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An Application of Anaerobic-Aerobic Combined Bioreactor Efficiency in COD Removal

Abstract: Over the past few decades, anaerobic-aerobic wastewater treatment systems have been widely used in industrial and municipal wastewater treatment. This study was conducted to examine the effects of combined anaerobic-aerobic bioreactors in the removal of chemical oxygen demands (COD) while reducing phosphate concentrations in synthetic wastewater. In this project, a bioreactor with the dimensions of 10 cm × 10 cm × 80 cm with respective Kaldnes packing ratios of 90 and 30% for the anaerobic and aerobic sections was designed. A combined anaerobic-aerobic reactor's structure made changing hydraulic retention times only possible by adjusting the volume of its aerobic and anaerobic sections. In the first case, the anaerobic and aerobic sections of the reactor occupied 30 and 50 cm of its height, respectively. The height of the anaerobic section decreases to 12.5 cm in the second case. In aerobic and anaerobic sections, pH was within a neutral range, temperature was 37°C. MLSS (mixed liquor suspended solids) was 1220 and 1030 mg/L, and attached growth was 743 and 1190 mg/L respectively. In order to evaluate COD in the wastewater, three different initial phosphorus concentrations were tested: 12.8, 32.0 and 44.8 mg/L, as well as four COD: 500, 1000, 1200 and 1400 mg/L. Considering the results, COD removal is greater than 80% when the valve 2 is in the anaerobic section outlet regardless of the concentration of phosphate. In this case, the best result is for inlet COD of 500, where the reactor can eliminate more than 90%. When the COD concentration reaches 1000 to 1400 ppm, the reactor's COD removal efficiency declines to 60%.

Keywords: hydraulic loading, anaerobic-aerobic combined reactors, COD removal, fixed bed bioreactor, Kaldnes packing, municipal and industrial wastewater

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1. Introduction

Managing municipal and industrial wastewater successfully requires the proper combination and sequencing of treatment methods. A variety of industrial wastewaters including textiles, food, paper, pharmaceuticals, starch, municipal waste and sewage, and olive oil factory effluents have been treated using anaerobic and aerobic bioreactors [1, 2]. Anaerobic-aerobic systems using high-rate bioreactors have a short residence time of several hours to several days and a high COD removal rate (more than 70%) [3]. Anaerobic-aerobic bioreactors have a greater degree of complexity to optimize COD removal than simple aerobic or anaerobic bioreactors due to the simultaneous operation of both sections [4]. Optimizing the treatment system is crucial to determining the optimal size of each reactor part, which is based on the anaerobic or aerobic processes [5]. The problem with conventional treatment plants is that they present several challenges, including the need for a large amount of space, the emission of pollutants into populated areas, the low efficiency of the process, the large amount of sludge produced, and high energy costs [6]. In contrast, combined anaerobic-aerobic bioreactors require less aeration and consume less energy [7]. It is essential to control aeration time and oxygen limitation scenarios within anaerobic segments in anaerobic-integrated structures. Based on Chan et al.'s research, integrated bioreactors are classified into four types: anaerobic-aerobic sequencing batch reactors (SBR), combined anaerobic-aerobic culture systems, and integrated bioreactors with or without physical separation of anaerobic-aerobic zones. A bioreactor that integrates aerobic and anaerobic degradation pathways has the potential to enhance overall degradation efficiency [8]. Separation between the aerobic and anaerobic sections is necessary for an effective COD removal system [9]. Because of the complex structure and layout of incorporated bioreactors, the investment and construction costs are higher. An increase in the aerobic sector retention time correlated significantly with system performance, cell growth rate, COD removal, and sludge deposition capacity. In spite of this, it is not economically feasible to persist in the aerobic sector for a long period of time [10]. The two types of well-known anaerobic-aerobic systems which are similar to this pilot study are as follows.

