ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL IN WASTEWATER

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İZMİR

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as thesis for the degree of Doctor of Philosophy.

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ABSTRACT

Enhanced biological phosphorus removal involves design and operational modifications of the conventional biological treatment plants, incorporating an anaerobic operating phase somewhere in the process. Enhanced biological phosphorus removal systems support the growth of a biological population that has a much higher cellular phosphorus content. Discharge of phosphorus-rich waste solids from the system results in lower effluent phosphorus concentrations and higher waste sludge overall phosphorus content of 3-6 percent. Phosphorus removal capacity in an enhanced biological phosphorus removal system is mainly related to the organic matter content of the wastewater, and generally expressed as BOD/P or COD/P ratio.

In this study, of Bio-P removal processes, A/O process has been modified by adding an anoxic stage at the beginning of the system to remove the nitrate-nitrogen completely before entering the anaerobic zone. This modified process protects anaerobic stage from nitrates and hence maximizes the phosphorus removal at low sludge loading rates as well, where nitrification is unavoidable.

In the study, effect of hydraulic loading rate, organic loading rate, sludge loading rate and sludge age on enhanced biological phosphorus removal have been observed, on a piot-plant scale system fed and operated continuously with synthetically prepared wastewater. High organic matter concentrations applied to achieve high organic loading rates also resulted in the simulation of some industrial wastewaters and their treatability which are rich in phosphorus content.

Completely-mixed anoxic reactor in this system has been replaced with fixed-bed anoxic reactor in order to compare the sludge settling characteristic, which is a common problem in nutrient removal plants.

ÖZET

Biyolojik olarak fosfor giderimi, konvansiyonel biyolojik arıtma tesislerinde prosesin bir aşamasında anaerobik bir kademenin yer almasını öngören tasarıma ve işletmeye dayalı değişiklikler yapılmasını içerir. Biyolojik olarak fosfor giderim sistemleri, hücreleri içerisinde gereğinden daha fazla miktarlarda fosfor barındırabilen biyolojik populasyonların büyümesini (çoğalmasını) temin eder. Fosfor yönünden zengin bir içeriğe sahip bu hücrelerin (mikroorganizmaların) sistemden uzaklaştırılmasıyla arıtılmış çıkış suyundaki fosfor konsantrasyonu azalırken atık çamurdaki fosfor içeriği %3-6 değerlerine kadar yükselir. Bir biyolojik fosfor arıtım sisteminde fosfor giderim kapasitesi, başlıca, atıksuyun organik madde içeriğine (konsantrasyonuna) bağlıdır ve genellikle BOI/P yada KOI/P biçiminde ifade edilir.

Bu çalışmada biyolojik olarak fosfor giderim proseslerinden A/O prosesi, nitratların anaerobik kademeye gelmeden önce tamamen giderilmesi için sistemin başlangıcına bir anoksik kademe konulması suretiyle modifiye edilmiştir. Modifiye edilmiş bu proses anaerobik kademeyi nitratlardan koruması sayesinde nitrifikasyonun kaçınılmaz olduğu düşük çamur yükleme hızlarında bile maksimum düzeyde fosfor giderimini temin etmektedir.

Yapılan çalışmada, hidrolik tutulma süresi, organik yükleme hızı, çamur yükleme hızı ve çamur yaşının biyolojik olarak fosfor giderimine olan etkisi sentetik olarak hazırlanan atıksu ile sürekli besleme yapılmak suretiyle işletilen pilot tesis düzeyinde bir sistem üzerinde gözlenmiştir. Yüksek organik yüklemeler elde etmek için tatbik edilen yüksek organik madde konsantrasyonları, fosfor yönünden de zengin olan bazı endüstriyel atıksuları ve bunların arıtılabilirliğini simule etmiştir.

Bu sistemde, tam karışımlı anoksik reaktör yerine sabit yataklı reaktör konulması suretiyle, nütriyent gideren arıtma tesislerinin genel bir problemi olan çamurun kötü çökelebilirlik özelliği mukayese edilmiştir.

CONTENTS

Page

Chapter One
INTRODUCTION

Chapter Two
ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL

(Con't.)

Page

Chapter Three
EXPERIMENTAL STUDIES

Chapter Four
EFFECT OF OPERATING PARAMETERS AND CONDITIONS

Chapter Five
DISCUSSION OF RESULTS

Chapter Six
CONCLUSIONS

LIST OF TABLES

LIST OF FIGURES

(Con't.)

Page

CHAPTER ONE

INTRODUCTION

Accelerated eutrophication, loss of resources, and undesirable changes in aquatic life have been attributed to the nutrients discharged into the surface waters and thereof in recent years considerable emphasis has been placed on reducing the quantities of nutrients discharged, i.e., nitrogen and phosphorus. Moreover it is widely accepted that the effluent discharged from sewage treatment plants is one of the major sources of phosphorus emissions.

Increasing concern on phosphorus removal from wastewaters is due to the fact that phosphorus in rivers, lakes and reservoirs is the main nutrient enhancing eutrophication; very well-known that some free-living bacteria can fix the nitrogen from the air without necessitating any nitrogen supply from wastewaters.

The potential impact of discharged nutrients can best be illustrated by looking at the amounts of organic matter that can be generated in the receiving media. The biomass is generated from photosynthesis and inorganic elements, depending upon the phosphorus present in the media. Thus the discharge of 10mg/l phosphorus could potentially result in COD production equivalent to 1380mg/l, assuming algal composition can best be presented by $C_{106}H_{263}O_{110}N_{16}P$ (Randall C.W., Barnard J.L. & Stensel H.D. 1992).

It is recognized that much of the algal biomass will slowly biodegrade, but the organics will build in the bottom sediments where long-term biodegradation occurs, and it is likely that a high percentage of the oxygen demand will eventually be exerted, in that phosphorus is a conservative substance and it will accumulate within biomass in the system in repetitive cycles.

This results in the conclusion that all comprehensive eutrophication control efforts, to protect the freshwater environments, would include phosphorus removal from the discharged wastewaters. However, most treatment plants built up to now have been designed to remove only carbonaceous organic matter, and in some installations for nitrogen removal as well. Thus retrofitting the existing plants to obey the new regulations concerning nutrient discharge limitation will be unavoidable.

Phosphorus from wastewaters can be removed by physical, chemical and biological treatment methods such as crystallization in a fluidized-bed pellet reactor, magnetic separation, chemical precipitation and enhanced biological P-removal. Physical treatment methods are costly and not convenient for domestic wastewaters. The annual operating costs of enhanced Bio-P removal in sidestream are comparable with those of the simultaneous precipitation, while the costs of the fluidized-bed pellet reactor and magnetic separation are twice as much and not convenient for municipal wastewater treatment (Starkenburg W., Rensink, J.H. & Rijs G.B.J. 1993). Chemical treatment methods are more economic for wastewaters up to a population equivalence of about 100.000 (Starkenburg *et al.*, 1993). For higher population equivalents biological treatment methods are better to employ due to no need for chemicals and avoiding excess sludge production.

Chemical precipitation involves lime addition or metal salt addition (aluminum and iron) and formation of phosphate precipitates. Effluent phosphorus levels can be controlled by metal salt dosages to maximum efficiency levels while chemical cost, high sludge production with bad dewatering characteristics are the disadvantages. On the other hand, the lime addition process produces a substantial amount of sludge, even greater than with metal salt addition but very high phosphorus removal achievable. Lime addition process is not widely used because of high capital and operating costs, as well as high sludge production (Bowker R.P.G. & Stensel H.D. 1990).

Enhanced biological phosphorus removal is a recently developed technique to remove soluble phosphorus from wastewater in suspended growth activated sludge systems and seems to be most promising technique for P-removal. Sludge quantities generated by biological phosphorus removal processes are comparable to sludge production from conventional activated sludge systems and can be implemented easily at existing activated sludge plants. However, phosphorus removal performance being controlled by the BOD/TP (total phosphorus) ratio of the wastewater, requirement of highly efficient secondary clarifier performance to achieve low-level total effluent phosphorus, difficulty in retrofitting into fixed-film biological systems, and potential for phosphorus release in the sludge handling system are the disadvantages of enhanced biological phosphorus removal (Bowker & Stensel, 1990).

It is commonly accepted that COD concentration of the influent wastewater is the main factor influencing the degree of phosphorus removal in enhanced biological phosphorus removal (BPR) systems. Various researchers recommended different COD/P ratios, ranging from 15/1 to 100/1, to effectively remove phosphorus in BPR systems. It is also postulated that the presence of nitrates in the anaerobic reactor affect the phosphorus removal efficiency negatively (Barnard, 1976; Hascoet *et al.*, 1984; Rabinowitz *et al.*, 1985; Comeau *et al.*, 1985) though it is still under discussion because of the suspicious denitrifying characteristic of polyP organisms (Barker & Dold, 1996). Conflicting evidence is also coming from researchers on the effect of sludge loading rate and sludge retention time in the system; some are postulating that long sludge retention times result in decay due to endogenous respiration which in turn supply organic matter for polyP organisms (Wentzel *et al.*,1988) though others are stating that longer sludge retention times cause lower sludge production and thereby lower amount of phosphorus removal since phosphorus is removed within the waste sludge.

In the study a pilot-plant scale continuos-flow biological phosphorus removal system has been operated, with a proposed new configuration of the existing biological phosphorus removal process options. Aim of the process configuration was to protect the anaerobic stage from nitrates and hence to maximize the performance of the anaerobic reactor at high to low sludge loading rates. Aiming to remove only phosphorus from wastewater, the process is similar to A/O (anaerobic/oxic) process. However proposed process operates much better than A/O process if phosphorus removal is desired to an attainable extent, due to system's ensuring complete removal of nitrates before entering the anaerobic zone.

In the system, effect of hydraulic loading rate, organic loading rate, sludge loading rate and sludge age on enhanced biological phosphorus removal have been investigated on a proposed anoxic/anaerobic/aerobic process. High organic matter concentrations applied to achieve high organic loading rates also resulted in the simulation of some industrial wastewaters and their treatability which are rich in phosphorus content. The system has also been operated as A/O process (without anoxic stage) to see the effect of nitrates on phosphorus removal. Completely-mixed anoxic reactor in the proposed system has been replaced with fixed-bed anoxic reactor in order to compare the resulting sludge settling characteristic in the system which is a common problem in nutrient removal plants.

CHAPTER TWO

ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL

2.1 Historical Background

Although it has been stated that " In 1955, Greenburg *et al.* (1955) proposed that activated sludge could take up phosphorus at a level beyond its normal microbial growth requirements" (Bowker & Stensel, 1990, p14), some other authors stated that the phenomenon of phosphorus removal (uptake) by the activated sludge in excess of normal metabolic requirements was first observed and reported by Sniarth *et al.* (1959) in 1959 in India, although this discovery was accidental, and later in 1961 by Alaron (1961) in America (Day & Cooper, 1992; Yeoman S., Stephenson T., Lester J.N. & Perry R. 1987). However they were unable to predict any mechanism for this excess phosphorus removal. Day and Cooper (1992) stated that Levin and Shapiro (1965) were the first who investigated a mechanism based on metabolic pathways, proposing that aerated activated sludge took up P, while unaerated released P. This has been the basis for the future research activities for phosphorus removal using activated sludge process. Levin & Shapiro (1965) also postulated that aeration stimulated phosphorus uptake and prolonged aeration caused phosphorus release, implying that stored phosphorus was associated with the active fraction of the sludge and endogenous respiration was responsible for this active phosphorus release.

Among the many species available in activated sludge, *Acinetobacter Spp* have been suggested to be responsible for Bio-P removal. Buchan (1981) and Lotter (1984) postulated that significant levels of *Acinbetobacter* have been observed in biological phosphorus removal systems.

It is also postulated that microbial composition of the sludge plays an important role in Bio-P removal. Yeoman *et al.* (1987) stated that

... Wells (1969) found that a highly reactive sludge could remove phosphorus up to a rate of 65mg/liter.h, whilst other sludges could carry out the same 90% to 95% BOD removal but took up phosphorus at a rate of only <1mg/liter.h. This fast uptake was attributed to the microbial composition of the sludge.

Fuhs & Chen (1975) stated that the anaerobic zone is an elementary part of the excess phosphorus removal system to encourage the development of the anaerobic microflora which produce carbohydrates such as ethanol, acetate, and succinate which serve as carbon sources for *Acinetobacter*.

Various investigators have observed a decrease in soluble substrate and an increase in orthophosphate concentrations in the anaerobic zone of anaerobic-aerobic sequenced biological phosphorus removal systems. Hong *et al.* (1982) observed a soluble BOD_5 concentration decrease from 45 to 15 mg/l and an orthophosphate concentration increase from 6 to 24 mg/l in the anaerobic zone.

Observations on storage of carbohydrate products within biological cells as polyhydroxybutyrate (PHB) in the anaerobic zone increased the understanding of biological phosphorus removal (BPR) mechanism. PHB has been found inside the *Acinetobacter* in biologically-removed phosphorus sludges by Timmerman (1979), Nichools and Osborn (1979), Lawson and Tonhazy (1980), Deinema *et al.* (1980). Buchan (1981) reported that PHB storage in bacterial cells increased while polyphosphate granules decreased in size in the anaerobic zone of biological phosphorus removal systems.

It has been stated that the generally accepted theory for biological phosphorus removal involved sequential anaerobic-aerobic stages resulting in a competitive substrate utilization and selection of phosphorus-storing microorganisms (Marais Gv.R., Loewanthal R.E. & I.P. Siebritz, 1992; Stensel H.D. 1982).

Several models with regard to the biochemistry of the process have been developed in the last twenty years, but two of them have been widely accepted; by Wentzel *et al.* (1986) based on

Comeau *et al.* (1985), and Mino *et al.* (1987) which was later modified by Wentzel *et al.* (1991). Also two different mechanisms with regard to the transport of acetate through the cellular membrane has been proposed; Marais *et al.* (1983) and Abu-ghararah & Randall (1990) suggested the existence of an active transport in which acetate enters the cell at the expense of ATP, while Wentzel *et al.* (1991) claimed that acetate is transported by means of a diffusion process.

2.2 Bio-P Removal Mechanism

Biological P-removal techniques are based on the principle that certain bacteria are able to accumulate phosphates in their cells, provided that right conditions are ensured. ***Acinetobacter*,** an organism normally present in activated sludge, is able to store phosphates more than required for cell synthesis. However, *Acinetobacter Spp* is available in low amounts in activated sludge and hence an anaerobic stage is incorporated to increase the amount of phosphorus-removing organisms.

Bio-P removing organisms require low weight volatile fatty acids as a sole carbon source in anaerobic phase to store in their cells as poly-ß-hydroxybutrate (PHB). Hence anaerobic conditions provide the right environment for acidic fermentation to convert complex organic molecules to low-weight volatile fatty acids (VFAs). Under these circumstances facultative anaerobic bacteria produce low fatty acids, and in the subsequent aerobic phase phosphates are stored by *Acinetobacter Spp* as energy-rich polyphosphate granules. When the sludge is returned to the anaerobic phase, the beginning of the BPR system, polyphosphates degrade and release energy by way of ATP. Using the energy liberated by hydrolysis of polyphosphates, low weight fatty acids are taken up and stored as PHB in bacterial cells.

During the following aerobic zone *Acinetobacter* metabolizes the stored material via oxidation and synthesis of new cells. This cycle repeats itself until the point when after an aerobic zone the polyphosphate accumulated in *Acinetobacter* is discharged with the surplus sludge. It can be concluded that the more volatile fatty acids there are in the anaerobic zone, the higher is the P-release, the more is the growth of *Acinetobacter* and hence the more P-removal occurs.

2.3 Factors Affecting Bio-P Removal

There are many factors that affect the phosphorus removal efficiency in BPR systems. These factors are related to wastewater characteristics, system design and operational methods, and thereof improving the removal efficiency is to a large extent is under the control of the design engineer.

i. Wastewater characteristics (BOD/P ratio)

Wastewater begins to be fermented following its delivery into the sewer system and limited amount of acetate is produced. However organic content of wastewater, biodegradable ratio of organic matter, temperature and transportation time in the sewer influence the fermentation process. Figure 2.1 represents the portion of volatile fatty acids in a raw domestic wastewater.

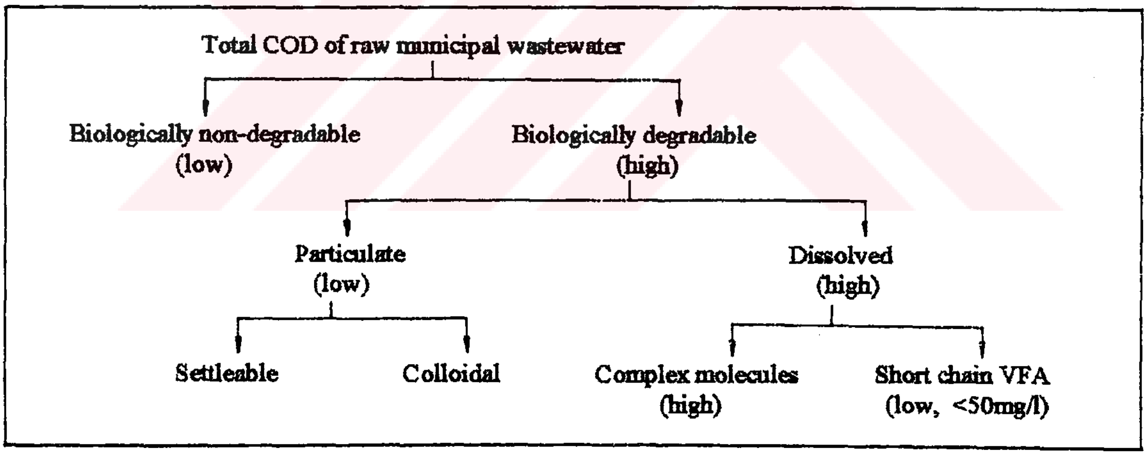

Figure 2.1 Schematic Representation of Organic Matter Composition in Raw Domestic Wastewater

The amount of phosphorus that can be removed in an enhanced biological phosphorus removal system is a function of the volatile fatty acids available. Since all of the sewage organics are not available for BPR, the COD utilized to P removal ratio increases. Fortunately sewage fermentation results in formation of primarily acetic acid, the most readily consumed substrate by phosphorus-removing organisms.

Ekama and Marais (1984) stated that COD consumption during biological phosphorus removal for municipal wastewater is about 50 to 59 mgCOD/l per mg/l of phosphorus removed.

