an anoxic zone for denitrification. The detention period in the anoxic zone is approximately 1 h. The anoxic zone is deficient in dissolved oxygen, but chemically bound oxygen in the form of nitrate or nitrite is introduced by recycling nitrified mixed liquor from the aerobic zone. Use of anoxic zone minimizes the amount of nitrate fed to the anaerobic zone in the recycled activated sludge. The Phoredox concept was next combined with the Bardenpho process for the new Goudkoppies plant in Johannesburg, South Africa, which went on-line in 1978 and was known as the five-stage modified Bardenpho process. The Bardenpho process can be modified for combined nitrogen and phosphorus removal. The staging sequence and recycling methods are different from the A^2 / O process. The 5-stage system provides anaerobic, anoxic, and aerobic steps for phosphorus, nitrogen, and carbon removal. A second anoxic stage is provided for additional denitrification using nitrate produced in the aerobic stage as the electron acceptor, and the endogenous organic carbon as the electron donor. The final aerobic stage is used to strip residual nitrogen gas from solution and to minimize the release of phosphorus in the final clarifier. Mixed liquor from the first aerobic zone is recycled to the anoxic zone. The 5-stage process uses a longer SRT (10 to 20 days) than A^2 / O process, and thus increases the carbon oxidation capability of the organisms. Subsequent studies by many investigators during the 1980s demonstrated that BPR could be accomplished with a wide variety of system configurations.

Configurations with multiple oxidation ditches have also been developed in Denmark for the biological removal of nitrogen alone, or of both nitrogen and phosphorus removal (Bungaard, 1988) and was labeled as BioDenitro and Bio-Denipho processes, respectively.

Marais and his co-workers determined the detrimental effects of nitrates entering the anaerobic zone on the performance of BPR process. They developed a modification of the three-stage Phoredox process that eliminated the recycle of nitrates in the RAS to the anaerobic zone. This process was named as the University of Cape Town (UCT) process. The UCT process was developed to minimize the nitrate content in wastewater entering the anaerobic contact zone. The amount of nitrate in the anaerobic zone is critical to the biological phosphorus removal efficiency. The UCT process is similar to the A^2 / O process with two exceptions. The return activated sludge is recycled to the anoxic stage instead of the aerobic stage, and the internal recycle is from the anoxic stage resulting in elimination of nitrate from the anaerobic stage, thereby improving the uptake of phosphorus in the anaerobic stage. The internal recycle feature provides increased organic utilization in the anaerobic stage. The mixed liquor from the anoxic stage contains substantial soluble BOD but little nitrate. The recycle of the anoxic mixed liquor provides almost optimal conditions for fermentation uptake in the anaerobic stage. Because the mixed liquor is at a lower concentration, the anaerobic detention time must be longer than that used in the Phoredox process, and is in the range of 1 to 2 h. The anaerobic recycle rate is typically 2 times the influent flowrate. The UCT process was later modified to provide even better protection of the anaerobic zone from nitrate recycle. The return activated sludge was directed to an anoxic reactor that did not receive internal nitrate recycle flow. The nitrate was reduced in this tank, and the mixed liquor from the reactor was recycled to the anaerobic tank. The second anoxic tank follows the first anoxic tank and receives internal nitrate recycle flow from the aeration tank to provide the major fraction of nitrate removal for the process.

Randall (1984) recommended utilization of the UCT configuration as a high-rate BNR system for economical treatment of municipal wastewaters in the U.S.A. This concept was piloted by CH2M/HILL with consultation from Randall for the Hampton Roads Sanitation District (HRSD), as a new design for replacement of their Lambert' s Point wastewater treatment plant, which was providing only primary treatment (Daigger et al., 1987). The pilot study was very successful, and the process was patented as a public domain patent by CH2M/HILL and HRSD as the Virginia Initiative Project (VIP) process. The VIP process is similar to the A^2 / O and UCT processes except for the methods used for recycle systems. In the VIP process, all the zones are staged consisting of at least two completely mixed cells in series. The return activated sludge is discharged to the inlet of the anoxic zone along with nitrified recycle from the aerobic zone. The mixed liquor from the anoxic zone is returned to the head end of the anaerobic zone. The VIP process is also designed as a high-rate system, operating with much shorter SRTs, which maximize biological phosphorus-removal efficiency. The combined SRT of the anaerobic and anoxic zones is generally 1.5 to 3 d, while the anaerobic and anoxic hydraulic retention time values are typically 60 to 90 min each. The aeration zone is designed for nitrification.

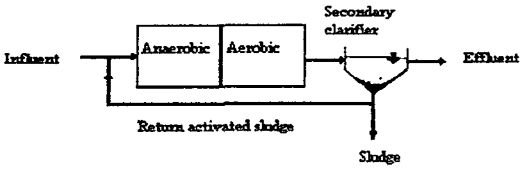
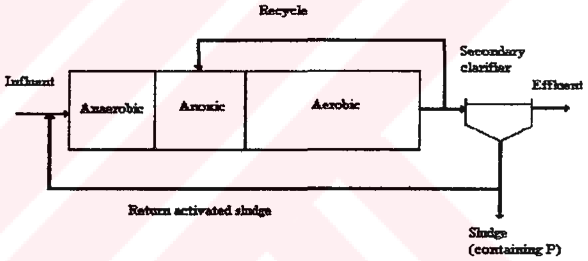
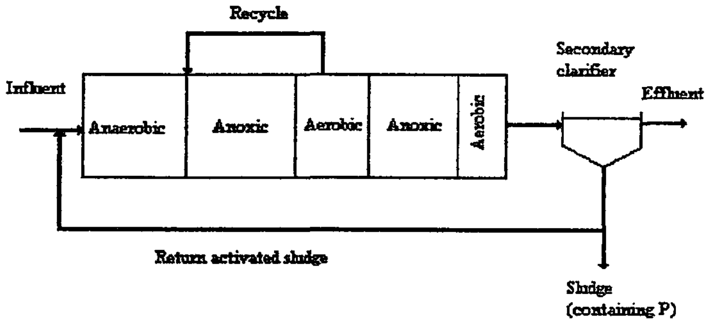
The sequencing batch reactor (SBR) is a modification of conventional continuous flow activated sludge sewage treatment. The SBR is a fill and draw system that operates in a batch rather than in a continuous mode. A conventional activated sludge (CAS) system carries out aeration and sedimentation/clarification simultaneously in separate tanks. The SBR process performs these operations sequentially in the same tank. An SBR system is comprised of either a storage tank and an SBR tank, or a minimum of two SBR tanks to handle continuous influent. Process operation and performance have been thoroughly described by Irvine and co-workers (1983, 1985, 1987). A modification of the SBR process, the Intermittent Cycle Extended Aeration System (ICEASR), manufactured by Austgen Biojet, operates with a continuous feed and intermittent withdrawal. A baffle wall installed in the ICEASR treatment tank buffers this continuous inflow (Austgen Biojet Waste Water Systems, Inc., May 1991).

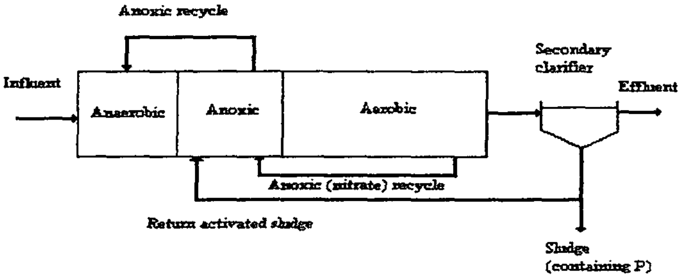
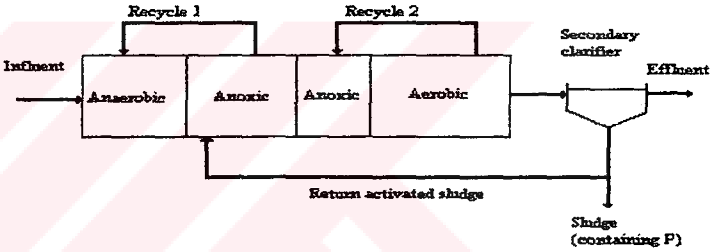
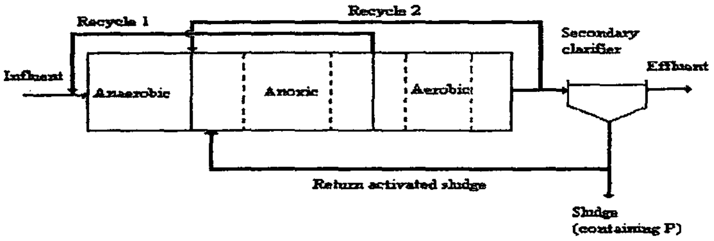
A sequencing batch reactor (SBR) is an activated sludge biological treatment process that is applicable to treatment of municipal and industrial wastewater for small to medium flow rates (0 to 5 mgd). An SBR treatment cycle consists of a timed sequence which typically includes the following steps: fill, react, settle, decant, and idle. Figure 1.1. illustrates this sequence of events. When biological nutrient removal (BNR) is desired, the steps in the cycle are adjusted to provide anoxic or anaerobic periods within the standard cycles.

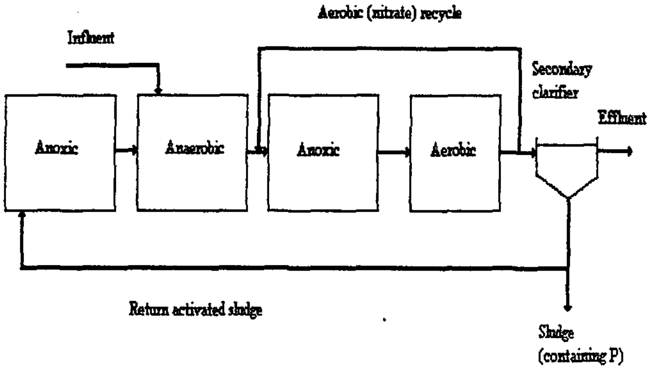
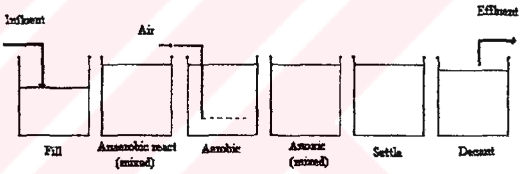
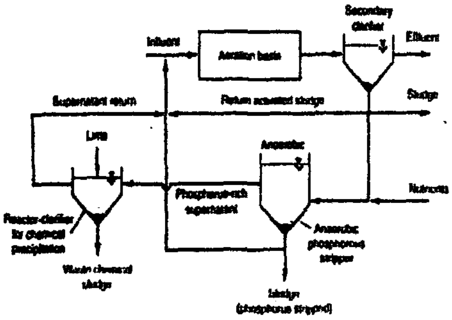
Aeration in an SBR may be provided by fine or coarse bubble diffusers, floating aerator / mixers or jet aeration devices. The SBR process is usually preceded by some type of preliminary treatment such as screening, communition or grit removal. Because the SBR process operates in a series of timed steps, reaction and settling can occur in the same tank, eliminating the need for a final clarifier.

The SBR technology has the advantage of being very flexible in terms of matching react and settle times to the strength and treatability characteristics of a particular waste stream, both nitrogen and phosphorus removal are possible, process is easy to operate, mixed-liquor solids cannot be washed out by hydraulic surges and quiescent settling may produce lower effluent TSS concentration.

Table 1.1. Biological Nutrient Removal (BNR) Processes

Types of BNR process	A schematic diagrams of the process
Phoredox (A/O)	
A^2 / O	
Modified Bardenpho (5-stage)	

UCT (standard and modified)	
	
VIP	

Johannesburg process	
SBR	
PhoStrip	

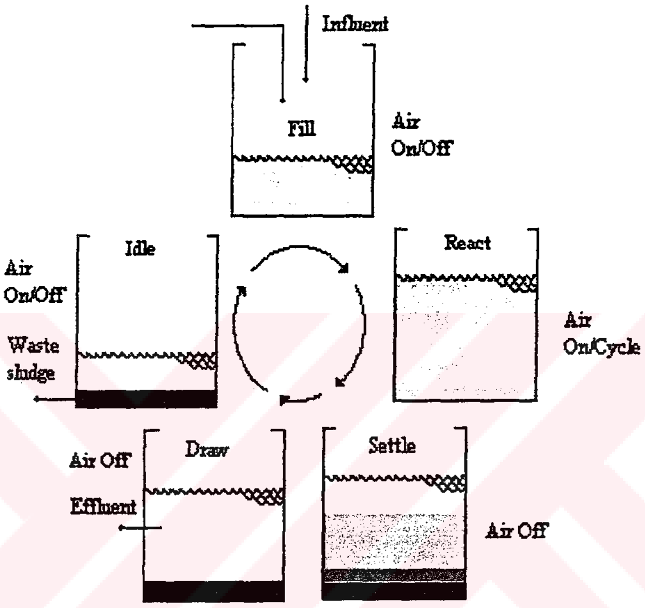


Figure 1.1. Typical sequencing batch reactor (SBR) operation for one cycle.

1.2. LITERATURE SURVEY

Biological processes based upon suspended biomass (i.e. activated sludge processes) are effective for organic carbon and nutrient removal in municipal wastewater treatment plants. It is known that sequential batch reactors (SBR) are suitable for treating wastewaters containing high nitrogen and phosphorus for small and medium-size cities of high population density. The SBR has the following advantages in a small-scale system: flexibility in operation, low construction and maintenance cost and simultaneous removal of nitrogen and phosphorus.

Especially, the increase of nitrogen and phosphorus discharged into a river from sewage and industrial wastewater has made self-cleaning function of the river ineffective and promoted abnormal increase in algae growth resulting in rapid eutrophication.

Sequencing batch reactors (SBR) were originally used for COD and phosphate removal from wastewaters (Tasli et al., 1997; Baozhen et al. 1998; Ramirez & Martinez, 2000; Belia & Smith, 1997; Shin & Jun, 1992; Danesh & Oleszkiewicz, 1997; Carucci et al., 1997; Colunga & Martinez, 1996; Colmenarejo et al., 1998). Because of recent regulations on nutrient discharge limitations, SBR systems were modified to achieve nitrification, denitrification along with COD and phosphate removal. SBR treatment systems consist of a sequencing operation including the steps of fill, react, settle, decant and idle (Metcalf & Eddy, 1991). When biological nutrient removal is desired, the steps in the react cycle are adjusted to provide anaerobic, anoxic and aerobic phases in certain number and sequence. Under anaerobic conditions bacteria release phosphate and synthesize polyhydroxy butyrates (PHB) by using carbonaceous compounds; COD removal, nitrification and phosphate uptake take place in the aerobic step (Muyima & Cloete, 1995) and denitrification occurs under anoxic conditions. (Process Design Manual for Nitrogen Control, EPA,1993).

Numerous studies were reported in the literature on nutrient removal (Arora et al., 1985; Umble & Ketchum, 1997; Chang & Hao, 1996; Pastorelli et al., 1999; Furumai et al., 1999; Keller et al., 1997; Subramaniam et al., 1994; Demoulin et al., 1997; Demuynck et al., 1994; Andreottola et al., 1997; Ho et al., 2000; Zuniga & Martinez, 1996; Sang-Ill et al., 1997).

Shin and Jun (1992) studied biological phosphorus removal mechanisms in an activated sludge wastewater treatment system. The objective of their studies was to develop the excess phosphorus removal system in a short start-up period and to find the optimal operating conditions. Both glucose and acetate can be utilized as carbon sources in the anaerobic phase, and the uptake rate of each substrate was shown during the first one hour aerobic phase but the uptake rate of glucose was decreased during the later part of aerobic phase. In case of using both acetate and glucose, the uptake rate and amount was higher than using glucose alone. The removal rates of both TOC and phosphorus were above 98% in one week operation (Shin and Jun, 1992).

Bortone et al.(1994) studied the biological nitrogen and phosphorus removal in an anaerobic/anoxic sequencing batch reactor with a separated biofilm nitrification step. Piggery wastewater, because of its low COD/N ratio, was used as the feed. After feeding, the An/Ax SBR was operated under anaerobic conditions for organic carbon sequestering and phosphorus removal. An/ Ax SBR resulted in satisfactory N and P removal capacities with excellent sludge settling properties (Bortone et al., 1994).

Demuynck et al.(1994) studied SBR plants for nutrient removal and found that a sequence of short aerobic/anoxic phases was better than the usual sequence of aerobic/anoxic phases. Nearly complete removal of nitrogen was obtained by supplementary COD addition to the anoxic phase to achieve denitrification (Demuynck et al., 1994).

Subramaniam et al.(1994) studied biological nutrient removal from a high strength wastewater using combined anaerobic-sequencing batch reactor treatment. The abattoir (slaughter house) wastewater used in their studies was high both in nutrient and carbon concentrations. The removal of COD, TKN, TP and SS were greater than 95%, 92%, 90% and 94%, respectively. The results showed that the combination of anaerobic pond-SBR treatment was effective in treating high strength abattoir wastewater for COD and nutrient removal (Subramaniam et al., 1994).

Leung and Tam (1994) studied the operation strategy of a SBR for simultaneous removal of wastewater organic matter and nutrients. Laboratory-scale reactors were used to evaluate the feasibility of incorporating alternative aerobic-anoxic-aerobic steps within the "react period" for simultaneous removal of organic matter, N and P. Two cycles of SBR process per day were maintained. Under the operation strategy of 0.75 h fill, 8 h react (with continuous aeration), 3.25 h settle, draw and idle periods, the treatment performance became consistent after running the system for two to four cycles (1-2 days). The percentages of both BOD_5 and COD removal were around 94% from cycle 2 onwards, the BOD_5 content dropped from initial 251 mg/L to less than 14 mg/L in the final effluent. A steady nitrification (about 97%) was obtained from cycle 4 onwards, with 1 mg NH_4-N/L and 25 mg NO_3-N/L present in the final effluent. The findings also show that 4 h aeration during the react period was long enough to achieve more than 90% nitrification. With the incorporation of a 3 h anoxic stage after the initial 4 h aeration of the react period, a satisfactory denitrification process was observed, with nitrate level dropped from 27 to around 8 mg/L within 3 h. A 12 hour cyclic SBR system with the incorporation of 4 h aerobic, 3 h anoxic and final 1 h aerobic steps into the 8 h react period was demonstrated to be able to remove C, N and P simultaneously (Leung and Tam., 1994)

Malaspina et al.(1995) studied treatment of the high strength cheese whey effluent that still contains high amounts of COD, ammonia nitrogen and phosphorus requiring post treatment to meet standard limits. Tests of post treatment were carried out during two years with a sequencing batch reactor (SBR). The SBR was tested at various F/M values with different durations of anoxic-anaerobic-oxic cycles. Under certain conditions, more than 90% removal of COD, nitrogen and phosphorus were obtained (Malaspina et al., 1995).

Zuniga and Martinez (1996) investigated the possibility of joining phosphorus and nitrogen removal in a biofilm sequencing batch reactor using an operation strategy with four reaction phases: Anaerobic/ Aerobic/ Anoxic/ Aerobic. After operating the system for 615 days, optimal operating conditions were established to obtain the highest removal rates with a well established microbial community. Adequate cycle and phase durations were established and organic loading values were obtained for different treatment purposes. The system worked successfully resulting in COD, phosphates and ammonia nitrogen removals of 89±1%, 75±15%, and 87±10%, respectively. Simultaneous nitrification and denitrification during the aerobic phase could be observed when a 36 h cycle length was used. Denitrification was effectively achieved with an anoxic phase after the aerobic phase (Zuniga and Martinez, 1996).

De Sousa and Foresti (1996) investigated the technical feasibility of the UASB-SBR system for organic matter removal and nitrification. The system composed of an UASB reactor followed by two SBRs was efficient in removing COD (95%), TSS (96%) and TKN (85%) (De Sousa and Foresti, 1996).

Colunga and Martinez (1996) studied the effects of population displacements on biological phosphorus removal in a biofilm SBR. A biofilm SBR was operated for 400 days in order to determine the effects of different operating strategies on the capacity of the biofilm to remove nutrients (C, N and P). The operation was controlled with an industrial programmable timer. The treatment cycles were adjusted with four steps: filling, anaerobic phase, aerobic phase and draw of treated wastewater. Cycles of 8 and 12 h were tested with different anaerobic/aerobic time ratios. The highest COD and PO_4-P removals were obtained with a 12 h cycle and phase durations of 37/63 percent for the anaerobic/aerobic phases. The best results regarding phosphate removal and nitrification were obtained when the mean organic load was 3 g COD/m^2.days (Colunga and Martinez , 1996).

Bernardes and Klapwijk (1996) developed a strategy for biological nutrient removal (nitrogen and phosphorus) in a sequencing batch reactor (SBR) treating domestic wastewater. For this purpose, the performance of an SBR with nitrification, denitrification, carbon oxidation and phosphorus removal was evaluated. During this study the influent used was pre-settled domestic wastewater from Bennekom-Municipal Treatment Plant (The Netherlands). The average influent COD, TKN and phosphate were 443 mg COD/L, 71 mg N/L and 7 mg P/L, respectively. The effluent had, in average, phosphate concentration lower than 1 mg P/L and nitrogen concentration lower than 12 mg N/L (Bernardes and Klapwijk, 1996).

Important process parameters affecting the performance of an SBR were investigated by Chang and Hao (1996). When the feed BOD was changed between 100 mg/L and 200 mg/L maximum nitrogen and phosphate removal efficiencies were obtained with 1/ 3/ 2 h of anaerobic/ aerobic/ anoxic phases. COD, total nitrogen and phosphate removals of 91%, 98% and 98%, were obtained, respectively in an SBR with a sludge age of 10 days and total cycle time of 6 h (Chang and Hao, 1996).

Umble and Ketchum (1997) used a sequencing batch reactor for biological nutrient removal from municipal wastewater. BOD_5, TSS, and NH_3-N removals of 98%, 90% and 89% were obtained, respectively with a 12 h cycle time (Umble and Ketchum, 1997).

An algorithm was developed by Andreottola et.al. (1997) for optimization of the cycle length and phase distribution to minimize effluent nitrogen concentration. Effluent concentrations of nitrate, nitrite and ammonia were 2.9 mg/L, 0.04 mg/L and 0.06 mg/L, respectively with anoxic and anaerobic phase durations of 3.3 h and 4.2 h (Andreottola et.al., 1997).

In order to find an alternative carbon source of waste origin, Sang-Ill et al. (1997) used fermented swine waste instead of acetate in an SBR. No difference in performance of the reactors supplemented with either acetate or fermented swine waste was observed. Total nitrogen and phosphorus removals of 90% and 89% were obtained, respectively with both carbon sources (Sang-Ill et al., 1997).

Carucci et al.(1997) investigated biological phosphorus removal with different organic substrates in an anaerobic/aerobic sequencing batch reactor. The results showed that the bacteria growing in alternating anaerobic/aerobic systems can remove organic substrates under anaerobic conditions even without using the hydrolysis of phosphates or the transformation of glucogen into poly-hydroxyalkanoates as the energy sources for the uptake and storage of substrate. However, in the case of acetate plus glucose feed, enhanced biological phosphorus removal (EBPR) can be steadily established with typical PolyPhosphate-bacteria like metabolism, even if most of the COD removal takes place under not truly anaerobic conditions (Carucci et al., 1997).

Demoulin et al.(1997) studied the dependence of the efficiency of co-current nitrification/denitrification and biological phosphorus removal on set point dissolved oxygen concentrations and associated ORP (oxidation reduction potential) profiles. The effect of operation with over aeration was demonstrated through its impact on biomass metabolic activity . It was shown that the oxygen demand supply quotient is an important operating parameter for both nitrogen and phosphorus removal. Effluent quality of less than 10 mg/L total nitrogen, 3 mg/L ammonia nitrogen and 2 mg/L of total phosphorus was routinely obtained at and below 8 °C, with an aerated solids retention time of around 10 days and an organic loading of 0.1 kg COD/kg MLSS.days. Filamentous sludge bulking control was demonstrated in the cyclic process (Demoulin et al., 1997).

Johansen et al.(1997) operated a full-scale SBR for nutrient removal. Excellent nutrient removal was obtained at a small SBR wastewater treatment plant. The criteria outlined in the Danish Water Action Plan were easily met, resulting in COD<75 mg/L, BOD<15 mg/L, TN<8 mg/L, TP<1.5 mg/L. Approximate, removal efficiencies of COD, TN, NH_4, TP were 86%, 80%, 93%, 63%, respectively (Johansen et al., 1997).

Belia and Smith (1997) demonstrated that the addition of a pure culture of *Acinetobacter lwoffii* to an activated sludge without phosphorus removal capabilities, resulted in the development of EBPR in 14 days. A control reactor allowed to develop an enhanced culture of polyphosphate bacteria, reached the same removal rates after 58 days. Both the control and bioaugmented reactors achieved 90% COD and nitrogen removal rates and both had similar sludge settling properties (SSVI 80-150 mL/g). The sludge produced shows resilience to low DO (<0.5 mg/L) during the aerobic phase and to biomass replacement of up to 70% of VSS (Belia and Smith, 1997).

Rao et al.(1997) evaluated the biological nutrient removal performance of three full-scale sequential batch reactor (SBR) plants. The plants were designed to handle an average flow of 0.023, 0.025, 0.001 m^3/s, respectively. These SBR systems were designed to achieve nitrification, denitrification and biological phosphorus removal. Influent and effluent samples were analyzed for carbonaceous biochemical oxygen demand ($CBOD_5$), TSS, ammonia nitrogen, nitrate nitrogen, total phosphorus, pH and temperature. The SBR performance data showed that typical SBR designs can meet effluent $CBOD_5$ and TSS concentrations of less than 10 mg/L. With some additional design modifications, SBRs can successfully nitrify to limits of 1-2 mg/L NH_3. The processes also achieved denitrification and phosphorous removal when properly designed (Rao et al., 1997).

Danesh and Oleszkiewicz (1997) developed a two-stage anaerobic-aerobic sequencing batch reactor (SBR) system (PAF-SBR) to enhance biological phosphorus removal in the sequencing batch reactors. The system performance was evaluated against a conventional SBR system in parallel to lab-scale reactors at room temperature, using the degritted raw wastewater as the feed. The SRT for the anaerobic SBR which is named as PAF (Primary Acid Fermenter) was 12 days, and for both BNR reactors the SRT was 10 days. All reactors were run at 3 cycles per day. The results indicated that by using the pre-fermentation step, the anoxic/anaerobic period in the BNR-SBR could be controlled and reduced to less than 50 minutes, which would reduce the total cycle time from 8 h to 6 h. Higher efficiency in phosphorus removal could be achieved by shortening the anoxic/anaerobic period. Reduction of this period prevents or minimizes the change in the secondary release of the phosphorus (Danesh and Oleszkiewicz, 1997).

Keller et al.(1997) studied nutrient removal from industrial wastewater using single tank sequencing batch reactors. This research and demonstration project addressed the issue for abattoir (slaughterhouse) effluent. It was found that a certain degree of anaerobic pretreatment can reduce part of the carbon concentration most efficiently while still leaving sufficient COD required for successful BNR. Despite high influent concentrations of approximately 190 mg/L N and 50 mg/L total P, good effluent quality of less than 20 mg/L total N and less than 5 mg/L total P has been achieved. Furthermore the operation of the small SBR systems has proved to be simple and reliable (Keller et al., 1997).

