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Simultaneous removal of organic carbon, nitrogen, and phosphorus from a domestic wastewater using anaerobic sequencing batch reactors

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ABSTRACT This research demonstrated the feasibility of using anaerobic sequencing batch reactors (An A^2/O^2 SBR) to achieve simultaneous removal of organic carbon, nitrogen, and phosphorus from a domestic wastewater. The effects of influent carbon to nitrogen (C/N) ratio, solids retention time (SRT), and maximum system loading capacity on process performance were investigated. It was found that a minimum influent chemical oxygen demand (COD) concentration of 300 mg/L and a corresponding COD to total Kjeldahl nitrogen (COD/TKN) ratio of 7 were required in order to obtain a satisfactory (over 90%) phosphorus removal level. Since the wastewater used was deficient in carbon, addition of glucose as an external carbon source was necessary to maintain the above influent COD/TKN ratio. Furthermore, the percent total phosphorus (TP) removal can be correlated either to the influent COD concentration or to the COD/TKN ratio in a quantitative manner using polynomial expressions. An increase in SRT from 20 to 30 days did not affect COD performance; however, it improved remarkably both TKN and TP removal efficiencies. On the other hand, an increase in the organic loading rate to a level of 0.63-0.66 kg COD/m^3-d or higher appeared to reduce significantly the ability of the system regarding the phosphorus removal, and to a lesser extent the nitrogen removal efficiency.

(Anaerobic sequencing batch reactor, carbon and nutrient removal, solids retention time, maximum loading capacity)

INTRODUCTION

Increasing population growth coupled with industrial and economic development have become the foremost causes of water pollution worldwide. Eutrophication is a form of water pollution that is mainly associated with the unconrolled discharge of nutrients (nitrogen and phosphorus) to receiving waters. The effects of eutrophication can be more serious and far-reaching than simply an increase in aquatic plant growth and may extend from stress or loss of aquatic life to interference with water supply treatment systems. Since conventional municipal wastewater treatment does not remove phosphorus and nitrogen adequately, in order to minimize the eutrophication potential it is necessary to introduce biological nutrient removal (BNR) processes prior to discharging to water bodies [1].

A BNR process may be incorporated into any standard activated sludge treatment scheme since it typically consists of a sequence of anaerobic, anoxic, and aerobic zones. Various modifications have been proposed and applied, including the anaerobic/anoxic/aerobic (A^2/O), the five-stage Bardenpho, the University of Cape Town (UCT), and the Virginia Initiative Plan (VIP) processes [2]. However, the above mentioned processes are characterized by significant land requirements and operational complexity. The sequencing batch reactor (SBR) system can serve as an attractive alternative solution, particularly when land availability as well as flexibility and simplicity of operation are of concern [3, 4]. SBR technology has been traditionally employed in the biodegradation of organic compounds from municipal and industrial wastewaters [5, 6, 7]. Although in recent years SBRs have been applied either in nitrogen or phosphorus biotransformation processes, limited data are available on SBR use in simultaneous nitrogen and phosphorus removal from wastewaters [8, 9].

This study introduces the concept of a five-stage anaerobic/anoxic/oxic reactor operating in a BNR mode. The modified sequence, involving a series of anaerobic/anoxic/oxic/anoxic/oxic cycles respectively, has been defined as "AnA^2/O^2". The "An" term refers to the anaerobic nature of the process (since the system is sealed to prevent any air entrapment), while the A^2/O^2 term refers to the alternating anoxic/oxic stages. It has been observed that organic carbon, nitrogen, and phosphorus removal are possible in a single tank, if the operating environment is properly modified to incorporate anaerobic, anoxic, and aerobic conditions into a time cycle [10, 11]. However, further investigation is needed to identify the optimal operating conditions that are required to achieve simultaneous removal of all targeted compounds.