1.1. Upflow Anaerobic Sludge Blanket (UASB) and Aerobic Fluidized Bed (AFB) System

In liquid bed reactors, particles covered with biofilm are fluidized by the circulation of liquid through mobile supports. The stationary bed process usually has inherent limitations related to substrate diffusion. Several advantages can be attributed to the aerobic fluidized bed (AFB) reactor, including a high biomass concentration, a high organic loading rate (OLR), a short heat recovery time (HRT), a low number of bed clogs, a small external mass transfer resistance, and a large surface area for mass transfer [11]. Due to their very high liquid recirculation ratios, AFBs have some limitations that prevent their application on a large scale. These include the control of the bed expansion, thickness of the biofilm, and oxygen distribution system as well as high energy consumption [12]. Several factors have been highlighted as reasons why the UASB-AFB system may be beneficial in the biological treatment of industrial wastewaters with a medium strength, such as high pH tolerance, reduced sludge formation, and stabilization of COD removal [8]. Space constraints make the UASB-AFB configuration an attractive technical, economic, and environmental option.

1.2. Integrated Anaerobic-Aerobic Fluidized Bed Reactor

Recently, the compact high-rate bioreactor for wastewater treatment has drawn considerable attention as it can meet stringent requirements regarding space, odor, and view, as well as producing biosolids. A feasible alternative to the conventional bioreactor is the integrated bioreactor, which combines aerobic and anaerobic processes into a single pilot [13]. When aerobic and anaerobic degradation pathways are combined in a single reactor, the degradation efficiency can be enhanced [14]. Compared to anaerobic-aerobic systems, integrated bioreactors have lower costs, higher efficiency and smaller footprints [9, 15]. Although integrated anaerobic-aerobic bioreactors are in their infancy, only a few studies have explored their design, operation, and process development.

This article distinguishes itself from other papers on the subject by combining an anaerobic and anaerobic bioreactor with a Kaldnes packing ratio of 90% in the anaerobic section and 30% in the aerobic section in order to remove COD from waste water by considering phosphate. This type of bioreactor has low energy requirements, a low capacity, and an efficient organic matter removal process.

2. Materials and Methods

2.1. Characteristics of Bioreactor

This reactor, which was made of plexiglass, had the dimensions of 10 cm × 10 cm × 80 cm. As a part of the process of removing COD from synthetic wastewater, the synthetic wastewater is first sent to the anaerobic reactor and then to the aerobic reactor through the inlet valve located at the lowest point of the column height (5 cm). A series of outlet valves at different heights is installed on the opposite side of the reactor in order to investigate the change in phosphorus and COD concentrations as they move along the reactor at different heights within the reactor. Each of the valves on the column is fitted with a tube that is used to sample a liquid more homogeneous at its center and which is more easily identified. Figure 1 provides a schematic of the pilot during phase 1 of this study.