In a study by Choi et al. (1997), an existing 2 stage aerobic nightsoil treatment plant (25 m^3/day capacity) was converted from a conventional continuous flow system to a single stage SBR unit for nutrient removal. Studies with duration of ten months improved organic carbon and nutrient removals drastically. Nutrient removal efficiencies were found to be greatly affected by pH changes due to denitrification and nitrification. Increased pH due to denitrification stimulated chemical precipitation of phosphate as struvite and hydroxyapatite. In contrast, decreased pH in aerobic stage due to nitrification dissolved the previously formed precipitates resulting in increase of PO_4-P. SBR modification could improve organic and nutrient removal efficiencies without increase of tank volumes and blower capacity: The efficiency were 97% for organic carbon, 99% for nitrogen and 78% for soluble phosphorus removal. Oxygen requirements were reduced to 40-53% (Choi et al., 1997).

Rim et al.(1997) studied a full-scale pilot plant using SBR process treating an actual wastewater emanating from a recreational center. The main purpose of this investigation was to evaluate applicability in the field and process removal efficiencies in terms of BOD, SS, TN and TP and its corresponding kinetic parameters. Influent quality were 139 mg/L BOD, 72 mg/L SS, 45 mg/L TN, 4 mg/L TP. The flow rates were 58.3 m^3/day during the weekends and 47.3 m^3/day during the weekdays (an average was 52.8 m^3/day). Effluent concentrations were 7.3 mg/L BOD, 10.4 mg/L SS, 13.6 mg/L TN and 0.9 mg/L TP. The removal efficiencies were 95%, 89%, 70% and 77% for BOD, SS, TN and TP, respectively. Denitrification/nitrification conversion rates during anaerobic/aerobic processes were 4.5 mg/kg MLSS.h and 1.5 mg/kg MLSS.h, respectively (Rim et al., 1997).

Taşlı et al.(1997) evaluated the effects of different organic substrates and their combinations on EBPR, in a sequencing batch reactor. The experimental results showed that high EBPR could be obtained in a lab-scale anoxic / anaerobic-aerobic SBR using synthetic wastewater containing acetate, protein and glucose. Phosphorus removal gradually declined as acetate addition was lowered and compensated with glucose. When the influent TKN / COD ratio was increased with the resulting increase of NOx-N input to the anaerobic phase, the phosphorus removal efficiency was also observed to decrease due to reduced fermentation (Taşlı et al., 1997).

Rustrian et al.(1998) studied an integrated process for simultaneous removal of carbon, nitrogen and phosphorus from industrial wastewaters. The process consisted of a-two step anaerobic digestion reactor, for carbon removal, coupled with a sequencing batch reactor (SBR) for nutrient removal. Experiments on the SBR were carried out for a period of 210 days during which the SBR was connected to the acidogenic and methanogenic reactors. It was shown that nitrification of ammonia took place in the SBR reactor during the aerobic phase. Furthermore, denitrification and VFA production were achieved together in the acidogenic reactor, when the efflux of nitrates from the SBR reactor was added to the first reactor influx. The proposed process was fed with a synthetic industrial wastewater, the composition of which was, total organic carbon (TOC) = 2200 mg/L, total Kjeldahl nitrogen (TKN)= 86 mg/L, phosphorus in phosphate form (PO_4-P)= 20 mg/L. Under these conditions, removals of carbon, nitrogen and phosphorus were 98%, 78% and 95%, respectively. The results showed that the combination of the two-step anaerobic digestion reactor and an SBR reactor was effective for simultaneous carbon, nitrogen and phosphorus removal (Rustrian, 1998).

Baozhen et al.(1998) studied the mechanism of phosphorus removal in an SBR using submerged biofilm system. The DNP (2,4 dinitrophenol) and nuclear magnetic resonance methods were employed to verify the mechanism of phosphorus removal by bacteria with the phosphorus release in anaerobic phase and uptake in oxic and anoxic phases. Some mathematical models for simulating phosphorus release in the anaerobic phase and phosphorus uptake in the oxic phase were developed as well (Baozhen et al., 1998).

Colmenarejo et al.(1998) studied major factors influencing biological phosphorus removal (BPR) in a sequencing batch anaerobic / aerobic reactor. The process was modelled on 3 key parameters: phosphorous release, COD uptake and MLSS level. Mixed liquor phosphorous content was also found to be an easily measured parameter to assess the overall efficiency of the process for biological phosphorous removal (Colmenarejo et al., 1998).

Rodriguez et al.(1998) studied the performance of an SBR reactor fed with anaerobically fermented wastewater. The objective was to determine the capacity of the system to remove nitrogen and phosphorus. Two SBR reactors, each one with a volume of 980 L, were used: one used as fermenter and the other as activated sludge SBR. Using 8 h cycles. the reactors were operated for 269 days. The fermenter produced an effluent with an average value of 223-224 mg/L of volatile fatty acids. The activated sludge SBR were tested under 3 organic loading rates of 0.13, 0.25, and 0.35 kg COD total/kg TSS.day. For the three tested organic loading rates, PO_4-P concentrations under 1.1 mg/L and COD between 37 and 38 mg/L in the effluent were consistently achieved (Rodriguez et al., 1998).

In a study by Ghigliazza et al.(1998), *Acinetobacter lwoffi* culture was subjected to anaerobic / aerobic conditions in a sequencing batch reactor (SBR) in order to study the ability of the strain in biological phosphorus removal process. The results revealed a phosphorus removal efficiency of 75-80% (Ghigliazza et al., 1998).

Lee and Park (1999) developed a neural network modeling for on-line estimation of nutrient dynamics in a sequentially-operated batch reactor. A bench-scale sequentially-operated batch reactor (SBR) used for advanced wastewater treatment (BOD plus nutrient removal) was employed to develop the neural network model. In order to improve the network performance, the structure of neural network was arranged in such a way of reflecting the change of operational conditions within a cycle (Lee and Park, 1999).

Baetens et al. (1999) studied the temperature effects in bio-P removal. An SBR was operated in an anaerobic-aerobic sequence to cultivate an enriched biological phosphorus removing sludge. The aerobic phosphorus uptake rate showed a maximum in the interval between 15 and 20 °C. All other anaerobic and aerobic conversion rates increased with increasing temperature (Baetens et al., 1999).

Rustrian et al.(1999) proposed a sequencing batch reactor (SBR) connected with a two step anaerobic digestion system in order to investigate the possibility of simultaneous C, N and P removal from wastewater. The system was operated using synthetic wastewater. In this system, the effluent of nitrate from the SBR reactor was added to the acidogenic reactor influent. Nitrate elimination and VFA production were then achieved together in the acidogenic reactor. The performances of three lab-scale reactors, operated for C, N and P biological removal were analyzed. The removals of TOC, TN and TP were greater than 96%, 75% and 86%, respectively (Rustrian et al., 1999).

Furumai et al.(1999) studied the effect of sludge retention time (SRT) on nutrient removal in sequencing batch reactors. Two bench-scale activated sludge sequencing batch reactors (SBRs) were operated on synthetic wastewater at sludge retention times (SRT) of 7 days (Reactor 1) and 15 days (Reactor 2), respectively. Biological phosphorus and nitrogen removals were investigated in the systems to elucidate nitrification, denitrification, and phosphorus removal kinetics. Excellent enhanced biological phosphorus removal was achieved in both reactors within 21 days (Furumai et al., 1999).

Pastorelli et al.(1999) used a pilot moving–bed sequencing batch biofilm reactor (MBSBBR) fed with primary settled wastewater, to study organic carbon, phosphorus and nitrogen removal with and without external carbon sources. Organic carbon uptake and phosphorus release has been achieved in the anaerobic phase of the cycle, while nitrification, simultaneous denitrification and phosphorus uptake was observed in the aerobic phase (Pastorelli et al., 1999).

Furumai et al.(1999) studied the modeling longterm nutrient removal in a SBR. Better phosphorus dynamics were achieved by considering the sub-model of denitrification by phosphorus accumulating organisms (Furumai et al., 1999).

Banas et al.(1999) evaluated the treatment efficiency and process performance during 2 years of plant operation, including studies of nitrification, denitrification and biological phosphorus removal from combined municipal and tannery wastewaters. As a result, despite a high chromium content in the influent, a good efficiency of N and P removal has been obtained. Low nitrification rates are more likely to be associated with temperature effects than with process inhibition by Cr (Banas et al., 1999).

Intrasungkha et al.(1999) studied biological nutrient removal efficiency in treatment of saline wastewater. Experimental data showed that the SBRs achieved good biological nutrient removal (BNR) when salinity levels in the influent were low (0.03% to 0.2% NaCl); but, showed difficulties with biological phosphorous removal at salinity levels of 0.5% (Intrasungkha et al., 1999).

Ghigliazza et al.(1999) investigated the possibility to obtain biological phosphorus removal under strictly aerobic conditions. Tests were carried out in a continuous stirred tank reactor inoculated by a culture of *Acinetobacter lwoffi* and the influence of sludge retention time was investigated. It was shown the that enhanced biological phosphorus removal (EBPR) was achived by a culture mainly constituted by *Acinetobacter lwoffi* under only aerobic conditions. This behaviour was probably due to the ability of the used microorganisms to accumulate phosphorus utilizing organic compounds with low molecular weight (i.e. acetate) directly, as energy source, The results showed that increasing SRT up to 8 days resulted in increases in phosphorus removal efficiency. Further increases in biomass age resulted in an adverse effect in the reactor performance. Removal efficiency of COD and phosphorus were 96% and 85%, respectively (Ghigliazza et al., 1999).

Ramirez and Martinez (2000) studied the kinetics of phosphate uptake during the aerobic phase in a biofilm reactor operated under the sequencing batch procedure. The process of phosphate uptake did not fit to the classical Michaelis-Menten kinetic model. The results obtained from the intrinsic association constant confirmed that the biological process was independent of the operation mode (cycle duration) of the reactor (Ramirez and Martinez, 2000).

Martinez et al.(2000) investigated the relationship between the mean cellular retention time (sludge age) and the ability of activated sludge to remove phosphate and ammonium. SBR was fed with municipal wastewater and was operated under four different organic loading rates to obtain sludge ages of 23, 16, 6, and 3 days. Biological phosphate removal was achieved with sludge ages from 6 to 23 days. The highest PO_4-P removal rate observed was 98% which corresponds to a 16-days sludge age. Percent phosphate removal increased with the sludge age. A sludge age of 3 days resulted in a chemical oxygen demand (COD) removal efficiency of 81% and a sludge age of 23 days resulted in a removal efficiency of 99%. Full nitrification was observed with a sludge age of 16 days. Nitrification increased with the sludge age. The operation with 3-days sludge age did not allow nitrification. The phosphate concentrations in the biomass were inversely proportional to the sludge age (Martinez et al., 2000).

Chang et al. (2000) carried out experimental studies in a small-scale SBR system of 30 L to define important parameters affecting the process performance. Varying HRTs with the BOD concentrations of 100, 200 mg/L could yield optimized removal rates of N and P within a shorter cycle time. Six hours of cycle time with 1-3-2 h (anaerobic-aerobic-anoxic) with 200 mg/L BOD concentration was found to have the best removal rates for N and P (Chang et al., 2000).

Kargi and Uygur used a five-step SBR for nutrient removal from a synthetic wastewater. Effects of the sludge age (SRT), hydraulic retention time (HRT) feed wastewater composition and carbon sources on nutrient removal performance were investigated. Sludge age of 10 days and a wastewater composition of COD / N / P : 100 / 3.33 / 0.69 were determined as optimal values resulting in maximum nutrient removal (Kargi and Uygur, 2002, 2003).

As can be seen from the literature reports on biological nutrient removal, the operating strategy mainly depends on wastewater composition and nutrient loading rates. Different operating strategies were used for different wastewaters. In the light of the aforementioned studies, the major objective of this thesis is to systematically investigate the effects of operating parameters on the performance of an SBR used for nutrient (C, N, P) removal and to optimize the conditions to obtain maximum removal efficiency in a minimum operation period.

1.3. OBJECTIVES AND SCOPE

Major objective of the proposed study is to maximize the removal efficiency of nutrients (carbon, nitrogen, phosphate) by adjusting the operating parameters in a sequencing-batch operation.

Objectives of the proposed study can be summarized as follows:

1. To investigate the effects of different processes consisting of different number of steps on nutrient removal performance of an SBR in order to achive maximum biological nutrient removal.

2. To determine the effects of anaerobic (1-3 h), anoxic (1-3 h), oxic (3-6 h) cycle retention times on the nutrient removal performance of the SBR.

3. To determine the effects of sludge age (5-30 days) on the nutrient (C, N, P) removal efficiency in SBR operation.

4. To investigate the effects of different carbon sources on nutrient removal performance of a three-step SBR operation.

5. To investigate the effects of wastewater composition (COD / N / P ratio) on the rate and extent of nutrient removal in an SBR operation and to determine the optimal ratio resulting in maximum nutrient removal.

6. To investigate the effects of specific COD, nitrogen and phosphate loading rates on the nutrient removal performance of the system.

The ultimate goal is to maximize the nutrient removal efficiency and minimize the number and total retention times of the cycles. Depending on the wastewater composition (COD / N / P ratio) the number, order and retention times of the cycles vary and optimal conditions can only be determined for a given composition.

Experiments were performed by using suspended organisms in a synthetic wastewater prepared in the laboratory. The mixed microbial culture contained COD removing heterotrophic bacteria, nitrifying and denitrifying bacteria and luxury phosphate uptaking bacteria.

CHAPTER TWO

MATERIALS AND METHODS

2.1. Experimental set-up

A schematic diagram of the experimental set up is depicted in Figure 2.1. A fermenter (Bioflo IIC, New Brunswick) with 5 L working volume was used as the sequencing batch reactor (SBR). The fermenter was microprocessor controlled for aeration, agitation, pH and dissolved oxygen (DO). Aeration was provided by using an air pump and a sparger. Agitation speed was varied between 25-200 rpm. pH, dissolved oxygen (DO) and oxidation-reduction potential (ORP) of the nutrient medium were continuously monitored by the relevant probes.

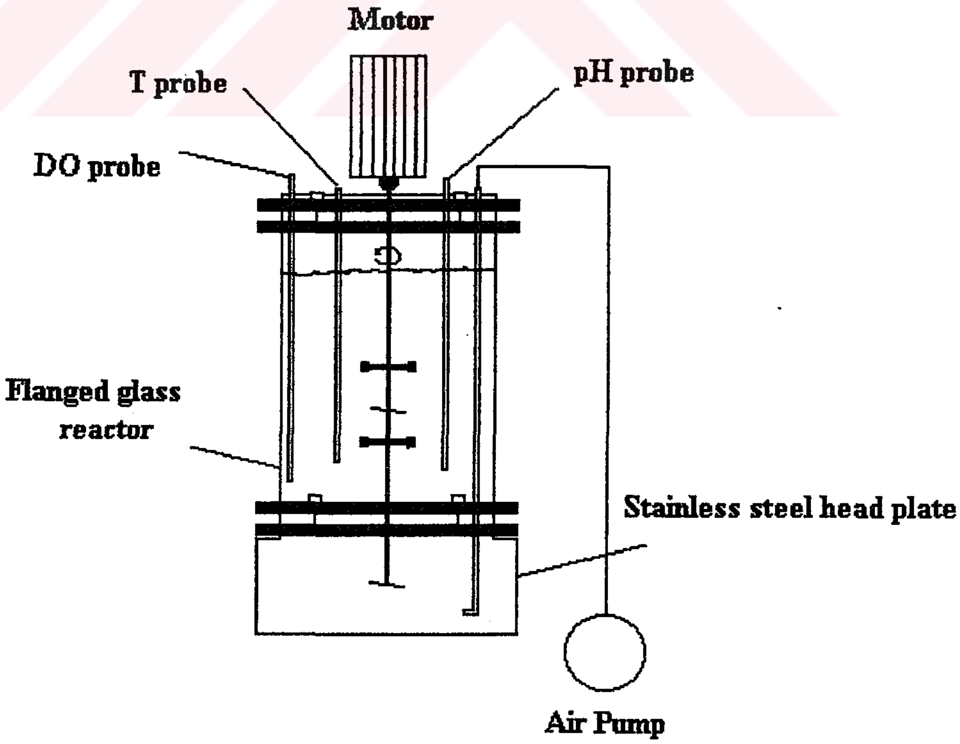


Figure 2.1. A schematic diagram of the sequencing batch reactor

2.2. Experimental procedure

Before starting sequencing batch operation, the reactor was filled with the synthetic wastewater, inoculated with a mixed culture of microorganisms and was operated batchwise with aeration and mixing for several days to obtain a dense culture to start with. After sedimentation of the organisms, 4 L of the clear supernatant was removed and the reactor was filled up to 5 L total volume with the defined nutrient media. Then, anaerobic, anoxic, oxic operations were applied in sequence. Nitrogen gas was passed through the media only during anaerobic operation. Agitation speed during anaerobic and anoxic cycles was 25 and 50 rpm, respectively. The media was aerated and agitated (200 rpm) vigorously during oxic (aerobic) cycle. Samples were withdrawn from the reactor at the beginning and at the end of each cycle for analysis. At the end of each SBR operation, the organisms were sedimented for 3/4 h and 4 L of the treated wastewater was removed. Sedimented organisms were used for the next treatment operation with the addition of 4 L fresh medium. A fraction of the culture was removed from the reactor before sedimentation everyday to adjust the sludge age to the desired level. Temperature and pH was controlled around T = 25 °C and pH= 7-7.5. Dissolved oxygen (DO) concentration in oxic (aerobic) phase was kept above 2 mg/L, while the DO during anaerobic and anoxic phases was zero. The ORP values during the oxic, anoxic and anaerobic phases were approximately +200 mV, +60 mV and -200 mV, respectively.

In studies to investigate the effects of the sludge age, sludge age were varied between 5 and 30 days while hydraulic retention times (HRT) of each step were kept constant throughout the experimental study. Five step nutrient removal process consisting of anaerobic/ anoxic/ oxic/ anoxic / oxic steps with HRT's of 2 / 1 / 4.5 / 1.5 / 1.5 h was used. Experiments were carried out three times at each sludge age tested. The first run was used to adapt and develop the culture and the other runs were for collection of data.

In studies for elucidation of the effects of nutrient wastewater composition on the system performance, a five-steps nutrient removal process consisting of anaerobic/ anoxic/ oxic/ anoxic/ oxic steps with HRT's of 2/ 1/ 4.5/ 1.5/ 1.5 h was used while the sludge age was constant at 10 days. COD / N and COD / P ratios in the nutrient medium were varied while initial COD was kept constant at 1200 mg COD/L. COD / NH_4-N ratio was varied between 10-50 and COD / PO_4-P was between 40-250. Percent COD, NH_4-N and PO_4-P removal performances were investigated as a function of the independent variables and the optimal ratios were determined. Experiments were carried out three times for each experimental condition tested. The first run was used to adapt the culture to the experimental conditions and the other runs were for collection of data.

In nutrient loading rate studies, initial COD concentrations were varied between 600 and 4800 mg/L while hydraulic retention times (HRT) of each step were kept constant throughout the experimental study. Five step nutrient removal process consisting of anaerobic/ anoxic/ oxic/ anoxic/ oxic steps with HRT's of 2/ 1/ 4.5/ 1.5/ 1.5 h was used at a sludge age of 10 days. Experiments were carried out three times at each loading rate. Since the data were almost the same with less than 5% variations for the last two runs, no further experiments were carried out.

2.3. Wastewater composition

Synthetic wastewater used throughout the studies was composed of glucose, sodium acetate, NH_4Cl, KH_2PO_4, $MgSO_4.7H_2O$, $NaHCO_3$ for alkalinity and certain concentrations of trace salt minerals (NaCl= 100mg/L, KCl = 20 mg/L, $CaCl_2.2H_2O$ =50 mg/L and $FeCl_3.6H_20$ = 50 mg/L). The concentrations of nutrients were adjusted to obtain different COD / N / P ratios. A typical composition of the synthetic wastewater was COD_0=1000 mg/L, N_T=50 mg/L and P_T=15 mg/L, resulting in COD / N / P = 100/5/1.5. $MgSO_4$ and $NaHCO_3$ concentrations in the feed were 0.1 g/L and 0.708 g/L, respectively throughout the experiments with different hydraulic retention times and different number of steps.

For the experiments performed to investigate the effects of sludge age, typical composition of the synthetic wastewater was COD_0=1200 mg/L, N_T=60 mg/L and P_T=18 mg/L, resulting in COD/N/P = 100/5/1.5.

In studies designed to investigate the effects of different carbon sources, the synthetic wastewater was composed of a carbohydrate such as glucose, lactose, sucrose, maltose and an organic acid such as acetic, citric, propionic, butyric acid as carbon source and also NH_4Cl, KH_2PO_4, $MgSO_4.7H_2O$, $NaHCO_3$. Certain concentrations of trace salt minerals such as NaCl (100 mg/L), KCl (20 mg/L), $CaCl_2.2H_2O$ (50 mg/L) and $FeCl_3.6H_20$ (50 mg/L) were also included in the media. Composition of the synthetic wastewater was COD_0=1200 mg/L, N_T=60 mg/L and P_T=18 mg/L, resulting in COD / N / P = 100 / 5 / 1.5. $MgSO_4$ and $NaHCO_3$ concentrations in the feed were 0.1 g/L and 0.5 g/L, respectively. Carbohydrate concentrations were 1292 mg glucose/L, 1313 mg lactose/L, 962 mg sucrose/L, 1004 mg maltose/L and 646 mg glucose/L + 502 mg maltose/L, respectively when they were used as the sole carbon sources. When a mixture (50/50) of glucose and organic acids were used, COD concentrations of each component were equal resulting in total COD of 1200 mg/L.

When the effects of wastewater composition on nutrient removal was investigated, COD / NH_4-N ratio was varied between 10-50 and COD / PO_4-P was between 40-250, while the feed COD was kept constant at 1200 mg/L. $MgSO_4$ and $NaHCO_3$ concentrations in the feed were 0.1 g/L and 0.5 g/L, respectively. In experiments with different nutrient loading rates, synthetic wastewater used was composed of glucose and sodium acetate as carbon sources. Initial COD concentration was varied between 600 and 4800 mg/L, while initial NH_4-N and PO_4-P concentrations were between 20-160 mg/L and 4.1- 33.1 mg/L, respectively. COD / N / P ratio in the feed wastewater was kept constant at 100 / 3.33 / 0.7. $MgSO_4$ concentration in the feed was 0.1 g/L and $NaHCO_3$ was varied between 0.236 g/L and 1.89 g/L to adjust the alkalinity to the theoretical value of 8.65 mg HCO_3/mg NH_4-N.

2.4. Organisms

A mixed microbial population composed of heterotrophic organisms capable of oxidizing carbonaceous compounds and denitrification; autotrophic nitrifying organisms; anaerobic organisms (acid producers) and excess phosphate uptaking organisms (*Acinetobacter sp.*) were used as inoculum culture. Nitrification organisms (*Nitrosomonas and Nitrobacter*) were obtained from Clemson University, SC, USA. The growth media used for cultivation of nitrification organisms contained 382 mg/L NH_4Cl, 1510 mg/L $NaHCO_3$, 93 mg/L glucose, 60 mg/L KH_2PO_4, 20 mg/L $CaCl_2.2H_2O$ and 40 mg/L $MgSO_4.7H_2O$ at pH=7.5. Heterotrophic culture obtained from Çiğli Municipal Wastewater Treatment Plant, Izmir was used as a component of the inoculum culture for carbon and nitrogen removal. The growth media for denitrifying organisms contained 800 mg/L glucose, 50 mg/L KH_2PO_4, 610 mg/L $NaNO_3$, 20 mg/L $MgSO_4.7H_2O$ and 10 mg/L $Na_2S_2O_3$ at pH=7. *Acinetobacter calcoaceticus* (NRRL-552) obtained from the USDA, National Research Laboratories, Peoria, IL, USA was used for luxury phosphate uptake. The growth media for *Acinetobacter calcoaceticus* was composed of 5000 mg/L glucose, 3000 mg/L KH_2PO_4, 1000 mg/L NH_4Cl, 500 mg/L yeast extract, 3000 mg/L NaCl and 50 mg/L $MgSO_4.7H_2O$ at pH=7. Heteterotphic organisms were cultivated in the same synthetic nutrient media used in the experiments. These cultures were mixed in equal volumes before used as inoculum for the reactor.

2.5. Analytical methods

Samples were withdrawn from the liquid media at the beginning and at the end of each treatment period (anaerobic, anoxic, aerobic) and were centrifuged at 6000 rpm (5000 g) for 1/2 h to remove microorganisms from the liquid medium. Clear supernatants were analyzed for COD, ammonium/nitrate nitrogen and phosphate contents. Standard kits (Merck-Spectroquant) and spectrometric methods were used for nitrogen and phosphorous analysis. These measurements were carried out by using Photometer SQ300 Merck. COD, total solids (TS) and total suspended solids (TSS) concentrations were determined by using the Standard Methods (1998). DO measurements were carried out by using a WTW Oxi 330 Analyzer and a DO probe. ORP and pH measurements were done by using the relevant probes and WTW inoLab Analyzer. Biomass concentrations (MLSS) were determined by filtering the samples through 0.45 micron millipore filter and drying in an oven at 105 °C until constant weight.

2.6. Box-Wilson experimental design

Box-Wilson statistical experimental design was used to determine the effects of nutrient media composition on percent nutrient removals in a five-step SBR operation. The independent variables were X_1 = COD / NH_4-N and X_2 = COD / PO_4-P ratios while the dependent variables (Y) were either one of the percent COD, NH_4-N and PO_4-P removal. X_1 and X_2 were varied between 10-50 and 40-250, respectively. Table 2.1. summarizes the experimental conditions according to the Box-Wilson statistical design. The experiments were consisted of four axial (A), four factorial (F) and a centre point (C). The centre point was repeated three times resulting in eleven experiments in total.

The following response function was used to correlate the percent nutrient removals (Y) with the independent variables, X_1 and X_2. A computer program of Statistica 5.0 was used for determination of the response function coefficients by regression analysis using the experimental data.

$$Y = b_o+b_1 X_1+b_2 X_2+ b_{12} X_1 X_2 + b_{11} X_1^2 + b_{22} X_2^2 \qquad (1)$$

Table 2.1. Experimental conditions of the Box-Wilson statistical design

Axial points	X_1	X_2	Factorial points	X_1	X_2
A_1	10	145	F_1	44.2	219.5
A_2	50	145	F_2	44.2	70.5
A_3	30	40	F_3	15.8	219.5
A_4	30	250	F_4	15.8	70.5
			Centre point	30	145

CHAPTER THREE

RESULTS AND DISCUSSION

3.1. Effects of the number of steps on nutrient removal in SBR

Three different SBR operations consisting of three, four and five steps were used and nutrient removal performances were compared.

3.1.1. Percent nutrient removals

Figure 3.1 summarizes percent COD removals at the end of the cycle for each SBR operation. Percent COD removals varied between 94% and 96% depending on the number of steps used. The difference in percent COD removal performances of the three, four and five step operations was negligible. Three-step operation may seem to be more advantageous on the basis of percent COD removals since the operation requires lower operating time of 7 h.

Nutrient media contained only ammonium as the nitrogen source. However, nitrate ions were produced as a result of nitrification of ammonium in the oxic (aerobic) steps. Therefore, the final levels of both ammonium-N and nitrate-N are important in terms of effluent wastewater quality. Figure 3.1 depicts percent NH_4-N removals at the end of total operating period of the three, four and five-step operations. Percent ammonium-N removals varied between 90% and 92% depending on the operation. The three-step operation resulting in nearly 92% percent NH_4-N removal may seem to be a logical choice because of lower operating time of 7 h.