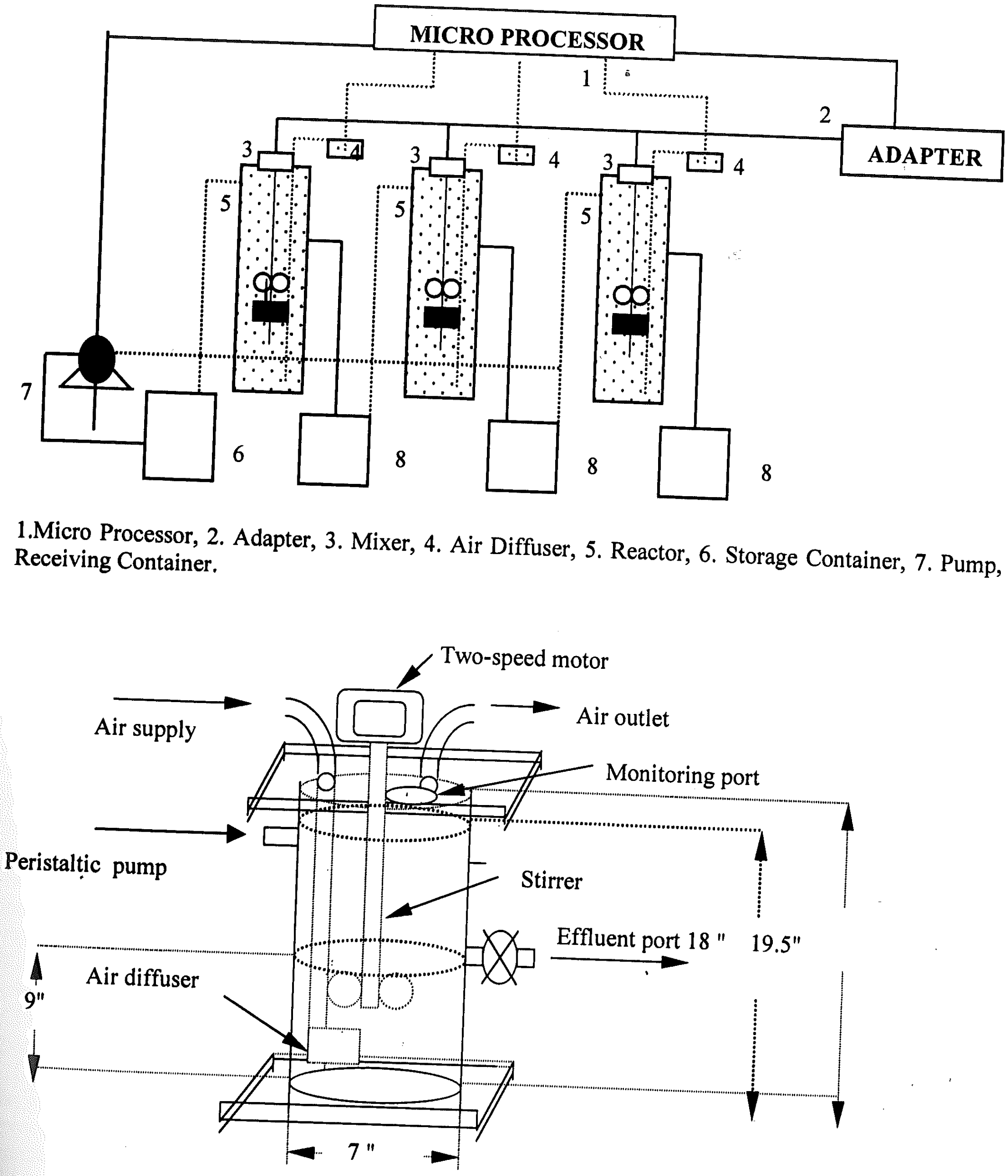
The overall objective of this research was to investigate the feasibility and effectiveness of an anaerobic sequencing batch reactor (AnA^2/O^2 SBR) in the simultaneous removal of organic carbon, nitrogen, and phosphorus from a domestic wastewater. In order to meet the above objective, a 24-month bench-scale research program was carried out. The findings from this program can be summarized in 3 distinct parts: (1) concept development, feasibility and optimal operating condition; (2) process optimization and maximum system loading capacity; and (3) system recovery using a step-loading reduction approach, and development of design criteria. The results from the first part have been published elsewhere [12]. This paper explores issues related to process optimization regarding the influent carbon to nitrogen (C/N) ratio and solids retention time (SRT), as well as the maximum loading capacity with respect to chemical oxygen demand (COD) loading.

