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Original Article

Baffle and fixed media effects on coliform removal and bacterial die-off rate coefficient in waste stabilization ponds (a case study in Ahvaz)

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Abstract
Background: The use of waste stabilization ponds is one of the cheapest wastewater treatment processes. This study evaluated the effects of baffles and fixed media on coliform removal in facultative lagoons.
Methods: In this study, the settled wastewater from four pond systems of the city of Ahvaz was used as input. Each system was composed of two ponds that were connected to each other serially. Three of them were equipped with two, three, and four baffles. Packages of fixed media were installed in the first baffled pond equal to the number of baffles. During a 12-month sampling period from March 2016 to February 2017, the capability of each system to remove coliform with different detention times was studied.
Results: The control system with no baffle and no media reduced the coliform index by an average of 67% in a detention time of 6 to 12 days. Increasing the baffles and fixed media in the ponds improved the coliform removal efficiency; systems with two, three, and four baffles achieved coliform removal in the amounts of 77%, 81%, and 83%, respectively. The coliform die-off coefficients (K_b) were higher in the attached growth systems than in the control system. The coefficients were determined to be 0.21, 0.26, 0.29, and 0.31 d^{-1} for the second ponds of the control, two-, three-, and four-baffle systems, respectively.
Conclusion: This method can be used to upgrade the existing waste stabilization pond and to design new ponds with at least two baffles in the facultative lagoons.
Keywords: Waste stabilization ponds, Baffle, Fixed media, Die-off coefficient, Coliform removal
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Introduction

Waste stabilization ponds (WSPs) system is one of the important natural processes in developing countries, especially in tropical areas, because this process does not require electrical or mechanical equipment. WSPs treat a variety of wastewaters from domestic to complex industrial wastewater, and they function under a wide range of weather conditions, from tropical to arctic (1). Pollutants such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, phosphor, and pathogens can be removed by WSPs. One benefit of WSPs is pathogen reduction. The most important factors that lead to pathogen removal in the ponds are temperature, solar radiation, pH, food shortage, predator organisms, and toxins (2). The main advantage of this process is its lower costs compared with other wastewater treatment processes in terms of construction and operational costs (3). These ponds are easily operated and need no electrical or mechanical equipment as oxygen is supplied by micro-algae in the facultative lagoons. However, a larger area of land is necessary compared with energy-based processes such as activated sludge (4). In addition, occasionally, a high concentration of suspended solids is seen in the effluent that refers to the algae cells. Odor production and water loss due to evaporation are its other disadvantages (5). The concentration of pollutants in pond effluent is a function of the ponds number in series, geometry, hydraulic retention times (HRT), and the number of internal and external factors of ponds (6). To improve the quality of the effluent, it is recommended that processes such as coagulation and flocculation, microstrainer, supplementary ponds, and rock filters be used in the end of the ponds (7). Wetland can also be added to supplement the treatment process (8). Another way to improve the treatment process is to put baffles in the ponds to improve system operations, increase retention time, and reduce the dispersion number (9,10). In addition to baffles, putting the fixed media in the ponds provides more surface area for the growth of microbial films and makes it receive more hydraulic loads (11,12). Attached growth process was introduced in England in 1893 and provided a trickling filter. Conventional attached growth processes include rotating biological discs, bioreactors with submerged beds, floating biofilm reactors, and integrated attached and suspended processes (13). Nielson et al studied the performance of three baffled ponds compared to an unbaffled model in four organic and hydraulic loading rates on the laboratory scale and reported that a considerable effect of the baffling was observed in lower hydraulic detention times (14). Pearson et al studied the effects of configuration, depth of the facultative lagoon and supplementary pond, and baffles on pond operations in pollutant removal and concluded and demonstrated that installing baffles in a supplementary pond improved its efficiency in removing organic materials and pathogens (15). Mattamara and Puetpaiboon evaluated the performance of baffles in WSPs on the laboratory scale and showed that baffled ponds gave higher COD, nitrogen, and coliform removal compared with normal ponds (16). Abbas et al studied the effects of length to width and number of baffles on the performance of ponds and showed that a ratio of 4:1 with two and three baffles is the most appropriate geometric shape for stabilization ponds (17). Babu highlighted four pilots in which one was without a baffle and three others had 15 baffles with similar surfaces and different configurations and reported that the pond equipped with baffles with vertical flows was the most effective pond in terms of reducing short-circuit current (18). In a system in which rock media was placed in the facultative lagoon with three baffles, Al-Sa`ed et al reported the more suitable performance of a baffled attached growth system relative to a control system in the elimination of COD, total suspended solids (TSS), NH4, and coliforms (19). Ouali et al studied a wastewater treatment plant the process of which was conventional activated sludge followed by three maturation ponds in a series acting as a tertiary treatment. The results showed that the installation of two baffles in the first maturation pond improved coliform removal efficiency (20). This research studied the effects of number of baffles and fixed media packages on the performance of WSPs in the removal of total coliforms of settled wastewater from Choneibeh wastewater treatment plant in the city of Ahvaz.