Tetreault *et al.* (1986) have recommended a TBOD/TP (total BOD to total P) ratio of greater than 20-25 to achieve an effluent soluble phosphorus concentration below 1.0 mg/l.

Groenestijn *et al.* (1985) and Nicholls *et al.* (1984) stated that,

...pure cultures of acinetobecter yielded o.42g solids/g acetate, with a phosphorus content of 6-10 percent. If cell phosphorus content is assumed 10%, then 1 g of phosphorus requires 25 g of HAc, yielding an approximate BOD/P ratio of 17/1.

...COD/P ratio in the range of 20-30 may provide an effluent P concentration less than 1 mg/l in short sludge retention times.

...Hong et al. (1980) have recommended an influent SBOD/SP (soluble BOD to soluble P) ratio of at least 15 to achieve low level effluent phosphorus concentrations in short SRT, and if SRT increases BOD/P ratio should increase as well.

Yeoman *et al.* (1987) stated that favorable BOD or COD to phosphorus ratios required for effective enhanced biological phosphorus removal have been suggested by various researchers as follows:

Reference	COD/P Ratio
Bates & Trobian (1981)	>100/1
Raper (1983)	>100/2
Maier et al. (1985)	>100/1 (BOD/P)
Arvin et al. (1985)	>100/1
Vinconneau et al. (1985)	>100/2
Tseyen et al. (1985a)	>100/3

However, these ratios are poor for enhanced biological phosphrous removal because a BOD_5/P ratio of 100/1 is already required for the biological oxidation of organic substances by activated sludge microorganisms in a conventional treatment system.

ii. Nitrate-nitrogen in the anaerobic zone

Barnard (1976) was the first researcher who pointed out that nitrate-nitrogen in anaerobic zone reduces the phosphorus removal efficiency of the system, depending upon the amount of nitrate present. However he attributed this to an increase in the redox potential of the reactor. Comeau *et al.* (1985) also noted that the presence of nitrates reduces the phosphorus removal capacity and proposed another mechanism, implying that nitrates are used as oxygen source by BiO-P organisms in the anaerobic phase, performing aerobic metabolism. An improved understanding indicated that nitrate reduction in the anaerobic zone utilizes substrates that would otherwise be available to phosphorus-storing microorganisms. Supporting this idea, Hascoet *et al.* (1984) reported that in the anoxic stage *Acinetobacter* released phosphorus provided that substrate availability was in relatively high levels.

Rabinowitz (1985) in his batch test experiments using acetate as substrate observed that the denitrification of nitrate in the anaerobic stage had the effect of reducing the availability of substrate for phosphorus release. He added that substrate consumption for denitrification was found to be 3.6 mg/l per mg/l nitrate-nitrogen reduced.

Ekama and Marais (1984) stated that 8.6 mgCOD/l of municipal wastewater is needed to reduce 1 mg/l of nitrate-nitrogen to nitrogen gas.

Nutrient Control (1983) stated that 5.0 mgSCOD/l reduced 1 mgNO_3-N/l for complete denitrification in an anoxic-aerobic pilot-plant system treating domestic wastewater.

Kang *et al.* (1985) stated that even though the average effluent nitrate nitrogen concentration ranged from 6.7 to 11.6 mg/l, the effluent soluble phosphorus concentration was consistently below 1.0mg/l which was attributed to a high BOD/P ratio.

Tetreault *et al.* (1986) also stated that relatively high influent BOD/P ratio produced low effluent soluble phosphorus concentrations.

Simpkins and McClaren (1978) reported a total phosphorus removal efficiency reduction from 90 to 55 percent in a Modified Bardenpho Process when the effluent nitrate-nitrogen concentration increased from 4.0mg/l to 6.7 mg/l.

Vinconneau *et al.* (1985) showed that the effluent total phosphorus concentration decreased from 2.0 to 0.9 mg/l as the effluent nitrate-nitrogen decreased from 3.4 to 0.6 mg/l at similar influent BOD/P ratios and operating F/M loadings.

Yeoman et al. (1987) stated that,

...Barnard (1984a) disputed the applications of these guidelines, suggesting that the COD/TKN (total Kjedahl nitrogen) ratio was unimportant provided there was a sufficient concentration of volatile fatty acids in the influent to the anaerobic zone.

Dold and Barker (1996) stated that conflicting evidence exists in the literature concerning the fate of nitrates in enhanced biological phosphorus removal systems. Dold and Barker (1996) pointed out that some researchers proposed that the polyP organisms are unable to utilize nitrate as an electron acceptor and there is no competition for substrate between polyP and non-polyP organisms under anoxic conditions though others postulated that in contrast a significant fraction of the polyP organisms can use nitrate as an electron acceptor in the absence of oxygen for oxidation of stored PHB and simultaneous uptake of phosphorus.

iii. Organic loading rate

It has been stated that a high organic loading rate is required in terms of readily biodegradable substrate for good excess phosphorus removal (Barnard, 1976).

Yeoman *et al.* (1987) stated that,

...in pilot plant experiments, the addition of 100mg/l acetic acid to dilute wastewater, i.e. at low sludge loadings, improved phosphorus removal to >90% (Rensink et al., 1985).

...Kerdachi & Roberts (1983) postulated that high loading rates contributed to enhanced natural precipitation and adsorption of phosphorus compounds.

iv. Sludge loading rate and sludge age

Maier *et al.* (1984) found in pilot plant studies that the rate of phosphorus uptake per unit of mixed liquor solids decreased by a factor of 2.6 as the F/M loading was decreased from 0.2 to 0.1kgBOD/kgMLVSS.d. Tracy and Flammino (1985) reported that for identical influent TBOD/TP ratios of 16, the rate of phosphorus uptake in the aerobic zone decreased by a factor of 3 as the F/M loading was decreased from 0.44 to 0.24 kgTBOD/kgMLVSS.d in bench-scale studies.

These findings indicate that operation at lower SRT values will decrease the efficiency of phosphorus removal per unit of BOD removed.

To maximize biological phosphorus removal, systems should not be operated with SRT values in excess of that required for overall treatment needs. Systems that require nitrification and denitrification and extended aeration systems promoting sludge stabilization will require much higher influent TBOD/TP ratios to produce soluble phosphorus concentrations below 1.0mg/l.

Long sludge retention times affect biological phosphorus removal negatively, causing a lower sludge production which results in a lower amount of biological phosphorus removal, since the phosphorus is removed within the waste sludge.

Barth and Stensel (1981) suggested a TBOD/TP removal ratio of 33 at an SRT of 25 days and a ratio of 25 at an SRT of 8 days. Fukase *et al.* (1984) found in an anaerobic-aerobic pilot plant system treating municipal wastewater that the TBOD/TP removal ratio increased from 19 to 26 as SRT was increased from 4.3 to 8.0 days and at the same time the phosphorus content of activated sludge decreased from 5.4 to 3.7 percent. They claimed that the phosphorus removing organisms are not affected by SRT, which at present has not been verified or refuted, less phosphorus removal is just due to less sludge production.

Some authors postulated that factor affecting Bio-P removal is nitrate, not sludge age or sludge loading rate, in BPR systems. Starkerburg *et al.* (1993, p320) stated that "sludge load and sludge age are both indirect factors which affect biological P-removal. A high sludge load or a low sludge age means a low degree of nitrification and thus a low nitrate concentration".

Wentzel *et al.* (1988) stated that SRT plays an insignificant role in P-removal since Bio-P organisms have a low endogenous decay rate of $0.05d^{-1}$, as opposed $0.24d^{-1}$ for normal heterotrophic organisms, and he added that at longer MCRTs active organic mass from decayed heterotrophic organisms will be taken up by *Acinetobacter*, with a resultant higher phosphate content.

v. Anaerobic retention time

Anaerobic retention time should be higher than 2 hours for phosphorus release and subsequent uptake for domestic wastewaters (Fuhs & Chen, 1975). Deakeyne *et al.* (1984) and Beccari *et al.* (1985) claimed that anaerobic retention times less than 4 hours are sufficient for excess phosphorus removal from municipal wastewaters.

Yeoman *et al.* (1987) stated that,

...Gerber and Winter (1984) ... achieved high phosphorus removals when the anaerobic retention time was increased 6 to 12h or longer.

...a longer anaerobic retention time increased phosphorus removal by 30% to 40% (Rensink et al., 1985).

..Malnou et al. (1984) observed the complete aerobic uptake of phosphorus, irrespective of the previous anaerobic retention time.

...T'Seyen et al. (1985a) postulated that shorter anaerobic retention times produced more acetate for phosphorus removing bacteria. ...the addition of a second anaerobic reactor doesn't influence the biological mechanism of phosphorus removal, but appears to enhance chemical precipitation (Ramadori et al., 1985).

vi. Aerobic retention time

Aerobic conditions entail the uptake of soluble phosphorus. However no definitive field study has been done to evaluate the effect of hydraulic retention time in aerobic reactor, though some batch studies indicated that 1-2 hours seems a feasible operating range (Sedlak, 1991).

Activated sludge systems are mainly for BOD removal, as well as for nitrification, and overaeration and long hydraulic retention times in the aerobic zone are believed to release phosphorus into solution and thereof the effluent.

vii. Wastewater temperature

Temperature has effect on both storage and release of phosphates of BiO-P organisms. Increasing temperature increases the phosphate releasing capacity and decreases the phosphate storage capacity of the Bio-P organisms.

Shapiro (1967) showed that the specific phosphorus release rate for a batch activated sludge increased by a factor of 5 as the temperature increased from 10°C to 30°C.

It is claimed that phosphorus removal was approximately 40 percent higher at 5°C with effluent discharge of 0.8mg/l, compared to when the system was operated at 15°C or above (Sell *et al.*, 1981; Vinconneau *et al.*, 1985).

Sedlak (1991) stated that the phosphorus content of the sludge at 5°C operation was 4.7 percent compared to a range of 3.5 to 4.9 percent for higher temperature.

vii. pH in aerobic zone

It has been stated that most biological phosphorus removal occurs at pH values from 7.5 to 8.0.

Groenestijn and Deinema (1985) observed that the maximum specific growth rate of a strain of Acinetobacter was 42 percent higher at a pH of 8.5 compared to that at pH of 7.0.

Tracy and Flammino (1985) studied the effect of pH on the specific phosphorus uptake rate (gP/gVSS.hr) in the aerobic phase. They claimed that phosphorus uptake rate declined steadily below a pH of 6.5 and duplicated as the pH is increased.

Levin & Shapiro (1965) added lime and an increase in pH from 8 to 9 during aeration reduced phosphorus removal.

Nagashima *et al.* (1979) stated that phosphorus removal was improved from 42 to 92 percent as the pH was increased from 5 to 8.

ix. pH in anaerobic zone

Acidification of sludge results in the release of phosphorus, which led to a proposed treatment flow scheme of exposing return sludge to acidic conditions and stripping of phosphorus.

Fuhs and Chen (1975) and Deinema *et al.* (1984) stated that lowering the pH in anaerobic phase, by adding carbon dioxide, promoted phosphorus release rate significantly.

Levin & Shapiro (1965) reported that orthophosphate secretion from sludge microorganisms occurred between pH 5 and 6. The requirement of a low pH (<6) has also been demonstrated by Milbury *et al.* (1971).

x. Dissolved oxygen

The effect of dissolved oxygen in the anaerobic zone is explained by the same fundamental mechanisms as nitrate addition. In the presence of oxygen, aerobic microorganisms will oxidize organic matter containing fatty acids, thus reducing its availability for the uptake by *Acinetobacter*. Particular attention should therefore be paid to reducing sources of dissolved oxygen such as in the wastewater and from the return activated sludge.

High dissolved oxygen concentration plays a positive role for the uptake of phosphates in the aerobic zone. It is suggested that phosphorus uptake in aerobic zone occurs when the dissolved oxygen concentration is above 2mg/l in plug-flow systems.

xi. Metal ions

It is suggested that metal ions are required by the phosphate storing organisms for the formation of complexes of polyphosphates with mono and divalent ions within cells (Groenestijn and Deinema, 1985; Randall ***et al.***,1992; Patterkine ***et al.***, 1991; Buchan 1981).

Yeoman *et al.* (1987) stated that,

...In a laboratory-scale activated sludge system, Mg^{2+} and Ca^{2+} were released, together with phosphorus, probably as a result of the change in the concentration and electrochemical gradient across the cell membrane, arising from polyphosphate hydrolysis, subsequently increasing the negative charge inside the cell (Potgieter & Evans, 1983).

Patterkine *et al.* (1991) stated that cation concentrations in low amounts in a case study didn't influence the biological phosphorus removal.

xii. Reactor type

It has been stated that biological phosphorus removal plants should be operated in a plug flow mode (Vacker ***et al.***, 1967; Milbury ***et al.***, 1971).

Existing plants can be retrofitted by the addition of baffles into anaerobic and aerobic zones. Yeoman ***et al.*** (1987) stated that 80% or more of phosphorus from municipal wastewater has been removed operating with a four-baffled plug flow aerobic reactor and completely mixed anaerobic reactor.

2.4 Bio-P Removal Process Configurations

Biological phosphorus removal is a technique of designing suspended growth activated sludge systems to remove phosphorus from wastewater. Main process variations on this phenomenon have been described below: These processes can be classified as substream and mainstream processes, in which Phostrip is the only substream process while all the other developed processes are mainstream processes.

Phostrip Process

Phostrip Process was first proposed by Levin and Shapiro (1965) in 1965. This process takes a sidestream from the return activated sludge and that recycle is subjected to anaerobic condiditons. Anaerobic conditions lead to phosphorus release, which is subsequently precipitated with lime. Since only 20 to 30 percent of the plant flow passes through the anaerobic stage, the amount of lime required is much less than the amount of lime required in a mainstream system, resulting in less sludge production. Hence Phostrip Process combines both biological and chemical phosphorus removal methods and effluent concentrations of less than 1mg/l total phosphorus can be achieved, with less dependence on the BOD strength of the influent wastewater (Figure 2.2a).

A/O Process

The A/O (anaerobic/oxic) process is generally designed as a high-rate, non-nitrifying activated sludge system and only phosphorus is removed from the effluent. Relatively short design SRT and high design organic loading rates result in greater sludge production and more phosphorus removal per unit of COD removed in the system (Figure 2.2b).

Bardenpho Process

Barnard (1973) observed excess phosphorus removal in a pilot plant with two anoxic zones in a four-stage plant and thereof the first biological nitrogen and phosphorus removal plant, known as the Bardenpho, was developed.

The second anoxic zone is for complete denitrification. The mixed-liquor passes through short reaeration zone after the second anoxic zone to enable the mixed liquor to remain aerobic during settlement (Figure 2.2c).

Phoredox Process

The five stage process configuration called Pheredox or the Modified Bardenpho Process, increases P removal by reducing the concentration of nitrates entering the anaerobic zone.

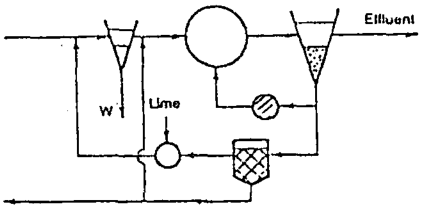

Figure 2.2a Phostrip Process

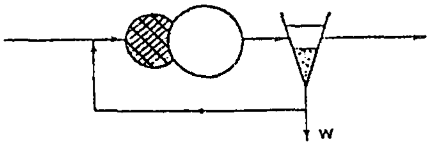

Figure 2.2b A / O Process

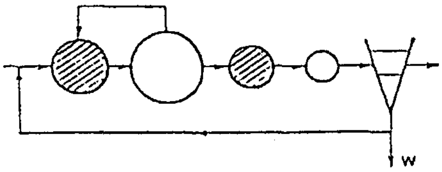

Figure 2.2c Bardenpho Process

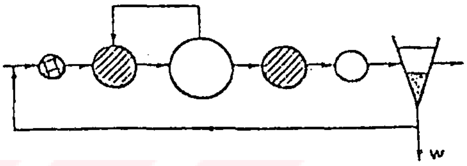

Figure 2.2d Phoredox Process

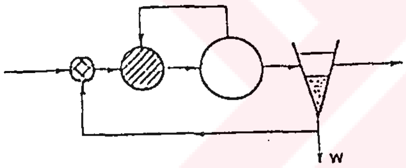

Figure 2.2e A^2 / O Process

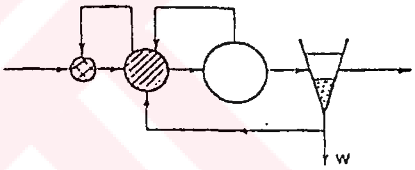

Figure 2.2f UCT Process

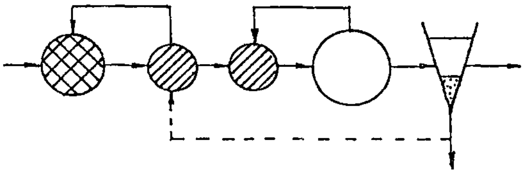

Figure 2.2g Modified UCT Process

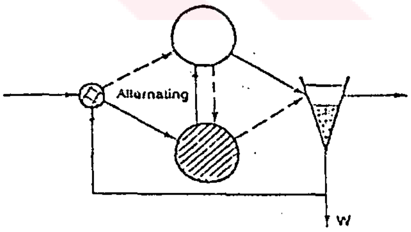

Figure 2.2h Bio-Denipho Process

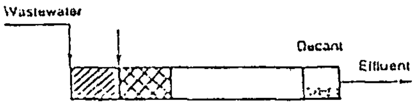

Figure 2.2i Sequenching Batch Reactor Process

⊗ Anaerobic
▨ Anoxic
○ Aerobic
W Waste sludge

Figure 2.2 Process Options for Suspended Biomass Biological Phosphorus Removal

Pheredox Process is generally designed at relatively low overall loading rates due to nitrification and denitrification (Figure 2.2d).

A^2O Process

A^2/O Process (anaerobic/anoxic/oxic) process is also termed as three-stage Bardenpho Process or Modified Phoredox Process which incorporates an anoxic stage for denitrification between the anaerobic and aerobic stages in its flowscheme.

The low rate of denitrification in the second anoxic zone in Phoredox Process, due to low organic material concentrations, led to the development of the three-stage process in which the final two zones were eliminated (Figure 2.2e).