Percent nitrate-N removal also varied depending on the operation time and the number of steps used. This variation is presented in Figure 3.1. The five-step operation clearly resulted in larger percent NO_3-N removal of nearly 64% as compared to the four-step (56%) and three-step (50%) operations. This is probably because of denitrification of nitrate during the second anoxic phase of the five-step operation. Since the three-step and four step operations contain only one anoxic step for denitrification resulting in nitrate in the effluent, the five-step operation was more favorable in terms of percent NO_3-N removal performance.

Variations of percent phosphate-P removal for different operations are depicted in Figure 3.1. The five-step operation resulted in larger percent PO_4-P removal (57%) at the end of the operation, probably because of luxury phosphate uptake during the second oxic phase. Percent phosphate-P removals for the four-step and three-step operations were nearly 50%. The results clearly indicated that the five-step operation was more advantageous in terms of percent phosphate-P removal.

Percent COD and NH_4-N removals were not significantly different for the different operations tested. However, percent NO_3-N and PO_4-P removals obtained by using the five-step operation were clearly larger than those of the other operations. Although the total operating time for the five step operation was larger than the other operations tested, five-step operation was more favorable because of lower nutrient levels in the effluent.

3.1.2. Effluent nutrient concentrations

In order to satisfy the effluent discharge standards, nutrient concentrations at the end of the operation were considered as an important criteria for the selection of the most suitable operation. Effluent nutrient concentrations are presented in Figure 3.2 for different operations.

The influent and effluent nutrient concentrations along with percent nutrient removals are also summarized in Table A1.2 for each operation. Effluent COD for the three, four and the five-step operations were 28 mg/L, 25 mg/L and 37 mg/L, respectively. Apparently, the four-step operation resulted in the lowest effluent COD. However, the effluent COD levels for the three and the five-step operations were also within the limits of the effluent discharge standards. Effluent NH_4-N was minimum (3.2 mg/L) with the three-step operation; although the five-step operation resulted in comparable final NH_4-N concentration (5.6 mg/L). The final nitrate-N (0.9 mg/L) and phosphate-P (3.2 mg/L) concentrations with the five-step operation were significantly lower than the other operations indicating clear advantage of using the five-step operation.

3.1.3.Nutrient concentration profiles for the five-step operation

COD, NH_4-N, NO_3-N and PO_4-P concentration profiles during the 10.5 h operating time of the five-step operation are depicted in Figure 3.3. COD concentration dropped steadily with time reaching a final concentration of 37 mg/L from an initial value of 632 mg/L. Most of the percent COD removal took place within the first six hours. The last two steps were mainly for percent nitrogen and phosphate removal rather than percent COD removal.

Ammonium-N remained almost constant during the first 2.5 h (anaerobic and anoxic phases) and decreased significantly during the first aerobic (oxic) phase as a result of assimilation and nitrification. NH_4-N concentration did not change significantly during the last two steps and ended up as 5.6 mg/L at the end of the operation.

Unlike changes in COD and NH_4-N, nitrate-N concentration showed a rather variable trend at different phases of the operation. Nitrate-N decreased during the first two phases as a result of denitrification of nitrate, but increased during the first oxic phase because of nitrification of ammonium ions. With further denitrification of nitrate during the second anoxic phase, the NO_3-N concentration reached a final level of 0.9 mg/L at the end of the operation.

Phosphate-P slightly increased during the first two phases because of phosphate release during anaerobic and anoxic phases. However, as a result of assimilation and luxury phosphate uptake during the first and second oxic phases, the final PO_4-P concentration was nearly 3.2 mg/L which was considerably lower than the initial level of 7.4 mg/L.

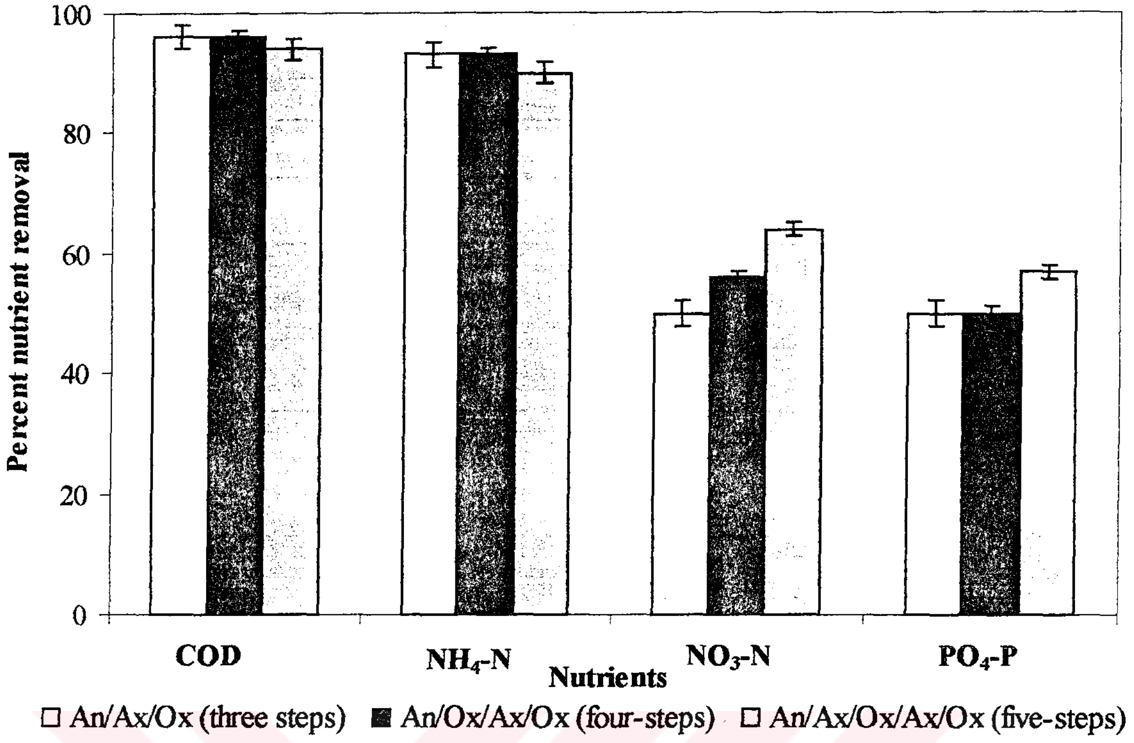


Figure 3.1. Variation of percent nutrient removal with different operations.

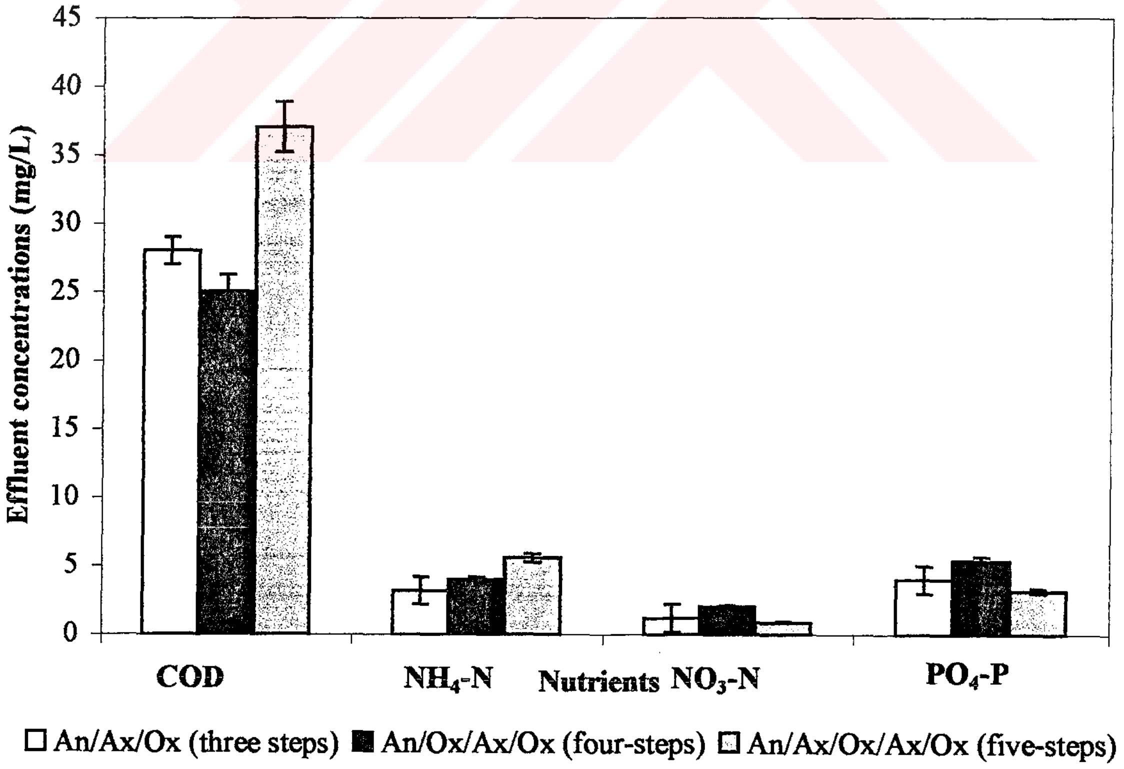


Figure 3.2. Variation of effluent nutrient concentrations with different operations.

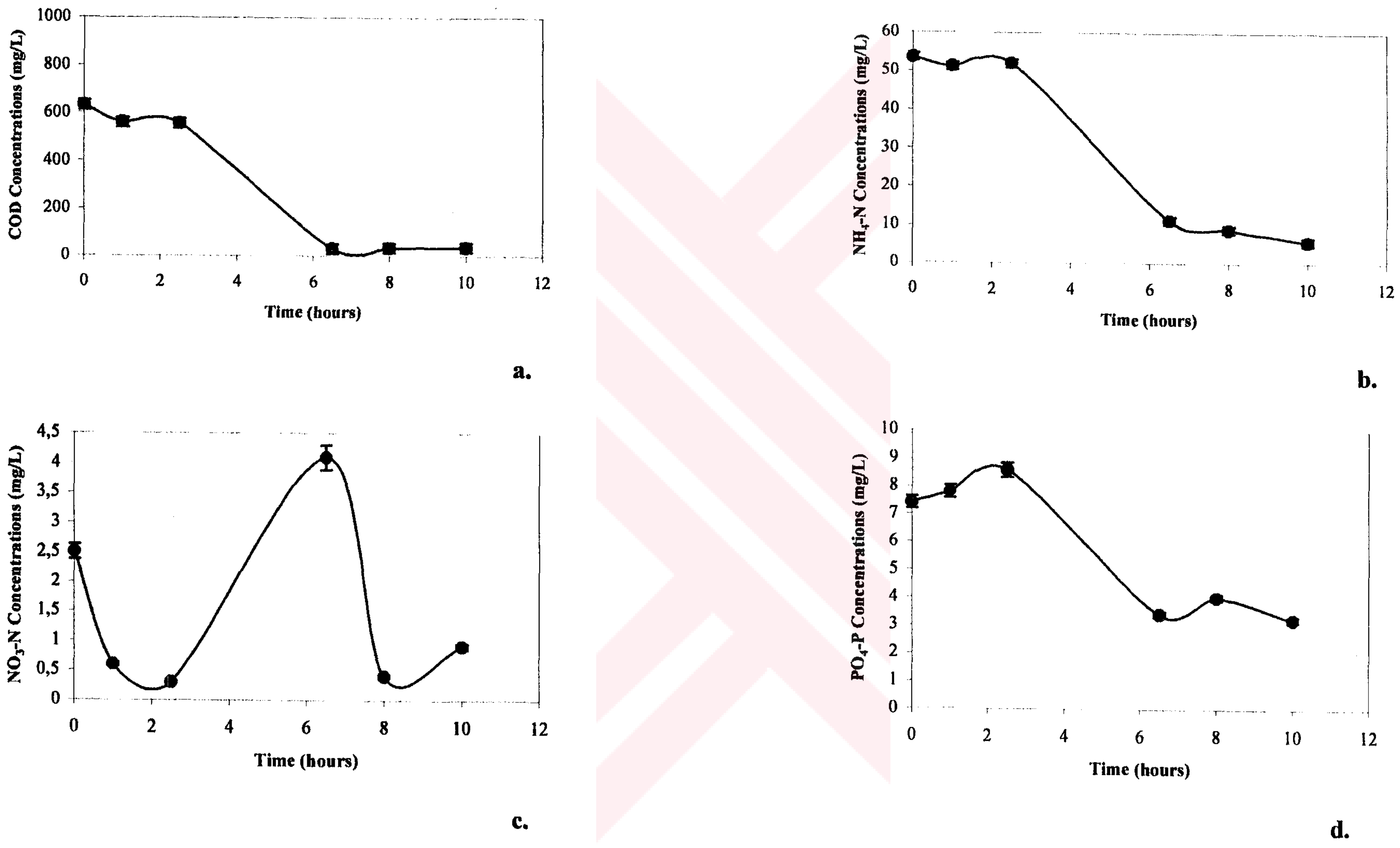


Figure 3.3. Nutrient concentration profiles in the SBR with five-step operation.
a. COD **b.** NH_4-N **c.** NO_3-N **d.** PO_4-P

3.2. Effects of hydraulic retention time on nutrient removal in SBR

Five-step SBR operation was used. The HRT of each step was varied at four different levels while the other HRT's were kept constant. The most suitable HRT resulting in maximum percent nutrient removal was determined for each step.

3.2.1. Anaerobic step

Variations of percent COD, ammonium-N, nitrate-N and phosphate-P removals with HRT (θ_H) in this step are depicted in Figure 3.4. The HRT of the anaerobic step was varied between 1-2.5 h, while the HRT's of the other anoxic I, oxic I, anoxic II, oxic II steps were kept constant at 1.5 h, 4.5 h, 1.5 h and 1.5 h, respectively. Percent COD removal was maximum (nearly 96 %) at HRT values around 1.5-2 h and dropped to nearly 68% at retention time of 2.5 h. Percent ammonium-N removal was maximum (88%) at HRT value of 1.5 h. Percent nitrate–N removal showed a clear maximum of 90% at HRT of 2 h. Percent phosphate-P removal increased with HRT and reached a maximum level of nearly 71% at HRT of 2 h. On the basis of these results, the most suitable HRT for the anaerobic step was selected as 2 h resulting in overall, percent COD, NH_4-N , NO_3-N and PO_4-P removals of 96%, 88%, 90% and 71% , respectively. Biomass concentrations in the reactor varied between 1150 mg/L and 1250 mg/L for different HRT's of the anaerobic step.

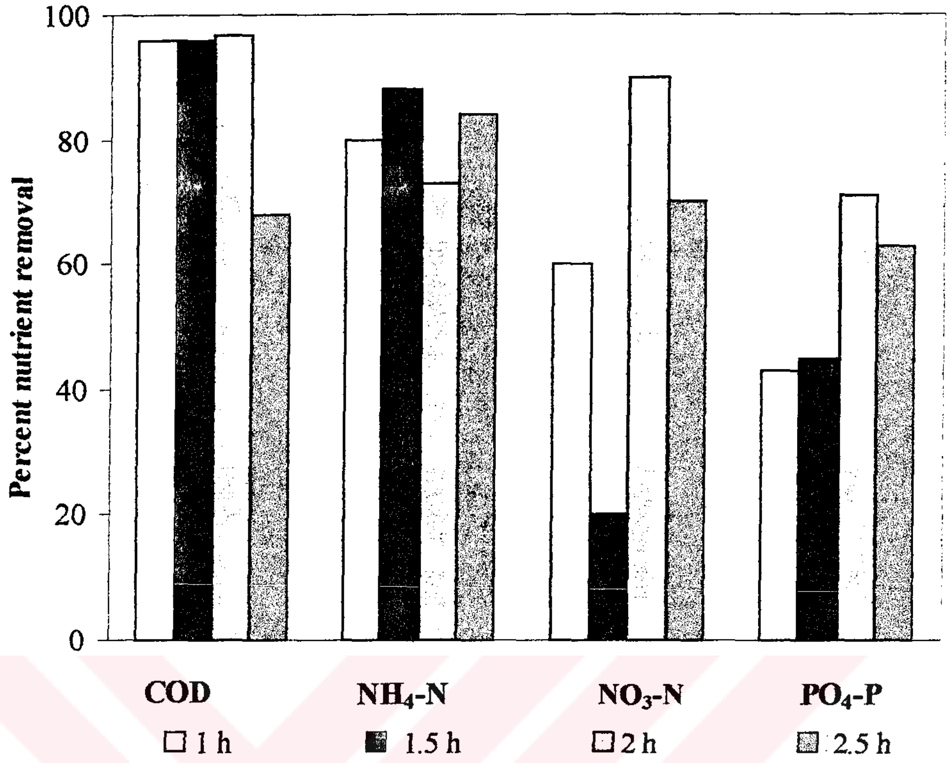


Figure 3.4. Overall percent nutrient removal at different hydraulic retention times of the anaerobic step

3.2.2. First anoxic step

Figure 3.5 depicts variations of percent COD, ammonium-N, nitrate-N and phosphate-P removals with the HRT of the first anoxic step. The HRT of the this step was varied between 1-2.5 h while the HRT's of anaerobic, oxic I , anoxic II and oxic II steps were kept constant at 2 h, 4.5 h, 1.5 h, 1.5 h , respectively. The major functions of the anoxic step are denitrification and COD removal. Overall percent COD removal varied between 96% and 98% for HRT values between 1-2.5 h. Percent ammonium-N removal showed a minimum at HRT value of 1.5 h and became maximum (87%) at HRT of 1h. Percent nitrate-N removal was maximum (90%) at HRT= 1.5 h and showed a minimum at HRT of 2 h. HRT of 1 h also resulted in maximum percent phosphate-P removal (90%). Since almost all percent nutrient removals were maximum at HRT of 1h, this retention time was selected as the most suitable one for the first anoxic step. Overall percent COD, NH_4-N, NO_3-N and PO_4-P removals at HRT of 1 h were 98%, 87%, 90 % and 90%, respectively. Biomass concentrations in the reactor was between 1200 mg/L and 1300 mg/L for different HRT's of the first anoxic step.

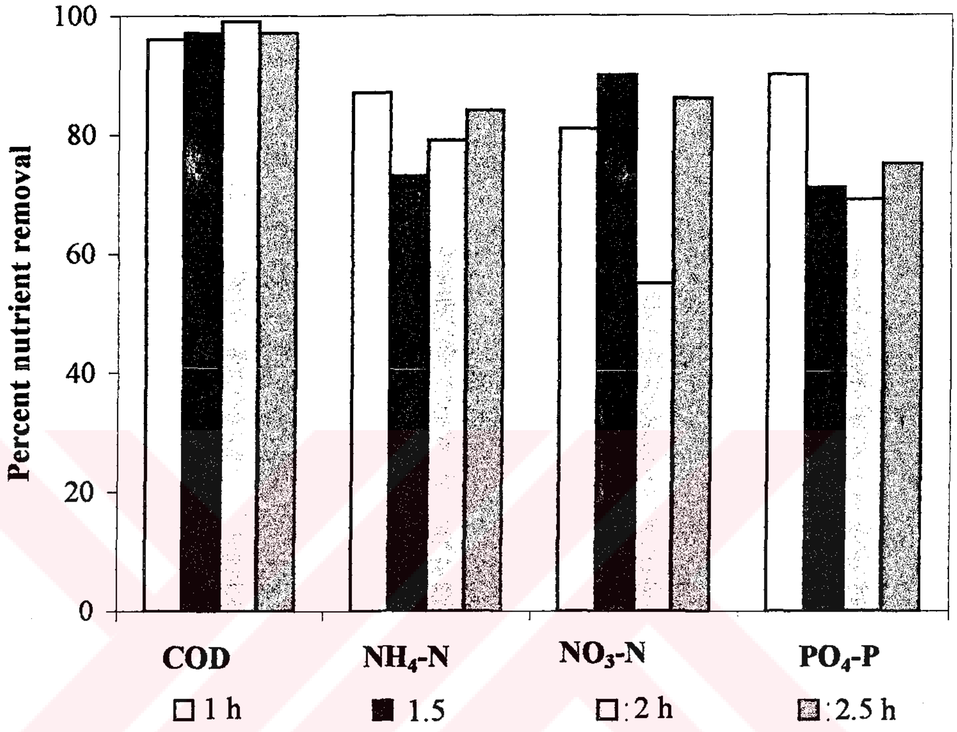


Figure 3.5. Overall percent nutrient removal at different hydraulic retention times of the first anoxic step

3.2.3 First oxic (aerobic) step

Variations of percent COD, ammonium-N, nitrate-N and phosphate-P removals with HRT of this step are depicted in Figure 3.6. The HRT of this step was varied between 2 and 6 h while the HRT's of anaerobic, anoxic I, anoxic II, and oxic II steps were kept constant at 2 h, 1 h, 1.5 h and 1.5 h, respectively. The major functions of the oxic (aerobic) step are COD removal, nitrification and excess phosphate uptake. Percent COD removal showed a slight change with HRT indicating a maximum (98%) at HRT of 4.5-6 h. Percent ammonium-N and percent nitrate-N removals were also maximum (87% and 81%, respectively) at HRT of 4.5 h. HRT of 4.5 h also resulted in maximum percent PO_4-P removal (90%). Therefore, the most suitable hydraulic retention time for this step was selected as 4.5 h resulting in overall percent COD, NH_4-N, NO_3-N and PO_4-P removals of 98%, 87%, 81% and 90 %, respectively. Biomass concentrations in the first oxic step varied between 1350 mg/L and 1450 mg/L for different HRT's tested.

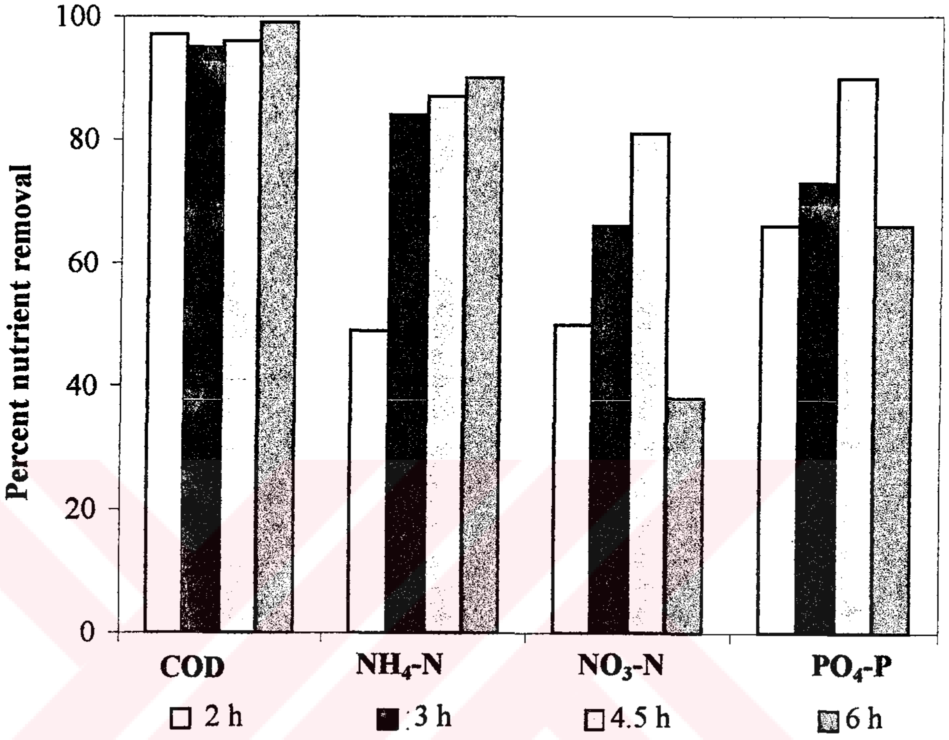


Figure 3.6. Overall percent nutrient removal at different hydraulic retention times of the first oxic step

3.2.4 Second anoxic step

Figure 3.7 presents variations of percent COD, ammonium-N, nitrate-N and phosphate-P removals with the HRT of this step. The major function of the second anoxic step is COD removal and denitrification of nitrate ions produced during the first oxic step as a result of nitrification. The HRT of this step was varied between 1-2.5 h while the HRT's of the anaerobic, anoxic, oxic I, and oxic II steps were kept constant at 2 h, 1 h, 4.5 h, and 1.5 h, respectively. Percent COD removals at all HRT's tested were above 95% and close to each other. Percent ammonium-N removal increased with HRT and showed a maximum (90%) at HRT of 2 h while the efficiency was close to this value (87%) at HRT of 1.5 h. Unlike percent ammonium-N, percent nitrate-N removal decreased steadily with HRT indicating a maximum (81%) at HRT of 1.5 h and a minimum (50%) at HRT of 2.5 h. Percent phosphate removal was maximum (90%) at HRT of 1.5 h. On the basis of these results, 1.5 h retention time was selected as the most suitable one resulting in overall percent COD, NH_4-N, NO_3-N and PO_4-P removals of 97%, 87%, 81% and 90%, respectively. Biomass concentrations in the second anoxic step varied between 1450 mg/L and 1600 mg/L for different HRT's tested.

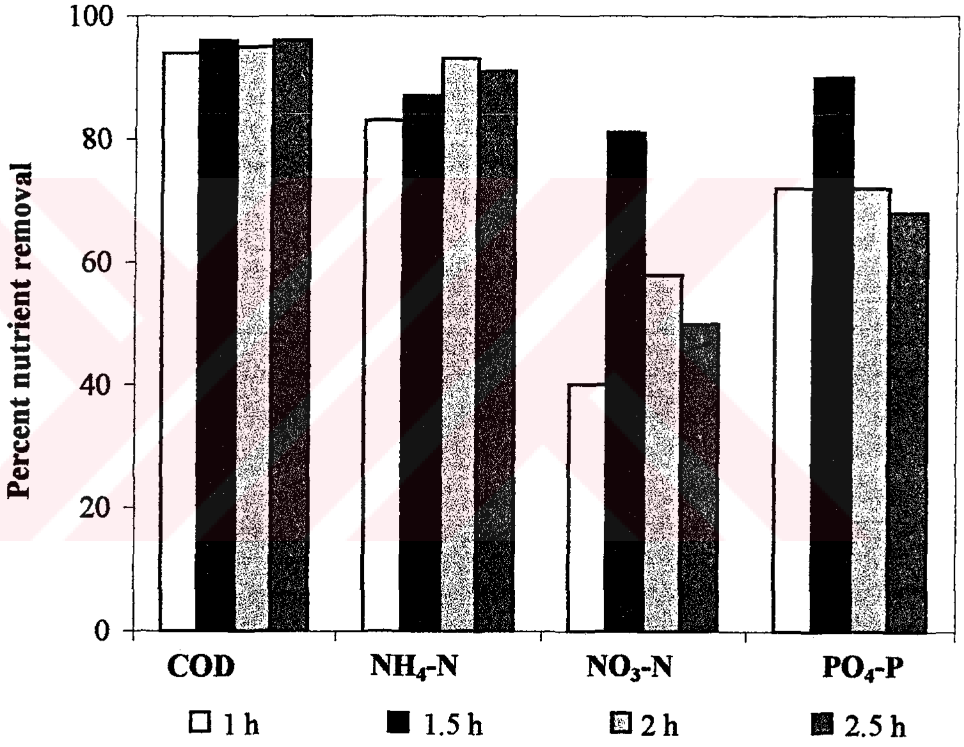


Figure 3.7. Overall percent nutrient removal at different hydraulic retention times of the second anoxic step

3.2.5 Second oxic (aerobic) step

Percent nutrient (COD, NH_4-N, NO_3-N and PO_4-P) removals as a function of HRT of this step are depicted in Figure 3.8. The HRT of this step was varied between 1.5-3 h while the HRT's of the other anaerobic, anoxic I, oxic I, and anoxic II steps were kept constant at 2 h, 1 h, 4.5 h, and 1.5 h, respectively. Percent COD removals were above 95% at all HRT's tested. Percent ammonium–N removal was maximum (87%) at HRT of 1.5 h and 3 h. Percent nitrate-N removal decreased with HRT resulting in a maximum value of 81% at HRT of 1.5 h. Percent phosphate-P removal was also maximum (90%) at HRT of 1.5 h. Therefore, the most suitable hydraulic retention time for this step was found to be 1.5 h, resulting in overall percent COD, NH_4-N, NO_3-N and PO_4-P removals of 97%, 87%, 81% and 90%, respectively. Biomass concentrations varied between 1350 mg/L and 1450 mg/L for different HRT's of this step.