MATERIALS AND METHODS

The laboratory-scale experiment conducted involved the use of 3 identical SBR systems, operating in a parallel mode. The reactors were made of plastic (acrylic) material and had an internal diameter of 17.8 cm (7 in) and a height of 49.5 cm (19.5 in). The operating liquid volume was 10 L, while 5 L were wasted at the end of each operating cycle. Each reactor was equipped with a cover plate, a rubber stopper, an air diffuser and a stirrer. Other accessories included feeding pumps, influent and effluent containers, valves, air compressors, and microprocessor time controllers. A schematic representation of the SBRs employed is depicted in Figure 1.

The reactors were initially seeded with sludge obtained from the Sri-Phraya Domestic Wastewater Treatment Plant, located in Bangkok, Thailand. In order to allow the biomass to get acclimatized, a step-by-step feeding approach was followed. That is, starting with a liquid volume of 5 L, the system was allowed to achieve at least 80% COD removal under a reasonably stable operation (i.e., no more than 5 to 10% fluctuation in COD removal values), before a further increase in volume by 1 L was introduced. This process was repeated until the full operating liquid volume of 10 L was achieved. The 24-hour cycle of SBR operation was consisted of the following steps : 5 hours filling, 5 hours operating on the first anoxic time, 3 hours on the first oxic time, 5 hours on the second anoxic time, 3 hours on the second oxic time, 1.5 hours settling, 0.5 hour drawing, and 1 hour idle time. The air supply during the oxic periods was adjusted to maintain a minimum dissolved oxygen concentration of 2 mg/L. During the SRT optimization study, each reactor was operated at a different SRT; namely 20, 25, and 30 days, respectively. The reactors were fed with raw domestic wastewater collected from the same treatment facility mentioned previously.

The average COD, total Kjeldahl nitrogen (TKN), and total phosphorus (TP) concentrations of the raw domestic wastewater were 241, 53.5, and 8.2 mg/L, respectively. However, since the wastewater was found to be deficient regarding the carbon content (as discussed later), glucose was added as an external carbon source in a step-by-step fashion, until the COD in the feed reached a value of 543 mg/L. Furthermore, in order to determine the maximum system loading capacity at a 30-day SRT, the volumetric loading rates were increased gradually in a step-by-step fashion from 0.17-0.20 to 0.73-0.79 kg COD/m^3-d, until the system was overloaded. Each loading rate was maintained until a reasonably stable operation was reached, (i.e., exhibiting over 80% COD removal with no more 10% variation). This was usually achieved within 2 to 3 system HRTs. Throughout this study, influent and effluent samples were collected twice a week and analyzed for COD, TKN, and TP. In addition, the influent flow rate, mixed liquor suspended solids (MLSS), and dissolved oxygen (DO) were measured daily. All analytical determinations



1.Micro Processor, 2. Adapter, 3. Mixer, 4. Air Diffuser, 5. Reactor, 6. Storage Container, 7. Pump, 8. Receiving Container.

Figure 1. Schematic drawing of the SBR system.

were performed in accordance with the Standard Methods [13]. Details for all analytical procedures followed can be found elsewhere [14, 15].

RESULTS AND DISCUSSION

Influent C/N Ratio and SRT Optimization

In order to explore the potential of the AnA^2/O^2SBR process in removing the pollutants effectively, all three reactors were initially operated at an SRT of 20 days. During the acclimatization period when a step-feeding procedure was followed, the average COD, TKN, and TP removal efficiencies were 93.2, 96.8, and 18.8 % respectively. Although all reactors, under reasonably stable conditions, achieved a high COD and TKN removal from the early stages of their operation (i.e., within 2 to 3 HRTs), the corresponding TP removal was significantly lower. This may be due to insufficient organic carbon available for the growth of phosphorus removing (Bio-P) microorganisms [14]. It was therefore decided to increase the amount of influent organic carbon available by adding glucose as an external source in a step-by-step mode. The percent COD, TKN, and TP removal efficiencies for the first 30 days after the addition of glucose are depicted in Figure 2. It is obvious that TP removal improved dramatically (from less than 20% to over 50%) within about a week after glucose addition, while it exceeded the 80% level approximately one additional week later and, afterwards, it remained consistently high. At the same time, both COD and TKN removal efficiencies were always at high levels.