UCT Process

A further modification of the Modified Bardenpho Process developed at the University of Capetown in South Africa has been termed UCT Process, aiming at eliminating all recirculation of the nitrates and dissolved oxygen in the return sludge to the anaerobic zone. It is claimed to operate at low COD/P ratios (Figure 2.2f).

VIP (Virginia Initiative Plant) is a UCT-type process operated as a staged reactor (at least two cells per zone), with a short hydraulic retention time and low sludge age with the capacity of reducing the concentration of phosphorus in the effluent to approximately 1 to 2 mgP/l.

Modified UCT Process

In Modified UCT Process, the first anoxic zone is designed to reduce only the nitrate-nitrogen in the return activated sludge. The second anoxic zone is designed for complete removal of nitrates from the effluent (Figure 2.2g).

Bio-Denipho Process

Bio-Denitro Process is based on biological nitrification and denitrification in a one-sludge activated sludge system. Two tanks serving as alternate anoxic and aerobic zones, with one permanent anaerobic zone at the head of the plant, termed as Bio-Denipho Process (Figure 2.2h).

SBRs and Other Process

Sequencing batch reactors, rotating biological contactors (RBCs), biological filters, and submerged aerated biological filters are also under investigation for enhanced phosphorus removal.

Sequencing biological reactors use essentially the same principle as the Bio-Denipho but alternating the conditions as anaerobic, anoxic, aerobic in one or more reactors each capable of treatment and settlement. Each reactor (or period) processes waste through a series of five periods, consisting of fill, react, settle, draw and idle (Figure 2.2i).

RBCs and biological filters can also be adapted for biological P-removal. This would entail the provision of anaerobic/anoxic zones and the recycling of solids. A difficulty is apparent in guaranteeing anaerobic, anoxic and aerobic conditions in the attached biomass biological filters, however the basic principles can be applied.

2.5 Bulking Sludge Control in Nutrient Removal Plants

"Sludge bulking" doesn't have a scientific definition and is generally expressed by Sludge Volume Index (SVI). Sludge settling is measured by different approaches in the international community as: Sludge Volume Index (SVI_{30} and SVI_{60}), Settled Sludge Volume (SSV_{30}), Stirred SVI (SSVI) and so on. Though these procedures need to be universally standardized, SVI_{30} is the most commonly used technique for expressing sludge settling.

Sludge bulking is due to excessive growth of filamentous microorganisms. Though the occurrence of non-filamentous bulking is not commonly reported, bulking exhibiting a slime or jelly-like characteristic of the sludge solids are apparent (Hale and Garver, 1983).

The main cause of filamentous bulking is attributed to specific environment that supports the filamentous growth. A change of 5-10% of the sludge mass from non-filamentous to filamentous species can produce a bulking condition, without the need to be the dominant mass in the sludge (Randall *et al.*, 1982). High to low F/M, high and low DO, fresh and septic wastewater have caused the growth of filamentous organisms.

The design of biological reactor (as CFSTR or PFR) as well as the environment maintained within the biological reactor are the main causes of sludge bulking.

Growth of bulking sludge is also linked to the presence of soluble substrates, more specifically the presence of low molecular weight soluble substrate, in the aerobic reactor (Randall *et al.*, 1992).

Growth of bulking sludge is linked to the absence of adequate mineral nutrients as well.

Latest regulations required also the nitrogen and phosphorus removal from wastewaters, which require much higher SRTs in the system than are necessary for carbonaceous BOD, resulting in bad sludge settling characteristics in the settling tank, which appears to be more common to nutrient removal plants. Though 50ml/g is a typical value of Sludge Volume Index for well-operated some biological phosphorus removal systems, it increases to about 120ml/g with the incorporation of nitrogen removal into the system (Randall et al.1992).

Until recent years, use of chlorine or peroxide were the only effective methods to suppress the growth of filamentous organisms in the system.

The use of fixed-film reactors; trickling filters and rotating biological conductors gives better results for the control of bulking organisms. However, at present, fixed-film reactors are not quite well-known systems for nutrient removal, though intensive research studies are going on.

Another newly developed technique for sludge bulking control is the use of selectors that promote the growth of non-filamentous organisms such as the use of fully oxic systems, aerated low DO systems, anoxic selectors, anaerobic selectors, and intermittent feeding systems.

Anaerobic and/or anoxic zones placed ahead of aerobic zones act as biological selectors and discourage the growth of filamentous organisms, resulting in improved sludge settling properties. Regarding anoxic selectors, Shao and Jenkins (1989) stated that the design of the anoxic selector should provide for a SCOD of less than 100mg/l to ensure bulking control.

2.6 Approaches to Improve Bio-P Removal Efficiency

i. Addition of a digester

Soluble BOD content of many municipal wastewaters vary 40 to 60 % of the total BOD in the wastewater. Thus a considerable amount of organic matter exists in the particulate form that may be convertible to VFAs.

To improve the production of VFAs, settled solids from the primary settling tank can be fed to a digester with high organic loading rates to encourage only acid fermentation.

Eastmen and Ferguson (1981) stated that three-day solids retention time in primary sludge fermentation reactor is necessary for conversion to VFAs. They also claimed that only 30 percent of the primary solids could be converted to VFAs, since a large fraction of the solids (40%) were lipids, that could not be broken down under acid fermentation conditions.

Rabinowitz and Oldham (1985) stated that a SRT range of 3.5 to 5.0 days was optimal for primary sludge fermentation.

Sedlak (1991) stated that fermented primary clarifier sludge fed to the Bardenpho system decreased the effluent phosphorus concentration to 0.5mg/l.

ii. Filtration of effluent suspended solids

The overall performance of biological phosphorus removal is also affected by the effluent suspended solids concentration. Since phosphorus is stored in microbial solids, wasting of these solids in effluent decreases removal efficiency. This is more critical for the mainstream processes because the mixed-liquor suspended solids (MLSS) produced in these systems are higher in phosphorus content than the Phostrip Process.

If the effluent total phosphorus concentration requirement is less than 1.0mg/l, and the phosphorus content of the MLSS is 5 percent, the effluent TSS concentration has to be 10mg/l or less if the effluent soluble phosphorus concentration is assumed to be 0.5mg/l. The greater the ratio of phosphorus to solids, then the more critical solids removal occurs.

Since effluent filtration removes only phosphorus-containing solids, if the phosphorus has not been accumulated within the cells of bacteria during biological treatment then effluent filtration will have no effect on the soluble phosphorus.

iii. Chemical precipitation

Experience with the operation of full-scale biological removal systems shows that effluent total phosphorus concentrations of less than 1mg/l are not always achieved. Therefore in many cases some chemical addition (metal salts like alum) becomes necessary to meet effluent phosphorus limits.

iv. Treatment of sludge

Sludge treatment at biological phosphorus removal plants must avoid the recycling of phosphorus to the activated sludge plant. To achieve this, sludge is quickly treated maintaining aerobic conditions to prevent phosphorus release into solution.

Sludge from biological phosphorus removal plant must be thickened by dissolved air flotation, and further treatment prior to sludge disposal must involve either aerobic stabilization or dewatering or both.

Anaerobic digestion should be avoided if sludge or supernatant is recycled because of the lysis of bacteria cells, releasing phosphorus into solution (Day & Cooper, 1992).

It should be kept in mind that sludges from phosphorus removal plants have a high fertilizer value because of the high phosphorus content.

2.7 Retrofit Considerations of the Existing Treatment Plants

The high influent COD/P ratio favors the selection of a mainstream process. On the other hand, wastewaters with a low influent COD/P ratio favor the selection of Phostrip Process, chemical treatment alternatives, or a mainstream process coupled with primary sludge fermentation.

Phostrip process can readily be adapted in retrofitting existing facilities, because of its sidestream feature. The design features for retrofitting are similar to the design aspects of a new facility. A/O Process or Modified Bardenpho Process could be a design choice for mainstream retrofit alternatives.

It is quite simple to modify the existing system to operate in the A/O Process. Modified Bardenpho Process is preferable if high level of nitrogen removal, in addition to COD and phosphorus removal is required, while UCT and A^2/O processes are employed for a lesser degree of nitrogen removal.

Many plants can be easily modified to create fermentation zones by turning off the selected aerators and adding mixers at the head of the plug flow aeration basins for retrofitting purposes. However, the hydraulic and physical arrangements of the specific plant will also be a factor in selecting the most economical modification. Though the choice of the retrofit system will depend on wastewater characteristics, treatment objectives and economics, biological removal retrofit design should be compared to the chemical treatment alternatives in all cases.

CHAPTER THREE

EXPERIMENTAL STUDIES

3.1 Employed Process Option

In this study, a pilot-plant scale continuous flow biological phosphorus removal (BPR) system has been operated, with a new configuration of the existing biological phosphorus removal process options. Aim of the developed process configuration was to protect the anaerobic stage from nitrates and hence to maximize the performance of the anaerobic reactor at high to low sludge loading rates. Aiming to remove only phosphorus from wastewater, the process is similar to A/O process (anaerobic/oxic). However employed process operates much better than A/O process if phosphorus removal is desired to an attainable extent, due to system's ensuring complete removal of nitrates before entering the anaerobic stage (Figure 3.1).

The system has been fed with synthetically prepared wastewater. Daily prepared wastewater has been pumped from raw wastewater reservoir to the system, consisting of anoxic-anaerobic-aerobic and settling units. Processes occurring in each unit of this system can be schematized as illustrated in Figure 3.2 & Figure 3.3.

Synthetic wastewater has been prepared by adding acetic acid to the raw wastewater reservoir, previously filled with tap water, and then neutralized with sodium hydroxide.

Urea (NH_2CO) has been added to the reservoir as N-source, and potassium dihidrogen phosphate (KH_2PO_4) as P-source. Some other elements have also been added in trace amounts (Ca<6mg/l; Mg<2mg/l; Fe <0.1mg/l and Mn<0.1mg/l).

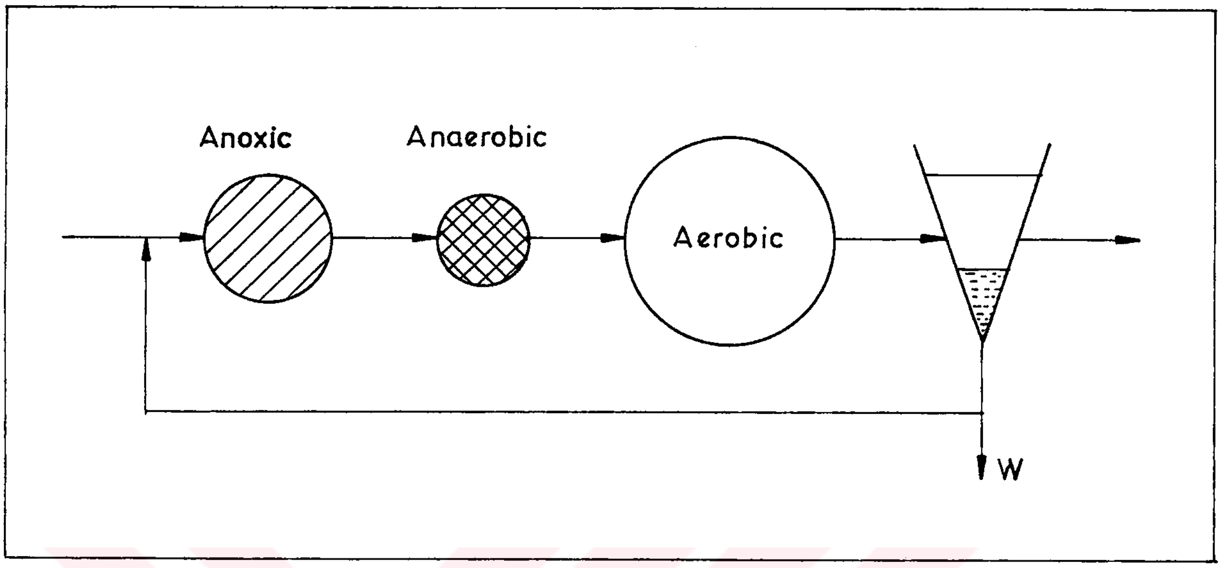

Figure 3.1 Flow Diagram of the Anoxic/Anaeroic/Aerobic Process

Before adding HAc to the reservoir, each time sodiumthiosulphate ($Na_2S_2O_3$) has been added to the stored tap water in the reservoir and agitated for a few minutes in order to remove the free chlorine present in the tap water.

Acetic acid is a weak acid and dissociates completely when NaOH is added in stoichiometrically computed amounts, and then acetate becomes available to microorganisms. Theoretically chemical oxygen demand of acetate can be computed by considering the following chemical equation: this equation also states that chemical oxygen demand of the synthetically prepared wastewater of acetate organic compound is equal to ultimate biochemical oxygen demand of that compound (Haandel, 1994).

$$CH_3COOH + 2O_2 \longrightarrow 2CO_2 + 2H_2O$$

In the system, aerobic reactor has been operated as completely-mixed reactor aerated by diffused aeration, which also provided mixing. Anaerobic reactor has been mixed slowly by a mechanical mixer without creating any surface renewal in the liquid-air interface.

Anoxic reactor was a fixed-bed reactor filled with plastic pipes cut into irregular shapes with an average of 5cm length and 3cm diameter. Anoxic reactor has also sometime been operated as completely-mixed reactor by using a mechanical mixer in order to compare the sludge settling

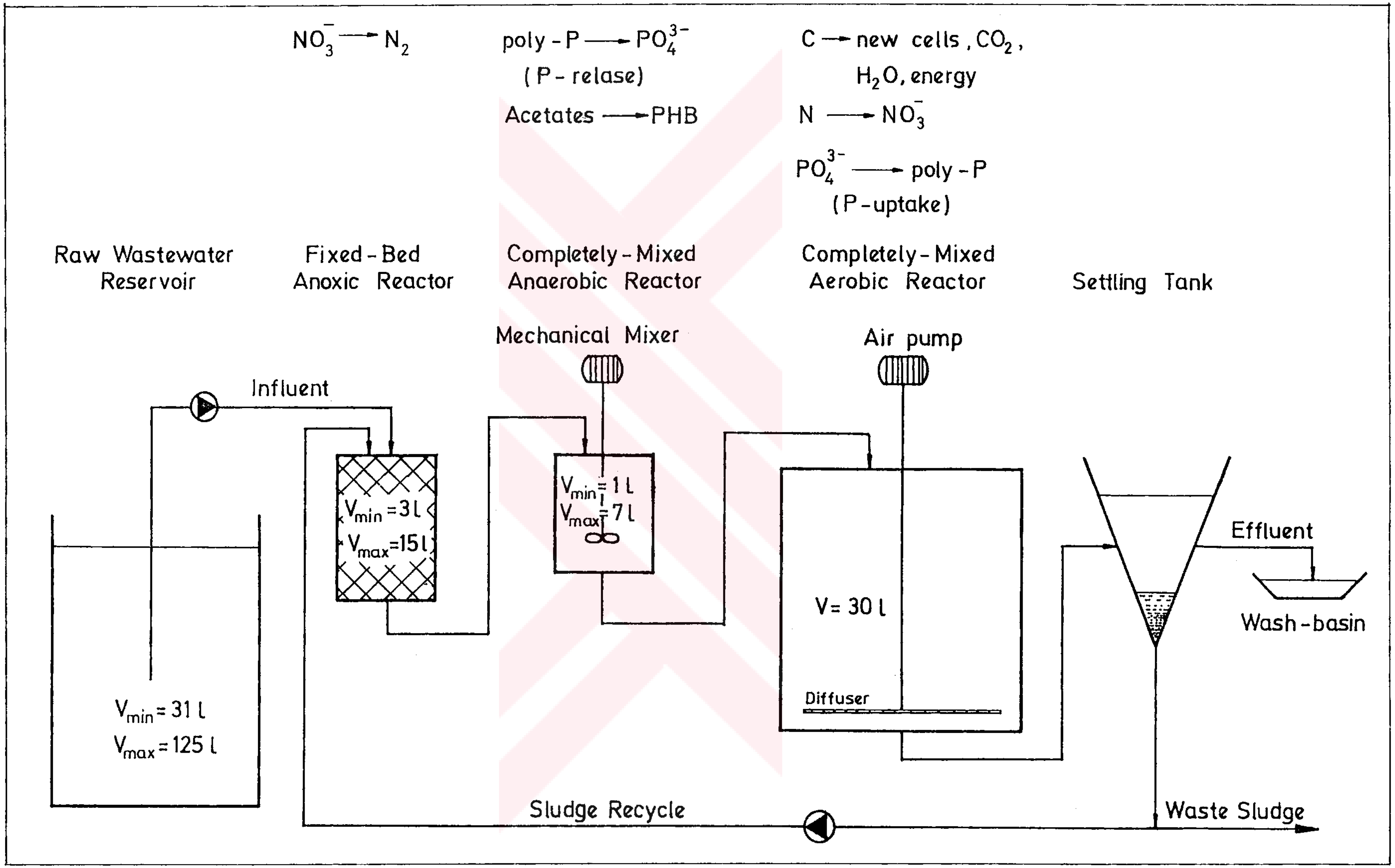

Figure 3.2 Schematic of the Experimental Set-Up for Anoxic/Anaerobic/Aerobic Process.

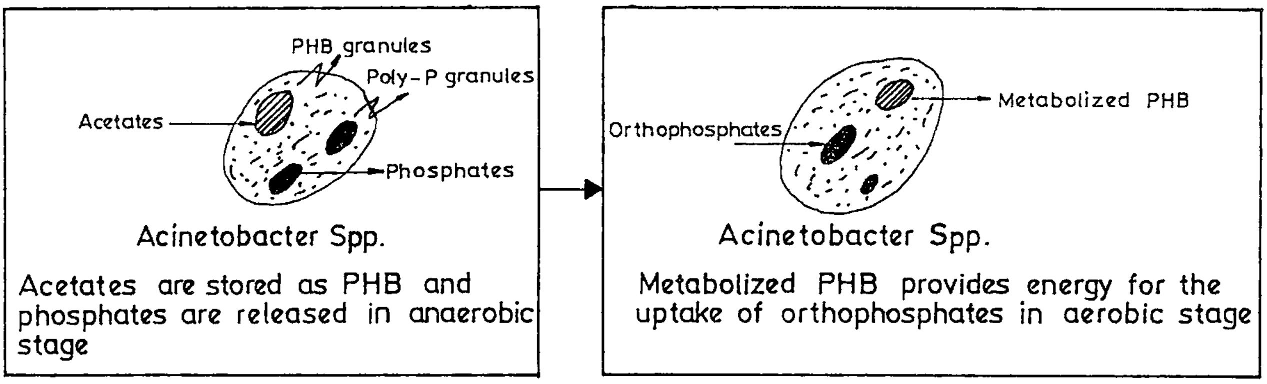

Figure 3.3 Biological P-Removal Pathway of *Acinetobacter Spp.*

(sludge volume index) results with that of the system's operated with fixed-bed anoxic reactor and hereby investigate the effect of anoxic reactor type on sludge settling.