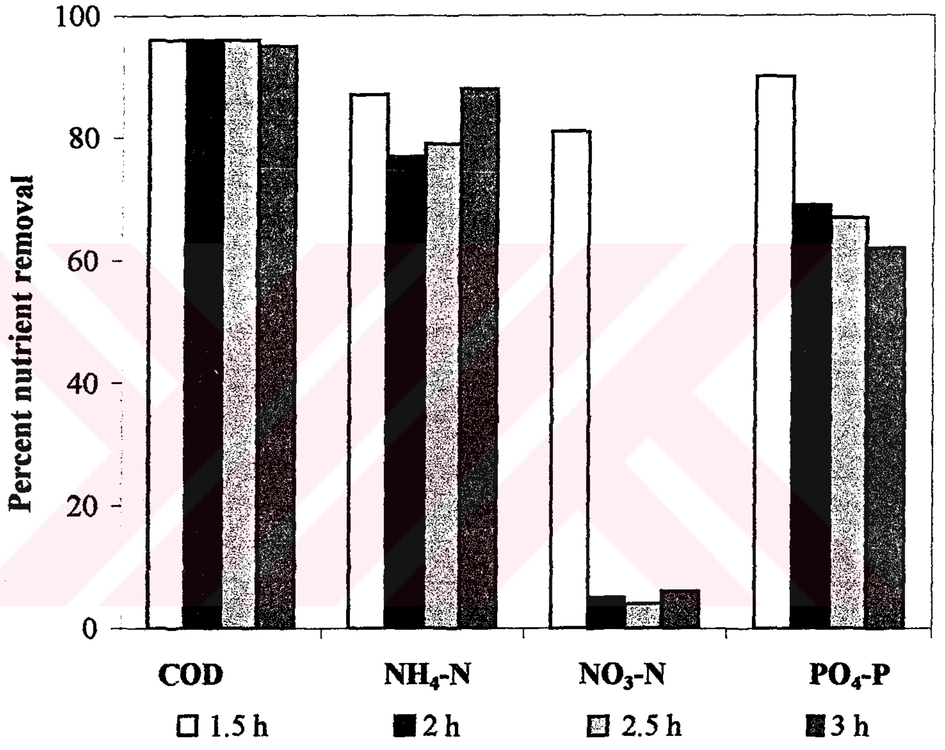


Figure 3.8. Overall percent nutrient removal at different hydraulic retention times of the second oxic step

3.2.6 Nutrient concentration profiles at the most suitable HRT's

Figure 3.9 shows variations of nutrient (COD, NH_4-N, NO_3-N, PO_4-P) concentrations with time when the system was operated at the most suitable HRT values of each step. COD concentration dropped steadily reaching a level of below 40 mg/L within 8 h. NH_4-N concentration decreased rather slowly and reached a level of nearly 6 mg/L from an initial value of 45 mg/L at the end of 10.5 h of operation. NO_3-N concentration dropped significantly within the first three hours of operation as a result of denitrification in anaerobic / anoxic steps and then increased because of nitrification of ammonium ions during the oxic step. Nitrate-N was minimum (1 mg/L) at the end of the second anoxic step and showed a slight increase at the end of the second oxic step (1.4 mg/L). Phosphate-P concentration was nearly constant during the first two anaerobic/ anoxic steps and decreased significantly during the oxic (aerobic) step because of excess phosphate uptake. The final concentration of PO_4-P was nearly 0.4 mg/L at the end of 10.5 h operation. Nutrient concentrations at the end of 5 step SBR operation were 34 mg/L, 6 mg/L, 1.4 mg/L and 0.4 mg/L for COD, NH_4-N, NO_3-N and PO_4-P, respectively when the system was operated at the most suitable HRT of each step.

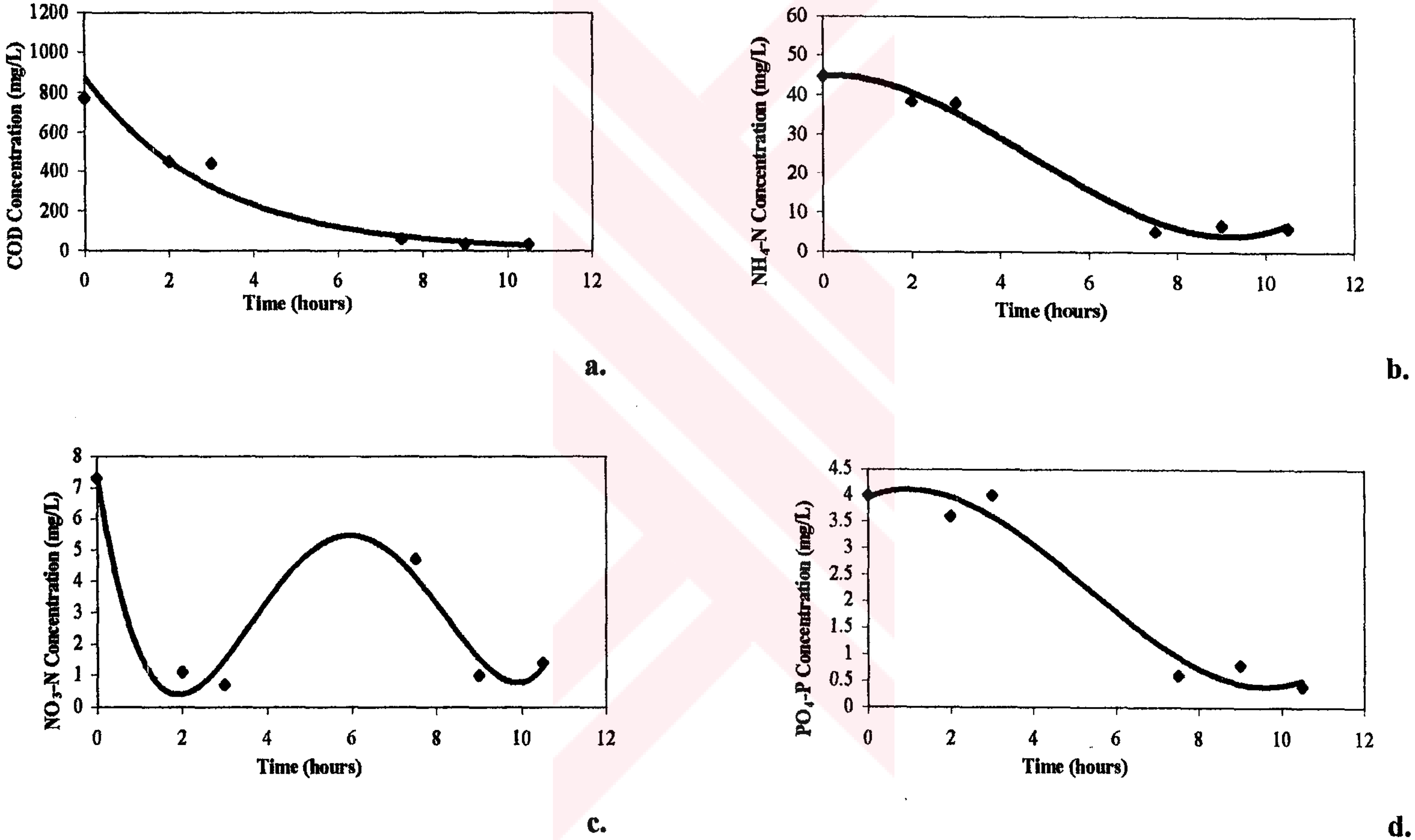


Figure 3.9. Nutrient concentration profiles at optimal HRT' s in SBR operation
a. COD **b.** NH$_4$-N **c.** NO$_3$-N **d.** PO$_4$-P

3.3. Effect of sludge age on nutrient removal in five-step SBR

Sludge ages were varied between 5 and 30 days while hydraulic retention times (HRT) of each step were kept constant at the predetermined values throughout the experimental study.

Variation of percent COD removal with the SRT is depicted in Figure 3.10a. Percent COD removals at every SRT tested were above 90% with some minor differences. The highest percent COD removals were obtained at sludge ages of 10 days, 15 days and 25 days which were 94%, 95% and 96%, respectively. Percent COD removals obtained at SRT's of 5 days, 20 days and 30 days were 93%, 91% and 92%, respectively.

Percent ammonium-N removals were also affected from sludge age variations as shown in Figure 3.10b. Maximum percent NH_4-N removal (84%) was obtained at a sludge age of 10 days, while the efficiency obtained at SRT of 15 days was slightly lower than this value (83%). Percent NH_4-N removals decreased with the sludge age above 15 days of sludge age, resulting in 68% removal at 25 days of sludge age. The optimal sludge age for NH_4-N removal was 10 or 15 days. Old population of the nitrification-denitrification organisms at high sludge age values may be responsible for low NH_4-N removal performance.

Nitrate was not present in the feed wastewater and was produced by nitrification of ammonium during oxic steps. The initial nitrate-N concentrations were lower than 1.5 mg/L in every experiment which were produced as a result of nitrification from the previous experiments. The final NO_3-N concentrations varied between 0.5 and 2 mg/L which were acceptable levels. Therefore, nitrate removal was not considered as an evaluation criterion since the initial levels were so low. The final NO_3-N was nearly 1.3 mg/L at 10 days of sludge age while the maximum was 2 mg/L at 25 days of sludge age. (Figure 3.10c.)

Figure 3.10d. depicts variation of percent phosphate-P removal with the sludge age. The maximum percent PO_4-P removal (70%) was obtained at the sludge age of

10 days while the removal at the sludge age of 15 and 25 days were close to this level (67% and 68%). On the basis of the results, 10 days of SRT seemed to be better than the others tested. When all the results were examined, 10 days of sludge age turned out to be the optimal value resulting in nearly maximum percent removals for COD, NH_4-N and PO_4-P.

In addition to nutrient removal performances at different sludge ages, variation of biomass concentration (MLSS) and sludge volume index (SVI) with the sludge age were also investigated. Variation of biomass concentration with the sludge age is depicted in Figure 3.11. Since the sludge age was gradually increased starting from 5 days, biomass concentration increased with the sludge age as a result of sedimentation and transfer of the biomass to the next step. Biomass concentration of 1730 mg/L at sludge age of 5 days increased to 3760 mg/L at sludge age of 30 days. The increase in the biomass concentration at sludge age values above 20 days was negligible.

Sludge volume index (SVI) is an important parameter affecting the performance of the system. Low SVI values ($SVI< 100$ mL/g) indicate good sedimentation characteristics of the sludge yielding high biomass concentrations in the aeration tank; whereas high SVI values ($SVI>100$ mL/g) results in bulking sludge and low biomass concentrations in the aeration tank. Sedimentation characteristics of the sludge are presented in Figure 3.12, in form of SVI as a function of the sludge age. Sludge volume index (SVI) was low (52 mL/g) at low sludge ages of 5 d and 10 days and increased to 66 mL/g at sludge ages of 25 d and 30 days. Therefore, 10 days of sludge age was also optimal resulting in minimum SVI and the best sedimentation characteristics.

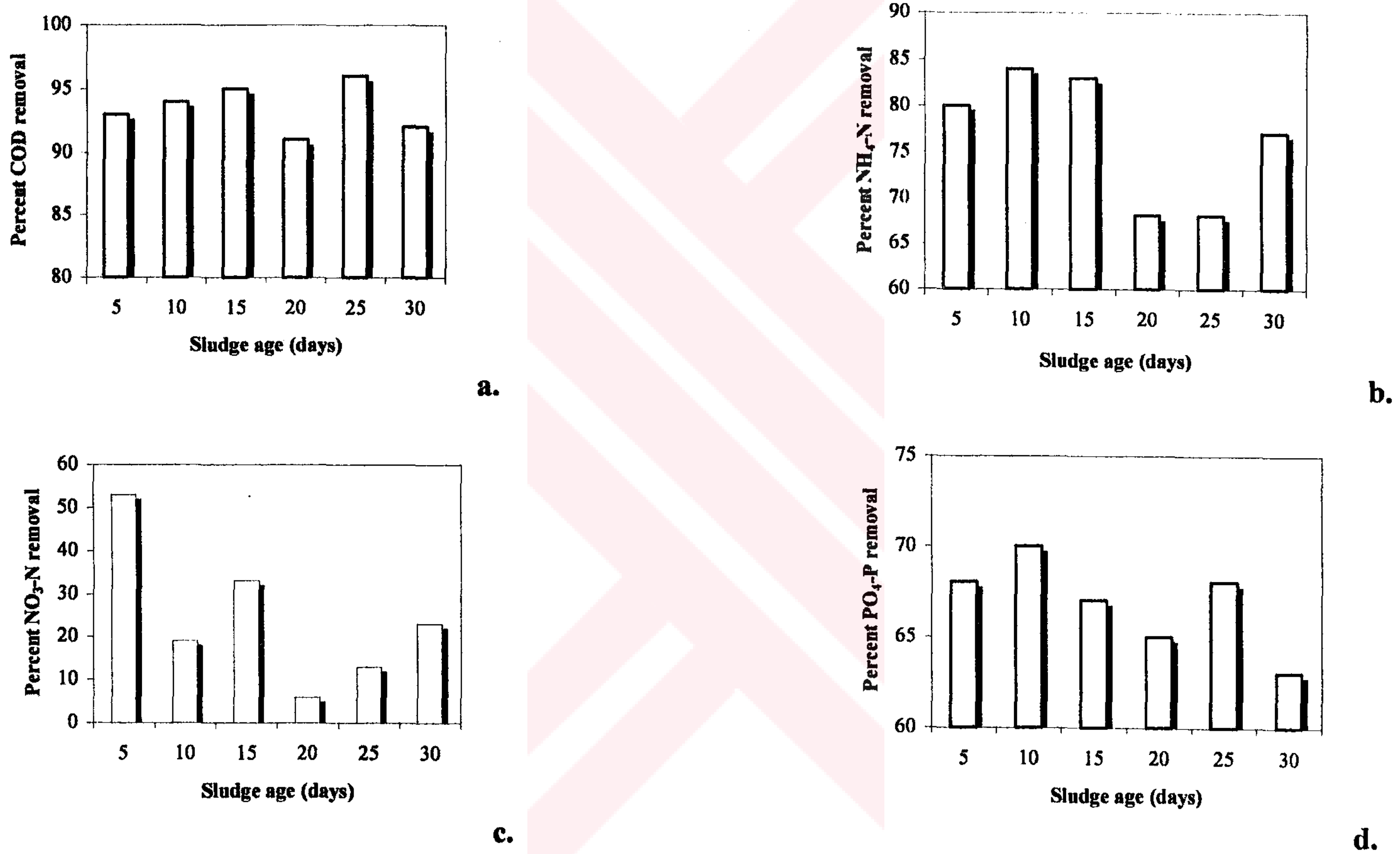


Figure 3.10. Variations of percent nutrient removal with sludge age
a. COD **b.** NH_4-N **c.** NO_3-N **d.** PO_4-P

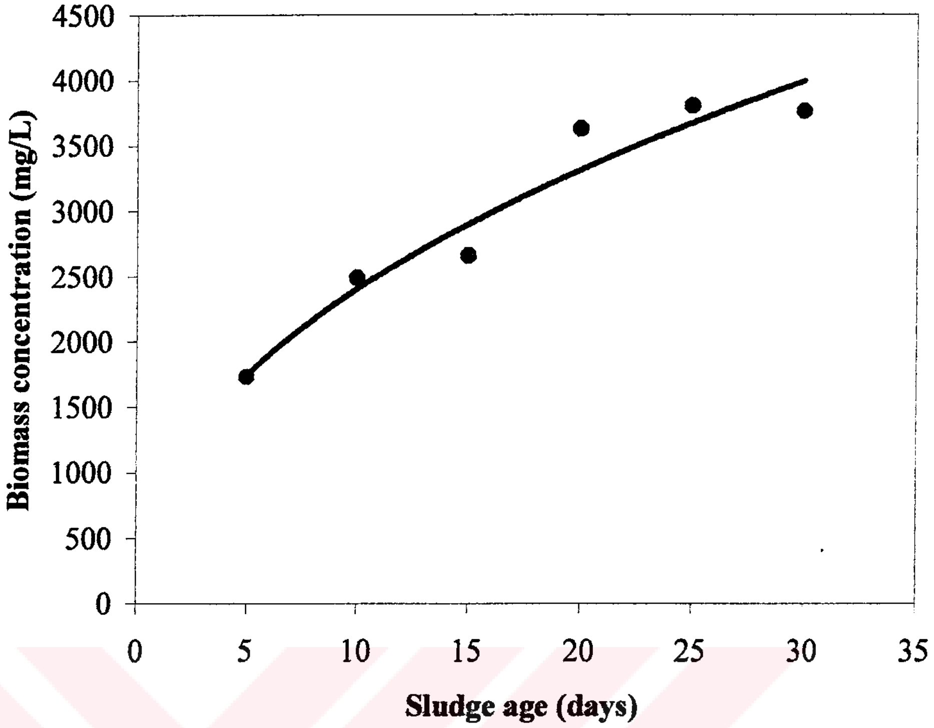


Figure 3.11.. Variation of biomass concentration (MLSS) with the sludge age

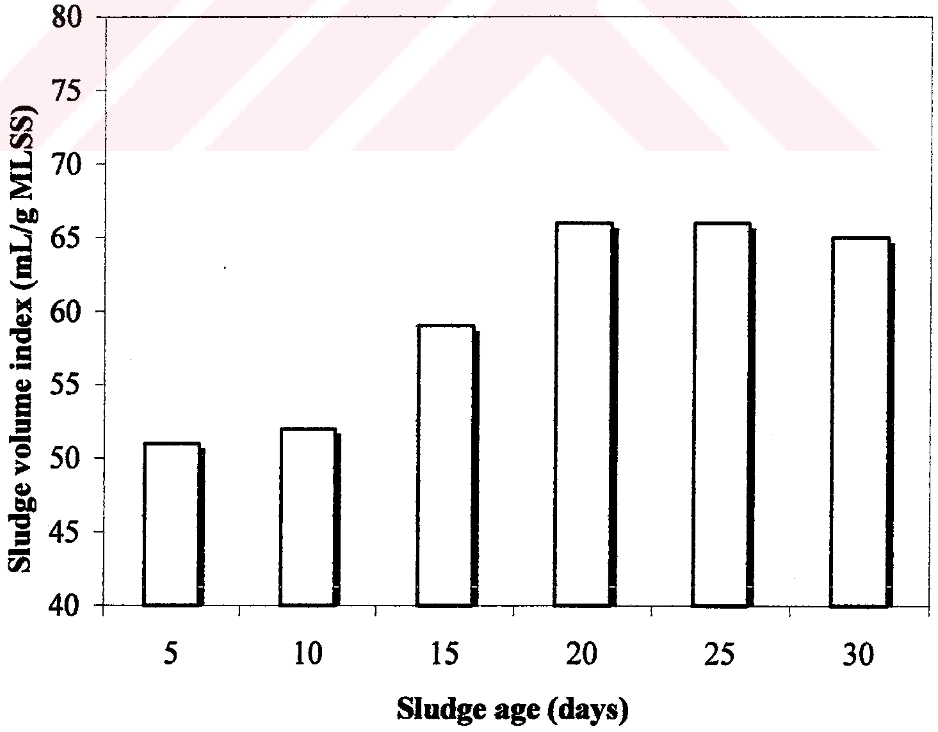


Figure 3.12. Variation of sludge volume index (SVI) with the sludge age

3.3.1. Nutrient concentration profiles at the optimal sludge age

Figure 3.13 shows variations of nutrient (COD, NH_4-N, NO_3-N, PO_4-P) concentrations with time when the system was operated at the optimal sludge age of 10 days. COD concentration dropped steadily reaching a level of below 70 mg/L at the end of 10.5 h of operation. Major fraction of COD was removed within the first three steps. NH_4-N concentration increased slightly during anaerobic step and than decreased in anoxic step. Most of the NH_4-N was removed during the first oxic (aerobic) step by assimilation and nitrification. The last two steps did not contribute significantly to the removal of NH_4-N resulting in nearly 7 mg/L NH_4-N concentration at the end of the operation. Initial nitrate-N concentration of 1.1 mg/L nearly constant for the first two steps (3 h of operation) and increased to 4.3 mg/L the end of the first oxic step because of nitrification. As a result of denitrification in the second anoxic step NO_3-N concentration decreased down to 0.9 mg/L and ended up as 1.3 mg/L at the end of the operation. Initial phosphate-P concentration of 12.2 mg/L increased up to 13.6 mg/L at the end of the first anoxic step because of phosphate release by the luxury phosphate uptaking organisms. As a result of phosphate uptake in the first oxic step PO_4-P concentration dropped significantly down to 3.6 mg/L. The last two steps did not change PO_4-P concentration and the final PO_4-P concentration was 3.6 mg/L at the end of the operation. Dissolved oxygen (DO) concentration was also monitored and controlled at the desired levels during the operation. DO concentrations were less than 0.1 mg/L during the first two steps and increased to 4.65 mg/L by vigorous aeration during the oxic step. DO values were 0.2 mg/L and 3.1 mg/L during the second anoxic and oxic steps.

Therefore, by a five step SBR operation (10.5 h) nearly 94% of COD, 84% of NH_4-N and 70% of PO_4-P were removed at the optimal sludge age of 10 days, resulting in final COD of 70 mg/L, NH_4-N of 7 mg/L, NO_3-N of 1.3 mg/L and PO_4-P of 3.6 mg/L (Figure 3.14).

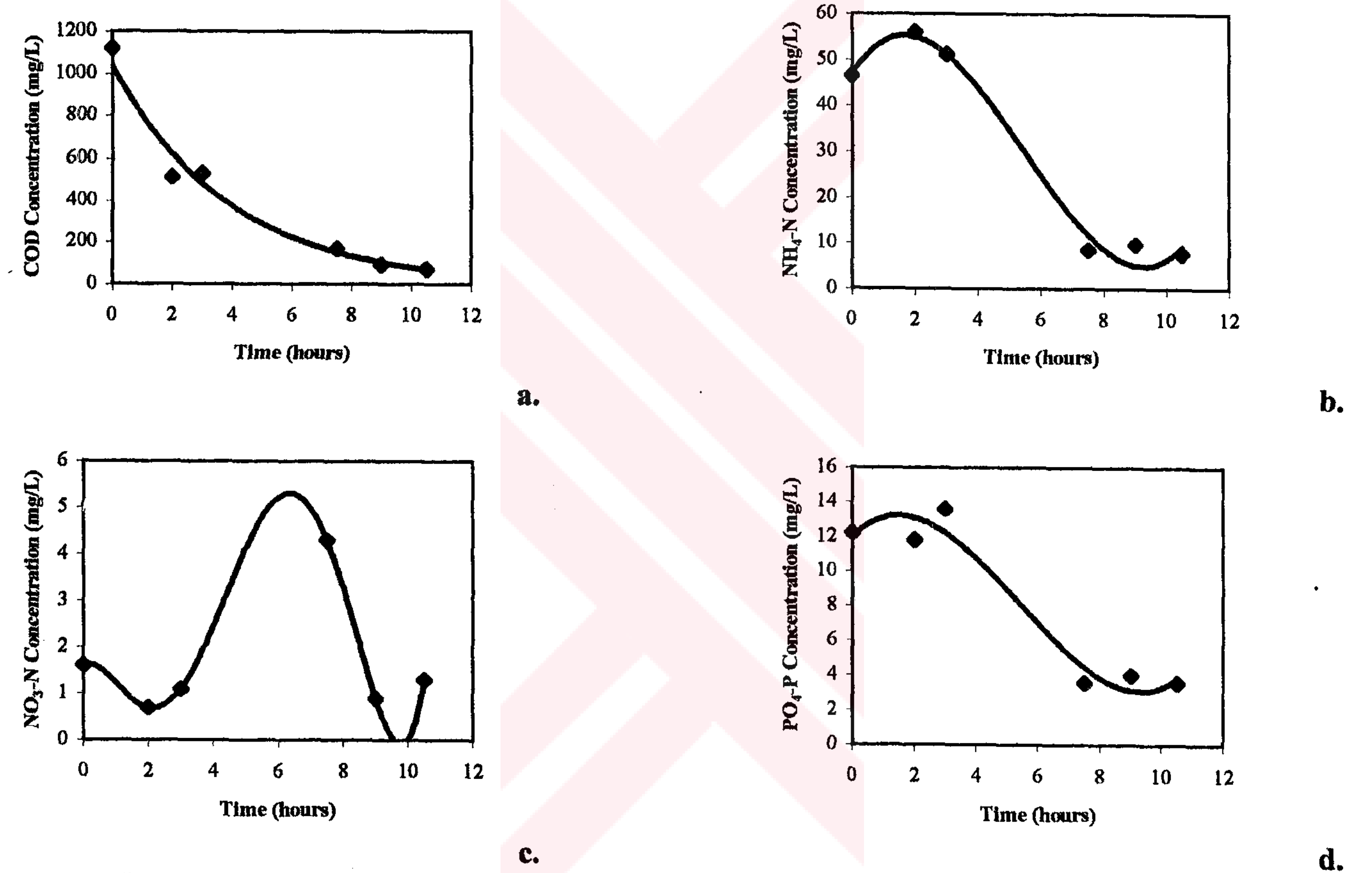


Figure 3.13. Nutrient concentration profiles for sludge age 10 days in an SBR operation
a. COD **b.** NH_4-N **c.** NO_3-N **d.** PO_4-P

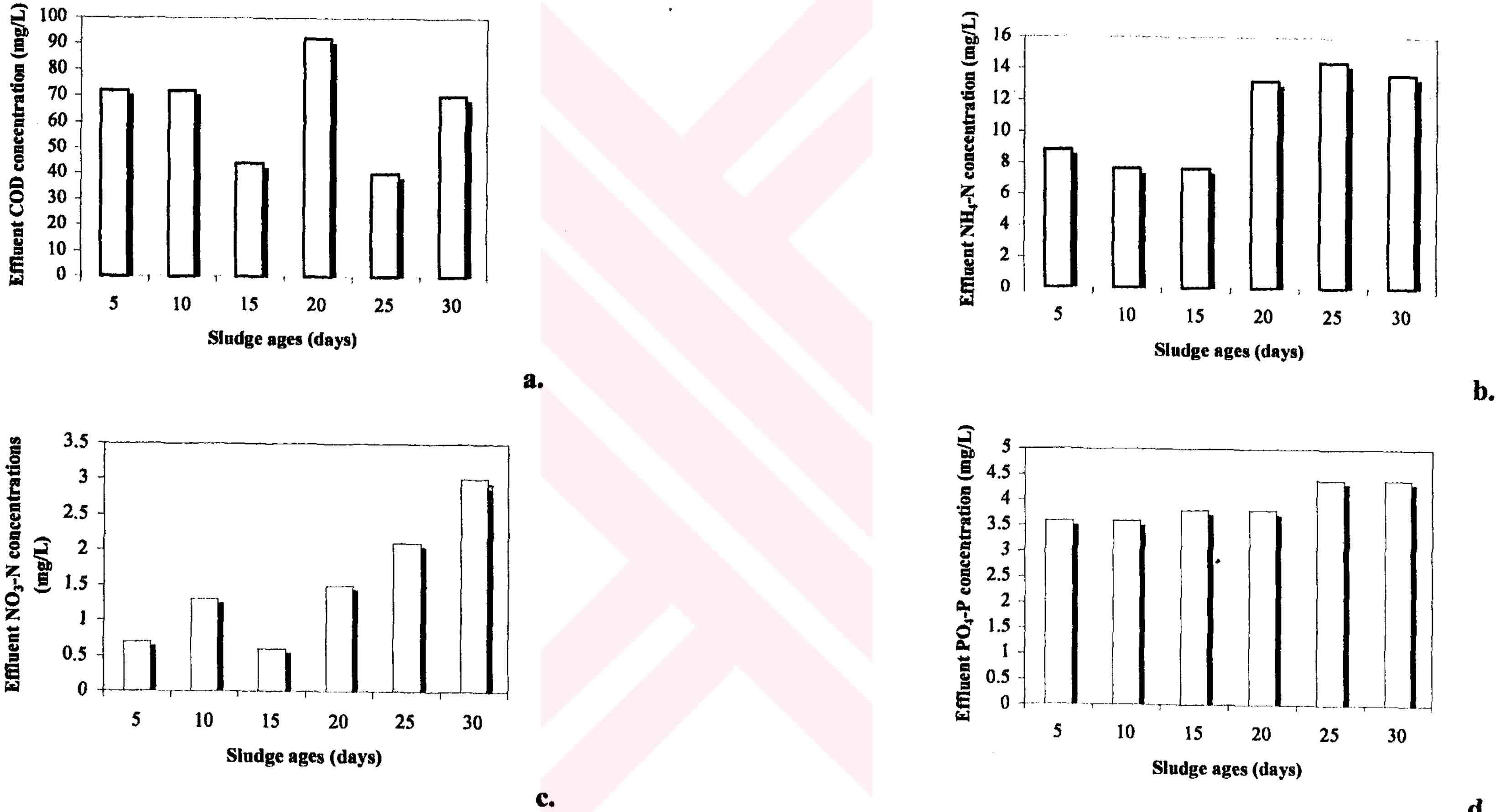


Figure 3.14. Variations of nutrient effluent concentrations with sludge age
a. COD **b.** NH_4-N **c.** NO_3-N **d.** PO_4-P

3.4. Effects of different carbon sources on nutrient removal performance in a three-step SBR operation.

3.4.1. Selection of the most suitable carbohydrate

Variations of percent nutrient removals with different carbohydrate sources are depicted in Figure 3.15. Percent COD removals were 96 %, 95%, 95%, 97% and 92%, respectively when glucose, lactose, sucrose, maltose, glucose/maltose mixture (50/50) were used as the sole carbon source. The differences in percent COD removals with different carbohydrates were negligible. However, glucose and sucrose performed slightly better than the other carbohydrates when used as the sole carbon source.