It was also observed that the TP removal efficiency could be correlated to the influent COD concentration as well as the COD/TKN ratio. Using appropriate regression analysis techniques, the following quantitative

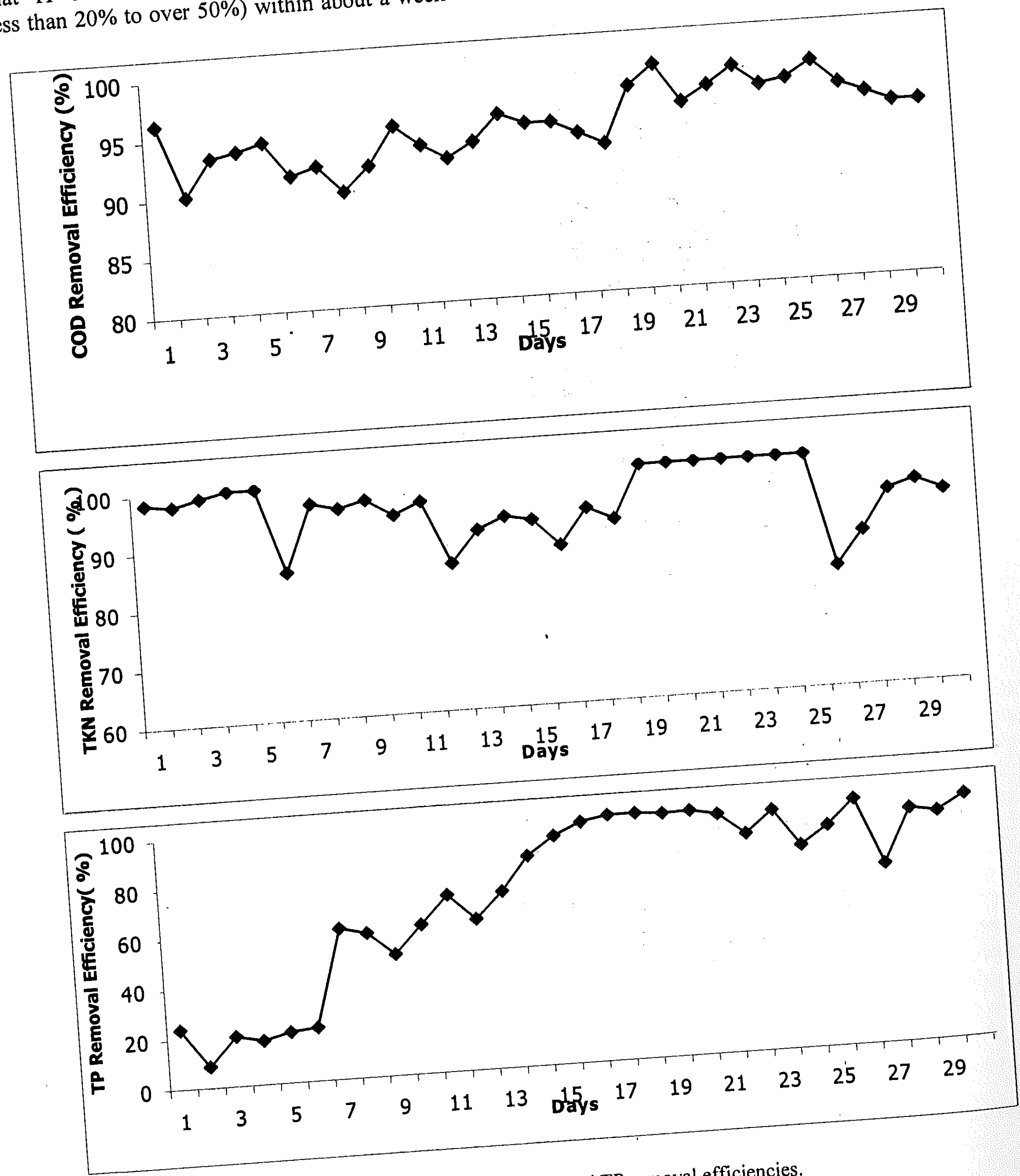


Figure 2. Percent COD, TKN and TP removal efficiencies.