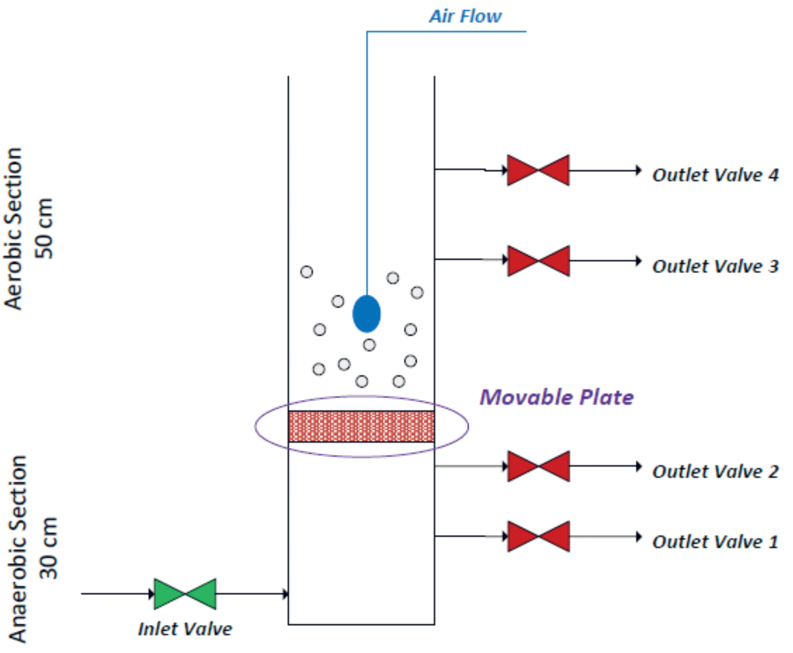

Fig. 1. Location of valves on the reactor in phase 1

This project investigated the percentage reduction of COD in anaerobic-aerobic integrated reactors in different retention times by considering phosphate as deterrent substance. However, due to the structure of anaerobic-aerobic integrated reactors, changing the retention time could only be accomplished by modifying the volumes of the anaerobic and aerobic sections. As a result, the tests were conducted in two volumes of anaerobic and aerobic sections. In phase 1, anaerobic parts were considered up to 30 cm from reactor columns, while aerobic parts were considered up to 50 cm. According to the input flow of 20 mL/min and the volume of the anaerobic and aerobic areas, the anaerobic residence time will be 2.5 h and the aerobic residence time will be 3.75 h. During the secondary residential time (phase 2), the outlet valve 1 would be the output of the anaerobic part, so about 1.042 h of residence in the anaerobic part during the secondary residential time, while there was approximately 5.21 h in the aerobic part. As the upper layers of the anaerobic zone are aerated, so the interface system will function anoxically. As a result, the whole height of a bioreactor is considered to be higher than a usual conventional reactor. To prevent the two areas from merging as much as possible, a fine mesh was installed to separate the aerobic and anaerobic zones. An air stone was used to aerate the water at a specified rate and, an aquarium heater was used to maintain the temperature of the aerobic zone at approximately 37°C in order to promote the growth of microorganisms. The COD values are set at 500, 1000, 1200, and 1400 for 1.2 L/h of influent. As the packing takes up 30% of the reactor volume in the aerobic sector, and since the area of the active surface is about 480 m^2/m^3, COD load is 22.23 g COD/(m^2·d). According to the reactor design, 90% of the reactor volume in the anaerobic section is occupied by the packing. Therefore, the anaerobic system's COD load is 11.1 g COD/(m^2·d).

2.2. Setup

Initially, a batch system was set up in a two-separator bioreactor for aerobic and anaerobic section with return sludge from the Ekbatan Treatment Plant, Tehran (MLSS of 2700 mg/L and COD of 420 mg/L). For forming a biofilm on the outer surface of the packing, the system was operated in batch mode for a period of 1.5 months. As part of the configuration of this system, it is essential to prepare both aerobic and anaerobic treated sludge; the second step, after such preparation, is to merge the two systems in the main reactor and allow them to operate simultaneously. Upon the formation of the biofilm on the packing, continuous operation began as soon as the sludge was transferred to the main reactor.

2.3. Sample Preparation

In order to investigate the performance of a combined anaerobic-aerobic reactor for removing COD, the wastewater entering the system is synthesized and the amount of inlet COD can be adjusted. Molasses, urea, and potassium phosphate dihydrogen were present in this artificial wastewater, which had a COD : N: P ratio of 100 : 5 : 1, and the molasses COD used was approximately 785 mg/L. Using COD values of 500, 1000, 1200, and 1400, the project evaluated the efficiency of the reactor in removing COD, as well as the effects of changing the ratio of phosphorus in the mentioned fraction from 1 to 2, 5 to 7, respectively.