Percent ammonium-N removals of 99%, 78%, 99%, 99% and 77% were obtained when glucose, lactose, sucrose, maltose and glucose / maltose mixture (50/50) were used as the sole carbon source, respectively. The highest percent NH_4-N removals were obtained when glucose, sucrose or maltose were used as the sole carbohydrate.

Percent phosphate removal was the determining factor in selecting the best carbohydrate source as shown in Figure 3.15. Percent phosphate-P removals of 94%, 92%, 94%, 57% and 76% were obtained when glucose, lactose, sucrose, maltose and glucose / maltose (50/50) were used as the sole carbohydrate source, respectively. Apparently, glucose and sucrose performed better than the other carbohydrates for percent PO_4-P removal (94%). Percent phosphate-P removal with lactose (92%) was close to those obtained with glucose and sucrose.

In terms of overall evaluation, maltose, lactose and glucose / maltose mixture resulted in unsatisfactory nutrient removals. However, glucose and sucrose resulted in better percent nutrient removal performances as compared to the others tested. Therefore, either glucose or sucrose can be used as the sole carbon source for effective nutrient removal in an SBR. For the sake of simplicity, glucose was selected as the most suitable carbon source and used in combination with the organic acids in further experiments.

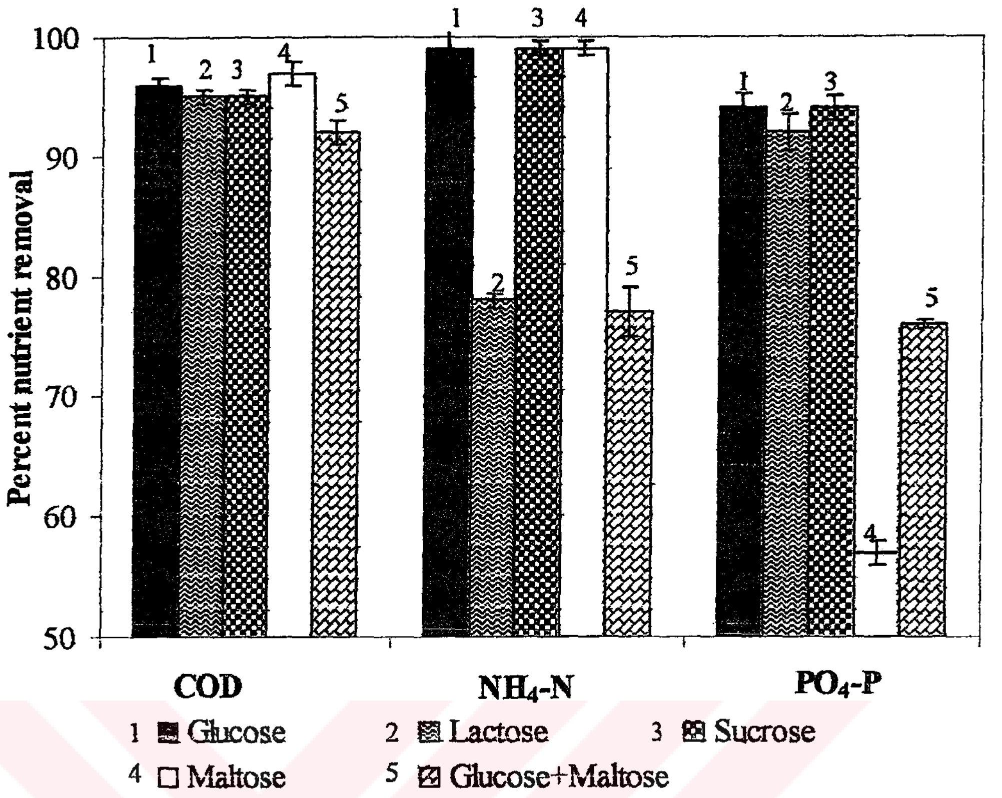


Figure 3.15. Variation of percent nutrient removals with different carbohydrates

3.4.2. Selection of the most suitable organic acid

Carbohydrates are usually used in combination with organic acids for effective nutrient removal. In order to determine the percent nutrient removal performance of combinations of different organic acids with the selected carbohydrate source, glucose was used in combination (50/50) with acetic, citric, propionic and butyric acids in the SBR operation. Percent nutrient (COD, NH_4-N, PO_4-P) removals for different glucose-organic acid combinations are depicted in Figure 3.16. Percent COD removals were 93%, 97%, 90% and 98%, respectively when glucose- acetic acid, glucose-citric acid, glucose-propionic acid and glucose-butyric acid mixtures (50/50) were used as carbon source. Apparently, glucose/citric acid and glucose/butyric acid mixtures resulted in better percent COD removals as compared to the other combinations. However, percent COD removal with glucose/acetic acid mixture was also comparable to the others tested.

Percent ammonium-N removals of 97%, 96%, 85% and 99.5% were obtained when a mixture (50/50) of glucose and acetic, citric, propionic and butyric acids were used, respectively as shown in Figure 3.16. Glucose-acetic acid and glucose-butyric acid mixtures resulted in better percent NH_4-N removal performances as compared to the others tested.

Percent phosphate removal was again the determining factor in selecting the best combination of glucose with the organic acids. Percent phosphate removals of 96%, 96%, 91% and 65% were obtained when a mixture (50/50) of glucose and acetic, citric, propionic and butyric acids were used, respectively. Apparently, combination of glucose with acetic or citric acid resulted in better percent PO_4-P removals as compared to the other combinations.

When all the results are evaluated, glucose-acetic acid or glucose-citric acid combinations resulted in better percent nutrient removals as compared to the other combinations. Since acetic acid is readily produced by anaerobic organisms in wastewater treatment systems as compared to citric acid, glucose-acetic acid mixture was selected as the most suitable combination for effective nutrient removal.

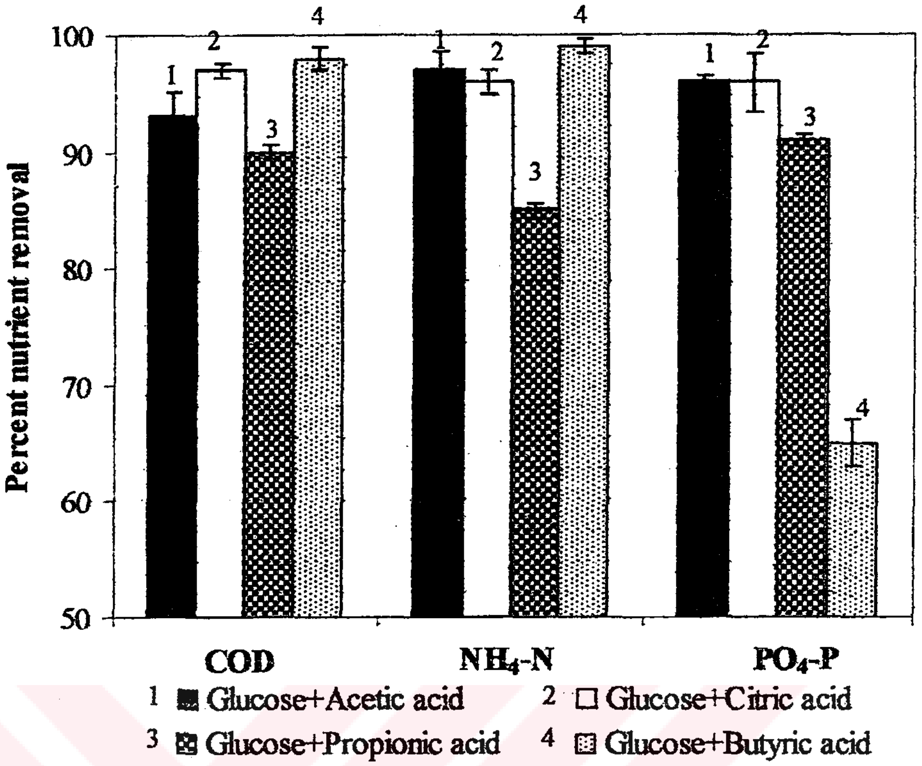


Figure 3.16. Variation of percent nutrient removals with different glucose and organic acid mixtures

3.4.3. Effect of glucose / acetic acid ratio on nutrient removal

In order to determine the most suitable ratio of glucose/acetic acid resulting in the highest percent nutrient removal, experiments were conducted with different glucose / acetic acid ratio. Figure 3.17 depicts variation of percent nutrient removals (COD, NH_4-N, PO_4-P) at different glucose / acetic acid ratios. Percent COD removals were 94%, 95%, 93% and 94%, respectively when the glucose / acetic acid ratios were 0/100, 25 /75, 50/50 and 75/25 percent. Since, the differences in percent COD removals were negligible for different glucose/acetic acid mixtures, Percent COD removal was not considered as the determining factor in selecting the most suitable glucose/acetic acid ratio.

Percent NH_4-N removals of 59%, 94%, 97% and 90% were obtained when glucose/acetic acid ratios were 0/100, 25/75, 50/50 and 75/25 percent, respectively. The highest percent NH_4-N removal (97%) was obtained with a 50/50 percent mixture of glucose-acetic acid. However, NH_4-N removal with the glucose/acetic acid ratio of 25/75 percent was close to this value. Percent ammonium-N removal was very low (59%) when acetic acid was used as the sole carbon source.

Percent phosphate-P removal also varied quite significantly with glucose/acetic acid ratio as shown in Figure 3.17. Percent phosphate-P removals of 54%, 74%, 96% and 47% were obtained when glucose/acetic acid ratios were 0/100, 25/ 75, 50/50 and 75/25 percent, respectively. The highest percent PO_4-P removal (96%) was obtained with a glucose-acetic acid mixture of 50 / 50 percent. Other ratios resulted in unsatisfactory percent removals of PO_4-P.

On the basis of these results, it is obvious that neither glucose nor acetic acid should be used as the sole carbon source for nutrient removal. A mixture of acetic acid and glucose resulted in better percent nutrient removal performance as compared to the other glucose-organic acid combinations. Since percent COD removals were always above 90%, percent ammonium-N and especially percent phosphate-P removals were the determining factors in selecting the best combination of glucose and acetic acid. On the basis of percent ammonium and phosphate removals, glucose/acetic acid ratio of 50/50 percent resulted in the highest percent nutrient removals for COD, NH_4-N and PO_4-P of 93%, 97% and 96%, respectively.

Glucose represents a typical carbohydrate which is used for energy production in bacterial metabolism. Acetic acid is preferentially used for poly-hydroxybutyrate (PHB) synthesis by the excess phosphate uptaking organisms such as the *Acinetobacter sp.* Therefore, presence of both a carbohydrate source (preferably glucose) and an organic acid (preferably acetic acid) are required for effective nutrient, especially phosphate removal.

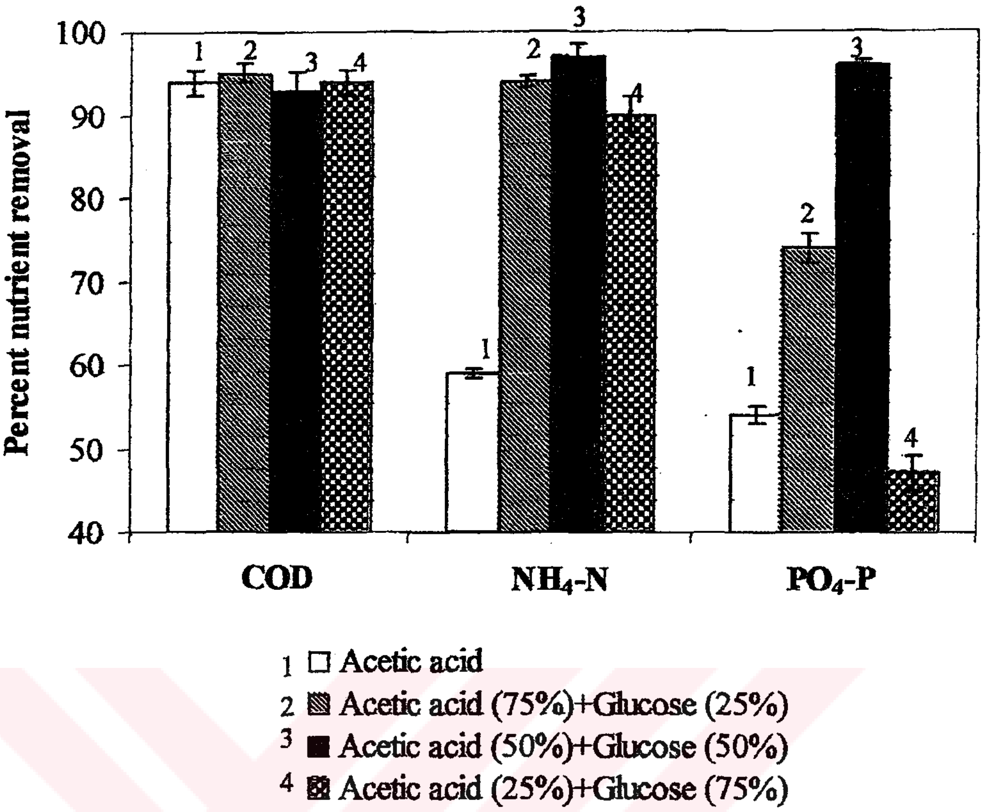


Figure 3.17. Variation of percent nutrient removals with different glucose/acetic acid ratios.

3.4.4. Nutrient concentration profiles

Samples withdrawn at the beginning and at the end of each step (anaerobic/ anoxic/oxic) were analyzed for COD, NH_4-N and PO_4-P concentrations. Typical nutrient concentration profiles are depicted in Figure 3.18, when a mixture of glucose and acetic acid (50/50) was used as carbon source. Percent COD removal mainly took place during the oxic step resulting in nearly 93% COD removal at the end of 7.5 h of SBR operation (S_o = 755 mg/L, S_e = 52 mg/L). Percent ammonium-N removal was rather slow within the first 2 h and became faster afterwards resulting in 1.6 mg NH_4-N/L at the end of the operation (S_o= 50.6 mg/L). Again most of the percent NH_4-N removal took place during the oxic phase by assimilation into cell biomass and nitrification. Phosphate-P concentration was 13.4 mg/L at the beginning and remained almost constant during the first two anaerobic and anoxic phases. However, because of excess phosphate uptake during the oxic step, phosphate-P concentration dropped down to 0.6 mg/L at the end of the SBR operation. The final COD, NH_4-N and PO_4-P concentrations of 52 mg/L, 1.6 mg/L and 0.6 mg/L were acceptable levels obtained with a glucose-acetic acid mixture of 50/50 percent.

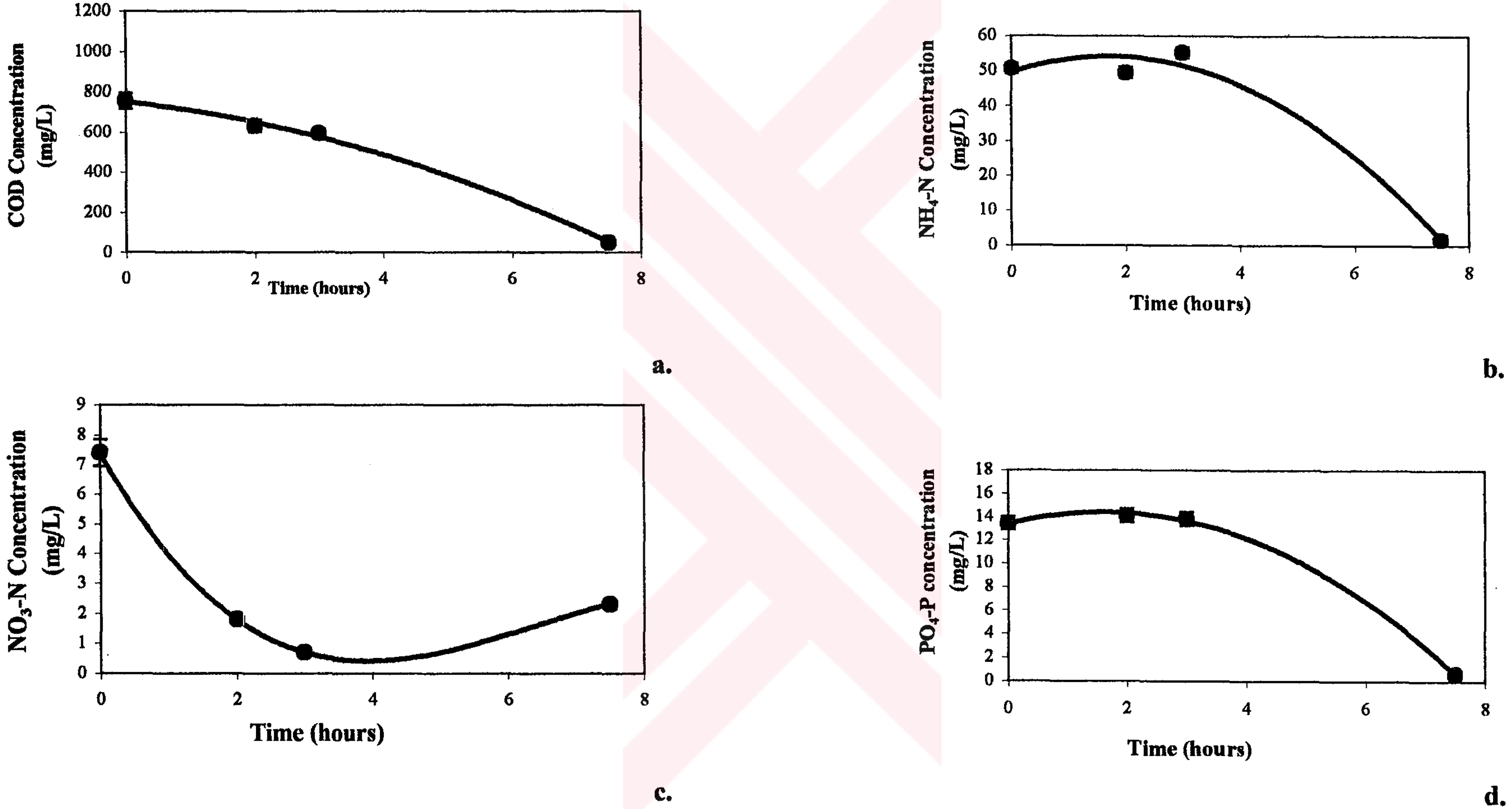


Figure 3.18. Nutrient concentration profiles in an SBR operation when glucose and acetic acid mixture (50/50) was used as carbon source
a. COD **b.** NH_4-N **c.** NO_3-N **d.** PO_4-P

3.5. Effects of synthetic wastewater composition (COD / N / P ratio) on nutrient removal in five-step SBR

A Box-Wilson statistical experiment design was used in order to investigate the effects nutrient composition on nutrient removal. COD/NH_4-N (X_1) and COD/PO_4-P (X_2) ratios were considered as independent variables while the initial COD was 1200 mg/L in the feed wastewater.

3.5.1. Percent COD removal

The results of the Box-Wilson statistical design experiments are presented in Table 3.1 along with the removals for percent COD, NH_4-N and PO_4-P predicted from the response functions. Table 3.2 summarizes the coefficients of response functions for each dependent variable which were determined by the regression analysis. The constants presented in Table 3.2 were used to predict the percent nutrient removals presented in Table 3.1. Percent nutrient removals predicted from the response functions were in good agreement with the experimental results indicating good fit of the regression analysis. Central point (X_1= 30, X_2 = 145) resulted in the best removals for percent COD, NH_4-N and PO_4-P.

Table 3.1. Experimental and predicted percent nutrient removals (E).

Experiment	E_{COD} (exp)	E_{COD} (pred)	E_{NH4-N} (exp)	E_{NH4-N} (pred)	E_{PO4-P} (exp)	E_{PO4-P} (pred)
A_1	97	97	70	74	91	94
A_2	96	96	99	96	90	94
A_3	94	94	96	93	55	61
A_4	95	95	99	99	80	80
F_1	95	95	98	98	92	91
F_2	95	95	95	99	79	74
F_3	97	97	95	90	88	87
F_4	96	96	77	76	82	77
C (ave)	97	97	99	99	94	94

exp: experimental, **pred:** predicted

Table 3.2. Coefficients of the response functions for different nutrients

	b_o	b_1	b_2	b_{12}	b_{11}	b_{22}	R^2
Y_{COD}	0.912	5.08×10^{-4}	7.35×10^{-4}	-2.37×10^{-6}	-9.24×10^{-6}	-2.15×10^{-6}	0.96
$Y_{NH4\text{-}N}$	0.251	3.26×10^{-2}	1.93×10^{-3}	-3.55×10^{-5}	-3.67×10^{-4}	-1.53×10^{-6}	0.92
$Y_{PO4\text{-}P}$	0.440	-2.48×10^{-3}	6.46×10^{-3}	2.00×10^{-5}	1.00×10^{-6}	-2.00×10^{-5}	0.91

Response functions with the calculated coefficients were used to predict the SBR's performance for nutrient removal from the synthetic wastewater. Figure 3.19 shows variations of percent COD removal (E_{COD}) with COD / PO_4-P ratio (X_2) at different values of COD / NH_4-N ratio (X_1). Percent COD removal increased with COD / P ratio (X_2) for X_2 values between 40 and 160 indicating COD limitations at low COD concentrations and then dropped for X_2 values above 160 indicating phosphate limitations at high COD, low phosphate levels. The maximum value for E_{COD} was around COD / P = 160. Increasing COD / NH_4-N ratios (X_1) from 10 to 50 resulted in decreases in percent COD removals steadily possibly because of ammonium limitations at high X_1 values. Maximum E_{COD} was obtained at COD / NH_4-N (X_1) of 10 and COD / PO_4-P (X_2) ratio of around 160.

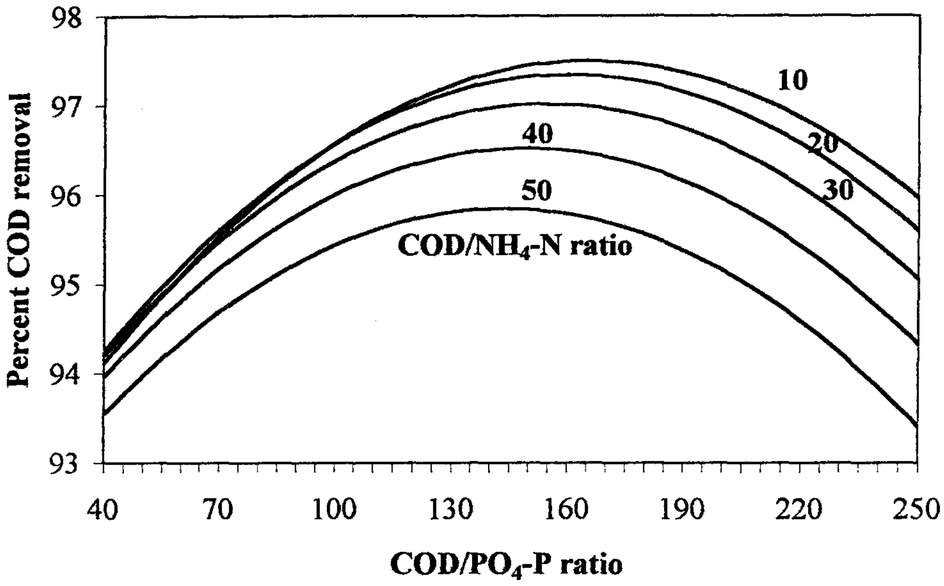


Figure 3.19. Variation of percent COD removal with COD / PO_4-P ratio (X_2) at different COD / NH_4-N (X_1) values

3.5.2. Percent NH_4-N removal

Variations of percent ammonium-nitrogen removal (E_{NH4-N}) with COD/ NH_4-N ratio (X_1) at different values of COD / PO_4-P ratio (X_2) are presented in Figure 3.20. Percent removal for ammonium-nitrogen increased with COD / NH_4-N ratio (X_1) between 10 and 40. Because of low COD values at low X_1 values, percent ammonium removals were low. E_{NH4-N} dropped for X_1 values above 40, possibly because of ammonium limitations. Increasing COD / PO_4-P ratios (X_2) resulted in steady increases in percent NH_4-N removals for X_2 values between 40 and 250 indicating adverse effects of high phosphate levels or COD limitations at low X_2 values. The maximum E_{NH4-N} value was obtained at COD / PO_4-P ratio (X_2) of 250 and COD / NH_4-N ratio (X_1) of nearly 40.