(polynomial) relationships were developed relating the influent COD concentration and the COD/TKN ratio to TP removal efficiency, respectively:

$$Y_1 = 0.0032X_1^3 - 0.2839X_1^2 + 8.7867X_1 + 0.6756 \quad (1)$$

$(r^2 = 0.729, n = 30)$

$$Y_2 = 0.0012X_2^4 - 0.0797X_2^3 + 1.5123X_2^2 - 4.614X_2 + 21.619 \quad (2)$$

$(r^2 = 0.907, n = 30)$

Where: X_1 = influent COD (mg/L)
X_2 = COD/TKN ratio
Y_1 or Y_2 = TP removal efficiency (%)

The above quantitative relationships have been illustrated in Figure 3. It can be seen, for example, that at an influent COD concentration of 300 mg/L and a corresponding COD/TKN ratio of 7.2, an average of 85 % TP removal can be obtained. The effect of COD/TKN ratio on BNR processes has also been addressed in several previous studies. For instance, it has been reported that phosphorus removal was limited when the influent COD/TKN ratio was lower than 7.5 [16]. Furthermore, Barnard [17] has pointed out that although a COD/TKN ratio higher than 10 was required to stimulate phosphorus removal, the ratio had minimal effect on nitrogen removal. On the other hand, other researchers have suggested that a COD/TKN ratio of over 12 is required to support adequately the denitrification process [18, 19]. Overall, the observations from this study regarding the COD/TKN ratio are in accordance with those presented in the cited literature.

In order to investigate the effect of SRT on the process, 3 different system SRTs were applied, namely 20, 25 and 30 days using the 24-hour operating cycle described previously. Data shown in Figure 4 clearly indicate that although an increase in SRT did not seem to affect the COD removal behavior, it did result however in a considerable improvement in both TKN and TP performance. The reactor operated at a 30-day SRT exhibited average COD, TKN and TP removals of 95, 91 and 94 %, respectively. It can therefore be concluded that the effectiveness of the AnA^2/O^2 SBR process to remove organic carbon, nitrogen, and phosphorus simultaneously from the domestic wastewater is depended upon the following: (1) an influent COD concentration of over 300 mg/L; (2) a COD/TKN ratio of over 7, and (3) a system SRT of 30 days.

Maximum System Loading Capacity

The AnA^2/O^2SBR system was designed and operated to provide the optimal conditions to stimulate the growth of an effective consortium of bacteria to stabilize organic matter and nutrients (nitrogen and phosphorus) simultaneously. However, if the system is being constantly overloaded from an organic matter point of view, process failure may occur. As shown in Figure 5, the system operated at a 30-day SRT was loaded in a step-by-step mode starting from 0.17-0.20 kg COD/m^3-d until it reached the maximum loading rate of 0.73-0.79 kg COD/m^3-d. As the loading rate kept increasing, the TP removal efficiency appeard to be the first performance parameter to be affected. A sharp drop in TP removal from over 90 % to below the 60 % level was observed when the rate was increased to 0.63-0.66 kg COD/m^3-d, while the corresponding average COD and TKN removal efficiencies were slighly affected being 95.3 and 88.9 %, respectively. At the maximum a loading rate of 0.73-0.79 kg COD/m^3-d the average removal efficiencies obtained for COD, TKN, and TP were 93.3, 77.2, and 43.4%, respectively. This was considered to be a treatment system "failure" (i.e., exhibiting an average removal efficiency below the 50 % level for any given performance parameter). Since the percent TP removal was siginficantly lower than the corresponding COD and TKN removal percentages, it appears that the performance of the Bio-P bacteria is more drasticaly affected at high organic loading conditions than the performance of the microbial groups involved in carbon or nitrogen biotransformation processes.

When the organic loading in the influent of any biological treatment process increases, it will eventually overload the system. Thus, it is important to monitor: (1) whether the system is close to the critical (or "failure" as defined above) point; (2) what operational tools are available; and (3) what changes in perfomance parameters actually occur under stressed conditions. In general, feed stoppage and influent loading reduction are recommended as short-term actions. In this 24-month bench-scale research program, the step loading reduction proved to be a practical and effective approach to recovery; however, further details will be provided in a follow-up publication.