The invariable volume of the aerobic reactor in the system was 30 liter regarding all cases (flowrates and organic concentrations) during the system's operation. Volume of the anoxic reactor has been altered depending upon the amount of nitrate-nitrogen entering the anoxic reactor, aiming at complete removal of nitrate-nitrogen before leaving the anoxic reactor. Anaerobic reactor volume has been subjected to be altered conditions due to hydraulic conditions in the system. In another words, its volume has changed, without any external interference, depending upon the changing positions of the anoxic reactor in the experimental set-up. However hydraulic retention times in each unit regarding every set of experiments are given in Table 3.1, Table 3.2, Table 3.3 and Table 3.4.

In the proposed process option, the effect of anoxic stage, hydraulic retention time (HRT), organic loading rate (OLR), sludge loading rate (SLR), sludge retention time (SRT), and mixed-liquor suspended solids concentration (MLSS) on biological phosphorus removal efficiency has been investigated. Moreover, improvements in sludge settling when using a fixed-bed anoxic reactor instead of completely-mixed reactor has been investigated.

In order to see the effect of OLR on BPR system, use of relatively high organic matter concentrations, as compared to that of domestic wastewater, also simulated some industrial wastewaters which are also rich in phosphorus content and resulted in a dilemma that whether or not applicability of the BPR systems is applicable for such wastewaters. Examples regarding some of these phosphorus-rich industrial wastewaters are given below (Nelson & Nemerow, 1971);

- Rice wastes in the preparation of edible rice with a composite characteristic of 1065mgBOD/l, 30mgP/l, 30mgN/l.
- Characteristic of pesticide wastes for raw parathion wastes (wastes from the production of chemicals used to make insecticides, herbicides, and pesticides): 3000mgCOD/l, 250mgPO_4/l and 20mgN/l.
- Process wastes of milk, milk products and cheese wastes with an average composition of 1890mgBOD_5/l, 59mgP/l, and 73.2mgTKN/l.

It is commonly accepted that COD concentration of the influent wastewater is the main factor influencing the degree of phosphorus removal in BPR systems. As stated in Chapter 2.3, various researchers recommended different COD/P ratios, ranging from 15/1 to 100/1, to effectively remove phosphorus in enhanced biological phosphorus systems.

Denitrifiers in the anoxic stage of the system consume carbonaceous organic matter for the nitrate-nitrogen removal depending upon the amount of nitrate-nitrogen entering the anoxic stage. Ekama and Marais (1984) stated that 8.6 mgCOD/l of municipal wastewater is needed to reduce 1mg/l of nitrate nitrogen to nitrogen gas. Regarding the subject Randall *et al.* (1992) postulated that the biochemical equation for denitrification when acetate is used as carbon source is as follows;

$$5\ CH_3COOH + 8\ NO_3^- \longrightarrow Na^+ + 10\ CO_2 + 6\ H_2O + 8\ 0H^-$$

According to this equation as suggested by Randall *et al.* (1992), 1mgNO_3-N/l requires 2.7mgHAc/l for complete denitrification.

The highest NO_3-N concentrations measured at the entrance of the anoxic reactor in the system when carrying out with the lowest flowrate (meaning that the highest HRT and lowest SLR) ranged from about 20 mgNO_3-N/l when the influent COD concentration was 2000mg/l to about 3mgNO_3-N/l when COD concentration of the influent wastewater was 250mg/l. Then 20mgNO_3-N/l, the highest NO_3-N concentration, consumes 54mgHAc/l which is equal to 58mgCOD/l according to above biochemical equation, and thereupon can be considered neglectible as compared to influent COD concentration of 2000mg/l. Correspondingly the lowest nitrate-nitrogen concentration, 3mgNO_3-N/l, consumes 8.6mgCOD/l, again relatively insignificant value as compared to the influent COD concentration of 250mg/l. Thus acetate consumed in the anoxic stage of the employed process option is not remarkable in deciding ΔCOD/ΔP removal ratios.

As only a part of the nitrate-nitrogen comes to anoxic reactor by sludge recycle line from the settling tank this process option saves the organic matter which would be consumed otherwise for the full denitrification of the wastewater nitrate-nitrogen whereas this system makes it available for BPR if nitrate-nitrogen removal is not required for the discharge into the receiving media.

3.2 Experimental Data

3.2.1. System Without Anoxic Stage (A/O Process)

The system was firstly operated without anoxic stage as A/O Process, comprising anaerobic/aerobic and settling units, to see the effect of anoxic stage on biological phosphorus removal. These experiments have been done on the system with an invariable 30 liter aeration volume. Volume of the anaerobic reactor changed depending upon the COD strength and influent flowrate of the wastewater as given in Table 3.1. In this study nitrogen has been added into the raw wastewater reservoir in accordance with a COD/N ratio of 20 all the time. System has been operated with an influent flowrate of 1.3 l/h and COD concentrations were 300 mg/l, 650 mg/l and 1500 mg/l for each experiment set. Experimental results are given in Table 3.1.

3.2.2 System With Anoxic Stage (Anoxic/Anaerobic/Aerobic Pocess)

After three sets of experiments have been done with A/O Process, an anoxic stage has been added to the system in order to completely remove the nitrates before entering the anaerobic stage, which comprised the sequence of anoxic/anaerobic/aerobic and settling units.

In this case, three set of experiments for the influent flowrates of 1.3 l/h, 2.6 l/h and 5.2 l/h have been done. Experiment sets have been repeated for the influent COD concentrations of 250 mg/l, 500 mg/l, 1000 mg/l and 2000 mg/l for each applied flowrate. Experimental data obtained for the influent flowrates of 1.3 l/h is given in Table 3.2

Later the influent flowraet increased two times as 2.6 l/h and three sets of experimentshave been done (Table 3.3). In this case, hydraulic retention time in aerobic reactor decreased half. The volumes of the anoxic and anaerobic reactors have been altered depending upon the COD strength of the wastewater, which are presented in Table 3.3.

Subsequently the influent flowrate increased four times as 5.2 l/h and hydraulic retention in aerobic reactor decreased four times. Respective anoxic and anaerobic reactor volumes and experimental data obtained is given in Table 3.4.

ΔCOD/ΔP Removal data given in Table 3.2, Table 3.3 and Table 3.4 were obtained with the system incorporating fixed-bed anoxic stage. The system has also been operated for a while with completely-mixed anoxic reactor in order to compare the sludge settling properties under these two different conditions (See Table 4.1 & Table 4.2)

3.3 Variations in ΔCOD/ΔP Removal in the Experimental Data

3.3.1 Variations Showing the Effect of Influent Flowrate of Wastewater

As can be seen in Figure 3.4, when the COD concentration of the influent wastewater increased variations lessened when the system was operated as A/O Process.

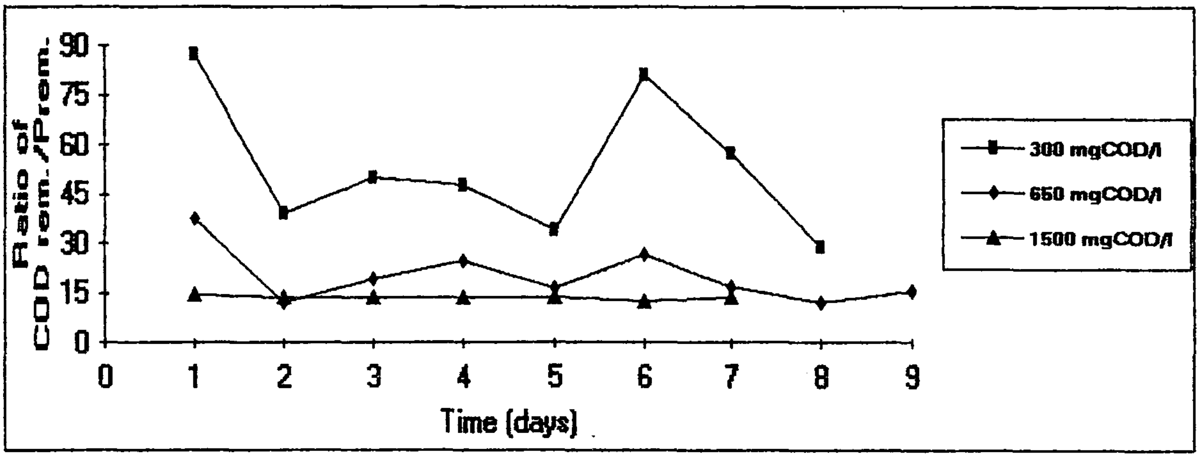

Figure 3.4 Variations In ΔCOD/ΔP Removal versus Sampling In A/O Process (Q=1.3 l/h).

Figure 3.5 displays the variations in ΔCOD/ΔP removal experimented with a variety of influent COD concentrations for an influent flowrate of 1.3 l/h. It can be seen from this figure that increasing influent COD strength of the wastewater improves the COD/P removal.

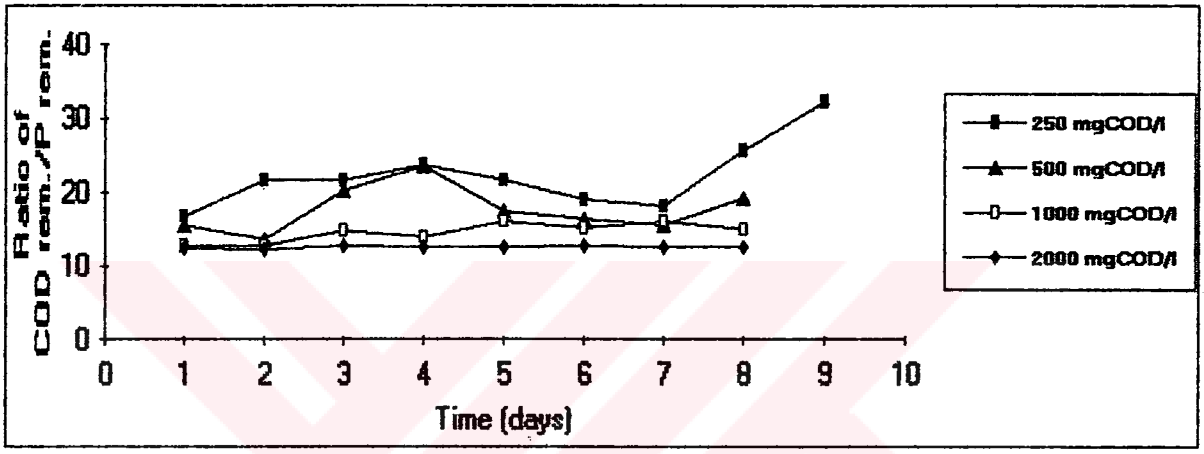

Figure 3.5 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (Q=1.3 l/h)

Figure 3.6 shows that increase in flowrate from 1.3 l/h to 2.6 l/h caused large variations in ΔCOD/ΔP removal especially for low influent COD concentrations.

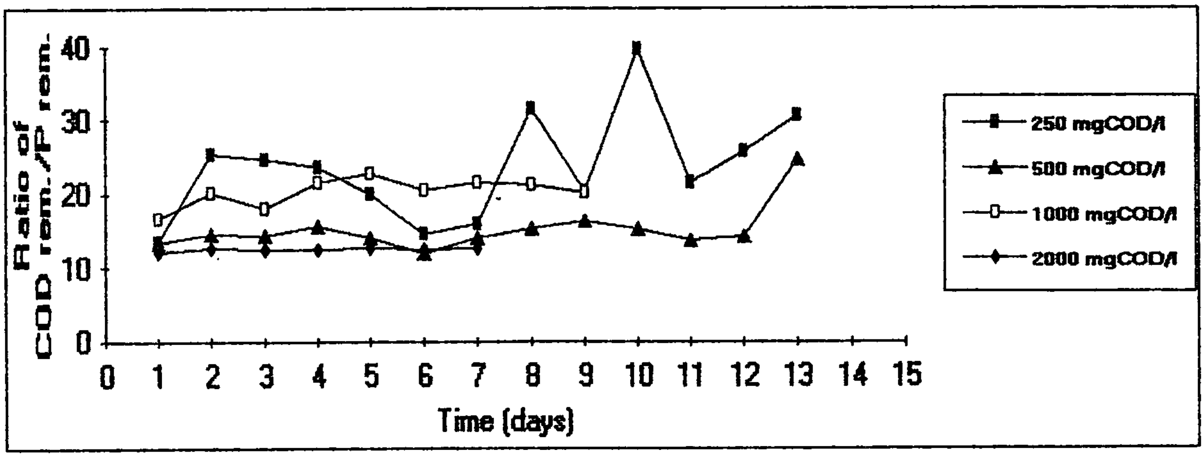

Figure 3.6 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (Q=2.6 l/h)

When the flowrate was increased to 5.2 l/h, variations in ΔCOD/ΔP removal sharpened and efficiency got worse particularly for low influent COD concentrations (Figure 3.7).

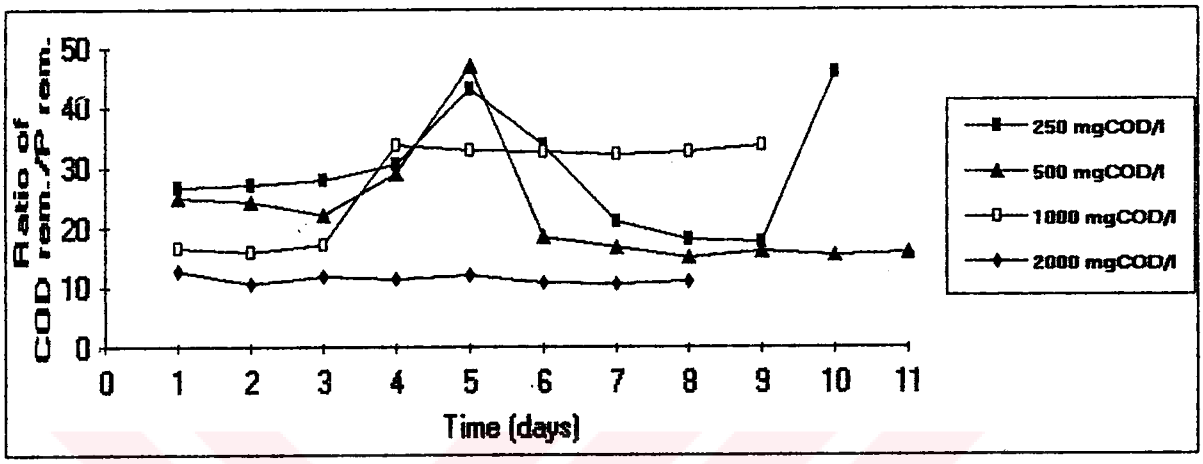

Figure 3.7 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (Q=5.2 l/h)

3.3.2 Variations Showing the Effect of Influent COD Strength of Wastewater

Figure 3.8 shows that variations are rather large in ΔCOD/ΔP removal for the influent of 250 mg/l, though variations are less for low influent flowrates.

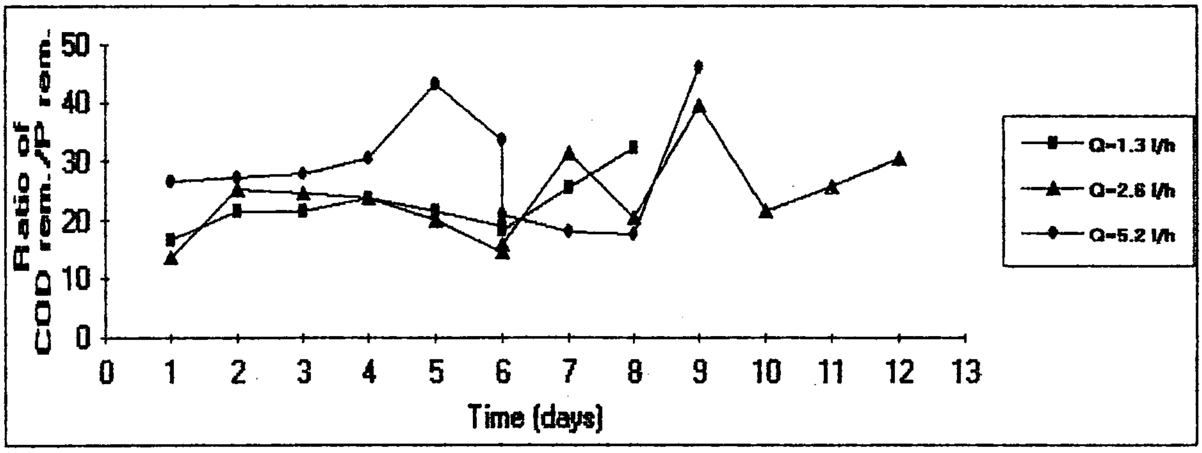

Figure 3.8 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (COD=250mg/l)

When the COD concentration increased two times as 500mg/l, variations in ΔCOD/ΔP removal lessened as compared to the that of 250mg/l (Figure 3.9).