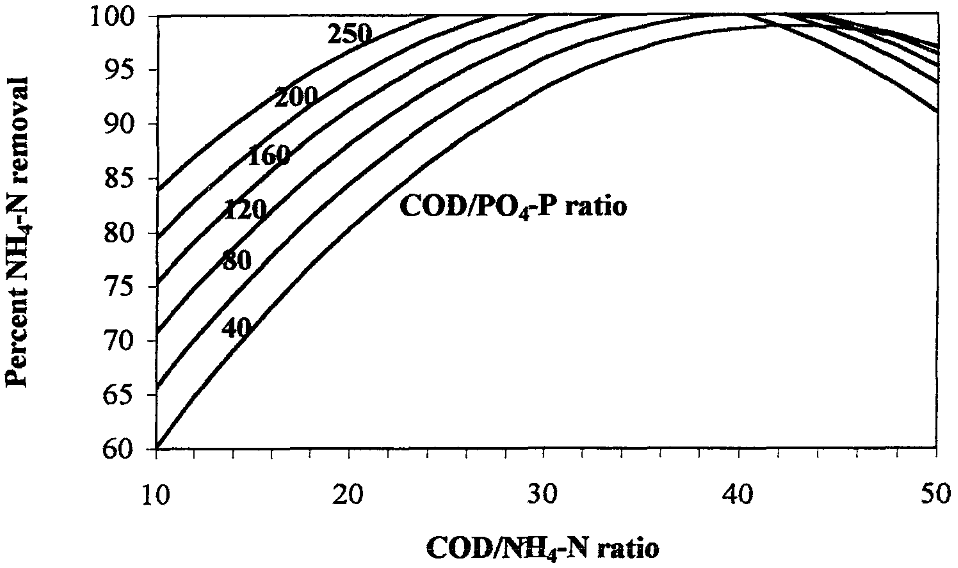


Figure 3.20. Variation of percent NH_4-N removal with COD / NH_4-N ratio (X_1) at different COD / PO_4-P (X_2) values

3.5.3. Percent PO_4-P removal

Percent phosphate removal (E_{PO4-P}) as a function of COD / PO_4-P (X_2) and COD / NH_4-N (X_1) ratios is presented in Figure 3.21. Increasing COD / PO_4-P (X_2) values from 40 and 160 resulted in increases in percent phosphate removal. Because of excess phosphate or COD limitations at low X_2 values the percent phosphate removal was low. The percent removal dropped for X_2 values above 200 because of phosphate limitations at high X_2 values. The maximum percent removal was obtained for X_2 values between 160 and 200. Increasing COD / NH_4-N (X_1) ratio from 10 to 50 resulted in increases in percent phosphate removal with the maximum percent removal at X_1= 50. Because of COD limitations at low X_1 values, percent phosphate removal was low.

In order to test the accuracy of the predictions by the response functions, three experiments different from the Box-Wilson design experiments were performed and the experimental results were compared with the predictions in Table 3.3. The first two experiments were within the range of independent variables (X_1 and X_2); but the third one was outside the range. Response function predictions were in good agreement with the experimental data indicating accuracy of the predictions by the response function even beyond the experimental points.

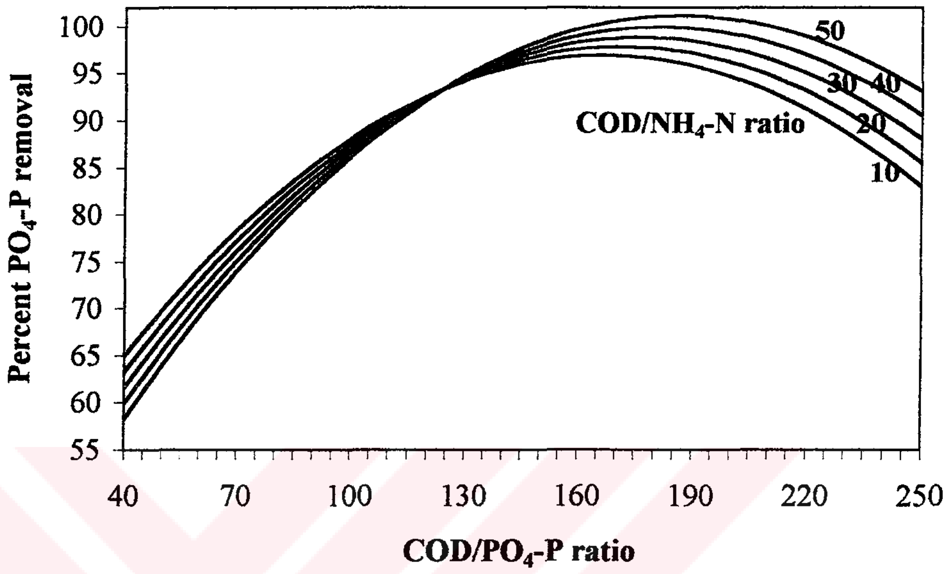


Figure 3.21. Variation of percent PO_4-P removal with COD / PO_4-P ratio (X_2) at different COD / NH_4-N (X_1) values

Table 3.3. Comparison of the experimental and predicted percent nutrient removals beyond the Box-Wilson design experiments

COD/NH_4-N/PO_4-P ratio	E_{COD} (exp)	E_{COD} (pred)	E_{NH4-N} (exp)	E_{NH4-N} (pred)	E_{PO4-P} (exp)	E_{PO4-P} (pred)
100/ 5/ 2	95	95	86	81	69	68
100/ 8/ 1	96	97	71	73	89	88
100/ 12/3.5	93	93	58	54	51	59

exp: experimental, **pred:** predicted

Percent COD removals varied between 93% and 97% for all X_1 and X_2 values. However, percent ammonium-N and phosphate-P removals varied between 60% and nearly 100% depending on X_1 and X_2 values. Therefore, the determining objective functions were percent ammonium and phosphate removals. The X_1 and X_2 values maximizing percent ammonium-N and phosphate-P removals were approximately, X_1= 40-50 and X_2 = 200-250 resulting in E_{COD} = 95%, E_{NH4-N} =99% and E_{PO4-P} = 98%.

A computer program was developed to determine the exact COD / NH_4-N/ PO_4-P ratios maximizing percent removals of the nutrients (COD, NH_4-N and PO_4-P). An optimization algorithm based on response function of each dependent variable was used to determine the optimal nutrient ratios. The results of the optimization program are presented in Table 3.4. The best percent removals were obtained when COD / NH_4-N / PO_4-P = 100/ 2/ 0.54 which corresponds to maximum percent phosphate removal. Centre point resulted in comparable percent removals.

Table 3.4. Optimal COD / NH_4-N / PO_4-P ratios resulting in maximum percent nutrient removal

Nutrient	**COD / NH_4-N / PO_4-P**	**E_{COD}**	**E_{NH4-N}**	**E_{PO4-P}**
COD	100/ 10/ 0.6	**97(max)**	76	97
NH_4-N	100/ 3.08/ 0.4	95	**99(max)**	89
PO_4-P	100/ 2/ 0.54	95	94	**99(max)**
Centre point	100/ 3.33/ 0.69	97	99	94

3.6. Effects of nutrient loading rates on nutrient removal in five-step SBR

3.6.1. Effect of specific COD loading rate on nutrient removal

Specific COD loading rate was varied between 40 mg COD/gX.h and 86 mg COD/g X.h. Average biomass concentrations were used in calculating the specific nutrient removal rates for each experiment. Variation of effluent COD concentration and percent COD removal with specific COD loading rate are depicted in Figure 3.22. Percent COD removal dropped from 99% to 97% when COD loading rate increased from 40 to 86 mg COD/gX.h. Percent COD removals were above 97% for every specific COD loading rate tested. Since COD/ N/ P ratio in the feed was optimized before (Kargi F. & Uygur A., 2003), changing the COD concentration in the feed while keeping the COD / N / P ratio at the optimal level did not affect percent COD removals at different loadings. However, the effluent COD levels increased from 6 mg/L to 120 mg/L (COD_o = 1200 mg/L) when specific COD loading increased from 40 to 86 mg COD/gX.h. In order to keep the effluent COD levels below 100 mg/L, the specific COD loading rate should be below 75 mgCOD/gX h.

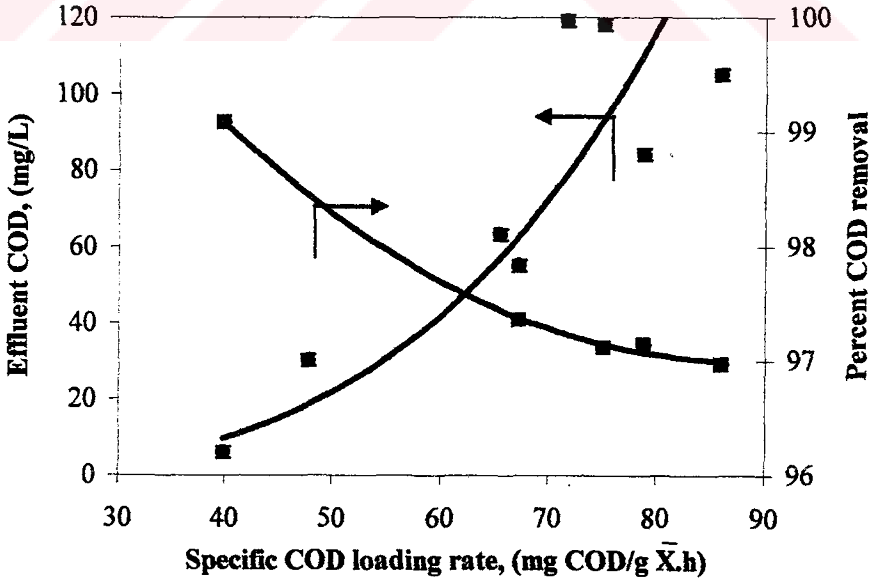


Figure 3.22. Variation of effluent COD concentration and percent COD removal with specific COD loading rate

3.6.2. Effect of specific NH_4-N loading rate on nutrient removal

Specific NH_4-N loading rates were varied between 0.9 mg NH_4-N/g X.h and 2.7 mg NH_4-N/gX.h while hydraulic retention times (HRT) of each step were kept constant. Variation of effluent NH_4-N concentration and percent NH_4-N removals with specific NH_4-N loading rate are depicted in Figure 3.23. Percent NH_4-N removal decreased and the effluent NH_4-N concentration increased with the increasing NH_4-N loading rate. Percent NH_4-N removal decreased from 99.9% to 99.6% and effluent NH_4-N concentration increased from 0.1 mg/L to 0.4 mg/L when specific NH_4-N loading rate increased from 0.9 to 2.7 mg N/gX.h. Apparently, variations in NH_4-N loading rate did not cause any significant changes in percent NH_4-N removals and the effluent NH_4-N levels because of low nitrogen content of the feed wastewater (NH_4-N / COD = 3.33 %).

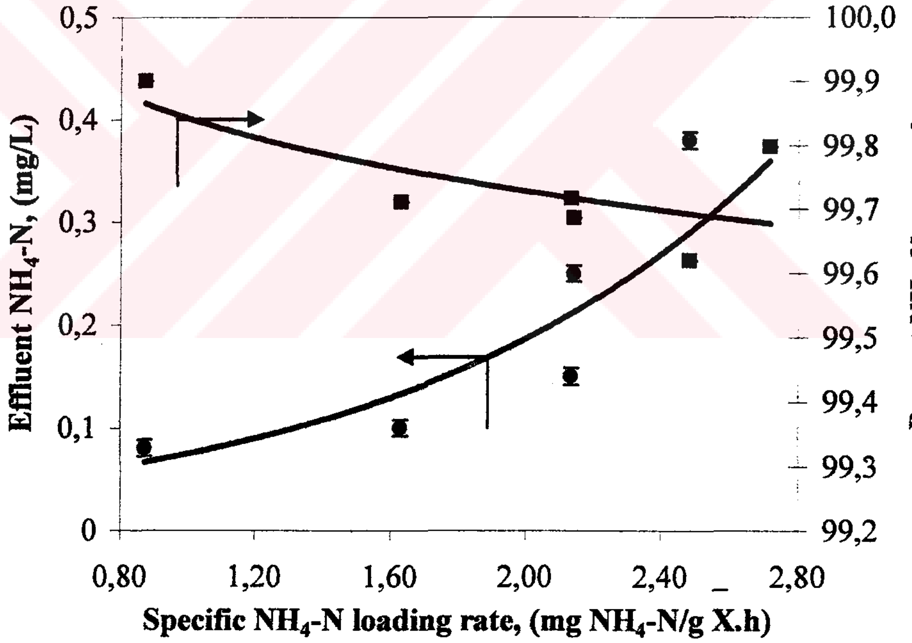


Figure 3.23. Variation of effluent NH_4-N concentration and percent NH_4-N removal with specific NH_4-N loading rate

3.6.3. Effect of specific PO_4-P loading rate on nutrient removal

Specific PO_4-P loading rates were varied between 0.09 mgPO_4-P/gX.h and 0.29 mg PO_4-P/gX.h.Variations of percent PO_4-P removal and effluent PO_4-P concentration with specific PO_4-P loading rate are depicted in Figure 3.24. Percent PO_4-P removals decreased and the effluent PO_4-P contents increased with increasing specific loading rates of PO_4-P. Percent phosphorous removal decreased from 97% to 85% and the final PO_4-P content increased from 0.1 mg/L to 2.4 mg/L when the PO_4-P loading rate increased from 0.09 mg PO_4-P/gX.h to 0.29 mg PO_4-P/gX.h. Phosphate loading rate apparently had a significant effect on percent PO_4-P removals. In order to keep the final PO_4-P below 0.5 mg/L or percent PO_4-P removals above 90%, the PO_4-P loading rate should be below 0.2 mg PO_4-P/gX.h.

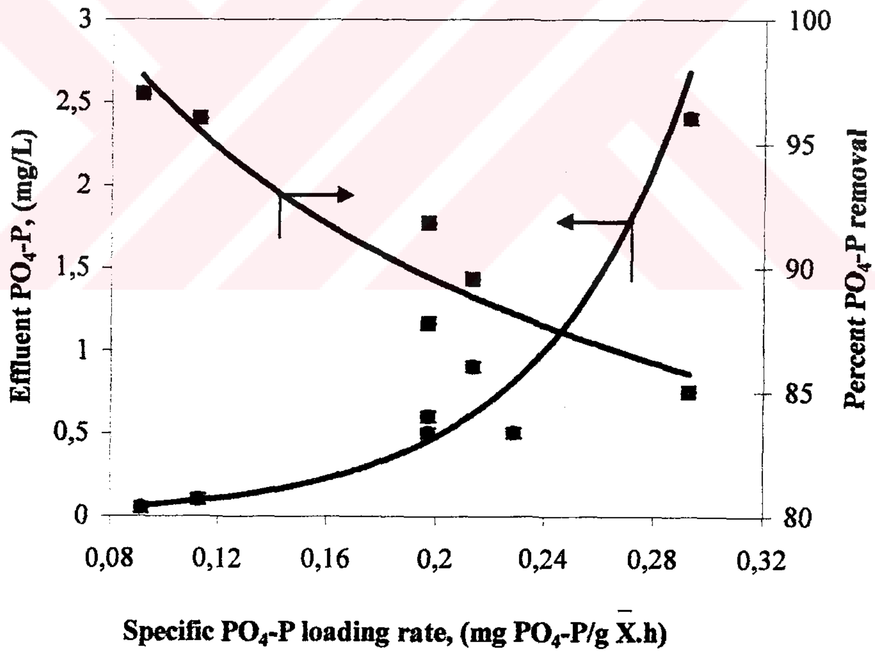


Figure 3.24. Variation of effluent PO_4-P concentration and percent PO_4-P removal with specific PO_4-P loading rate

3.6.4. Sludge volume index and biomass concentrations

Variation of sludge volume index (SVI) with COD loading rate is depicted in Figure 3.25. Sludge volume index decreased steadily with increasing COD loading rate as a result of high biomass concentrations at high COD loading rates. SVI value dropped from 85 mL/g to 46 mL/g when COD loading rate increased from 40 to 86 mg COD/gX.h.

Unlike the SVI values, biomass concentration increased with increasing COD loading rates as shown in Figure 3.26. Biomass concentration increased from 1.5 g/L to 3.84 g/L almost linearly when the COD loading rate increased from 40 to 86 mg COD/gX.h. High biomass concentrations at high COD loading rates improved the settling ability of the sludge resulting in low SVI values. However, the highest COD and therefore, the highest phosphate loading rates resulted in unacceptable effluent phosphate levels. In order to keep the effluent phosphate-P below 1 mg/L, phosphate loading rate should be lower than 0.25 mg PO_4-P/gX.h which corresponds to COD loading rate of 75 mg COD/gX.h and NH_4-N loading rate of 2.25 mg NH_4-N/gX.h. The effluent COD and NH_4-N levels at such loading rates are 80 mg/L and 0.25 mg/L which are within the acceptable limits. The SVI value at COD loading rate of 75 mgCOD/gX.h is approximately 52 mL/g which also indicates a good sedimenting sludge.

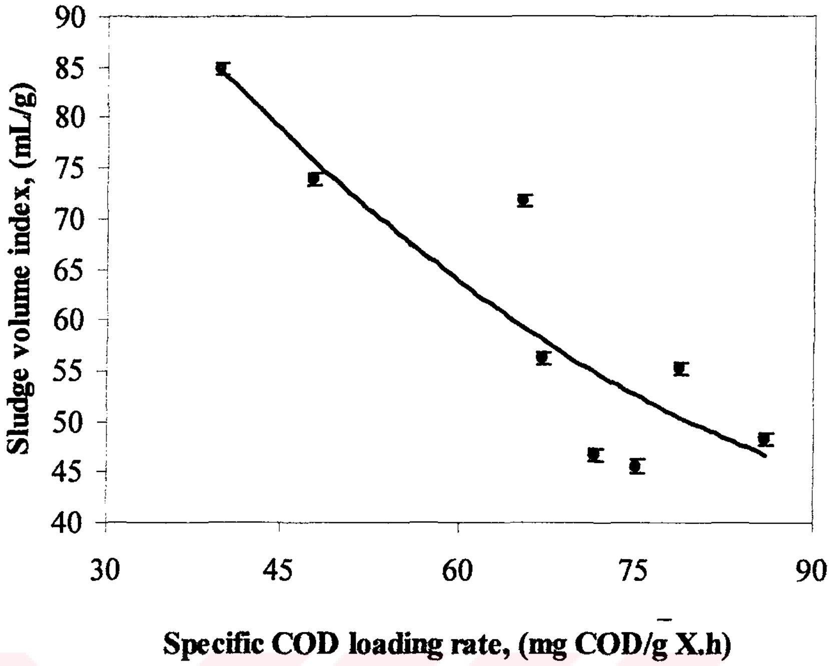


Figure 3.25. Variation of sludge volume index (SVI) with specific COD loading rate

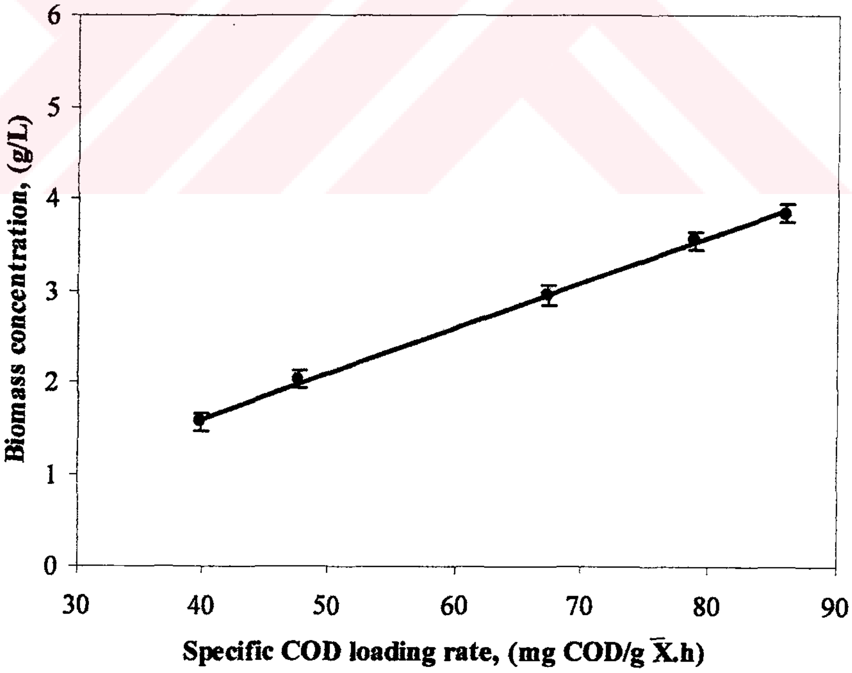


Figure 3.26. Variation of biomass concentration with specific COD loading rate

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

4.1. CONCLUSIONS

This study was performed to investigate the effects of important operating variables on nutrient removal performance of an SBR. The variables considered were, the number of steps, hydraulic retention time of each step (HRT), sludge age (SRT), carbon sources (carbohydrate and organic acids), feed wastewater composition (COD / N / P ratio) and nutrient loading rates. Variations of percent COD, NH_4-N, NO_3-N, PO_4-P removals, effluent concentrations and the sludge volume index with the aforementioned variables were investigated.

In the first phase of the thesis, nutrient removal from a synthetic wastewater was investigated by using an SBR operation consisting of different number of steps. Three (An/ Ax/ Ox), four (An/ Ox/ Ax/ Ox) and five-step (An/ Ax/ Ox/ Ax/ Ox) operations with different operating times were tested and percent nutrient removal performances were compared. Percent COD and ammonium-N removal performances of different operations were comparable, although the performance of the three-step operation was slightly better. This was because most of the COD and ammonium were removed during the first three steps. However, percent phosphate-P and nitrate-N removals were higher in the five-step operation as compared to the other alternatives tested. As a result of denitrification during the second anoxic phase and luxury phosphate uptake during the second oxic phase percent NO_3-N and PO_4-P removals improved significantly by the five-step operation. At the end of the five-step operation consisting of An/ Ax/ Ox/ Ax/ Ox phases of 1/ 1.5/ 4/ 1.5/ 2 h of duration , COD, NH_4-N, NO_3-N and PO_4-P concentrations dropped to 37 mg/L, 5.6 mg/L, 0.9 mg/L and 3.2 mg/L, respectively resulting in 94% COD, 90% NH_4-N, 64%

NO_3-N and 57% PO_4-P removals. On the basis of the experimental results, five-step operation was found to be superior to the three and four-step operations.

Effects of hydraulic retention times of each step on nutrient removal was investigated in the second phase of our experimental studies. Synthetic wastewater was treated in an SBR for nutrient removal by using a five step (anaerobic/ anoxic/ oxic/ anoxic/ oxic) operation at different HRT values for each step. Hydraulic retention time of each step was varied in order to obtain the most suitable HRT resulting in maximum percent removals of nutrients while the sludge age was kept constant at SRT of 10 days. Anaerobic and first anoxic steps should be operated at short retention times of 2 h and 1 h to obtain the best results. However the HRT of the first oxic (aerobic) step should be nearly 4.5 h, in order to obtain significant COD removal, phosphate uptake and nitrification. The next anoxic II and oxic II steps do not require large retention times for effective nutrient removal. Retention times of 1.5 h for each one of the last anoxic and oxic steps were sufficient for desired levels of nutrient removal. When the system was operated at a sludge age of 10 days and HRT's of 2/ 1/ 4.5/ 1.5/ 1.5 h for the anaerobic/ anoxic/ oxic/ anoxic/ oxic steps, percent COD, NH_4-N, NO_3-N, PO_4-P removals of 97%, 87%, 81% and 90% were obtained, respectively. The final nutrient concentrations were COD = 34 mg/L, NH_4-N = 6 mg/L, NO_3-N = 1.4 mg/L and PO_4-P = 0.4 mg/L at the end of 10.5 h of overall operation time, when each step was operated at the most suitable retention time.

Sludge age (solids retention time, SRT) was another important variable investigated in experimental studies. Five step SBR operation consisting of anaerobic/ anoxic/ oxic/ anoxic/ oxic steps was used for nutrient removal from a synthetic wastewater. Hydraulic retention times (HRT) were kept constant as 2/ 1/ 4.5/ 1.5/ 1.5 h for the aforementioned steps while the sludge age (solids retention time, SRT) was varied between 5 and 30 days.The optimal sludge age resulting in maximum percent COD (94%), NH_4-N (84%) and PO_4-P (70%) removals was 10 days, although 15 days of SRT resulted in slightly lower values. COD concentration decreased from 1120 mg/L to nearly 70 mg/L; NH_4-N and PO_4-P concentrations dropped from initial values of 46 mg/L and 12 mg/L to nearly 7 mg/L and 3.6 mg/L, respectively at the end of 10.5 h of SBR operation with 10 days of sludge age. Biomass concentration (MLSS) increased with the sludge age starting from 1730 mg/L at SRT of 5 days and reaching to nearly 3760 mg/L at SRT of 30 days. Sludge volume index (SVI) which is a measure of settling ability of the sludge varied between 52 mL/g and 66 mL/g depending on the sludge age. Minimum SVI (52 mL/g) was obtained at SRT of 5 days. However, SVI value (53 mL/g) obtained at SRT of 10 days was comparable with that of the 5 days. On the basis of the experimental results, the optimum SRT was found to be 10 days, resulting in maximum percent nutrient removal and minimum sludge volume index.

In order to determine the most suitable carbohydrate and organic acids as carbon source for nutrient (COD, NH_4-N, PO_4-P) removal from a synthetic wastewater in an SBR, different carbohydrates (glucose, lactose, sucrose, maltose, glucose-maltose mixture) and different organic acid-carbohydrate combinations (50/50) such as glucose with acetic, citric, propionic and butyric acid were used. When used alone, glucose or sucrose resulted in better percent nutrient (especially phosphate-P) removals as compared to the other carbohydrates tested. When glucose was mixed with the organic acids, the best percent nutrient removal performance (especially PO_4-P) was obtained with glucose/ acetic acid or glucose/ citric acid mixtures (50/50). Since acetic acid is readily produced by the acid forming organisms under anaerobic conditions and is more likely to be present in wastewater, it is preferred to citric acid as the source of organic acid. When different glucose/acetic acid ratios were used, 50/50 percent glucose/acetic acid mixture was found to result in better percent nutrient (especially NH_4-N and PO_4-P) removals as compared to the other combinations. Nearly, 93%, 97% and 96% removals were obtained for percent COD, NH_4-N and PO_4-P, respectively with the final concentrations of 52 mg/L COD, 1.6 mg/L NH_4-N and 0.6 mg/L PO_4-P when a 50/ 50 mixture of glucose/acetic acid was used.