3. Results and Discussion

In order to change the residence time between anaerobic and aerobic sections, the retaining plate must be moved. Thus, in the first stage (phase 1), the system was prepared to be anaerobic up to valve 2 and aerobic thereafter. This condition is maintained for one week to allow the system to adapt to continuous operation. Synthesized feed enters the system at a daily flow rate of 28.8 L. In the phase 1 of this study, the HRT in the anaerobic section is 2.5 h, while in the aerobic section is 3.75 h. So, as a result, the residence time in the whole reactor will be 6.25 h. COD concentrations were varied at four different concentrations of 500, 1000, 1200, 1400 during the experiments. To prevent any shock to the system, as well as to improve the system's ability to adapt to the new conditions, low concentrations are first checked. In second phase of the study, the HRT of the anaerobic section would be 1.042 h, while it would be in the aerobic section for 5.21 h, resulting in a total residence time of 6.25 h in the whole reactor. A similar procedure applies here. It is actually intended to investigate the impact of the ratio of anaerobic to aerobic retention time on the removal of COD. The following are line graphs showing the percentage of COD removal for different amounts of input phosphorus during the initial retention time, when valve 2 is anaerobic output considered as phase 1.

As shown in Figure 2, for COD = 500, 1000, 1200 as expected, the COD removal percentage increased and reached 73.84, 68.57 and 78.78 respectively, while for COD = 1400, the bed experienced dramatic fluctuations due to possible shocks caused by the combination of the two sections. Aeration is not zero in the upper part of the anaerobic section, and the reactor is approaching anoxic conditions. In addition, the results are also influenced by changes in temperature and fluctuations in the inlet flow. According to Figure 3, the concentration of phosphate as a disturbance increased, resulting in a feed composition of COD : N : P = 100 : 5 : 5. The removal of COD is greater than 75% across all four-line graphs, and for a COD of 1200, the removal is 84.14%, which indicates the effectiveness of this bioreactor. A significant effect of phosphate was observed on COD = 1000, resulting in a reduction in COD removal efficiency in the anaerobic section to 34.27%, which is significantly lower than the performance of the reactor in the previous case (52.85%). At the last step, increasing the phosphate concentration to a ratio of COD : N : P = 100 : 5 : 7 is considered to be a shock to the system, and its results are shown in Figure 4. Apart from COD = 1400, reactor performance in other cases was remarkable and COD was removed in the anaerobic and aerobic segments by just over 58 and 70%, respectively. It should be noted that despite the high phosphate concentration in the reactor, the final reactor efficiency is 87.18% even for COD = 500, which is close to domestic levels of COD. Therefore, phosphate has no extraordinary effect on the removal of COD.

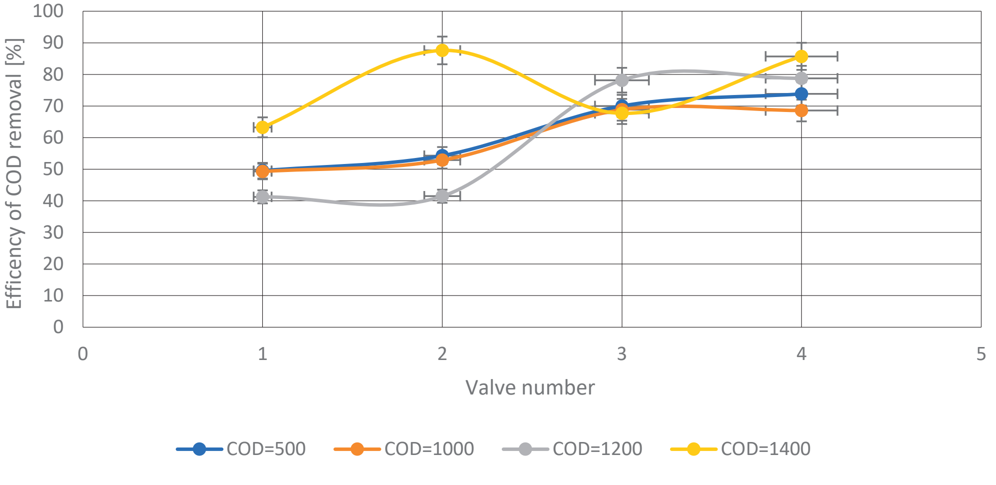

Fig. 2. Graph of COD removal percentage changes in the reactor, COD : N : P = 100 : 5 : 2 – valve 2 is the anaerobic outlet