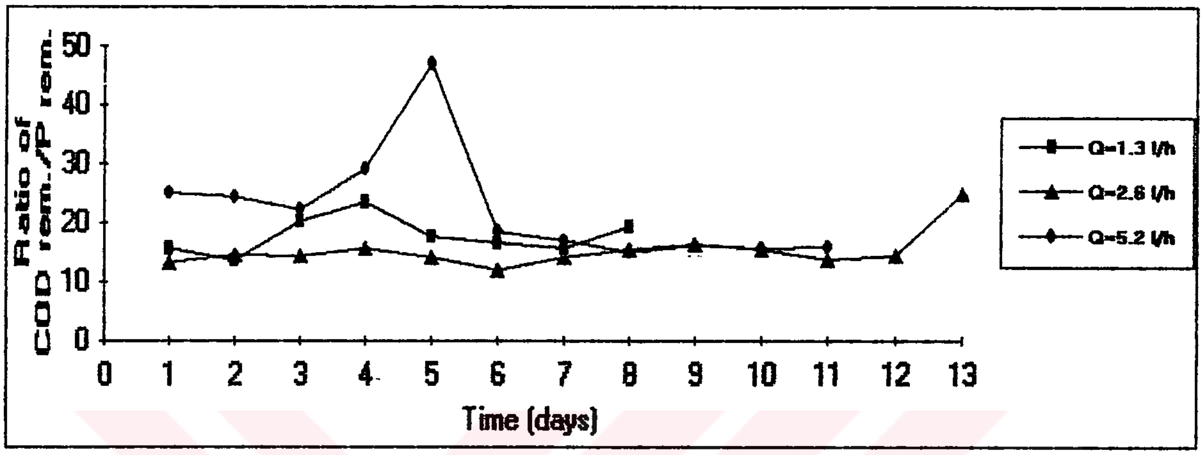

Figure 3.9 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (COD=500mg/l)

When the influent COD concentration was 1000mg/l, ΔCOD/ΔP variations were smooth with an exception that an abrupt change has been observed for the influent flowrate of 5.2 l/h (Figure 3.10).

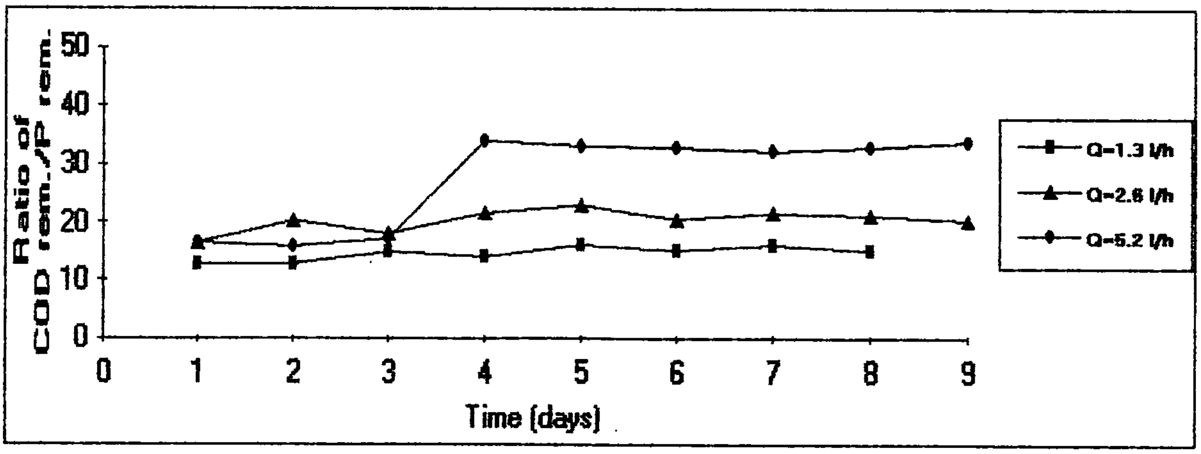

Figure 3.10 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (COD=1000mg/l)

When the COD concentration of the influent was 2000 mg/l, variations in ΔCOD/ΔP removal were too little, though biggest variations have been observed when the influent flowrate was 5.2 l/h (Figure 3.11).

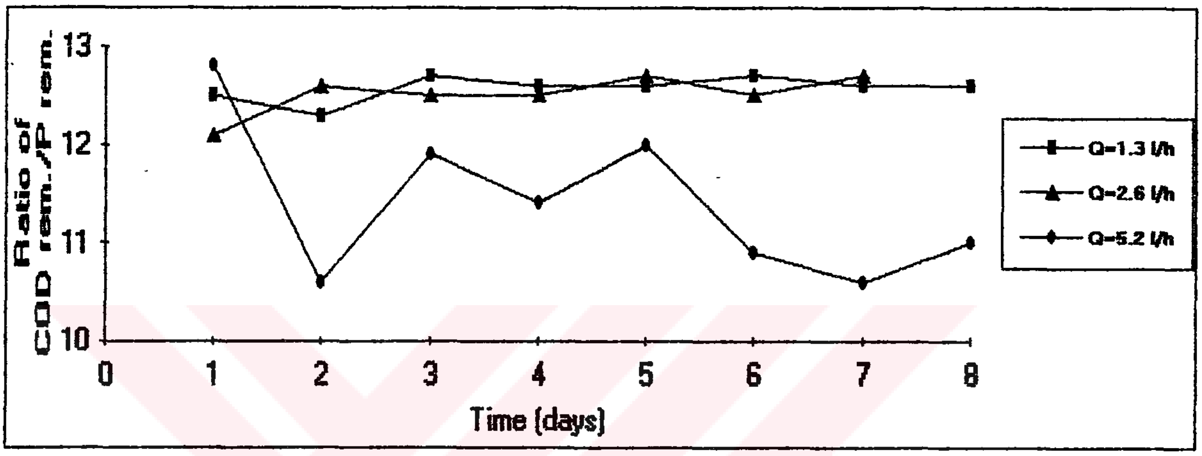

Figure 3.11 Variations In ΔCOD/ΔP Removal In Anoxic/Anaerobic/Aerobic Process (COD=2000mg/l)

3.4 Variations In ΔCOD/ΔP Removal Depending Upon pH Variations

pH in anaerobic stage

The measured pH values are the normally occurring pH values in the reactors without using any external chemical substance or interference. Effective P-removals have been observed at pH values between 6.5 to 8.2 (Figure 3.12, Figure 3.13 and Figure 3.14).

It can be seen from these figures that lower pH values resulted in better P-removal, due to the acidic conditions which promote phosphorus release as suggested by Fuhs &Chen (1975) and Deinema *et al.* (1984).

As can be seen from these figures, significant P-removals have also been observed at pH of around 8.0. However here it may be worth mentioning that feed substrate was acetate, already a low-weight volatile fatty acid, and hence fermentation process was not a function of the anaerobic reactor which requires low pH.

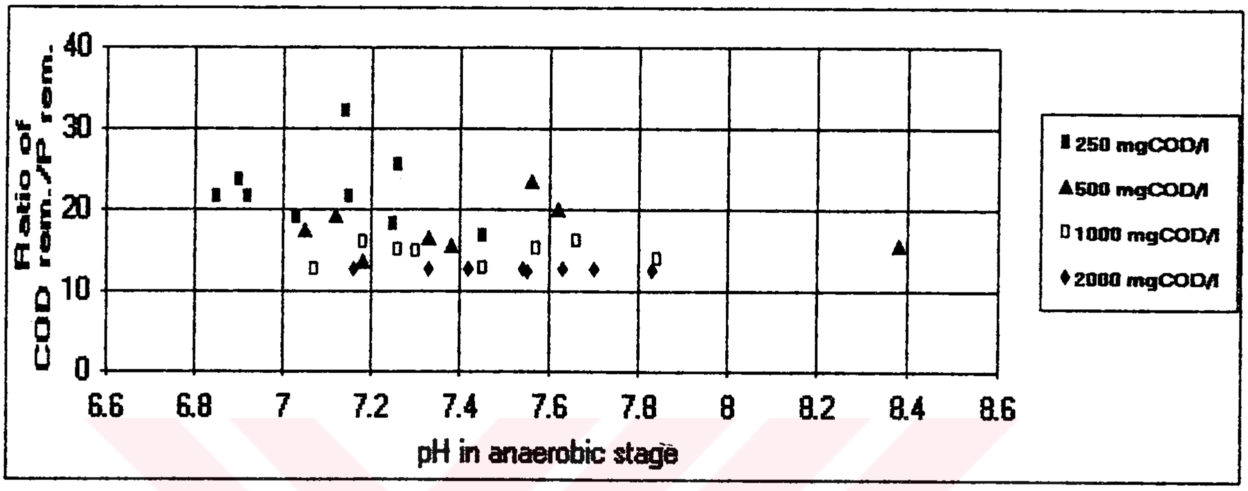

Figure 3.12 Phosphorus Removal versus pH Values Measured In the Anaerobic Stage of Anoxic/Anaerobic/Aerobic Process (Q=1.3 l/h).

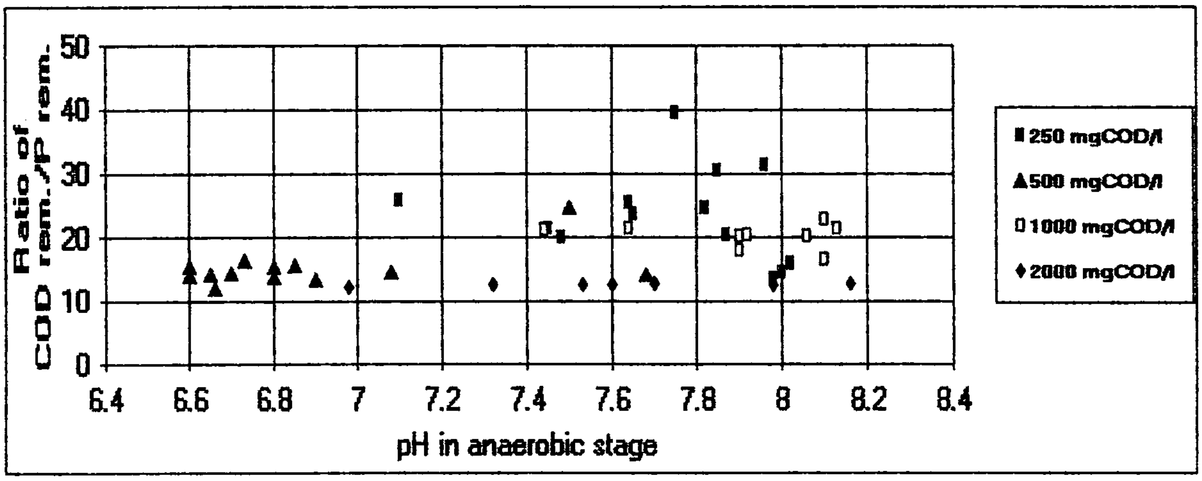

Figure 3.13 Phosphorus Removal versus pH Values Measured In the Anaerobic Stage of Anoxic/Anaerobic/Aerobic Process (Q=2.6 l/h).

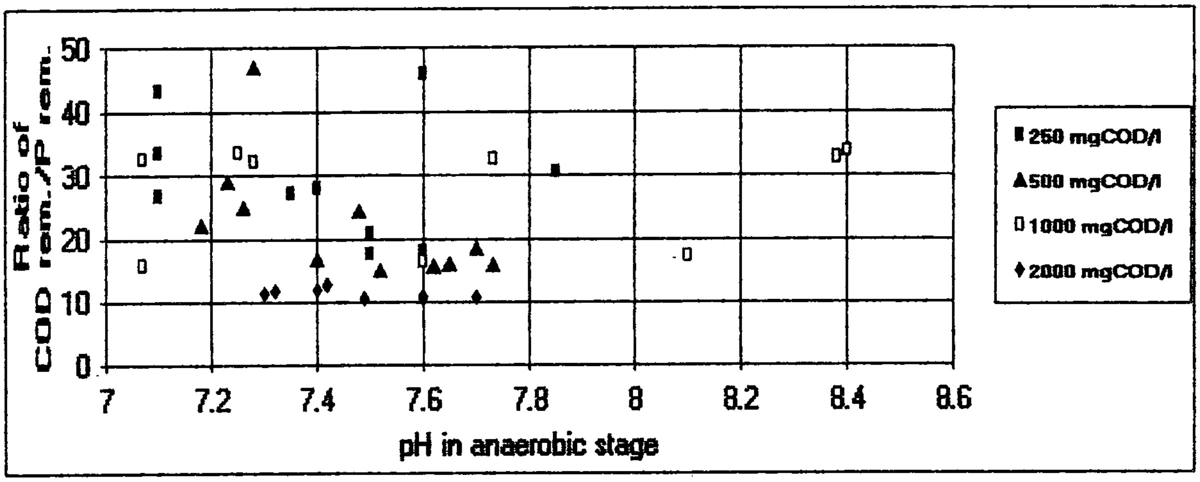

Figure 3.14 Phosphorus Removal versus pH Values Measured In the Anaerobic Stage of Anoxic/Anaerobic/Aerobic Process (Q=5.2 l/h).

pH in aerobic stage

Effective phosphorus removals were measured when the pH values higher than 8.0. (Figure 3.15, Figure 3.16 & Figure 3.17).

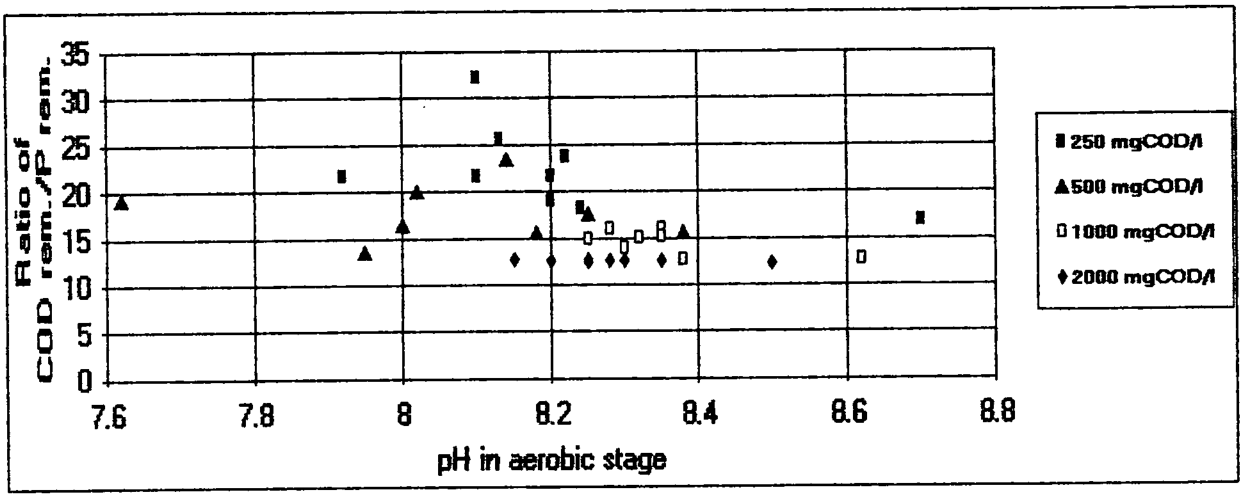

Figure 3.15 Phosphorus Removal versus pH Values Measured In the Aerobic Stage of Anoxic/Anaerobic/Aerobic Process (Q=1.3 l/h).

As the COD strength of the wastewater increased, P-removal (ΔCOD/ΔP ratio) is less affected by pH variations (Figure 3.15). However removal efficiencies displayed a decline as the pH exceeded 8.5. On the other hand increasing flowrates (less hydraulic aerobic retention times) made the P-removal more COD-dependent, rather than pH-dependent (Figure 3.16 and Figure 3.17).

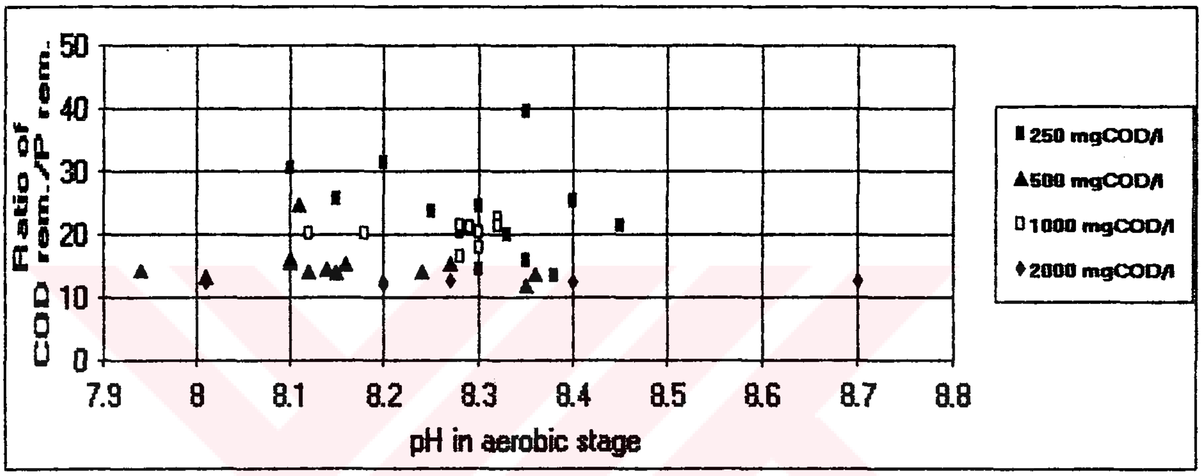

Figure 3.16 Phosphorus Removal versus pH Values Measured In the Aerobic Stage of Anoxic/Anaerobic/Aerobic Process (Q=2.6 l/h).

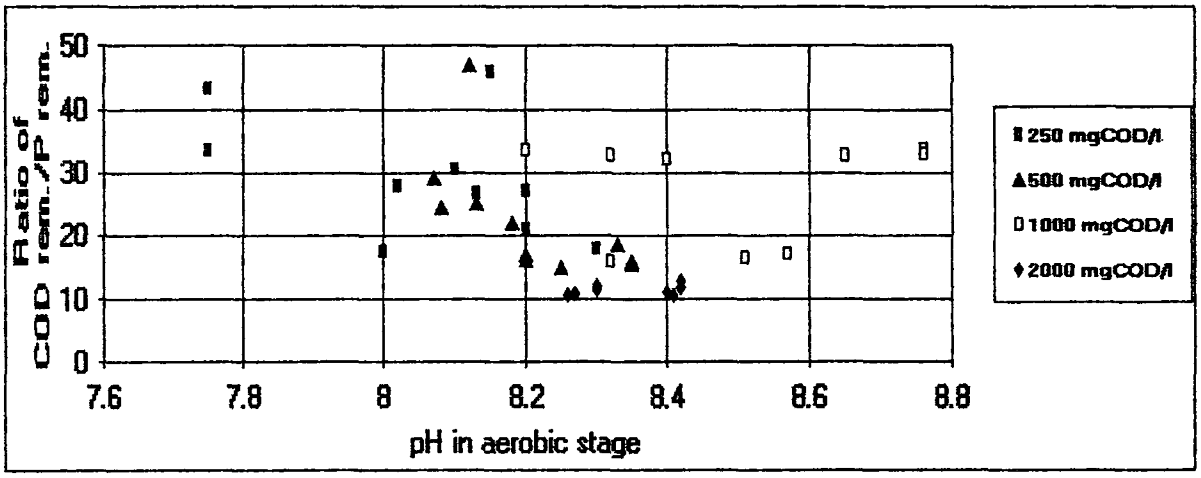

Figure 3.17 Phosphorus Removal versus pH Values Measured In the Aerobic Stage of Anoxic/Anaerobic/Aerobic Process (Q=5.2 l/h).