Methods

Wastewater quality

Choneibeh wastewater treatment plant is the only wastewater treatment plant of the city of Ahvaz. Its process is conventional activated sludge with an area of 13 hectares, covers 140 000 people, and treats 390 liters of wastewater per second (21). This study used the effluent of primary sedimentation as the pilot raw wastewater. Settled wastewater quality parameters in the sampling period (from March 2016 to February 2017) are presented in Table 1.

Pilot specifications

As shown in Figure 1, the pilot of the research was composed of a control system and three other systems. The control system included two facultative lagoons connected serially. The dimensions of the first and second ponds were (4 m × 1 m × 1 m) and (4 m × 0.8 m × 1 m), respectively. The other systems had the same sizes and dimensions as the control system. The first and second ponds of each system had two, three, and four baffles. Wooden vertical baffles were installed in the pond so that the baffle width was 70% of the pond width. For sealing ponds, there are many sealers that classified into three major categories: synthetic, cement, and natural.[1] In this research, first, the inner surface of the pilot was covered with cement sealer. Then a synthetic sealer was used as the final lining. It was made from an asphalt component that is usually applied to house roofs as waterproofing (LA4 model made in Iran Glass Wool Company). Mineral shells with a specific surface area of approximately 100 m^2/m^3 and average diameter of 5 cm was put in plastic boxes and used as fixed attached growth media. In the first pond of each baffled system, three boxes were installed over each other and beside each baffle according to Figure 1.

Pilot start up and operation

To evaluate the capability of ponds to remove pathogens, settled wastewater entered the pilot at a flow rate of 0.6 m^3/d. At this stage, since the ponds had high detention times to prevent the formation of anaerobic conditions in the pilot, instead of settled wastewater, the ponds were filled with a mixture of piping network water and effluent from the wastewater treatment plant. Then, settled wastewater was discharged into the ponds by a submerged open-propeller pump made in China by the Leo factory. Over a month, the ponds were monitored for color and for dissolved oxygen concentration which showed the amount of 1.5 to 2 mg/L. In this condition, grab samples were taken from the effluents of eight ponds at 10:00 o'clock at the end of each month (three times). In the second and third phases, the same four flows entered the pilot as shown in Figure 2.

Table 1. Quality of settled wastewater in sampling period

Parameter	Unit	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	February	Average	SD
BOD_5	mg/L	167	132	124	171	142	118	107	117	103	160	134	152	135.6	19.0
COD	mg/L	274	236	172	252	218	168	155	174	159	290	235	254	215.6	41.7
TSS	mg/L	86	62	63	68	55	81	75	69	78	84	63	71	71.3	8.0
TP	mg/L	2.8	2.4	3.9	2.3	2.6	1.8	2.2	2.0	2.5	2.9	2.2	2.7	2.5	0.4
TKN	mg/L	35	33.4	29.7	31	32	28	30	36	37	28	35	32	32.3	2.5
TC	MPN/100 m	8.5×10^{12}	8.7×10^{12}	7.9×10^{12}	7.8×10^{12}	8.2×10^{12}	8.8×10^{12}	7.6×10^{12}	7.1×10^{12}	7.8×10^{12}	8.9×10^{12}	7.3×10^{12}	8.6×10^{12}	7.8×10^{12}	5.1×10^{11}
pH	-	7.7	7.3	7.2	7.8	7.5	7.8	7.3	7.6	7.2	7.5	7.8	7.6	7.5	0.2

Abbreviations: BOD_5: biochemical oxygen demand in 5 days; COD: chemical oxygen demand; TSS: total suspended solids, TP: total phosphor, TKN: total Kjeldahl nitrogen, TC; total coliform.

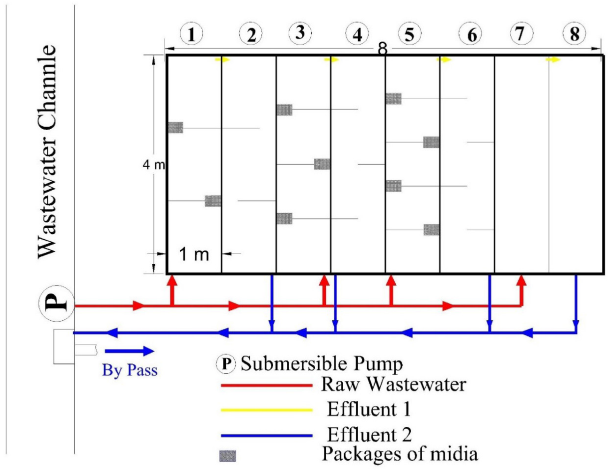

Figure 1. Plan and flow diagram of pilot.
Pilot was composed of four systems: 3 baffled systems and a control system that had no baffle and no fixed media. Ponds were numbered 1 to 8. Settled wastewater entered the first ponds of all systems and are shown with the numbers 1, 3, 5, and 7. The second ponds of all systems are shown with the numbers 2, 4, 6, and 8.