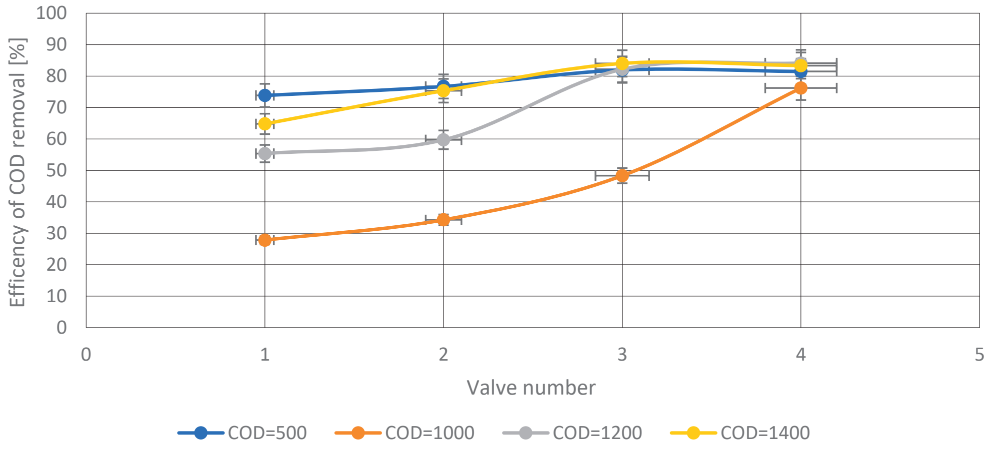

Fig. 3. Graph of COD removal percentage changes in the reactor, COD : N : P = 100 : 5 : 5 – valve 2 is the anaerobic outlet

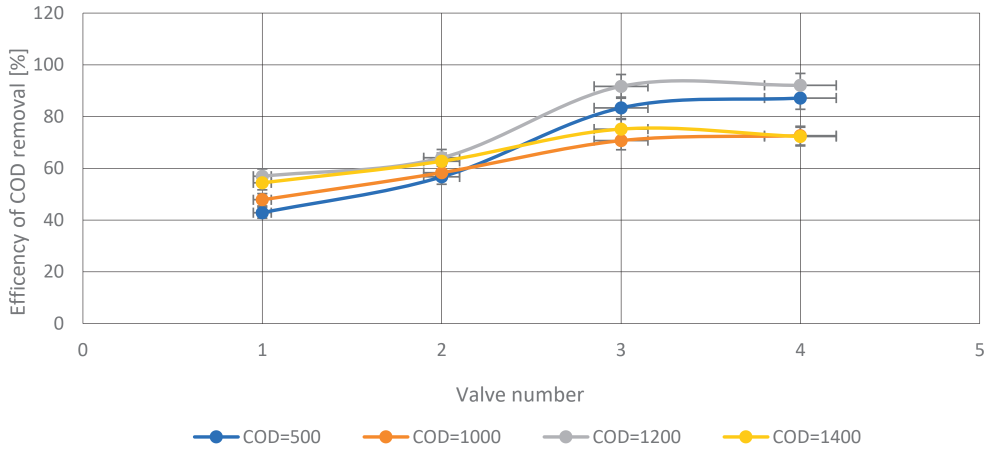

Fig. 4. Graph of COD removal percentage changes in the reactor, COD : N : P = 100 : 5 : 7 – valve 2 is the anaerobic outlet