In order to determine the affects of nutrient composition on percent nutrient removal in a five-step SBR, a Box–Wilson statistical experimental design was used by considering COD / NH_4-N (X_1) and COD / PO_4-P (X_2) ratios as independent variables, while initial COD was constant at 1200 mg/L. The objective functions were percent COD, NH_4-N and PO_4-P removals. Experimental results were correlated with a Box-Wilson response function and the coefficients were determined by regression analysis using the experimental data. Response function predictions were in good agreement with the experimental findings. Percent COD removal was always above 95 for all values of X_1 and X_2. Maximum percent ammonium-N removal was obtained at $X_1= 40$ and $X_2 = 250$, while the percent phosphate-P removal was maximum at $X_1= 50$ and $X_2 = 200$. A computer program was used to determine the optimal nutrient ratios maximizing the percent nutrient removals. COD / NH_4-N / PO_4-P ratio of 100/ 2/ 0.54 was found to maximize the percent nutrient removals. Percent removals obtained at the centre point were comparable with those of the optimum.

In the last phase of the experimental studies, effects of nutrient loading rates on nutrient removals were investigated. Five-step sequencing batch reactor (SBR) consisting of anaerobic/ anoxic/ oxic/ anoxic/ oxic steps was used for nutrient removal from a synthetic wastewater. Hydraulic retention times (HRT) were kept constant as 2 / 1 / 4.5 / 1.5 / 1.5 h for the aforementioned steps while the specific nutrient loading rates were changed. COD/ N/ P ratio in the feed wastewater was kept constant at 100/ 3.33/ 0.7, throughout the study. Specific COD loading rate was varied between 40 mg COD/gX.h and 86 mg COD/gX.h. Loading rates of the other nutrients were varied according to the constant COD/ N/ P ratio. Sludge age was constant at 10 days. Percent nutrient (COD, N, P) removals decreased and the final nutrient concentrations increased with increasing specific nutrient loadings. Percent COD and ammonium-N removals were not affected by the loading rates, significantly. Percent COD removals were above 97% and the final COD levels were below 120 mg/L for the loading rates tested. Percent NH_4-N removals were above 99.7% and the effluent NH_4-N contents were below 0.4 mg/L for all loading rates. However, percent phosphate-P removals and final concentrations were clearly affected by the changes in loading rates. Percent phosphate removal dropped from 97% to 85%, and the final PO_4-P level increased from 0.1 mg/L to 2.5 mg/L when the specific PO_4-P loading rate increased from 0.09 to 0.3 mg PO_4-P/gX.h. In order to keep the final PO_4-P level below 1mg/L, the specific PO_4-P loading rate should be lower than 0.25 mg PO_4-P/gX.h which corresponds to COD loading rate of 75 mg COD/gX.h and NH_4-N loading rate of 2.25 mg NH_4-N/gX.h. The final COD and NH_4-N levels would be lower than 80 mg/L and 0.3 mg/L, respectively at these loading rates. Sludge volume index (SVI) decreased with increasing specific COD loading rate as a result of high biomass concentrations at high COD loadings. The SVI values decreased from 85 mL/g to 46 mL/g and biomass concentration increased from 1.4 g/L to 3.84 g/L when specific COD loading rate increased from 40 to 86 mg COD/gX.h. Lower SVI values are preferred in order to obtain high biomass concentrations in the aeration tank. However, sludges with SVI values lower than 100 mL/g are known to be good settling sludges. For this reason any SVI value (SVI< 85 mL/g) obtained within the range of the loading rates are acceptable. For the aforementioned specific phosphate loading rate (SPLR < 0.25 mg PO_4-P/gX.h), resulting in acceptable final nutrient levels, the SVI value was 55 mL/g, which is considered as a good settling sludge.

4.2. RECOMMENDATIONS

1. Utilization of a biofilm sequencing batch reactor should be investigated and the nutrient removal performances should be compared with the present study.

2. Continuous processes for nutrient removal may be used under different operating conditions and the results may be compared with the SBR operation.

3. The SBR system may be used for nutrient removal from real industrial wastewaters after adjusment of the nutrient levels and the nutrient removal performances should be compared with the present study.

4. Effects of toxic compounds on nutrient removal may be investigated using a suspension culture or biofilm SBR.

5. Fed-batch and sequencing batch operations may be used in combination for nutrient removal.

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NOMENCLATURE

An / Ax / Ox	: Anaerobic / Anoxic / Oxic
An / Ox / Ax / Ox	: Anaerobic / Oxic / Anoxic / Oxic
An / Ax / Ox / Ax / Ox	: Anaerobic / Anoxic / Oxic / Anoxic / Oxic
A^2O	: Anaerobic / Anoxic / Oxic
UCT	: University of Cape Town
VIP	: Virginia Initiative Plant
CAS	: Conventional activated sludge
RAS	: Return activated sludge
ICEASR	: Intermittent cycle exdended aeration system
HRSD	: Hampton Roads Sanitation District
BNR	: Biological nutrient removal
EBPR	: Enhanced biological phosphorus removal
SBR	: Sequencing batch reactor
MBSBBR	: Moving-bed sequencing batch biofilm reactor
MLE	: The modified Ludzack-Ettinger
BOD	: Biological oxygen demand
BOD_5	: Biological oxygen demand for five days
TOC	: Total organic carbon
COD	: Chemical oxygen demand, mg/L
CODe	: Effluent chemical oxygen demand, mg/L
E_{COD}	: Percent COD removal, (%)
NH_4-N	: Ammonium-nitrogen, mg/L
NH_4-Ne	: Effluent ammonium nitrogen concentration, mg/L
$E_{NH4\text{-}N}$	: Percent ammonium-nitrogen removal, (%)

PO_4-P	: Phosphate-phosphorus, mg/L
PO_4-P	: Effluent phosphate-phosphorus concentration, mg/L
E_{PO4-P}	: Percent phosphate-phosphorus removal, (%)
NO_3-N	: Nitrate-nitrogen, mg/L
NO_3-Ne	: Effluent nitrate-nitrogen concentration, mg/L
E_{NO3-N}	: Percent nitrate-nitrogen removal, (%)
NH_4-N	: Ammonium-nitrogen
NO_2-N	: Nitrit nitrogen
N_2	: Nitrogen gases
CO_2	: Carbon dioxide
O_2	: Oxygen gases
H_2O	: Hydrogen di oxide
HPO_4^{-2}	: Hydrogen phosphate
H^+	: Hydrogen ion
ATP	: Adenozin three phosphate
ADP	: Adenozin di phopshate
VFA	: Volatile fatty acid
TKN	: Total Kjeldahl nitrogen
TN	: Total nitrogen
COD / N / P	: COD / NH_4-N / PO_4-P ratio
COD / NH_4-N	: Chemical oxygen demand/ ammonium-nitrogen ratio
COD / PO_4-P	:Chemical oxygen demand/phosphate-phosphorus ratio
SLNR	: Specific nutrient loading rates
F/M	: Food to biomass ratio
PHB	: Poly-hydroxybutyrate
E	: Percent removal, (%)
pH	: pH
DO	: Dissolved oxygen demand, mg/L
ORP	: Oxidation reduction potential, mV
T	: Temprature, °C
Rpm	: revolution per minute

θ_c : Sludge age, days

θ_H : Hydraulic retention time, h

HRT : Hydraulic retention time, h or day

SRT : Sludge retention time, h or day

MLSS : Mixed liquor suspended solids, mg/L

TS : Total solids, mg/L

TSS : Total suspended solids, mg/L

Xo : Initial amount of biomass in the reactor, mg/L

Xe : Final amount of biomass in the reactor, mg/L

Xr : Recycle amount of biomass in the reactor, mg/L

X : Average amount of biomass in the reactor, mg/L

V : Volume of the liquid in reactor, L

Vo : Initial volume of the liquid in the reactor, L

V_f : Fill volume of the liquid in the reactor, L

SVI : Sludge volume index, mL MLSS/g or mL TSS/g

A : Axial points

F : Factorial points

C : Centre points

X_1 : COD / NH_4-N ratio

X_2 : COD / PO_4-P ratio

Y : Dependent variables (COD, NH_4-N and PO_4-P)

APPENDICES

APPENDIX-A

Raw Data for the Experiments with Different Number of Steps

Table A.1. Composition of the synthetic wastewater used in experimental studies

Compounds	**Concentrations (mg/L)**
$C_6H_{12}O_6.H_2O$	538
$CH_3.COONa.3H_20$	1130
NH_4Cl	191
KH_2PO_4	66
$NaHCO_3$	590
$MgSO_4.7H_2O$	100
$NaCl$	100
KCl	20
$CaCl_2.2H_2O$	50
$FeCl_3.6H_20$	50

Table A.2. Influent and effluent nutrient concentrations for different number of steps.

Three- step (An/Ax/Ox)	**COD**	**NH_4-N**	**NO_3-N**	**PO_4-P**
Influent (mg/L)	695	48	2.4	8
Effluent (mg/L)	28	3.2	1.2	4
Percent Removal	**96**	**93**	**50**	**50**
Four-step (An/Ox/Ax/Ox)				
Influent (mg/L)	644	54	4.5	10.8
Effluent (mg/L)	25	4	2	5.4
Percent Removal	**96**	**93**	**56**	**50**
Five-step (An/Ax/Ox/Ax/Ox)				
Influent (mg/L)	632	53.6	2.5	7.4
Effluent (mg/L)	37	5.6	0.9	3.2
Percent Removal	**94**	**90**	**64**	**57**

Table A.3. Raw Data For An / Ax / Ox operation steps

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	695	48	8	2.4	7.75
ANAEROBIC	1	1	649	50	8.2	1	7.15
ANOXIC	1.5	2.5	526	48	9.4	0.5	6.87
OXIC	4	6.5	28	3.2	4	1.2	8.45
Percent removal			**96**	**93**	**50**	**50**	

So=1000 mg/L, COD/N/P=100/5/1.5, Xr=2020 mg/L, SVI=114 mL/g MLSS

Table A.4. Raw Data For An / Ox / Ax / Ox operation steps

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	644	54	10.8	4.5	7.35
ANAEROBIC	1.5	1.5	558	52	12.6	1	6.75
OXIC	4	5.5	21	16.8	6.8	3	8.31
ANOXIC	1	6.5	28	10.8	6	0.2	8.15
OXIC	2	8.5	25	4	5.4	2	8.55
Percent removal			**96**	**93**	**50**	**56**	

So=1000 mg/L, COD/N/P=100/5/1.5, Xr=3150 mg/L, SVI=95 mL/g MLSS

Table A.5. Raw Data For An / Ax / Ox / Ax / Ox operation steps

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	632	53.6	7.4	2.5	7.25
ANAEROBIC	1	1	561	51.2	7.8	0.6	6.94
ANOXIC	1.5	2.5	555	52	8.6	0.3	6.86
OXIC	4	6.5	31	11.2	3.4	4.1	8.4
ANOXIC	1.5	8	34	8.8	4	0.4	8.23
OXIC	2	10	37	5.6	3.2	0.9	8.64
Percent removal			**94**	**90**	**57**	**64**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=3150 mg/L, SVI=79 mL/g MLSS

APPENDIX-B

Raw Data for the Experiments with Different Hydraulic Retention Times

Table B.1. Raw Data for Anaerobic operation steps (HRT=1 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	663	56.4	9.4	15.6	7.7
ANAEROBIC	1	1	580	48	9.4	2.9	8.15
ANOXIC	1.5	2.5	510	50	9.2	2.4	7.65
OXIC	4.5	7	135	11.6	7	6.9	7.89
ANOXIC	1.5	8.5	38	17.6	6.6	5.2	7.67
OXIC	1.5	10	28	11.2	5.4	6.3	8.02
Percent removal			**96**	**80**	**43**	**60**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1150 mg/L, SVI=81 mL/g TSS

Table B.2. Raw Data for Anaerobic operation steps (HRT=1.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	679	59.6	8.4	3.4	7.31
ANAEROBIC	1.5	1.5	630	58	9.6	2.2	6.97
ANOXIC	1.5	3	596	54.8	9.2	1.5	6.66
OXIC	4.5	7.5	31	11.2	5	6.5	7.86
ANOXIC	1.5	9	22	8.4	4.8	2.8	7.66
OXIC	1.5	10.5	28	7.2	4.6	2.73	8.05
Percent removal			**96**	**88**	**45**	**20**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1170 mg/L, SVI=79 mL/g TSS

Table B.3. Raw Data for Anaerobic operation steps (HRT=2 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	657	49.6	4.2	6.1	7.01
ANAEROBIC	2	2	543	45.6	5.2	1	6.67
ANOXIC	1.5	3.5	510	50.4	4	0.5	6.42
OXIC	4.5	8	37	10	3	6.9	8.43
ANOXIC	1.5	9.5	21	6.4	2.6	0.3	8.3
OXIC	1.5	11	18	13.6	1.2	0.6	8.55
Percent removal			**97**	**73**	**71**	**90**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1340 mg/L, SVI=73 mL/g TSS

Table B.4. Raw Data for Anaerobic operation steps (HRT=2.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	666	39.2	8	3.3	7.61
ANAEROBIC	2.5	2.5	482	35.6	7.2	1.2	7.07
ANOXIC	1.5	4	473	34.8	7	0.6	7.09
OXIC	4.5	8.5	258	10.8	3.8	5.1	8.38
ANOXIC	1.5	10	206	8.4	3.4	1	8.27
OXIC	1.5	11.5	212	6.4	3	1	8.58
Percent removal			**68**	**84**	**63**	**70**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1250 mg/L, SVI=74 mL/g TSS

Table B.5. Raw Data for First Anoxic operation steps (HRT=1 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	771	44.8	4	7.3	7.66
ANAEROBIC	2	2	450	38.4	3.6	1.1	7.42
ANOXIC	1	3	441	38	4	0.7	7.33
OXIC	4.5	7.5	59	5.2	0.6	4.7	8.31
ANOXIC	1.5	9	34	6.8	0.8	1	8.19
OXIC	1.5	10.5	34	6	0.4	1.4	8.6
Percent removal			**96**	**87**	**90**	**81**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1220 mg/L, SVI=45 mL/g TSS

Table B.6. Raw Data for First Anoxic operation steps (HRT=1.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	657	49.6	4.2	6.1	7.01
ANAEROBIC	2	2	543	45.6	5.2	1	6.67
ANOXIC	1.5	3.5	510	50.4	4	0.5	6.42
OXIC	4.5	8	37	10	3	6.9	8.43
ANOXIC	1.5	9.5	21	6.4	2.6	0.3	8.3
OXIC	1.5	11	18	13.6	1.2	0.6	8.55
Percent removal			**97**	**73**	**71**	**90**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1340 mg/L, SVI=73 mL/g TSS

Table B.7. Raw Data for First Anoxic operation steps (HRT=2 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	763	42.8	9.8	2	7.65
ANAEROBIC	2	2	622	39.6	10.8	1.8	7.28
ANOXIC	2	4	625	46.4	10	0.8	7.25
OXIC	4.5	8.5	33	18.4	4	5.7	8.35
ANOXIC	1.5	10	21	11.2	4.4	1.1	8.18
OXIC	1.5	11.5	10	9.2	3	0.9	8.62
Percent removal			**99**	**79**	**69**	**55**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1310 mg/L, SVI=92 mL/g TSS

Table B.8. Raw Data for First Anoxic operation steps (HRT=2.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	758	57.6	11.8	2.9	7.51
ANAEROBIC	2	2	647	48.8	11.8	0.5	7.08
ANOXIC	2.5	4.5	626	48.8	11	0.2	7.02
OXIC	4.5	9	48	7.6	4.6	4.3	8.4
ANOXIC	1.5	10.5	22	10.4	4	0.5	8.2
OXIC	1.5	12	22	9.2	3	0.4	8.57
Percent removal			**97**	**84**	**75**	**86**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1260 mg/L, SVI=35 mL/g TSS

Table B.9. Raw Data for First Oxic operation steps (HRT=2 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	749	50	12.8	2.8	7.65
ANAEROBIC	2	2	613	52	12.6	0.6	7.05
ANOXIC	1	3	610	49.2	12.4	0.2	7.05
OXIC	2	5	31	14.8	5.8	1.4	8.37
ANOXIC	1.5	6.5	62	17.6	6.8	0.6	8.06
OXIC	1.5	8	22	25.6	4.4	1.4	8.51
Percent removal			**97**	**49**	**66**	**50**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1480 mg/L, SVI=32 mL/g TSS

Table B.10. Raw Data for First Oxic operation steps (HRT=3 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	730	54.8	10.2	3.2	7.46
ANAEROBIC	2	2	573	64.8	9.8	0.1	7.19
ANOXIC	1	3	564	54.4	9.6	0.3	7.11
OXIC	3	6	28	9.2	3.8	2	8.27
ANOXIC	1.5	7.5	25	4.4	4	1.4	8.09
OXIC	1.5	9	34	8.8	2.8	1.1	8.59
Percent removal			**95**	**84**	**73**	**66**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1420 mg/L, SVI=31 mL/g TSS

Table B.11. Raw Data for First Oxic operation steps (HRT=4.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	771	44.8	4	7.3	7.66
ANAEROBIC	2	2	450	38.4	3.6	1.1	7.42
ANOXIC	1	3	441	38	4	0.7	7.33
OXIC	4.5	7.5	59	5.2	0.6	4.7	8.31
ANOXIC	1.5	9	34	6.8	0.8	1	8.19
OXIC	1.5	10.5	34	6	0.4	1.4	8.6
Percent removal			**96**	**87**	**90**	**81**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1340 mg/L, SVI=73 mL/g TSS

Table B.12. Raw Data for First Oxic operation steps (HRT=6 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	666	53.2	11.8	5.3	7.5
ANAEROBIC	2	2	531	44.4	13.6	0.4	7.22
ANOXIC	1	3	540	52	12.4	0.8	7.17
OXIC	6	9	40	8.8	4.6	6.6	8.57
ANOXIC	1.5	10.5	37	5.2	5.2	3.7	8.44
OXIC	1.5	12	6	5.2	4	3.3	8.75
Percent removal			**99**	**90**	**66**	**38**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1770 mg/L, SVI=30 mL/g TSS

Table B.13. Raw Data for Second Anoxic operation steps (HRT=1 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	606	58.4	13.8	1.1	7.51
ANAEROBIC	2	2	557	53.2	13.2	0.8	7.09
ANOXIC	1	3	537	39.2	13.8	1.1	7.18
OXIC	4.5	7.5	28	3.2	4.4	4.5	8.55
ANOXIC	1	8.5	37	16	4.6	2.2	8.39
OXIC	1.5	10	37	10	3.8	0.66	8.60
Percent removal			**94**	**83**	**72**	**40**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1740 mg/L, SVI=27 mL/g TSS

Table B.14. Raw Data for Second Anoxic operation steps (HRT=1.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	771	44.8	4	7.3	7.66
ANAEROBIC	2	2	450	38.4	3.6	1.1	7.42
ANOXIC	1	3	441	38	4	0.7	7.33
OXIC	4.5	7.5	59	5.2	0.6	4.7	8.31
ANOXIC	1.5	9	34	6.8	0.8	1	8.19
OXIC	1.5	10.5	34	6	0.4	1.4	8.6
Percent removal			**96**	**87**	**90**	**81**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1340 mg/L, SVI=73 mL/g TSS

Table B.15. Raw Data for Second Anoxic operation steps (HRT=2 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)
t=0		0	657	53.2	13.8	1.2	7.55	29.6
ANAEROBIC	2	2	537	40.4	14.6	0.8	7.13	29.4
ANOXIC	1	3	553	53.2	15.6	0.7	7.11	31.4
OXIC	4.5	7.5	40	11.2	4.8	5.1	8.56	28.5
ANOXIC	2	9.5	34	7.2	5.2	0.5	8.31	29.1
OXIC	1.5	11	34	3.6	3.8	0.5	8.71	28.7
Percent removal			**95**	**93**	**72**	**58**		

So=1000 mg/L, COD/N/P=100/5/1.5, X=1940 mg/L, SVI=26 mL/g TSS

Table B.16. Raw Data for Second Anoxic operation steps (HRT=2.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)
t=0		0	654	54.8	15.2	1	7.63	28.6
ANAEROBIC	2	2	556	55.6	15.2	0.9	7.04	28.4
ANOXIC	1	3	559	48.8	15.6	0.6	7.09	28.6
OXIC	4.5	7.5	21	11.2	5	4.1	8.57	27.2
ANOXIC	2.5	10	21	4	5.4	1.4	8.29	28.4
OXIC	1.5	11.5	28	5.2	4.8	0.5	8.68	28.1
Percent removal			**96**	**91**	**68**	**50**		

So=1000 mg/L, COD/N/P=100/5/1.5, X=1650 mg/L, SVI=27 mL/g TSS

Table B.17. Raw Data for Second Oxic operation steps (HRT=1.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	771	44.8	4	7.3	7.66
ANAEROBIC	2	2	450	38.4	3.6	1.1	7.42
ANOXIC	1	3	441	38	4	0.7	7.33
OXIC	4.5	7.5	59	5.2	0.6	4.7	8.31
ANOXIC	1.5	9	34	6.8	0.8	1	8.19
OXIC	1.5	10.5	34	6	0.4	1.4	8.6
Percent removal			**96**	**87**	**90**	**81**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1340 mg/L, SVI=73 mL/g TSS

Table B.18. Raw Data for Second Oxic operation steps (HRT=2 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH
t=0		0	701	60.4	14.4	0.5	7.53
ANAEROBIC	2	2	532	53.2	14.8	0.6	7.08
ANOXIC	1	3	529	55.2	14.8	0.9	7.12
OXIC	4.5	7.5	25	7.2	5.2	3.8	8.55
ANOXIC	1.5	9	18	10.4	5.4	0.6	8.34
OXIC	2	11	25	14	4.4	0.47	8.74
Percent removal			**96**	**77**	**69**	**5**	

So=1000 mg/L, COD/N/P=100/5/1.5, X=1350 mg/L, SVI=29 mL/g TSS

Table B.19. Raw Data for Second Oxic operation steps (HRT=2.5 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)
t=0		0	644	65.6	16.8	1.7	7.31	31.6
ANAEROBIC	2	2	705	72.8	20.4	1.1	6.82	27.4
ANOXIC	1	3	638	75.6	20.8	1	6.83	28
OXIC	4.5	7.5	37	16	4.6	6.8	8.42	29.1
ANOXIC	1.5	9	28	11.2	4.6	2.5	8.31	29.5
OXIC	2.5	11.5	25	13.6	5.6	1.64	8.63	28.9
Percent removal			**96**	**79**	**67**	**4**		

So=1000 mg/L, COD/N/P=100/5/1.5, X=2520 mg/L, SVI=45 mL/g TSS

Table B.20. Raw Data for Second Oxic operation steps (HRT=3 h)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)
t=0		0	619	52	11	1.6	7.67	30.3
ANAEROBIC	2	2	576	54.4	12.8	1.1	6.96	30.3
ANOXIC	1	3	530	50.4	13.4	1.1	7.01	30.6
OXIC	4.5	7.5	31	7.2	4.8	4	8.58	29.7
ANOXIC	1.5	9	21	11.2	5	0.9	8.36	30.3
OXIC	3	12	31	6.4	4.2	1.5	8.7	29.5
Percent removal			**95**	**88**	**62**	**6**		

So=1000 mg/L, COD/N/P=100/5/1.5, X=1420 mg/L, SVI=33 mL/g TSS

APPENDIX-C

Raw Data for the Experiments with Different Sludge Ages

Table C.1. Raw Data for 5 days sludge age

θ_c=5 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1000	43.6	11.2	1.5	7.61	30.1	0.11
ANAEROBIC	2	2	600	44	13	0.8	7.17	29.7	0.22
ANOXIC	1	3	408	53.2	14.2	0.8	7.16	30.2	0.19
OXIC	4.5	7.5	144	5.6	4.2	3.3	8.5	29.8	4.58
ANOXIC	1.5	9	68	22.4	4.6	1.4	8.34	30.4	0.04
OXIC	1.5	10.5	72	8.8	3.6	0.7	8.61	29.7	5.99
Percent removal			**93**	**80**	**68**	**53**			

So=1200 mg/L, COD/N/P=100/5/1.5, X=1730 mg/L, SVI=51 mL/g MLSS

Table C.2. Raw Data for 10 days sludge age

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1120	46.4	12.2	1.6	7.43	28.9	0.14
ANAEROBIC	2	2	512	56	11.8	0.7	7.25	28.8	0.1
ANOXIC	1	3	528	51.2	13.6	1.1	7.21	29	0.11
OXIC	4.5	7.5	168	8.4	3.6	4.3	8.57	28.8	4.64
ANOXIC	1.5	9	94	9.6	4	0.9	8.38	28.1	0.29
OXIC	1.5	10.5	72	7.6	3.6	1.3.	8.66	28.2	3.03
Percent removal			**94**	**84**	**70**	**19**			

So=1200 mg/L, COD/N/P=100/5/1.5, X=2490 mg/L, SVI=52 mL/g MLSS

Table C.3. Raw Data for 15 days sludge age

θ_c=15 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	939	43.6	11.4	0.9	7.36	28.4	0.09
ANAEROBIC	2	2	608	77.2	14	0.6	7.38	28.5	0.2
ANOXIC	1	3	576	50	15.4	0.5	7.35	28.6	0.23
OXIC	4.5	7.5	104	17.6	4.6	4.2	8.57	28.5	4.01
ANOXIC	1.5	9	48	9.2	5	0.9	8.45	28.4	0.15
OXIC	1.5	10.5	44	7.6	3.8	0.6	8.64	28.3	3.8
Percent removal			**95**	**83**	**67**	**33**			

So=1200 mg/L, COD/N/P=100/5/1.5, X=2660 mg/L, SVI=59 mL/g MLSS

Table C.4.. Raw Data for 20 days sludge age

θ_c=20 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	976	41.2	10.8	1.6	7.46	27.7	0.23
ANAEROBIC	2	2	912	44.4	12.4	0.9	7.43	28.1	0.14
ANOXIC	1	3	944	49.2	12.8	0.5	7.47	28.3	0.07
OXIC	4.5	7.5	100	8.4	4.4	4.1	8.56	28.3	4.09
ANOXIC	1.5	9	76	12.8	4.8	1.2	8.36	28.6	0.71
OXIC	1.5	10.5	92	13.2	3.8	1.5	8.61	28.2	3.75
Percent removal			**91**	**68**	**65**	**6**			

So=1200 mg/L, COD/N/P=100/5/1.5, X=3230 mg/L, SVI=66 mL/g MLSS

Table C.5. Raw Data for 25 days sludge age

θ_c=25 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	997	45.2	13.6	1.6	7.23	26	0.15
ANAEROBIC	2	2	552	50	13.4	0.6	7.25	26.3	0.26
ANOXIC	1	3	464	54.8	14.2	0.7	7.34	26.1	0.21
OXIC	4.5	7.5	64	11.2	5.2	6.4	8.52	26	4.52
ANOXIC	1.5	9	74	12	5.8	2.2	8.39	26.1	0.74
OXIC	1.5	10.5	40	14.4	4.4	1.4	8.61	26.2	4.44
Percent removal			**96**	**68**	**68**	**13**			

So=1200 mg/L, COD/N/P=100/5/1.5, X=3800 mg/L, SVI=66 mL/g MLSS

Table C.6. Raw Data for 30 days sludge age

θ_c=30 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	856	58.4	12	3.9	7.12	26.1	0.24
ANAEROBIC	2	2	496	53.6	12.4	0.7	7.29	26.2	0.41
ANOXIC	1	3	456	56	13.2	0.8	7.45	26.2	0.4
OXIC	4.5	7.5	72	8.4	5	5.7	8.42	26.2	4.61
ANOXIC	1.5	9	96	11.6	6.4	2.6	8.2	26.4	0.66
OXIC	1.5	10.5	70	13.6	4.4	3	8.51	26.5	3.81
Percent removal			**92**	**77**	**63**	**23**			