Experiments procedure

All experiments were carried out based on the standard method (22). Grab samples were taken from effluents of the ponds and analyzed using the following methods: 5210 B for BOD, 5220 B for COD, 2540 D for TSS, 4500-NorgC for Total Kjeldahl nitrogen (TKN), 4500-P D for total phosphate (TP), and 9221 B for total coliforms (multiple tube fermentation technique). DO was measured using a DO meter made by the Hack Company (HQ40d model), and pH was measured using a pH meter made by the WTW Company (720 model).

Statistical analysis

Data was analyzed using XLSTAT software version 2016.5. Student's *t* test was applied to determine statistical differences. The level of significance was considered to be 95% and an error rate of less than 5% was acceptable (P value < 0.05).

Calculation of coliform die-off coefficient

Coliform die-off coefficient (K_b) in ponds is usually modelled assuming first-order kinetics (23). According to such an equation, K_b is directly proportional to the concentration of indicator organisms. These equations are different from the point of view of the pond hydraulic regime. There are three types of hydraulic regime: plug flow, complete mix, and dispersed flow. In fact, the hydrodynamic behavior of the ponds is not consistent with ideal plug flow or complete mix, but it does correspond to the dispersed flow. Thus, to determine the coliform die-off coefficient, the Wehner-Wilhelm equation was used (5).

$$N = N_0 \frac{4ae^{1/2d}}{(1+a)^2 e^{a/2d} - (1-a)^2 e^{-a/2d}} \quad (1)$$

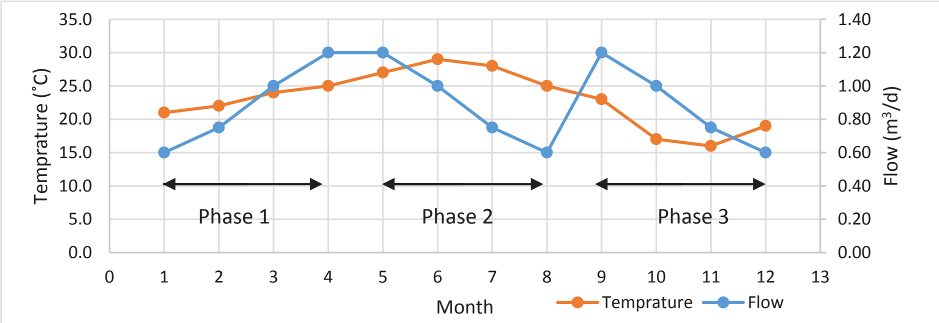

Figure 2. Flow and wastewater temperature in sampling duration.
The pilot operation was conducted in three phases. Each phase was composed of four months. Phase 1: 1st to 4th months, phase 2: 5th to 8th months, and phase 3: 9th to 12th months. In each month, settled wastewater entered each system with a fixed flow. In the duration of each phase, the wastewater flow was changed.

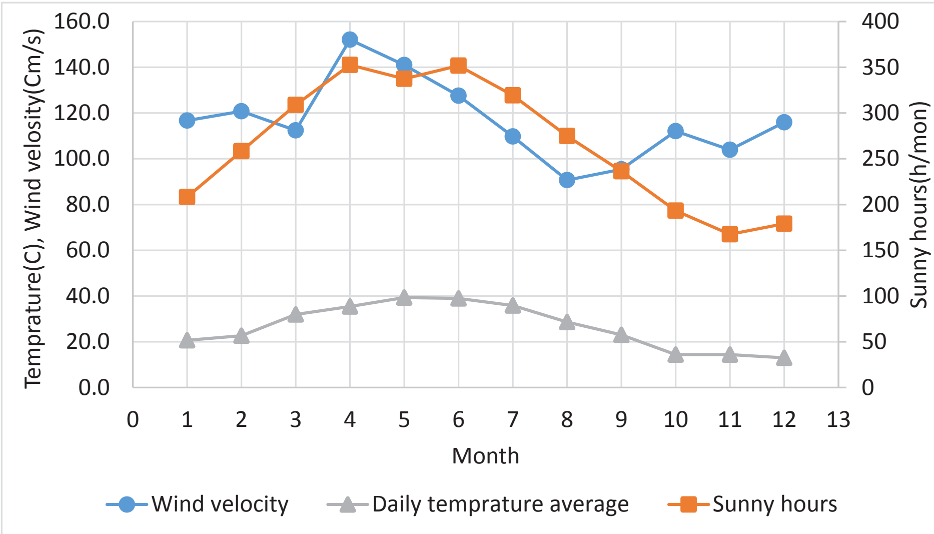

Figure 3. Climatological factors in sampling duration (24).