Table 3.1 Daily Experimental Data Obtained with A/O Process (for an influent flowrate of 1.3 l/h).

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed / P removed	pH in reservoir	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 300 mg/l									
30	100/10	30	26.9	87.2/1	7.33	6.82	8.28	0.8	23
30	100/10	45	23.5	39.2/1	7.47	6.82	8.32	0.8	23
30	100/10	40	24.8	50.0/1	7.05	6.75	8.30	0.8	23
30	100/10	20	24.1	47.6/1	7.50	6.60	8.25	0.8	23
30	100/10	20	21.8	34.2/1	7.20	7.00	8.32	0.8	23
30	100/10	30	25.6	81.3/1	7.41	6.72	8.35	0.8	23
30	100/10	35	25.4	57.2/1	6.90	6.84	8.32	0.8	23
30	100/10	25	20.5	28.8/1	7.02	6.88	8.25	0.8	23
For an influent COD of 650 mg/l									
65	100/10	80	49.8	37.5/1	7.66	6.98	8.25	0.8	23
65	100/10	35	15	12.3/1	7.38	6.98	8.35	0.8	23
65	100/10	40	33.1	19.1/1	7.04	6.72	8.15	0.8	23
65	100/10	50	40.9	24.9/1	7.64	7.02	8.2	0.8	23
65	100/10	35	27.5	16.4/1	7.5	7.16	8.3	0.8	23
65	100/10	30	41.6	26.5/1	7.05	7.06	8.2	0.8	23
65	100/10	30	28.1	16.8/1	7.2	6.85	8.27	0.8	23
65	100/10	40	15.8	12.4/1	7.2	6.85	8.3	0.8	23
65	100/10	20	24.6	15.6/1	7.05	6.8	8.27	0.8	23
For an influent COD of 1500 mg/l									
150	100/10	105	53.8	14.5/1	7.45	6.98	8.25	0.8	23
150	100/10	150	52.2	13.8/1	7.38	6.90	8.35	0.8	23
150	100/10	195	54.7	13.7/1	7.1	6.72	8.2	0.8	23
150	100/10	180	55.7	14/1	7.64	7.02	8.2	0.8	23
150	100/10	120	50.7	13.9/1	7.3	6.95	8.3	0.8	23
150	100/10	135	43.4	12.8/1	7.05	6.7	8.2	0.8	23
150	100/10	165	52.6	13.7/1	7.1	6.85	8.2	0.8	23

Table 3.2 Daily Experimental Data Obtained with Anoxic/Anaerobic/Aerobic Process (for Q=1.3 l/h).

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed / P removed	pH in reservoir	pH in anoxic reactor	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anoxic reactor (h)	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 250 mg/l											
25	100/10	40	12.5	16.8/1	8..0	7.75	7.45	8.70	2.5	0.8	23
25	100/10	10	13.9	21.6/1	5.98	6.96	6.92	7.92	2.5	0.8	23
25	100/10	25	14.6	21.6/1	6.70	7.35	6.85	8.10	2.5	0.8	23
25	100/10	30	15.7	23.7/1	6.80	7.30	6.90	8.22	2.5	0.8	23
25	100/10	30	14.8	21.6/1	7.30	7.70	7.15	8.20	2.5	0.8	23
25	100/10	15	12.6	19/1	7.10	7.10	7.03	8.20	2.5	0.8	23
25	100/10	35	13.2	18.2/1	6.80	6.90	7.25	8.24	2.5	0.8	23
25	100/10	20	16	25.6/1	7.42	7.22	7.26	8.13	2.5	0.8	23
25	100/10	25	18	32.2/1	6.56	7.53	7.14	8.10	2.5	0.8	23
For an influent COD of 500 mg/l											
50	100/10	41	20.5	15.60	6.38	8.12	8.38	8.38	2.5	0.8	23
50	100/10	68	18.3	13.60	7.18	7.35	7.18	7.95	2.5	0.8	23
50	100/10	28	26.5	20/1	6.54	7.65	7.62	8.02	2.5	0.8	23
50	100/10	48	30.8	0.00	6.55	7.53	7.56	8.14	2.5	0.8	23
50	100/10	35	23.4	17.5/1	7.32	7.42	7.05	8.25	2.5	0.8	23
50	100/10	56	22.8	16.5/1	6.90	7.48	7.33	8.00	2.5	0.8	23
50	100/10	25	19.6	15.6/1	7.10	7.24	7.38	8.18	2.5	0.8	23
50	100/10	40	26	19.2/1	6.50	7.03	7.12	7.62	2.5	0.8	23

Table 3.2 (*Cont.*)

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed / P removed	pH in reservoir	pH in anoxic reactor	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anoxic reactor (h)	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 1000 mg/l											
100	100/10	108	29.8	12.7/1	5.43	7.02	7.07	8.38	3.3	0.8	23
100	100/10	132	32	12.8/1	5.88	7.40	7.45	8.62	3.3	0.8	23
100	100/10	80	38.2	14.9/1	5.65	7.24	7.3	8.25	3.3	0.8	23
100	100/10	72	33.5	14/1	5.98	8.1	7.84	8.3	3.3	0.8	23
100	100/10	68	42	16.1/1	6.71	7.61	7.66	8.35	3.3	0.8	23
100	100/10	65	38.5	15.2/1	6.45	7.46	7.57	8.35	3.3	0.8	23
100	100/10	65	41.9	16/1	6.44	7.16	7.18	8.28	3.3	0.8	23
100	100/10	45	36.8	15.1/1	6.85	7.5	7.26	8.32	3.3	0.8	23
For an influent COD of 2000 mg/l											
200	100/10	50	44.6	12.5/1	5.45	7.23	7.83	8.26	5	2	23
200	100/10	40	44.2	12.3/1	7.15	8.18	7.55	8.50	5	2	23
200	100/10	30	44.6	12.7/	5.6	7.29	7.54	8.25	5	2	23
200	100/10	40	44.4	12.6/1	6.2	7.7	7.33	8.2	5	2	23
200	100/10	45	44.7	12.6/1	5.3	7.9	7.42	8.3	5	2	23
200	100/10	25	44.2	12.7/1	5.4	7.65	7.16	8.15	5	2	23
200	100/10	40	44.4	12.6/1	6.6	7.6	7.7	8.35	5	2	23
200	100/10	30	44.5	12.6/1	7.05	7.85	7.63	8.28	5	2	23

Table 3.3 Daily Experimental Data Obtained with Anoxic/Anaerobic/Aerobic Process (for Q=2.6 l/h).

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed / P removed	pH in reservoir	pH in anoxic reactor	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anoxic reactor (h)	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 250 mg/l											
25	100/10	130	16.2	13.6/1	7.93	7.72	7.98	8.38	2.6	1	11.5
25	100/10	85	18.5	25.4/1	7.20	7.60	7.64	8.40	2.6	1	11.5
25	100/10	56	17.1	24.6/1	7.30	7.75	7.82	8.30	2.6	1	11.5
25	100/10	30	15.7	23.7/1	7.15	7.44	7.65	8.25	2.6	1	11.5
25	100/10	80	16.5	20.0/1	7.48	7.56	7.48	8.33	2.6	1	11.5
25	100/10	80	13.3	14.5/1	7.20	8.00	8.00	8.30	2.6	1	11.5
25	100/10	48	12.3	15.9/1	7.50	7.78	8.02	8.35	2.6	1	11.5
25	100/10	30	18	31.4/1	7.60	7.65	7.96	8.20	2.6	1	11.5
25	100/10	28	14.1	20.4/1	7.40	8.30	7.87	8.28	2.6	1	11.5
25	100/10	12	19	39.6/1	7.35	7.40	7.75	8.35	2.6	1	11.5
25	100/10	24	14.5	21.5/1	7.00	6.50	7.45	8.45	2.6	1	11.5
25	100/10	26	16.3	25.8/1	7.10	7.60	7.10	8.15	2.6	1	11.5
25	100/10	48	18.4	30.6/1	7.10	7.75	7.85	8.10	2.6	1	11.5
For an influent COD of 500 mg/l											
50	100/10	120	21.3	13.3/1	6.80	7.14	6.90	8.01	2.6	1.6	11.5
50	100/10	105	23	14.6/1	6.95	7.30	7.08	8.14	2.6	1.6	11.5
50	100/10	70	24.1	14.4/1	6.00	6.55	6.70	7.94	2.6	1.6	11.5
50	100/10	50	21.2	15.6/1	6.60	7.16	6.85	8.10	2.6	1.6	11.5
50	100/10	50	18	14.1/1	7.10	7.02	6.65	8.12	2.6	1.6	11.5
50	100/10	85	15	11.9/1	7.75	7.21	6.66	8.35	2.6	1.6	11.5
50	100/10	40	17	14/1	7.20	7.20	6.60	8.15	2.6	1.6	11.5
50	100/10	50	20.5	15.3/1	7.40	7.45	6.80	8.27	2.6	1.6	11.5
50	100/10	40	21.7	16.3/1	7.25	7.65	6.73	8.10	2.6	1.6	11.5
50	100/10	40	20	15.3/1	7.14	7.26	6.60	8.16	2.6	1.6	11.5
50	100/10	40	16.5	13.7/1	7.75	7.26	6.80	8.36	2.6	1.6	11.5
50	100/10	40	17.6	14.2/1	7.30	7.25	7.68	8.24	2.6	1.6	11.5
50	100/10	40	31.4	24.7/1	7.07	7.47	7.50	8.11	2.6	1.6	11.5

Table 3.3 (*Con't*.)

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed /P removed	pH in reservoir	pH in anoxic reactor	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anoxic reactor (h)	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 1000 mg/l											
100	100/10	30	41.5	16.6/1	7.33	7.60	8.10	8.28	2.8	1.6	11.5
100	100/10	30	52	20.2/1	7.37	7.77	7.90	8.12	2.8	1.6	11.5
100	100/10	40	46.5	18/1	7.20	7.70	7.90	8.30	2.8	1.6	11.5
100	100/10	40	55.5	21.5/1	7.50	7.30	8.13	8.28	2.8	1.6	11.5
100	100/10	50	58.3	22.8/1	7.53	7.36	8.10	8.32	2.8	1.6	11.5
100	100/10	46	53.5	20.5/1	7.41	7.54	7.92	8.30	2.8	1.6	11.5
100	100/10	40	56	21.5/1	6.82	7.53	7.64	8.32	2.8	1.6	11.5
100	100/10	60	55.6	21.2/1	6.87	7.44	7.44	8.29	2.8	1.6	11.5
100	100/10	36	55.3	20.2/1	7.30	7.33	8.06	8.18	2.8	1.6	11.5
For an influent COD of 2000 mg/l											
200	100/10	120	44.5	12.1/1	5.66	7.07	6.98	8.20	2.5	1	11.5
200	100/10	40	44.3	12.6/1	6.38	7.73	7.98	8.40	2.5	1	11.5
200	100/10	60	44.3	12.5/1	5.44	6.92	7.32	8.01	2.5	1	11.5
200	100/10	60	44.3	12.5/1	5.68	7.2	7.53	8.2	2.5	1	11.5
200	100/10	30	44.8	12.7/1	5.7	8.23	8.16	8.7	2.5	1	11.5
200	100/10	50	44.6	12.5/1	6.2	7.8	7.6	8.2	2.5	1	11.5
200	100/10	30	44.4	12.7/1	6.05	7.65	7.7	8.27	2.5	1	11.5

Table 3.4 Daily Experimental Data Obtained with Anoxic/Anaerobic/Aerobic Process (for Q=5.2 l/h).

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed / P removed	pH in reservoir	pH in anoxic reactor	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anoxic reactor (h)	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 250 mg/l											
25	100/10	95	19.2	26.7/1	6.90	7.50	7.10	8.13	2.4	1.2	5.8
25	100/10	70	18.4	27.2/1	7.10	7.10	7.35	8.20	2.4	1.2	5.8
25	100/10	40	17.5	28/1	6.80	7.15	7.40	8.02	2.4	1.2	5.8
25	100/10	48	18.4	30.6/1	7.10	7.75	7.85	8.10	2.4	1.2	5.8
25	100/10	68	20.8	43.3/1	6.10	7.05	7.10	7.75	2.4	1.2	5.8
25	100/10	68	19.6	33.7/1	6.40	7.05	7.10	7.75	2.4	1.2	5.8
25	100/10	80	16.9	21/1	7.00	7.50	7.50	8.20	2.4	1.2	5.8
25	100/10	40	13.3	18/1	7.10	7.70	7.60	8.30	2.4	1.2	5.8
25	100/10	20	11.9	17.6/1	7.30	8.05	7.50	8.00	2.4	1.2	5.8
25	100/10	20	20.5	46/1	7.00	8.00	7.60	8.15	2.4	1.2	5.8
For an influent COD of 500 mg/l											
50	100/10	20	30.8	25/1	6.61	7.23	7.26	8.13	2.4	1.2	5.8
50	100/10	22	30.4	24.4/1	6.60	7.46	7.48	8.08	2.4	1.2	5.8
50	100/10	25	28.5	22.1/1	6.82	7.95	7.18	8.18	2.4	1.2	5.8
50	100/10	28	33.6	29.1/1	6.47	7.18	7.23	8.07	2.4	1.2	5.8
50	100/10	44	38.9	47/1	6.63	7.30	7.28	8.12	2.4	1.2	5.8
50	100/10	12	23.7	18.5/1	6.83	7.70	7.70	8.33	2.4	1.2	5.8
50	100/10	24	21.9	16.9/1	6.70	7.32	7.40	8.20	2.4	1.2	5.8
50	100/10	40	19.3	15/1	6.90	7.45	7.52	8.25	2.4	1.2	5.8
50	100/10	40	21.5	16.1/1	6.60	7.60	7.65	8.20	2.4	1.2	5.8
50	100/10	40	20.6	15.6/1	6.73	7.54	7.62	8.35	2.4	1.2	5.8
50	100/10	52	21.8	15.9/1	6.73	7.69	7.73	8.35	2.4	1.2	5.8

Table 3.4 (*Con't.*)

Influent phosphorus (mg/l)	Influent COD/P ratio	Effluent COD (mg/l)	Effluent phosphorus (mg/l)	Ratio of COD removed / P removed	pH in reservoir	pH in anoxic reactor	pH in anaerobic reactor	pH in aerobic reactor	Retention time in anoxic reactor (h)	Retention time in anaerobic reactor (h)	Retention time in aerobic reactor (h)
For an influent COD of 1000 mg/l											
100	100/10	52	42.5	16.5/1	6.55	7.71	7.60	8.51	2.5	1.4	5.8
100	100/10	68	41.3	15.9/1	6.44	6.98	7.07	8.32	2.5	1.4	5.8
100	100/10	68	45.7	17.2/1	7.32	8.12	8.10	8.57	2.5	1.4	5.8
100	100/10	28	21.3	33.8/1	7.40	8.40	8.40	8.76	2.5	1.4	5.8
100	100/10	24	20.4	32.9/1	7.44	8.40	8.38	8.76	2.5	1.4	5.8
100	100/10	12	19.8	32.7/1	6.85	7.60	7.73	8.65	2.5	1.4	5.8
100	100/10	24	19.7	32.2/1	6.60	7.30	7.28	8.40	2.5	1.4	5.8
100	100/10	40	20.7	32.7/1	6.44	6.98	7.07	8.32	2.5	1.4	5.8
100	100/10	40	21.5	33.7/1	6.68	7.35	7.25	8.20	2.5	1.4	5.8
For an influent COD of 2000 mg/l											
200	100/10	20	45.6	12.8/1	5.53	7.62	7.42	8.46	2.8	0.5	5.8
200	100/10	360	44.8	10.6/1	6.32	7.53	7.49	8.26	2.8	0.5	5.8
200	100/10	160	45.1	11.9/1	6.66	7.64	7.32	8.42	2.8	0.5	5.8
200	100/10	220	44.2	11.4/1	6.3	7.3	7.3	8.3	2.8	0.5	5.8
200	100/10	150	45.5	12.0/1	6.42	7.45	7.4	8.3	2.8	0.5	5.8
200	100/10	310	45.3	10.9/1	6.18	7.64	7.7	8.27	2.8	0.5	5.8
200	100/10	350	44.1	10.6/1	5.85	7.7	7.6	8.41	2.8	0.5	5.8
200	100/10	280	44.7	11.0/1	6.2	7.82	7.6	8.4	2.8	0.5	5.8

CHAPTER FOUR

EFFECT OF OPERATING PARAMETERS AND CONDITIONS

4.1 Results Obtained With A/O Process

Effect of Anoxic Stage on BPR Capacity

It has been stated by many authors (See Chapter 2.3) that if sufficient amount of VFA is available in the anoxic zone (more than required for denitrification), nitrates do not lead to a decrease in phosphorus removal. However, it has been observed on the process that though VFA was available in the anaerobic reactor much more than required for denitrification, some abrupt

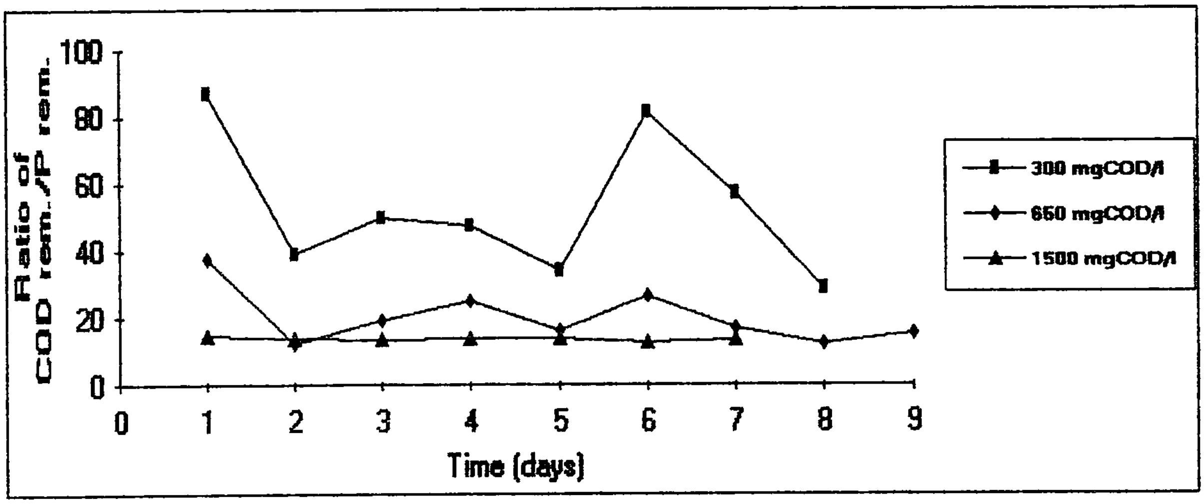

Figure 4.1 Phosphorus Removal versus Sampling Days In A/O Process

Table 4.1 Operational and Experimental Data for A/O Process (System Without Anoxic Stage)

Operating parameters (regarding aerobic reactor)			
Q (l/h)	1.3	1.3	1.3
COD (mg/l)	300	650	1500
Efficiency for COD removal (average,%)	89	93	90
HRT (h)	23	23	23
OLR (kgCOD/m3.d)	0.31	0.68	1.56
SLR (kgCOD/kgMLSS.d)	0.21	0.34	0.39
SRT (d)	59.2	13.8	11.4
MLSS (mg/l)	1500	2000	4000
SVI (ml/g)	460	310	200
Observed ratios of COD removed / P removed			
COD removed / P removed	87.2/1	37.5/1	14.5/1
"	39.2/1	12.3/1	13.8/1
"	50.0/1	19.1/1	13.7/1
"	47.6/1	24.9/1	14.0/1
"	34.2/1	16.4/1	13.9/1
"	61.3/1	26.5/1	12.8/1
"	57.2/1	16.8/1	13.7/1
"	28.8/1	12.4/1	
"		15.6/1	
Statistically evaluated data ragarding COD/P removal ratios			
N	8	9	7
MEAN	50.7/1	20/1	13.7/1
STDEV	18.44/1	8.16/1	0.51/1
MIN	28.80/1	12.30/1	12.80/1
MAX	87.20/1	37.50/1	14.50/1

variations in ΔCOD/ΔP removal ratio occurred, which can be seen from the Figure 4.1, which also shows that when the COD concentration of the raw wastewater increased, variations lessened and got smooth. Operational data for this option is presented in Table 4.1.