Figures 5–7 illustrate COD removal rates for different inputs of phosphorus concentrations when valve 1 is an anaerobic output during phase 2. Considering the increased volume of the aerobic section of the reactor, the resistance time in this section increased to 5.21 h. The resistance time in the anaerobic section decreased from 2.5 to 1.042 h. Figure 5 illustrates that the rate of COD removal in the reactor bed increased smoothly except for COD = 1400, which showed some tolerance. A maximum removal efficiency of 54.76 and 84.77% was achieved at inlet COD = 1000 in the anaerobic and aerobic sections, respectively. It is possible to conclude from comparing the data of this case with similar circumstances in phase 1 (Fig. 2) that the change in the HRT has no particular effect on the performance of the reactor. The data presented in Figure 6 were used to investigate the effect of phosphate on COD removal in phase 2. The removal of COD remains at around 70% with COD = 500, whereas in other cases, it significantly increases upon entering the aerobic section, and then becomes stable in the upper layer of the bioreactor. The most efficient results were achieved for an inlet COD of 1400, which had an efficiency of 87.93% in the removal process. Furthermore, as shown in the final case in Figure 7, the phosphate concentration increased significantly, resulting in a change in the inlet composition ratio to COD : N : P = 100 : 5 : 7 and considered a shock to the system. It can be seen that COD = 500 had the greatest impact with the total COD removal dipping dramatically to 45.25%. However, for an inlet COD of 1200, the removal efficiency remains stable and is approximately 85% in effluent.

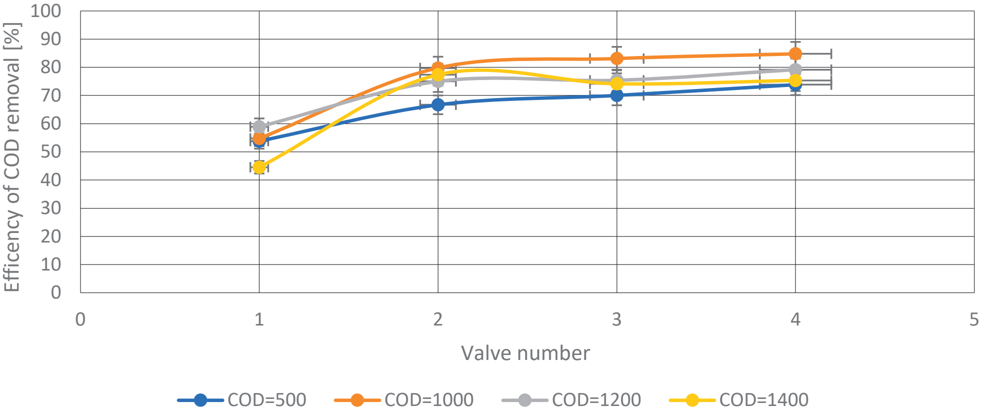

Fig. 5. Graph of COD removal percentage changes in the reactor, COD : N : P = 100 : 5 : 2 – valve 1 is the anaerobic outlet

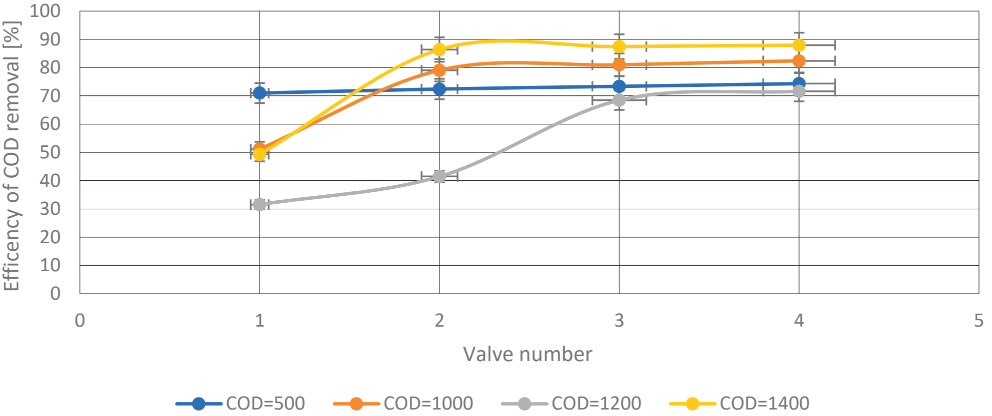

Fig. 6. Graph of COD removal percentage changes in the reactor, COD : N : P = 100 : 5 : 5 – valve 1 is the anaerobic outlet