So=1200 mg/L, COD/N/P=100/5/1.5, X=3760 mg/L, SVI=65 mL/g MLSS

APPENDIX-D

Raw Data for the Experiments with Different Organic Acids

Table D.1. Raw data for glucose (SRT =10 days)

Θ_c =10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	858	49.4	10.1	16.4	7.1	23.8	0.3
ANAEROBIC	2	2	405	47.4	10.2	0.7	6.71	24.9	0.2
ANOXIC	1	3	425	41	9.5	1	6.55	25.2	0.3
OXIC	4.5	7.5	36	0.29	0.6	1.5	8.45	25.9	2.6
Percent removal			**96**	**99**	**94**	**91**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2840 mg/L, Xe=3000 mg/L, Xr=15600 mg/L SVI=64 mL/g MLSS

Table D.2. Raw data for lactose (SRT =10 days)

θc =10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1095	53.2	7.9	24.6	7.6	22.7	0.4
ANAEROBIC	2	2	803	48.4	7	8.5	7.4	25.5	0.2
ANOXIC	1	3	789	47.4	6.3	13.3	7.15	25.3	0.2
OXIC	4.5	7.5	52	11.6	0.6	1.7	8.37	26.6	2.2
Perecent removal			**95**	**78**	**92**	**93**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2740 mg/L, Xe=3240 mg/L, Xr=15760 mg/L, SVI=63 mL/g MLSS

Table D.3. Raw Data for sucrose (SRT = 10 days)

θc=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	990	45.8	7.2	21.5	7.39	21.2	0.1
ANAEROBIC	2	2	488	42.8	4.8	1.8	7.23	25.7	0.1
ANOXIC	1	3	338	40.2	3.2	1.1	6.89	24.6	0.1
OXIC	4.5	7.5	54	0.18	0.4	1	8.26	26	2.9
Percent removal			**95**	**99**	**94**	**95**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2220 mg/L, Xe=2660 mg/L, Xr=16860 mg/L SVI=59 mL/g MLSS

Table D.4. Raw data for maltose (SRT = 10 days)

Θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	739	62.6	16.3	10.3	7.34	26	0.09
ANAEROBIC	2	2	675	47.4	20	8	7.18	27.9	0.08
ANOXIC	1	3	640	41.4	24.9	4.8	6.87	28.2	0.11
OXIC	4.5	7.5	21	0.15	7	4.3	8.53	29.3	3.39
Percent removal			**97**	**99**	**57**	**58**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=1980 mg/L, Xe=3120 mg/L, Xr=14740 mg/L SVI=68 mL/g MLSS

Table D.5. Raw data for glucose and maltose (50/50) mixture (SRT =10 days)

θc=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	880	32.6	17.3	10.5	7.31	24	0.2
ANAEROBIC	2	2	456	37.2	17.4	3	6.8	26.2	0.1
ANOXIC	1	3	391	29.8	18.2	1.3	6.4	26.8	0.1
OXIC	4.5	7.5	71	7.6	4.1	1.5	8.09	27.5	2.1
Percent removal			**92**	**77**	**76**	**86**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=3700 mg/L, Xe=4140 mg/L, Xr=23240 mg/L, SVI=43 mL/g MLSS

Table D.6. Raw data for glucose –acetic acid (50/50) mixture (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	755	50.6	13.4	7.4	6.35	25.7	0.3
ANAEROBIC	2	2	594	49.4	14.1	1.8	6.29	26.4	0.3
ANOXIC	1	3	632	55.2	13.8	0.7	6.26	26.1	0.1
OXIC	4.5	7.5	52	1.59	0.6	2.3	8.29	27.6	2.2
Percent removal			**93**	**97**	**96**	**69**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2760 mg/L, Xe=3000 mg/L, Xr=14400 mg/L, SVI=69 mL/g MLSS

Table D.7. Raw data for glucose-citric acid (50/50) mixture (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (^oC)	DO (mg/L)
t=0		0	693	55.2	30.8	7.8	5.53	24.2	0.2
ANAEROBIC	2	2	618	50.6	30.6	2.3	5.25	25.8	0.4
ANOXIC	1	3	568	55	37.5	3.5	5.28	26.2	0.3
OXIC	4.5	7.5	24	2.28	1.1	3.1	7.83	27.4	2.6
Percent removal			**97**	**96**	**96**	**60**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2920 mg/L, Xe=3540 mg/L, Xr=14340 mg/L, SVI=70 mL/g MLSS

Table D.8. Raw data for glucose- propionic acid (50/50) mixture (SRT =10 days)

θc=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (^oC)	DO (mg/L)
t=0		0	824	48	12.4	5.7	6.52	25.1	0.2
ANAEROBIC	2	2	556	53.8	13.5	1.3	6.29	26.2	0.2
ANOXIC	1	3	571	48.2	13.9	1.8	6.27	26.6	0.1
OXIC	4.5	7.5	80	7.32	1.1	2.1	8.56	27.9	3.1
Percent removal			**90**	**85**	**91**	**63**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2780 mg/L, Xe=3080 mg/L, Xr=14140 mg/L, SVI=71 mL/g MLSS

Table D.9. Raw data for glucose- butyric acid (50/50) mixture (SRT =10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	789	52	20.5	4.8	6.89	25.2	0.29
ANAEROBIC	2	2	666	45.6	21.8	0.8	6.33	26.9	0.14
ANOXIC	1	3	652	48.2	22.5	0.7	6.25	27.6	0.16
OXIC	4.5	7.5	18	0.1	7.1	1.5	8.13	28.2	5.21
Percent removal			**98**	**99**	**65**	**69**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2700 mg/L, Xe=3000 mg/L, Xr=14000 mg/L, SVI=71 mL/g MLSS

Table D.10. Raw data for acetic acid as the sole carbon source (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	892	55	15.5	2.1	5.05	24.6	2.53
ANAEROBIC	2	2	872	54.2	17.5	1.5	5.09	25.2	0.67
ANOXIC	1	3	830	51.8	18	1.1	5.15	25.6	0.52
OXIC	4.5	7.5	57	22.3	7.2	2.2	8.11	26.2	6.82
Percent removal			**94**	**59**	**54**				

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2347 mg/L, Xe=2817 mg/L, Xr=13522 mg/L, SVI=74 mL/g MLSS

Table D.11. Raw data for acetic acid (75%) and glucose (25%) mixture (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	817	56.2	23.1	2.1	6.57	25.7	1.84
ANAEROBIC	2	2	796	42	25	1.3	6.32	27.1	0.39
ANOXIC	1	3	714	54.4	26.4	1.5	5.35	27.4	0.54
OXIC	4.5	7.5	40	3.36	6.1	2.4	8.38	27.7	4.2
Percent removal			**95**	**94**	**74**				

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2388 mg/L, Xe=2724 mg/L, Xr=13075 mg/L SVI=76 mL/g MLSS

Table D.12. Raw data for acetic acid (50%) and glucose (50%) mixture (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	755	50.6	13.4	7.4	6.35	25.7	0.3
ANAEROBIC	2	2	632	49.4	14.1	1.8	6.29	26.4	0.3
ANOXIC	1	3	594	55.2	13.8	0.7	6.26	26.1	0.1
OXIC	4.5	7.5	52	1.59	0.6	2.3	8.29	27.6	2.2
Percent removal			**93**	**97**	**96**	**69**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2760 mg/L, Xe=3000 mg/L, Xr=14400 mg/L, SVI=69 mL/g MLSS

Table D.13. Raw data for acetic acid (25%) and glucose (75%) mixture (SRT = 10 days)

θ_c=10 day	**θ_H (h)**	**Time (h)**	**COD (mg/L)**	**NH_4-N (mg/L)**	**PO_4-P (mg/L)**	**NO_3-N (mg/L)**	**pH**	**T (°C)**	**DO (mg/L)**
t=0		0	1136	53.6	20.8	5.3	7.09	26.8	0.16
ANAEROBIC	2	2	920	52.6	22.1	1.4	6.39	27	0.13
ANOXIC	1	3	824	50.2	23	0.9	6.54	27.2	0.15
OXIC	4.5	7.5	68	5.18	11	3.7	8.58	27.8	4.21
Percent removal			**94**	**90**	**47**	**30**			

So=1200 mg/L, COD/N/P=100/5/1.5, Xo=2525 mg/L, Xe=2954 mg/L, Xr=14179 mg/L, SVI=71 mL/g MLSS

APPENDIX-E

Raw Data for the Experiments with Different Wastewater Compositions

Table E.1. Raw data for the axial point 1, A_1 (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	990	92.4	3.3	3.9	7.95	13.9	5.8
ANAEROBIC	2	2	792	98	1.3	2.4	8.43	17.2	0.4
ANOXIC	1	3	693	96.8	2.4	1.5	8.06	18	0.4
OXIC	4.5	7.5	22	62.8	0.3	0.4	8.57	21.2	5.1
ANOXIC	1.5	9	18	59.5	0.5	0.7	8.33	21	0.7
OXIC	1.5	10.5	30	28	0.3	0.5	8.8	21.2	5.4
Percent removal			**97**	**70**	**91**	**87**			

So=1200 mg/L, COD/N/P=100/10/0.69, Xo=1100 mg/L, Xe=2060 mg/L, Xr=31570 mg/L, SVI=32 mL/g MLSS

Table E.2. Raw data for the axial point 2, A_2 (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	971	18.5	2	3.6	7.55	19.2	3.3
ANAEROBIC	2	2	865	19.3	1.5	2.1	7.3	19.7	0.1
ANOXIC	1	3	636	18.5	1.8	1	7.15	20	0.1
OXIC	4.5	7.5	51	0.23	0.5	1.9	8.35	21.3	4
ANOXIC	1.5	9	47	0.2	0.7	1	8.75	21.3	0.1
OXIC	1.5	10.5	42	0.1	0.2	0.9	8.43	21	4.6
Percent removal			**96**	**99**	**90**	**75**			

So=1200 mg/L, COD/N/P=100/2/0.69, Xo=1090 mg/L, Xe=1950 mg/L, Xr=26330 mg/L, SVI=38 mL/g MLSS

Table E.3. Raw data for the axial point 3, A_3 (SRT=10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	964	37	21.4	4.6	7.58	14.1	3
ANAEROBIC	2	2	762	39	20.2	1.4	7.44	18.4	0.1
ANOXIC	1	3	641	36	20.3	1	7.3	18.9	0.1
OXIC	4.5	7.5	130	0.7	10.8	1.2	8.35	21.3	4.9
ANOXIC	1.5	9	92	0.97	11.9	0.7	8.39	21.4	0.1
OXIC	1.5	10.5	62	1.3	9.7	0.7	8.71	21.2	2.4
Percent removal			**94**	**96**	**55**	**85**			

So=1200 mg/L, COD/N/P=100/3.33/2.5, Xo=1030 mg/L, Xe=1930 mg/L, Xr=26790 mg/L, SVI=37 mL/g MLSS

Table E.4. Raw data for the axial point 4,A_4 (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	997	33.4	3	5.1	7.77	12.6	2.6
ANAEROBIC	2	2	861	32	2.6	3.1	7.49	14.7	0.2
ANOXIC	1	3	777	39.6	3.2	2.8	7.29	15.8	0.3
OXIC	4.5	7.5	47	0.58	0.7	0.5	8.3	20.5	2.5
ANOXIC	1.5	9	26	1.61	1	0.2	8.16	21.1	0.5
OXIC	1.5	10.5	45	0.26	0.6	0.6	8.75	21.3	5.1
Percent removal			**95**	**99**	**80**	**88**			

So=1200 mg/L, COD/N/P=100/3.33/0.4, Xo=1910 mg/L, Xe=2860 mg/L, Xr=29810 mg/L, SVI=34 mL/g MLSS

Table E.5. Raw data for the factorial point 1, F_1 (SRT= 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1048	35.6	1.2	2.3	7.69	14.9	4.3
ANAEROBIC	2	2	773	34.8	0.8	0.5	7.82	21	0.6
ANOXIC	1	3	729	32.8	0	0.2	7.48	21.1	0.6
OXIC	4.5	7.5	57	1.29	0.4	0.7	8.81	21.3	4.4
ANOXIC	1.5	9	31	0.84	0.6	0.7	8.44	20.2	1.2
OXIC	1.5	10.5	57	0.56	0.1	0.6	8.89	20.8	5.2
Percent removal			**95**	**98**	**92**	**74**			

So=1200 mg/L, COD/N/P=100/2.3/0.46, Xo=1740 mg/L, Xe=2900 mg/L, Xr=40070 mg/L, SVI=25 mL/g MLSS

Table E.6. Raw data for the factorial point 2, F_2 (SRT= 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	986	40.2	7.2	2.5	7.71	15.4	5
ANAEROBIC	2	2	787	24.2	5.6	0.6	8.15	20.8	0.4
ANOXIC	1	3	714	23	5.3	0.8	7.57	19.7	0.4
OXIC	4.5	7.5	19	2.25	2.4	0.2	8.85	20.7	4.9
ANOXIC	1.5	9	54	1.65	2.4	0.6	8.45	20.7	0.8
OXIC	1.5	10.5	45	1.9	1.5	0.5	8.91	22	3.1
Percent removal			**95**	**95**	**79**	**80**			

So=1200 mg/L, COD/N/P=100/2.3/1.4, Xo=1730 mg/L, Xe=2890 mg/L, Xr=41220 mg/L, SVI=24 mL/g MLSS

Table E.7. Raw data for the factorial point 3, F_3 (SRT =10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1068	97.2	0.8	4.2	7.76	16	5.5
ANAEROBIC	2	2	784	67.5	0.5	1	7.96	20.6	0.6
ANOXIC	1	3	751	68.25	0.4	0.4	7.44	21.8	1.1
OXIC	4.5	7.5	42	11.9	0.3	1.5	8.61	22.8	3.7
ANOXIC	1.5	9	116	9	1.2	0.1	8.06	22.4	0.6
OXIC	1.5	10.5	37	4.4	0.1	0.2	8.74	22.2	2
Percent removal			**97**	**95**	**88**	**95**			

So=1200 mg/L, COD/N/P=100/6.3/0.46, Xo=1310 mg/L, Xe=2520 mg/L, Xr=32060 mg/L, SVI=31 mL/g MLSS

Table E.8. Raw data for the factorial point 4, F_4 (SRT= 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	949	95.2	7.9	1.9	7.81	15.6	3.4
ANAEROBIC	2	2	648	53.25	5.6	0.8	8.06	17.8	0.5
ANOXIC	1	3	626	59.5	5.5	0.6	7.84	18.6	0.3
OXIC	4.5	7.5	39	23.6	2.5	0.3	8.76	22	4.9
ANOXIC	1.5	9	15	26	1.3	0.8	8.44	22.4	0.7
OXIC	1.5	10.5	34	22	1.4	0.5	8.79	22.7	5.4
Percent removal			**96**	**77**	**82**	**74**			

So=1200 mg/L, COD/N/P=100/6.3/1.42, Xo=1570 mg/L, Xe=2490 mg/L, Xr=32630 mg/L, SVI=31 mL/g MLSS

Table E.9. Raw data for the central point, C_1 (SRT = 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1044	49.4	3.1	4.5	7.54	11	5.4
ANAEROBIC	2	2	721	32.4	1.5	0.2	8.3	22.2	0.3
ANOXIC	1	3	710	33.6	1.3	0.8	7.87	22	0.3
OXIC	4.5	7.5	29	0.25	0.3	0.5	8.79	22.5	4.6
ANOXIC	1.5	9	25	1.02	0.5	0.3	8.34	21.8	1
OXIC	1.5	10.5	27	0.35	0.2	0.6	8.85	22	5.7
Percent removal			**97**	**99**	**94**	**87**			

So=1200 mg/L, COD/N/P=100/3.33/0.69, Xo=1490 mg/L, Xe=1930 mg/L, Xr=29290 mg/L, SVI=34 mL/g MLSS

Table E.10. Raw data for the central point, C_2 (SRT= 10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	964	41.6	2.2	2.8	7.66	13.1	5.6
ANAEROBIC	2	2	663	30.6	0.8	0.3	8.11	21.4	0.7
ANOXIC	1	3	641	30.9	0.5	0.6	7.59	21.6	0.1
OXIC	4.5	7.5	32	0.32	0.1	0.4	8.57	21.1	5.7
ANOXIC	1.5	9	29	0.16	0.2	0.3	8.17	20.8	1.2
OXIC	1.5	10.5	33	0.14	0.1	0.5	8.81	21.2	6.1
Percent removal			**97**	**100**	**95**	**82**			

So=1200 mg/L, COD/N/P=100/3.33/0.69, Xo=1330 mg/L, Xe=2020 mg/L, Xr=28320 mg/L, SVI=35 mL/g MLSS

Table E.11. Raw data for the central point 3, C_3 (SRT =10 days)

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	905	34	2.5	2.9	7.81	14	5.3
ANAEROBIC	2	2	677	35.6	0.5	0.4	7.84	24.2	0.2
ANOXIC	1	3	670	31.8	0.3	0.3	7.34	28.3	0.3
OXIC	4.5	7.5	31	0.16	0.3	0.4	8.79	24.9	5.5
ANOXIC	1.5	9	29	0.35	0.3	0.5	8.34	26	0.7
OXIC	1.5	10.5	28	0.25	0.2	0.4	8.34	26	0.7
Percent removal			**97**	**99**	**92**	**86**	8.83	26.40	6.00

So=1200 mg/L, COD/N/P=100/3.33/0.69, Xo=1470 mg/L, Xe=2190 mg/L, Xr=27650 mg/L, SVI=36 mL/g MLSS

Table E.12. Raw data for testing the Box-Wilson predictions (SRT = 10 days), COD/N/P = 100/5/2

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	997	65.7	15.4	4.1	7.62	12.7	2.4
ANAEROBIC	2	2	938	52	14.1	2.6	7.62	16.3	0.1
ANOXIC	1	3	836	65.6	13.7	2	7.42	17.4	0.1
OXIC	4.5	7.5	109	13.4	6.1	1.4	8.48	20.8	4.5
ANOXIC	1.5	9	38	12.2	6.9	0.5	8.13	21.2	0.1
OXIC	1.5	10.5	47	9.3	4.8	1	8.67	21	5.4
Percent removal			**95**	**86**	**69**	**76**			

So=1200 mg/L, COD/N/P=100/5/2, Xo=1520 mg/L, Xe=2800 mg/L, Xr=27580 mg/L, SVI=36 mL/g MLSS

Table E.13. Raw data for testing the Box-Wilson predictions (SRT=10 days), COD/N/P = 100/8/1

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	957	74.8	7.9	3.3	7.78	11.3	2.6
ANAEROBIC	2	2	839	93.2	6.7	2.7	7.87	14.1	0.1
ANOXIC	1	3	781	85.2	6.3	1.7	7.59	15.9	0.1
OXIC	4.5	7.5	56	42.4	1.5	1.7	8.65	21	2.2
ANOXIC	1.5	9	43	32.2	1.9	0.8	8.34	21.1	0.1
OXIC	1.5	10.5	40	21.9	0.9	0.8	8.67	20.9	4.6
Percent removal			**96**	**71**	**89**	**76**			

So=1200 mg/L, COD/N/P=100/8/1, Xo=1810 mg/L, Xe=2710 mg/L, Xr=27480 mg/L, SVI=36 mL/g MLSS

Table E.14. Raw data for testing the Box-Wilson predictions (SRT= 10 days), COD/N/P = 100/12/3.5

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	978	151	30.3	5.8	7.83	12.5	4.8
ANAEROBIC	2	2	872	130.5	30.1	4.1	7.92	15.6	0.1
ANOXIC	1	3	826	133.5	29.6	3.2	7.68	16.4	0.1
OXIC	4.5	7.5	51	101	16.3	1.5	8.64	21.4	2.3
ANOXIC	1.5	9	100	120	16.8	0.7	8.48	21.5	0.1
OXIC	1.5	10.5	67	62.8	14.8	0.8	8.76	21.3	2.1
Percent removal			**93**	**58**	**51**	**86**			

So=1200 mg/L, COD/N/P=100/12/3.5, Xo=1280 mg/L, Xe=1770 mg/L, Xr=17170 mg/L, SVI=58 mL/g MLSS

APPENDIX-F

Raw Data for the Experiments with Different Specific Nutrient Loading Rates

Table F.1. Raw data for CODo = 600 mg/L (SRT= 10 days), COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	653	14.3	1.5	4.7	7.19	21.2	0.2
ANAEROBIC	2	2	615	8.9	0.4	0.3	7.18	23.5	0.1
ANOXIC	1	3	594	6.4	0.2	0.8	7.06	22.8	0.1
OXIC	4.5	7.5	80	0.6	0.7	0.8	8.27	24.1	4.1
ANOXIC	1.5	9	103	0.57	0.6	1.1	7.77	24.3	0.1
OXIC	1.5	10.5	6	0.01	0.05	1	8.38	23.6	4.1
Percent removal			**99**	**99.9**	**97**	**79**			

So=600 mg/L, COD/N/P=100/3.33/0.69, Xo=1420 mg/L, Xe=1700 mg/L, Xr=11800 mg/L, SVI=85 mL/g MLSS

Table F.2. Raw data for CODo= 1200 mg/L (SRT=10 days) , COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1018	34.6	2.4	3.8	7.72	13.4	3
ANAEROBIC	2	2	916	32.8	2	3.2	7.48	16.5	0.2
ANOXIC	1	3	799	30	2.5	1.4	7.12	17.9	0.1
OXIC	4.5	7.5	34	0.98	0.6	0.7	8.68	21.6	4.2
ANOXIC	1.5	9	30	0.82	0.6	0.4	7.59	21.8	0.1
OXIC	1.5	10.5	30	0.1	0.1	0.8	8.57	21.7	5.1
Percent removal			**97**	**99.7**	**96**	**79**			

So=1200 mg/L, COD/N/P=100/3.33/0.69, Xo=1780 mg/L, Xe=2280 mg/L, Xr=13540 mg/L, SVI=74 mL/g MLSS

Table F.3. Raw data for CODo = 1800 mg/L (SRT=10 days), COD/N/P= 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	1627	53	4.9	6.7	7.5	11.7	2.9
ANAEROBIC	2	2	1422	41.6	3.9	4.6	7.3	16.2	0.2
ANOXIC	1	3	1407	46.2	4	3.6	7.11	17.2	0.1
OXIC	4.5	7.5	26	0.81	2.7	0.4	8.54	21.8	4
ANOXIC	1.5	9	72	0.42	0.8	0.6	8.02	21.6	0.1
OXIC	1.5	10.5	63	0.15	0.6	0.5	8.68	21.4	2
Percent removal			**96**	**99.7**	**88**	**93**			

So=1800 mg/L, COD/N/P=100/3.33/0.69, Xo=2170 mg/L, Xe=2560 mg/L, Xr=13940 mg/L SVI=72 mL/g MLSS

Table F.4. Raw data for CODo= 2400 mg/L (SRT = 10 days), COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	2081	84	6.1	11.5	7.46	14.2	2.8
ANAEROBIC	2	2	2008	63.6	5.1	6.3	7.22	18.7	0.2
ANOXIC	1	3	1934	61.6	4.6	3.9	7.02	18	0.1
OXIC	4.5	7.5	34	0.49	0.5	0.5	8.54	21.8	1.4
ANOXIC	1.5	9	171	0.24	0.6	0.5	7.94	22.1	0.1
OXIC	1.5	10.5	55	0.17	0.5	0.9	8.71	21.7	3.6
Percent removal			**97**	**99.8**	**92**	**92**			

So=2400 mg/L, COD/N/P=100/3.33/0.69, Xo=2680 mg/L, Xe=3210 mg/L, Xr=17820 mg/L, SVI=56 mL/g MLSS

Table F.5. Raw data for CODo = 3000 mg/L (SRT= 10 days), COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	2931	79.6	8.5	8.2	7.43	15.2	3.4
ANAEROBIC	2	2	2509	78.4	7.1	19.2	7.4	19.3	0.2
ANOXIC	1	3	2347	75.6	6.5	5.3	7.01	18.8	0.1
OXIC	4.5	7.5	121	0.29	0.4	0.4	8.57	22.8	1.5
ANOXIC	1.5	9	196	0.37	0.3	0.5	7.93	22.9	0.1
OXIC	1.5	10.5	84	0.25	0.5	1.1	8.78	22.6	4
Percent removal			**97**	**99.7**	**94**	**87**			

So=3000 mg/L, COD/N/P=100/3.33/0.69, Xo=3040 mg/L, Xe=4040 mg/L, Xr=18140 mg/L, SVI=55 mL/g MLSS

Table F.6. Raw data for CODo= 3600 mg/L (SRT= 10 days), COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	3463	100	8.6	11.2	7.46	20.7	2.8
ANAEROBIC	2	2	3096	99.2	7.6	12.9	7.35	20.5	0.1
ANOXIC	1	3	2968	99.6	6.2	12	7.06	21.7	0.1
OXIC	4.5	7.5	84	0.2	0.6	1.9	8.7	23.1	2
ANOXIC	1.5	9	125	1.4	0.7	0.9	8.19	23.3	0.1
OXIC	1.5	10.5	105	0.38	0.9	0.2	8.85	23.1	1.8
Percent removal			**97**	**99.6**	**90**	**98**			

So=3600 mg/L, COD/N/P=100/3.33/0.69, Xo=3520 mg/L, Xe=4150 mg/L, Xr=20780 mg/L, SVI=48 mL/g MLSS

Table F.7. Raw data for CODo = 4200 mg/L (SRT= 10 days), COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	3526	106.5	13.5	32.8	7.53	14.9	0.2
ANAEROBIC	2	2	3453	116.5	12.5	26.6	7.28	18.8	0.1
ANOXIC	1	3	2943	97	11.5	19.2	6.99	19.2	0.1
OXIC	4.5	7.5	46	0.1	1.1	1.5	8.92	23.1	1.4
ANOXIC	1.5	9	209	0.04	2.5	1.3	8.42	23.1	0.1
OXIC	1.5	10.5	119	0.66	0.8	0.3	8.99	22.5	0.5
Percent removal			**97**	**99.4**	**94**	**99**			

So=4200 mg/L, COD/N/P=100/3.33/0.69, Xo=3640 mg/L, Xe=5720 mg/L, Xr=21480 mg/L, SVI=47 mL/g MLSS

Table F.8. Raw data for CODo= 4800 mg/L (SRT= 10 days), COD/N/P = 100/3.33/0.69

θ_c=10 day	θ_H (h)	Time (h)	COD (mg/L)	NH_4-N (mg/L)	PO_4-P (mg/L)	NO_3-N (mg/L)	pH	T (°C)	DO (mg/L)
t=0		0	4081	123.6	15.9	27.4	7.29	20.3	0.1
ANAEROBIC	2	2	3877	122.5	14.3	19.4	7.13	22.5	0.1
ANOXIC	1	3	3628	119.5	14	7	6.89	22.2	0.1
OXIC	4.5	7.5	137	0.1	2.8	0.7	8.95	23.1	2
ANOXIC	1.5	9	254	0.02	2.7	0.6	8.44	22.9	0.1
OXIC	1.5	10.5	118	1.51	2.4	1	8.99	22.8	2.1
Percent removal			**97**	**98.8**	**85**	**96**			

So=4800 mg/L, COD/N/P=100/3.33/0.69, Xo=4340 mg/L, Xe=6000 mg/L, Xr=21960 mg/L, SVI=46 mL/g MLSS