4.2 Results Obtained for the Proposed Process Option (Anoxic/Anaerobic/Aerobic)

When the anoxic stage has been added to the A/O process the nitrates have been completely removed before entering the anaerobic zone. Respective operational data is given in Table 4.2.

Table 4.2 Operational and Experimental Data for Anoxic/Anaerobic/Aerobic Process

Operating parameters (regarding aerobic reactor)												
Q (l/h)	1.3	1.3	1.3	1.3	2.6	2.6	2.6	2.6	5.2	5.2	5.2	5.2
COD (mg/l)	250	500	1000	2000	250	500	1000	2000	250	500	1000	2000
Efficiency for COD removal (average, %)	90	91	93	98	79	88	96	97	78	95	96	89
HRT (h)	23	23	23	23	11.5/1	11.5	11.5	11.5	5.8	5.8	5.8	5.8
OLR (kgCOD/m3.d)	0.26	0.52	1.04	2.08	0.52	1.04	2.08	4.16	1.04	2.08	4.16	8.32
SLR (kgCOD/kgMLSS.d)	0.17	0.26	0.35	0.42	0.26	0.35	0.42	0.69	0.35	0.52	0.83	1.39
SRT (d)	416	28.8	14.5	9.7	45.2	16.1	10	4.8	20.8	7.3	3.9	2.3
MLSS (mg/l)	1500	2000	3000	5000	2000	3000	5000	6000	3000	4000	5000	6000
SVI (ml/g in CFSTR*)	320	240	180	165	290	185	150	130	220	180	165	130
SVI (ml/g in FBR**)	120	65	80	140	105	50	45	70	85	70	80	120
Observed ratios of COD removed / P removed												
COD removed / P removed	16.8/1	15.6/1	12.7/1	12.5/1	13.6/1	13.3/1	16.6/1	12.1/1	26.7/1	25.0/1	16.5/1	12.8/1
"	21.6/1	13.6/1	12.8/1	12.3/1	25.4/1	14.6/1	20.2/1	12.6/1	27.2/1	24.4/1	15.9/1	10.6/1
"	21.6/1	20.2/1	14.9/1	12.7/1	24.6/1	14.4/1	18.0/1	12.5/1	28.0/1	22.1/1	17.2/1	11.9/1
"	23.7/1	23.5/1	14.0/1	12.6/1	23.7/1	15.6/1	21.5/1	12.5/1	30.6/1	29.1/1	33.8/1	11.4/1
"	21.6/1	17.5/1	16.1/1	12.6/1	20.0/1	14.1/1	22.8/1	12.7/1	43.3/1	47.0/1	32.9/1	12.0/1
"	19.0/1	16.5/1	15.2/1	12.7/1	14.5/1	11.9/1	20.5/1	12.5/1	33.7/1	18.5/1	32.7/1	10.9/1
"	18.2/1	15.6/1	16.0/1	12.6/1	15.9/1	14.0/1	21.5/1	12.7/1	21.0/1	16.9/1	32.2/1	10.6/1
"	25.6/1	19.2/1	15.1/1	12.6/1	31.4/1	15.3/1	21.2/1		18.0/1	15.0/1	32.7/1	11.0/1
"	32.2/1				20.4/1	16.3/1	20.2/1		17.6/1	16.1/1	33.7/1	
"					39.6/1	15.3/1			46.0/1	15.6/1		
"					21.5/1	13.7/1				15.9/1		
"					25.8/1	14.2/1						
"					30.6/1	24.7/1						
Statistically evaluated data regarding COD/P removal ratios												
N	9	8	8	8	13	13	9	7	10	11	9	8
MEAN	22.3/1	17.7/1	14.6/1	12.6/1	23.6/1	15.2/1	20.3/1	12.5/1	29.2/1	22.3/1	27.5/1	11.4/1
STDEV	4.6/1	3.1/1	1.3/1	0.13/1	7.3/1	3.1/1	1.9/1	0.20/1	9.7/1	9.4/1	8.3/1	0.78/1
MIN	16.8/1	13.6/1	12.7/1	12.30/1	13.6/1	11.9/1	16.6/1	12.10/1	17.6/1	15/1	15.9/1	10.6/1
MAX	32.2/1	23.5/1	16.1/1	12.70/1	39.6/1	24.7/1	22.8/1	12.70/1	4.06/1	47/1	33.8/1	12.8/1

* Continious-flow stirred tank reactor

**Fixed-bed reactor

Hydraulic retention time (HRT)

Though Sedlak (1991) postulated that 1-2 hours seem a feasible range for phosphorus uptake , retention time up to 12 hours played an important role in P-uptake. Figure 4.2 shows that when the hydraulic retention time in aerobic reactor exceeds 12h, hydraulic retention time loses its effect. However it should be stressed that the effect of hydraulic retention time out this range (<5.8h & >23h) has not been conducted in the study.

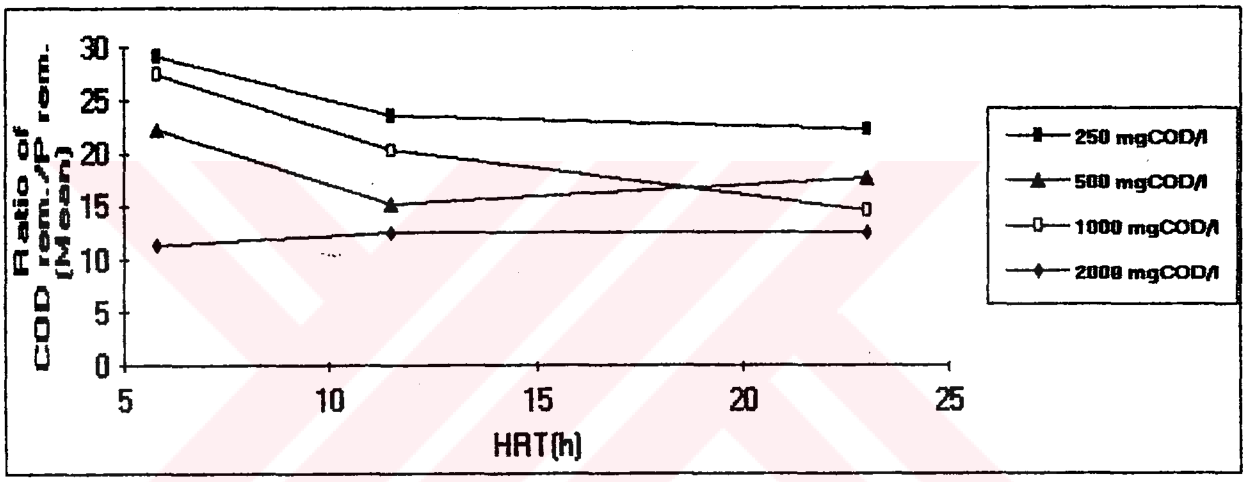

Figure 4.2 Phosphorus Removal versus Hydraulic Retention Time in the Aerobic Reactor

Organic loading rate (OLR)

Effect of organic loading rate on biological phosphorus removal is evidenced on graphs in Figure 4.3 and Figure 4.4. Since organic loading rate is directly related to the organic matter composition of the feed wastewater, these two figures present comparable results. It can be concluded from these figures that as organic loading rate increases, phosphorus removal efficiency increases as well, supporting the suggestions by Barnard (1976) and Yeoman *et al.*, (1987).

Only two values (OLR corresponding to the COD concentration of 1000mg/l) are out of declining order on the figures. As can be seen from Table 4.4 ΔCOD/ΔP removal ratio showed an abrupt increase when carrying out with the COD concentration of 1000mg/l for the flowrates of 2.6 l/h and 5.2 l/h, the reason of which not figured out, but may be attributed to a possible change in microbiological composition of the sludge (Yeoman *et al.*, 1987; Lettinga and Haandel, 1994).

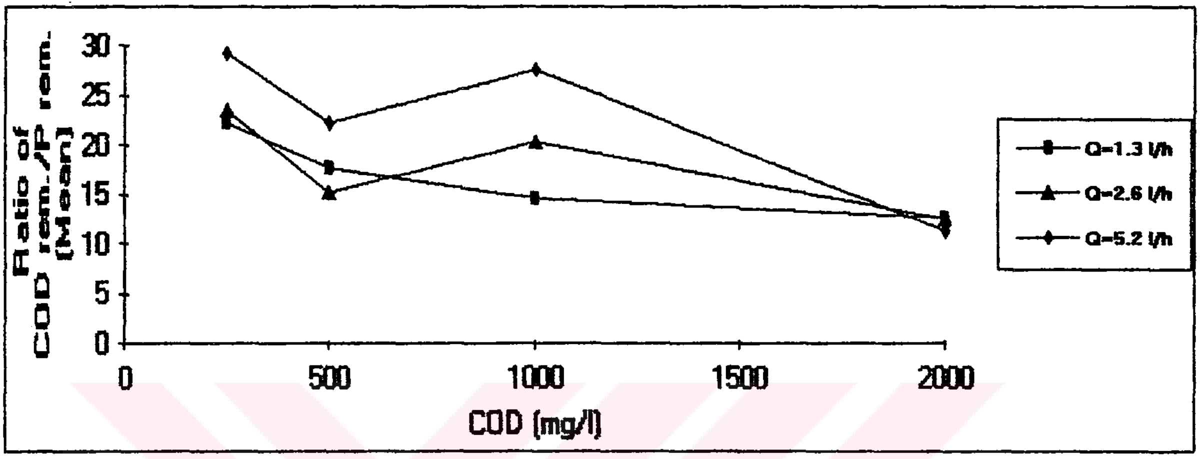

Figure 4.3 Phosphorus Removal versus COD Concentration of the Wastewater

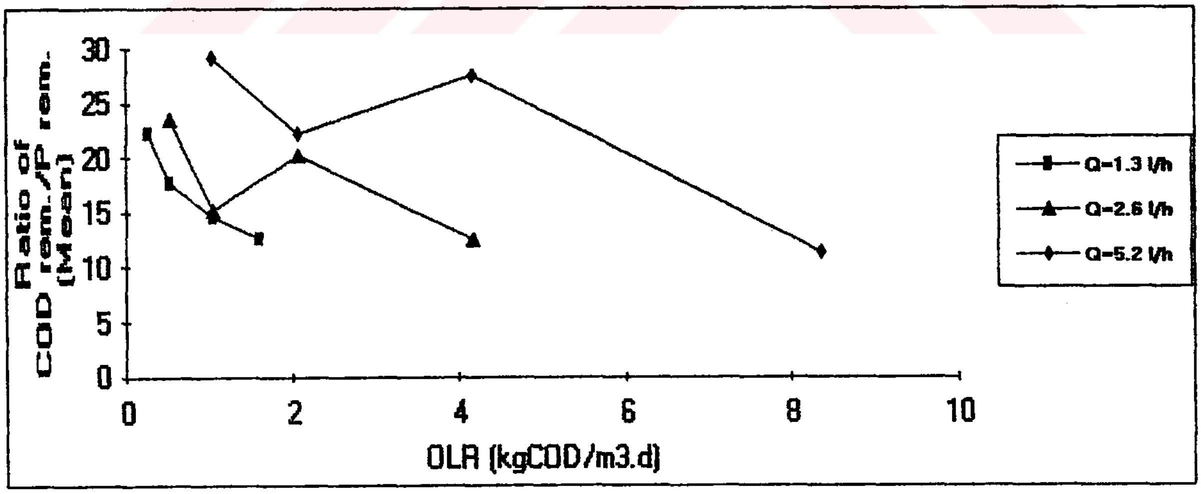

Figure 4.4 Phosphorus Removal versus Organic Loading Rate

Sludge loading rate (SLR) and Sludge retention time (SRT)

Since sludge loading rate and sludge retention time are related to each other, with an inverse relation, Figure 4.5 and Figure 4.6 show comparable results. Figure 4.5 displays that phosphorus removal efficiency is positively affected by the increasing sludge loading rate, or by the decreasing sludge retention time (Figure 4.6).

Similar to OLR, two values regarding ΔCOD/ΔP removal ratio for both SLR and SRT (both corresponds to the COD concentration of 1000mg/l) were again out of declining/inclining order on the figures.

These findings with regard to sludge loading rate and sludge retention time (sludge age) may support the suggestions made by Maier *et al.*, (1984), and Tracy and Flammino (1985) proposing that decrease in P-removal at low sludge loading rates is attributed to the endogenous decay rate of the microorganisms.

However the suggestion by Starkerburg *et al.*, (1993) stating that sludge load and sludge age do not, but nitrates affect Bio-P removal which is the result of low sludge loading rates can not be favored because complete removal of nitrates has been ensured before the flow entered the anaerobic stage in the process.

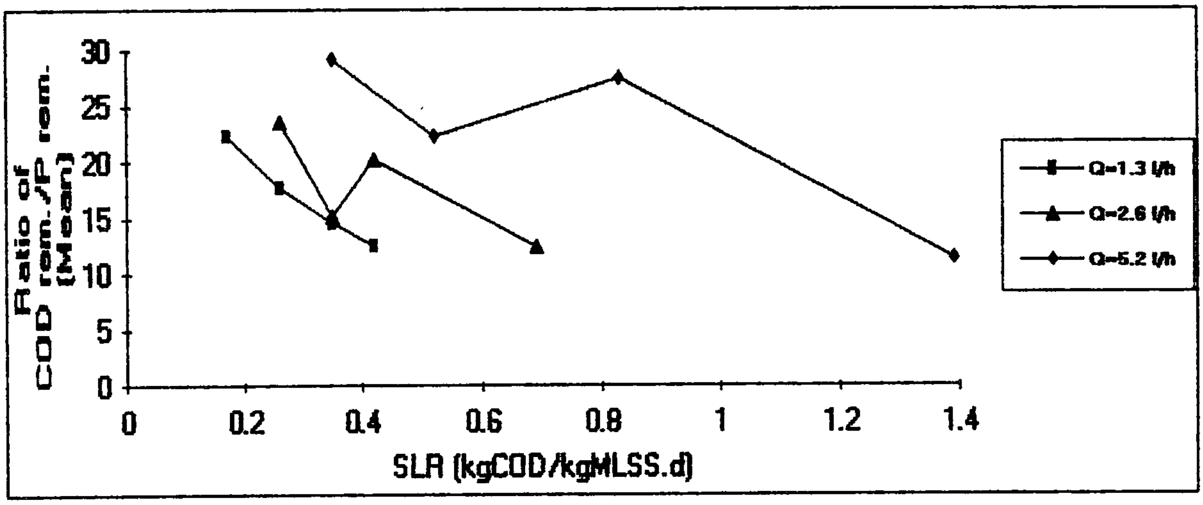

Figure 4.5 Phosphorus Removal versus Sludge Loading Rate

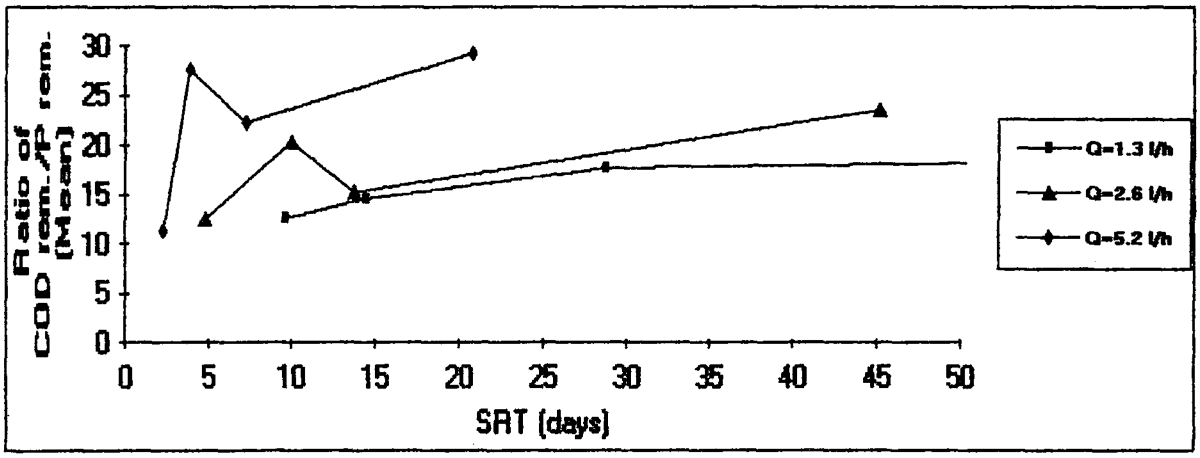

Figure 4.6 Phosphorus Removal versus Sludge Retention Time

Mixed-liquor suspended solids concentration (MLSS)

As can be seen in Figure 4.7, increasing MLSS concentrations in the aeration basin affect Bio-P removal efficiency positively. This can be attributed to the probable reality of a direct relation between the ratio of phosphorus-storing microorganisms to the total MLSS. Here also two values regarding MLSS concentration of 5000mg/l (corresponding to the COD concentration 1000mg/l) are out of declining order.