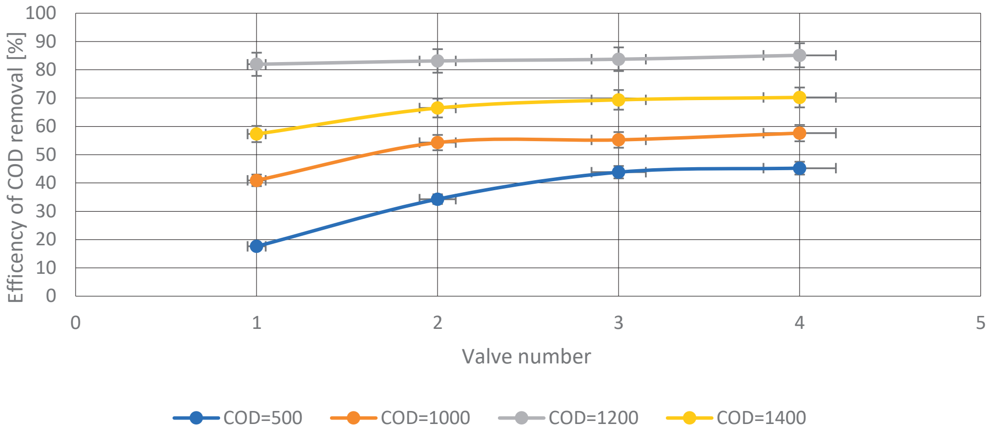

Fig. 7. Graph of COD removal percentage changes in the reactor, COD : N : P = 100 : 5 : 7 – valve 1 is the anaerobic outlet

Prior work has documented the effectiveness of sequential anaerobic-suspended growth aerobic systems in COD removal from domestic wastewater. Von Sperling et al. [16], for example, illustrated that up-flow anaerobic sludge bed UASB-AS[3] bioreactors have a total COD removal efficiency of 85–93% with HTR of 4 and 2.8 h for anaerobic and aerobic section respectively. La Motta et al. [17], in another study on these bioreactors, reported 87% COD removal for this bioreactor with HTR of 3.2 and 2.3 h for anaerobic and aerobic parts respectively. Moosavi et al. [18] studied the performance of up-flow anaerobic-aerobic fixed-bed (UA/AFB) combined reactor in COD removal. A single reactor was designed with anaerobic and aerobic parts integrated together. Four different runs were conducted, with organic loads varying between 0.8, 2.3, 4.7, and 7.6 kg COD/(m^3·d). The results indicate that an HRT of 9 h (5 h anaerobic and 4 h aerobic) is sufficient to achieve efficient COD removal rates of over 95% at all runs. A comparison of anaerobic-aerobic systems with two bioreactors connected in series with this pilot study is presented in Table 1.

However, these studies have not focused on the influence of phosphate concentrations as a disturbing substance. In this study, both anaerobic and aerobic section was combined in one pilot separated with plexiglass, with Kaldnes packing used for enhancing attached growth. The test was conducted in two resistance times with different phosphate and COD concentrations. In phase 1 of this study, for HTR of 2.5 and 3.75 h for anaerobic and aerobic section, COD removal in virtually all cases was above 80% and for COD of 500 it reached 90% removal, close to the concentrations found in domestic wastewater. The studies of Fdez-Polanco et al. [25] and Kuyukina et al. [26] emphasize that organic carbon was removed from municipal wastewater simultaneously using anaerobic-aerobic fluidized beds. The HRT of 24 h and an OLR of 1.2 kg COD/(m^3·d) resulted in COD removal efficiencies greater than 80%.

[3] Activated sludge.