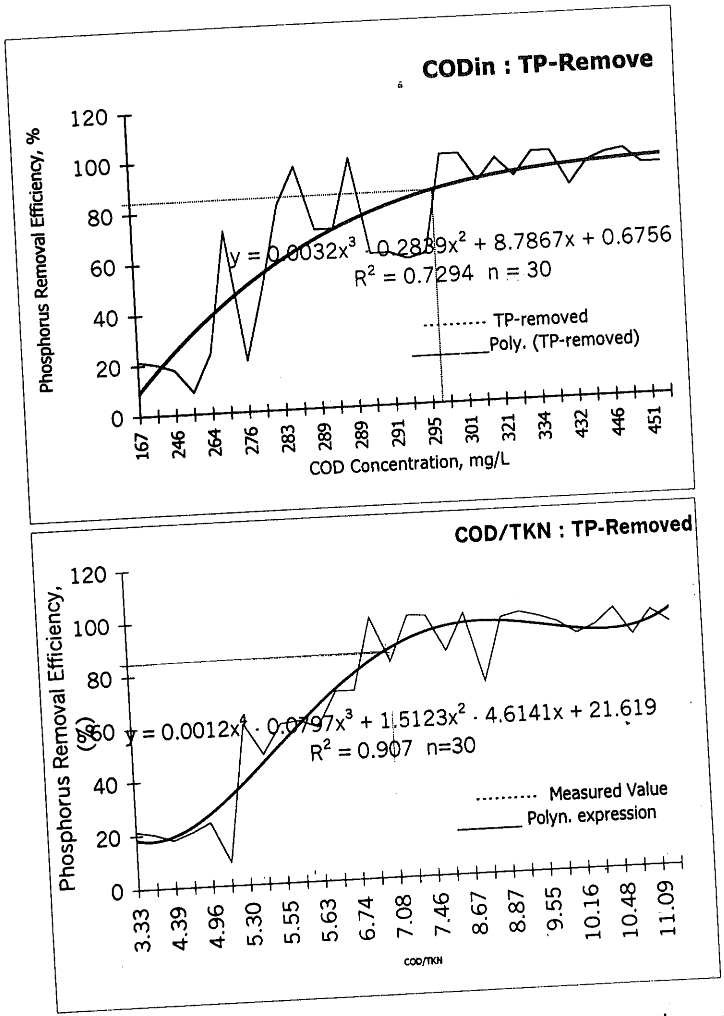


Figure 3. Phosphorus removal efficiency as a function of influent COD concentration and COD/TKN ratio.

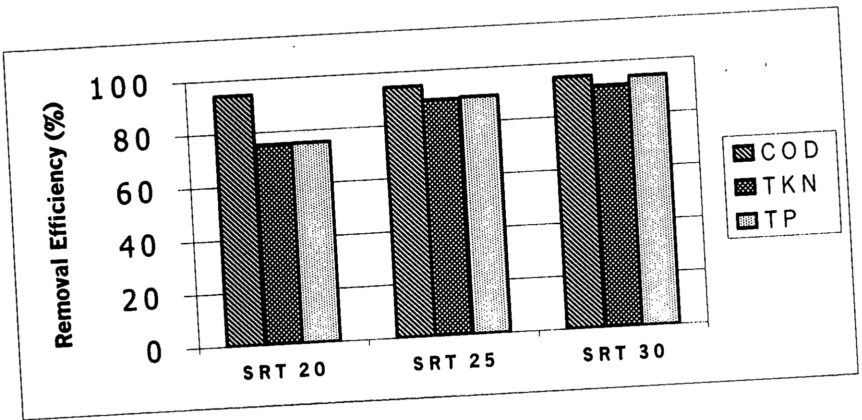


Figure 4. COD, TKN and TP Removal Efficiencies as a function of SRT.