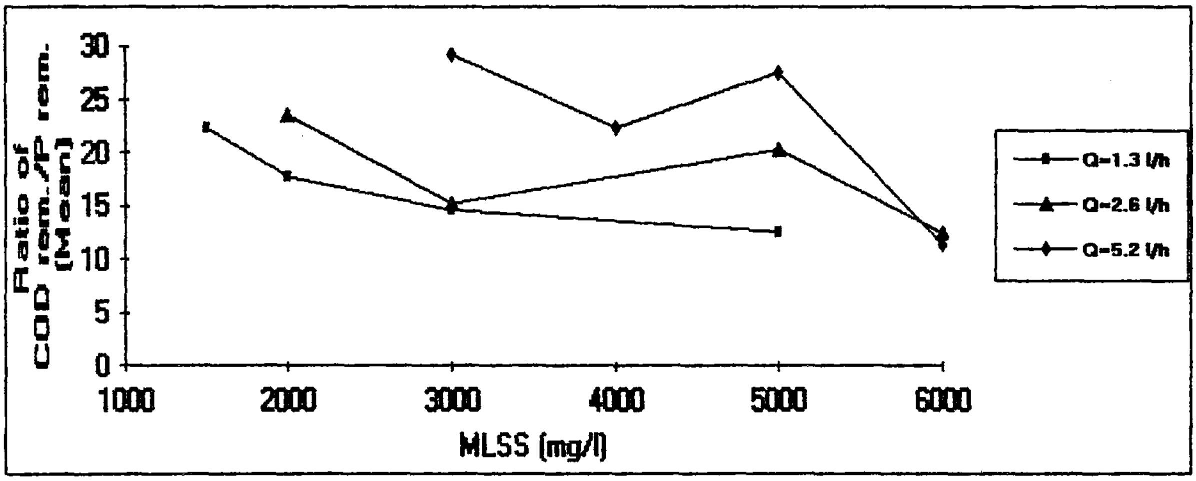

Figure 4.7 Phosphorus Removal versus Mixed-Liquor Suspended Solids in the Aerobic Reactor

Sludge Settling in the Process Option

In the system, settling unit is preceded with the aerobic reactor and it is suggested that such a configuration, employment of an oxic stage prior to settling, can be utilized as biological selector for sludge bulking control (Randall *et al.*, 1992). However sludge in the settling tank showed unfavorable settling characteristics, at low to high sludge loading rates when the system, comprising of anoxic-anaerobic-aerobic and settling units, was operated with completely-mixed anoxic reactor. Observed SVI_{30} values during this operation period were rather high (Figure 4.8).

Bad settling characteristics may be attributed to both the nature of completely-mixed aerobic reactor and soluble state of the feed substrate, which are postulated to support the growth of filamentous species (Randal *et al.*, 1992; Veenstra, 1994).

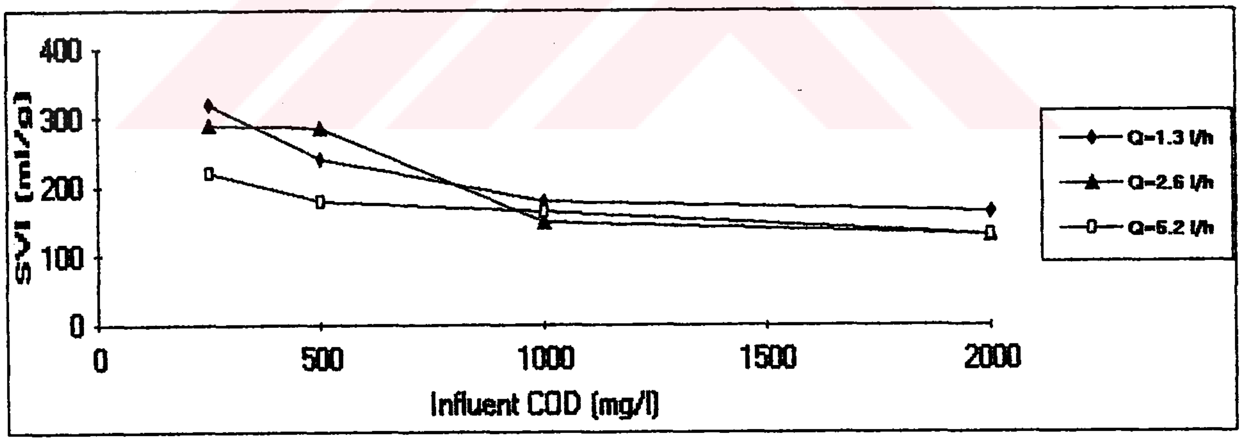

Figure 4.8 SVI_{30} Values Obtained During the Operation with Completely-Mixed Anoxic Reactor

When the completely-mixed anoxic reactor was replaced by a fixed-bed reactor, SVI_{30} values decreased significantly (Figure 4.9). It is thought that fixed-bed anoxic reactor suppresses the growth of filamentous organisms in a way.

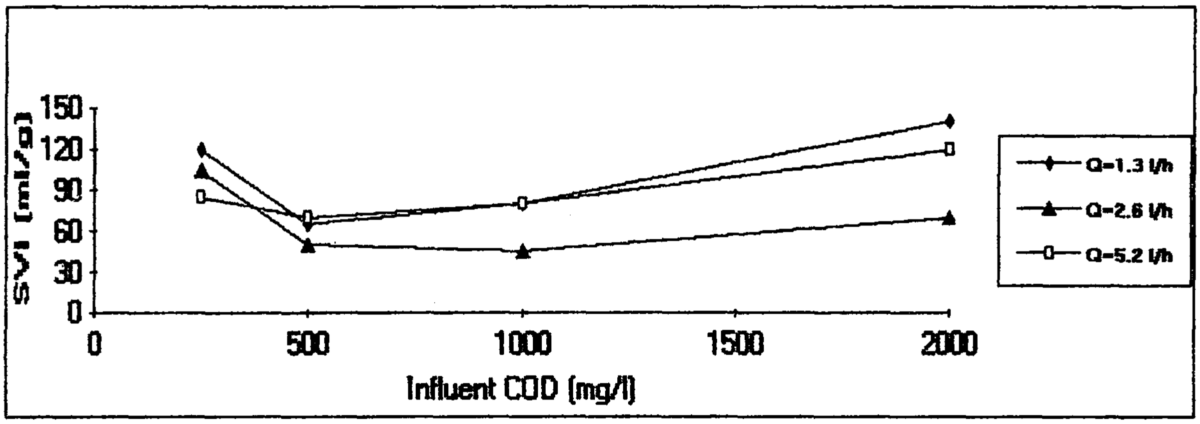

Figure 4.9 SVI_{30} Values Obtained During the Operation With Fixed-Bed Anoxic Reactor

CHAPTER FIVE

DISCUSSION OF RESULTS

Biological phosphorus removal is a new issue, especially for mainstream process, and most experience is coming from laboratory studies. With this purpose a phosphorus removal process has been proposed and set up at pilot-plant scale and operated continuously fed with synthetically prepared wastewater. In the proposed system a sequence of anoxic-anaerobic-aerobic and settling units with a sludge recycle from the settling tank to the anoxic stage has been designed, in such a way that maximizing phosphorus removal would be possible in a biological phosphorus removal process. This process can also be readily adapted for retrofitting purposes of the conventional suspended-growth biological treatment plants by inserting baffles into the plug-flow reactors, if a high degree of nitrogen removal is not required.

Ekama and Marais (1984) stated that 8.6mg/l of municipal wastewater is needed to reduce 1mg/l nitrate-nitrogen to nitrogen gas and similarly Randall *et al.* (1992) proposed a biochemical equation for nitrate reduction which offers that 1mgNO_3-N/l requires 2.7mgHAc/l for complete denitrification. As only part of the nitrate-nitrogen comes to anoxic reactor by sludge recycle line from the settling tank, this process option saves the organic matter which would otherwise be consumed for the full denitrification of the nitrate present in the wastewater whereas this system makes it available for biological phosphorus removal.

In the system, both aerobic and anaerobic reactors were operated as completely-mixed reactors. Since removals at completely-mixed reactors are lower than plug-flow reactors for the first or higher degree of biochemical conversions with a considerable difference at identical retention times; for which removal rates are expressed by $C=C_0/(1+k^*t)$ and

$C=C_0*e^{-k*t}$ respectively for first order reactions, it can be postulated that employment of plug-flow reactor instead of completely-mixed reactor could have produced higher phosphorus removals in the study (Vacker *et al.*, 1967; Milbury *et al.*, 1971).

Anaerobic zone in phosphorus removal systems is required for both acidic fermentation and biochemical interactions, such as phosphorus release and VFA uptake, of Bio-P organisms which also help increase the amount of phosphorus-removing organisms. However since the substrate was already a short-chain volatile fatty acid, anaerobic stage in the operated system has only been utilized for the activities of Bio-P organisms which enabled the anaerobic reactor to maximize its efficiency at any applied hydraulic loadings.

When the system was operated as A/O process (without anoxic stage), phosphorus removal showed abrupt variations with a bad efficiency at an influent COD concentration of 300mg/l. However these variations lessened and efficiency increased with the increasing COD strength of the wastewater. When experimenting with a COD concentration of 1500mg/l, variations got more smooth and efficiency maximized (Figure 4.1). This may result in a conclusion that when the COD strength of the wastewater increases, P-removal is not remarkably affected by the existence of nitrates. Suggestions by Rabinowitz (1985), Tetreault *et al.* (1986), Simpkins & McClaren (1978) and Vinconneau *et al.* (1985) stating that relatively high influent ΔCOD/ΔP ratios produce low effluent soluble phosphorus concentrations can be verified, but with an exception that VFA should be available ***much more*** than required for denitrification.

Two exceptional irregular variation in ΔCOD/ΔP observed (for the influent COD of 1000mg/l regarding the flowrates of 2.6 l/h and 5.2 l/h) with the varying operating parameters can be attributed to the bacterial population which develop compatible with the applied hydraulic and organic loads (Yeoman *et al.*,1987; Lettinga & Haandel, 1994). These irregular variations in ΔCOD/ΔP may also be attributed to probable occurrence of adsorption process which is more effective at high MLSS concentrations (Yeoman *et al.*, 1987).

Suggestion by Dold and Barker (1996) stating that conflicting evidence exists in the literature on the suspicious denitrifying characteristic of poly-P organism has been verified by the findings when the experimental set-up has been operated with and without anoxic stage. If poly-P organisms had denitrified, it would be possible to obtain better results for P-removal when the system was operated as A/O Process because all the substrate was in readily consumable soluble state and also was available in amounts much more than required for nitrate-nitrogen removal.

Findings also do not support the suggestion by Starkerburg *et al.* (1993) stating that P-removal is not affected by sludge load and sludge age which are the indirect indicators but affected by the presence of nitrates which is the result of low SLR and high SRTs. Though nitrates have been completely removed in the system before entering the anaerobic stage, durable effect of SLR and SRT in the system is apparent from Figure 4.5 and Figure 4.6.

When the effect of operating parameters is individually examined on graphs in Figures in Chapter Four, it can be concluded that increases in organic strength of the wastewater, organic loading rate, sludge loading rate and mixed-liquor suspended solids concentration improve P-removal efficiency, while increases in sludge retention time decrease P-removal efficiency (Figures 4.2, 4.3, 4.4, 4.5, 4.6 & 4.7). It may also be worth mentioning that increasing SLR in a system leads to lower COD removal, forming the opinion that P and COD removal are at a certain extent inversely related to each other.

It may be figured out from Table 5.1 that increasing SLR doesn't always contribute to an increase in P-removal, even sometimes causes a decrease. This behavior shows that it is difficult to verify either the suggestion by Yeoman *et al.* (1987) stating that endogenous respiration of microorganisms releases stored phosphates into the solution at long SRTs or the suggestion by Wentzel *et al.* (1988) stating that long SRT resulting in lysis increases the availability of organic substances for P-uptake of Bio-P removal microorganisms, thus leading to higher P-removal efficiency.

Irregular variations in P-removal under the effect of the various operating parameters can be attributed to the possible changing composition of the sludge (Yeoman *et al.*,1987; Lettinga and Haandel, 1994). This irregular behavior may also be attributed to the probable existence of adsorption process attracting phosphorus to the mixed-liquor suspended solids, which is more effective at high solids concentrations and relatively shorter hydraulic retention times where desorption is somewhat avoidable.

Though Levin and Shapiro (1965) reported that orthophosphate secretion from sludge microorganisms occurred between pH 5 and 6, significant P-removals have also been observed in the study at normally occurring pH values between 7 and 8 in anaerobic reactor. However here it may be worth mentioning that feed substrate was acetate, already a low-

Table 5.1 Effecet of HRT, OLR, SRT & SLR On Bio-P Removal Efficiency Tested With A Variety of Influent COD Concentrations.

HRT h	OLR $kgCOD/m^3.d$	SRT d	SLR kgCOD/kgMLSS.d	Ratio of $\Delta COD/\Delta P$ rem.
For an influent COD of 250mg/1				
23.0	0.26	416.0	0.17	22.3/1
11.5	0.52	45.2	0.26	23.6/1
5.8	1.04	20.8	0.35	12.5/1
For an influent COD of 500mg/1				
23.0	0.52	28.8	0.26	17.7/1
11.5	1.04	16.1	0.35	15.2/1
5.8	2.08	7.3	0.52	22.3/1
For an influent COD of 1000mg/1				
23.0	1.04	14.5	0.35	14.6/1
11.5	2.08	10.0	0.42	20.3/1
5.8	4.16	3.9	0.83	27.5/1
For an influent COD of 2000mg/1				
23	2.08	9.7	0.42	12.6/1
11.5	4.16	4.8	0.69	12.5/1
5.8	8.32	2.3	1.39	11.4/1

weight volatile fatty acid, and hence fermentation process was not a function of the anaerobic reactor which necessitates low pH.

At high sludge retention times bad sludge settling characteristic is a commonly encountered problem at biological wastewater treatment plants (Randall *et al.*,1992). It has also been suggested that employment of a completely-mixed aerobic reactor (Veenstra, 1994) and soluble COD (Randall *et al.*, 1992) contribute to the unfavorable settling characteristics, all of which have been the conditions involved in the operated system. Sludge settling is also important as it affects the total phosphorus removal efficiency due to the undesired carryover of the phosphate-accumulated cells from the settling tank.

Though Shao and Jenkins (1989) stated that the presence of an anoxic selector prevents sludge bulking for an influent SCOD of less than 100mg/l, good settling characteristics have been observed with much more higher influent COD concentrations when the completely-mixed anoxic reactor was replaced by a fixed-bed reactor (See Figures 4.8 & Figure 4.9). It may be thought that fixed-bed anoxic reactor suppresses the growth of filamentous organisms in a way.

CHAPTER SIX

CONCLUSIONS

Proposed process option in this study for enhanced biological phosphorus removal comprised a sequence of anoxic/anaerobic/aerobic units with a sludge recycle from the settling tank to the anoxic-stage. This system maximizes phosphorus removal due to complete removal of recycled nitrate-nitrogen within the recirculated sludge, before the flow enters the anaerobic stage.

Results on the process option showed that increasing (high) COD strength of the wastewater increase both P-removal and stability, even in the presence of nitrates in anaerobic stage (in A/O Process). However phosphorus removal improved remarkably, particularly for low influent COD concentrations, when the anoxic stage has been added. These two findings proves that the presence of nitrates affects Bio-P removal mechanism and they lose their effect when the COD concentration of the wastewater is in amounts ***much more*** than required for denitrification. It may thereby be concluded that bad phosphorus removal efficiency in the presence of nitrates can not solely be attributed to the denitrifying characteristic of poly-P organisms, if they are able to utilize nitrate as an electron acceptor. However, from a practical point of view, it can be concluded that the presence of nitrates in anaerobic stage of an enhanced biological phosphorus removal system for municipal wastewater will affect P-removal capacity, where COD concentration is low and volatile fatty acid concentration is generally less than 50mg/l.

Phosphorus removal ratio for the influent COD concentration of 250mg/l was around 25 and this ratio decreased to around 12 when the influent COD concentration of the wastewater increased to 2000mg/l, indicating that higher phosphorus removal is achievable in the treatment of industrial wastewaters. As the increasing COD concentrations resulted in more stable and higher phosphorus removal capacities, it is possible to conclude that the more volatile fatty acids there are in the anaerobic stage, the better is the resultant phosphorus removal.

Findings also showed that phosphorus is positively affected by increased aerobic hydraulic retention time, organic loading rate, sludge loading rate and mixed-liquor suspended solids concentrations whereas negatively affected by increased sludge retention time. However Table 5.1 shows that P-removal at the same time a function of all operating parameters altogether in a complex manner and it can not solely be related with a direct relation to any single operating parameter. However the operating parameter highly related to P-removal can be considered as sludge loading rate since it comprises all the operating parameters in its nature to an extent.

Significant P-removals have also been observed when the pH in the anaerobic stage of the process was between 7 and 8, other than 5 and 6, which indicates that orthophosphate secretion from microorganisms is also possible at this pH interval.

Bad sludge settling characteristic is a common problem in nutrient removal plants due to long retention times for the occurrence of nitrification and denitrification. Sludge settling in the process improved remarkably when the completely-mixed anoxic stage has been replaced with fixed-bed anoxic stage. Regarding this observation it can be postulated that fixed-bed anoxic reactor helps more to remove or suppress the growth of filamentous organisms in a way.

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