Table 1. Anaerobic-aerobic treatment of municipal wastewater

Reactor type / module configuration	Volume [L]	Temperature [°C]	Wastewater source	Influent COD [mg/L]	HRT [h]	MLSS	COD removal [%]	Reference
Membrane coupled conventional anaerobic systems								
Up-flow anaerobic reactor / side stream	180	25	pre-settled	540	12, 6, 4.5	14–80 g/L	88	[19]
CSTR / submerged	3	35	synthetic	465	3, 6, 12, 24	2–3 g VSS[d]/L	99	[20]
Sequential anaerobic-suspended growth aerobic systems								
Anaerobic SBR-aerobic SBR[a]	14	28	domestic wastewater	F/M[e]: 0.08	cycle time: 12	–	overall: 94 anaerobic: 75	[21]
UASB-SBR	anaerobic: 10 aerobic: 7	25	domestic wastewater	raw sewage: 587	anaerobic: 4 aerobic: sludge age: 9, 11, 15	–	overall: 92 anaerobic: 82	[22]
Sequential anaerobic-attached growth aerobic systems								
UASB-ABF[b]	19	20	domestic wastewater	OLR: 0.13	12	–	overall: 93 anaerobic: 88	[23]
UASB-DHS[c]	anaerobic: 155 aerobic: 136	15	domestic wastewater	anaerobic: 1.5 aerobic: OLR: 1.6	anaerobic: 8 aerobic: 2.7	–	overall: 90 anaerobic: 67	[24]
This study								
Combined anaerobic-aerobic bioreactor / phase 1	anaerobic: 3 aerobic: 4.5	37	synthetic	1200 (COD: N: P = 100: 5: 7)	anaerobic: 2.5 aerobic: 3.75	anaerobic: 1220 mg/L aerobic: 1030 mg/L	92.08	–
Combined anaerobic-aerobic bioreactor / phase 2	anaerobic: 1.25 aerobic: 6.25	37	synthetic	1200 (COD: N: P = 100: 5: 7)	anaerobic: 1.042 aerobic: 5.21	anaerobic: 1220 mg/L aerobic: 1030 mg/L	85.13	–

[a] SBR – sequencing batch reactor.
[b] ABF – aerated bio-filter.
[c] DHS – down-flow hanging sponge.
[d] VSS – volatile suspended solid.
[e] F/M – food to microorganism ratio [kg COD/(kg biomass · d)].

In phase 2, HRT in the anaerobic section was reduced to 1.042 h, while it increased to 5.21 h in the aerobic part. This change in residual time, make the reactor condition steadier with predictable results while the COD removal in the anaerobic section decreased in comparison to phase 1. Changes in inlet phosphorus concentrations are so effective at COD removal at low COD values (COD = 500) that the percentage of COD removed decreases from 73 to 45%. The increasing input of phosphorus concentrations reduces COD removal but not significantly, and the average COD removal percentage is 80% for COD values higher than 1000. Torres and Foresti [27] studies illustrate that for synthetic wastewater treated in UASB-SBR bioreactors, if HRT is 6 h in anaerobic unit and (cycle time) 24, 12, 6, 4 h in aerobic unit, anaerobic COD removal is 72%, resulting in 91% total COD removal.

Using low concentrations of COD (COD = 500) and phosphorus, the reactor results in high COD and phosphorus removal rates of 90 and 80%, respectively. The COD removal efficiency of the reactor declines to 60% when COD concentrations reach 1000 to 1400 ppm.

4. Conclusion

In this study, phosphate was added as a distractive component to determine if combined anaerobic-aerobic bioreactors were effective at removing COD. On the basis of the analysis provided, it can be concluded that the pilot performed quite well, with more than 90% COD being removed from an influent COD of 1200 in phase 1. Further examination of the behavior of this pilot indicates that increasing resistance time in the aerobic section plays a crucial role in the performance of the bioreactor. Essentially, the interface system will function anoxically since the upper layers of the anaerobic zone are aerated, so increasing the height of the aerobic section helps ensure that there is a totally aerated area. It should also be noted that disturbances like phosphate have an adverse impact on low input COD (COD < 500). This study has the potential to yield a wide range of conclusions but further research is necessary in order to validate them.

Author Contributions

The percentage of authors contribution in this project is as follows:
Rezvan Kavousi: 80%,
Seyyed Mehdi Borghei: 20%.

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