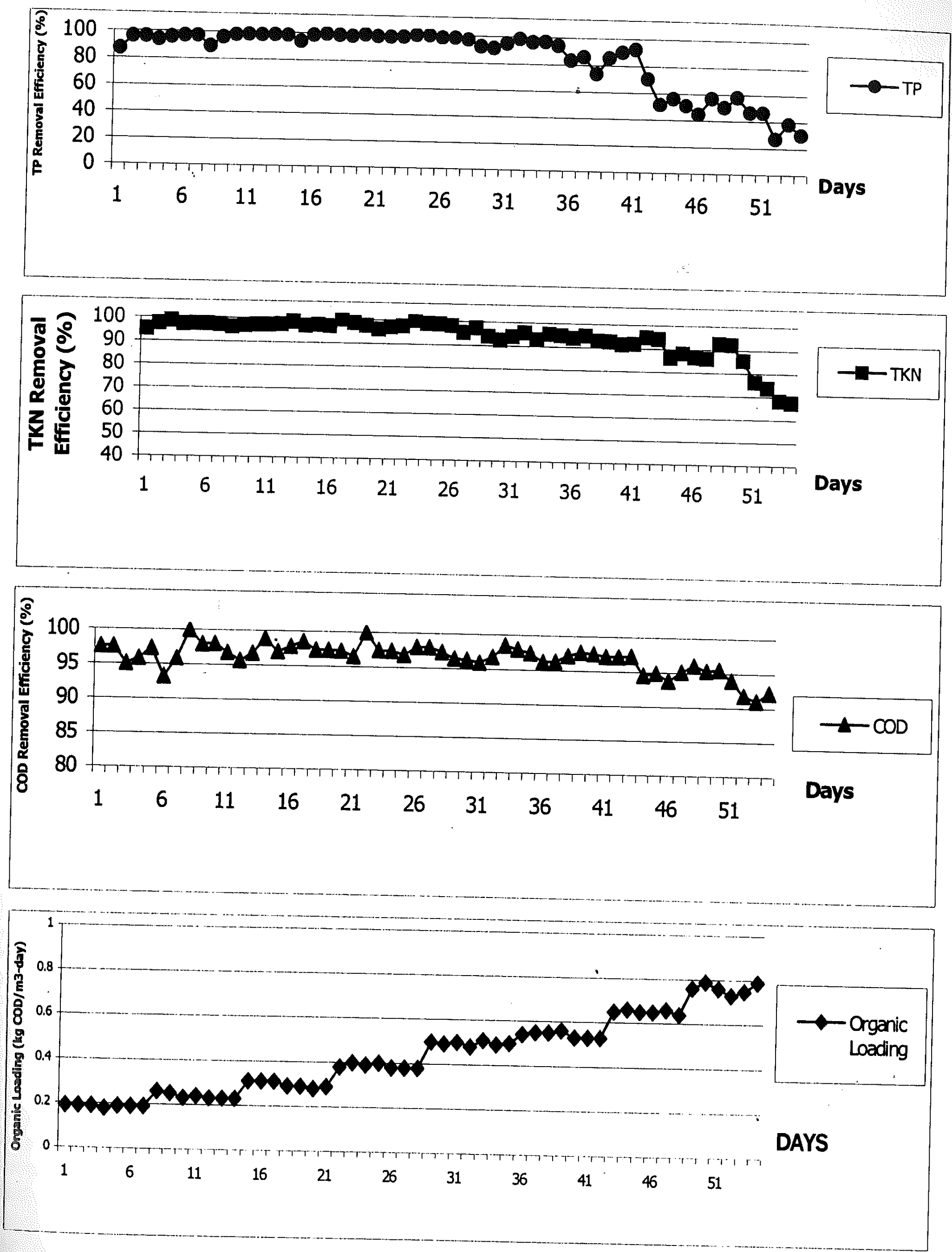


Figure 5. COD, TKN, and TP removal efficiencies as a function of organic loading.

CONCLUSIONS

The AnA^2/O^2 SBR process was successfully employed in the simultaneous removal of organic carbon, nitrogen, and phosphorus from a domestic wastewater. Overall, the C/N ratio in the influent was found to be a critical factor in achieving satisfactory TP removal. Since the wastewater used was deficient in organic carbon, glucose was added as an external carbon source. Results indicated that an influent COD concentration of at least 300 mg/L with a corresponding COD/TKN ratio of 7 were required in order to obtain a minimum 90 % TP removal efficiency. Furthermore, the relationship between the influent COD concentration or the COD/TKN ratio and TP removal efficiency can be expressed in the form of quantitative (polynomial) equations. It was also observed that a 30-day SRT resulted in the highest removal efficiencies for all parameters involved, within the SRT range investigated. Finally, an increase in the maximum loading rate affected much more drastically the TP removal efficiency than the corresponding COD or TKN percentage values.

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