$$a = \sqrt{1 + 4K_b.t.d} \tag{2}$$

In equation 1, *d* is the dispersion number. Values of *d* close to zero indicate plug flow regime and in large amounts indicate complete mix in the reactors. According to previous research, the dispersion number can be calculated using the following formula (6):

$$d = \frac{1}{\frac{L}{B}} \tag{3}$$

For ponds in which the number of baffles installed parallel to the pool width is *n*, the ratio of (L/B) can be calculated by the following equation (5):

$$\frac{L}{B} = \frac{B}{L}(n+1)^2 \tag{4}$$

L: pond length
B: pond width
n: The number of baffles

With the Wehner-Wilhelm model and using data from the ponds, it can be used to design the facultative lagoons and supplementary ponds (5). For this purpose, the first index (L/B) was calculated based on pond dimensions and number of baffles. Then the dispersion number (d) was determined using equation 3. After that, the K_b value was assumed and the theoretical HRT determined. Finally, the ratio of output coliform to input coliform (N/N_0) was calculated using the Wehner–Wilhelm equation. According to the values measured in the sampling, measured (N/N_0) can also be determined. If the measured ratio is equal to the calculated ratio, the assumed values will be correct; if not, the previous steps must be repeated to achieve the correct result by trial and error method. Since K_b is a function of temperature, in this study, it was assumed to be 20°C and modified to the real wastewater temperature using equation 5.

$$K_T = K_{b20} \times 1.07^{(T-20)} \tag{5}$$

Results

Coliform and BOD_5 concentrations

Average values of the main climatological parameters recorded for the investigated region are summarized in Figure 3. Figure 4A shows that effluent coliform concentrations of all systems in each month were higher than the permissible limits recommended by Iran's Department of Environment (DOE) for discharge to surface water and agricultural usage (1000 MPN/100 mL). Moreover, during the first phase, the coliform concentration had an ascending procedure that was related to increased HRT. The HRT of each system in the first month was 12 days, but it decreased to 6 days at the end of the process. As shown in Figure 2, wastewater temperature during this phase increased considerably from 21˚C to 25˚C. The results of sampling showed that during the first 2 months, the effects of HRT decrement dominated the effect of temperature increment for coliform removal. The coliform concentration increment happened in the effluent of each system (Figure 4A); however, it decreased in the third month. This may be related to the increment of wastewater temperature as 4˚C and sunny hours (Figure 3). In the fourth month, despite the increase in climatological factors, the coliform concentration decreased. It may refer to the HRT decrement as shown in Figure 2 that dominated the other factors. In the second phase, as shown in Figure 3, the warmest months of the year occurred; thus, hydraulic loading was applied in a descending procedure unlike the first phase. As shown in Figure 4A, coliform concentration decreased in this phase. In the third phase, the arrangement of hydraulic loads was the same as that of the second phase; thus, the coliform concentration decreased like in the previous phase, except in the 10th month. It seems that the considerable decrease in temperature and the sunny hours in this month dominated the effect of increased HRT (Figure 3). Another point is the improvement of effluent microbial quality of baffled systems compared to the control system. Figure 4A shows that the average coliform concentration in the two-, three-, and four-baffle systems decreased 29.2%, 41.7%, and 50% more than the control system, respectively. This refers to the role of the number of baffles and the amount of fixed media that increased real HRT and attached growth area, respectively, and resulted in better effluent quality (16,18). Figure 4B shows the BOD_5 concentrations of effluents from all systems. According to this figure, the average BOD_5 concentration in the control system effluent in the first phase was 64.9 mg/L. Like Figure 4A, concentration of BOD_5 decreased in the third month rather than second month. In the second phase, the average BOD_5 concentration was 56.3 mg/L, and BOD_5 concentration decreased during this phase (similar to coliform concentration). In the third phase, the average BOD_5 concentration was 78.3 mg/L; its maximum occurred in the 10th month. In this month, climatological factors such as temperature decreased at a high rate (Figure 3). It seems the worst quality of effluent was seen in this phase. According to Figure 4B, baffle and fixed media had a positive effect on decreasing BOD_5 concentration; the average BOD_5 concentrations throughout sampling were 65.5, 55.7, 50.0, and 45.8 mg/L in the control, two-, three-, and four-baffle systems, respectively.

Statistical analysis detected that *P* values were less than 0.0001 and 0.0005 for total coliform and BOD_5, respectively, and that indicates a significant difference for reported data.

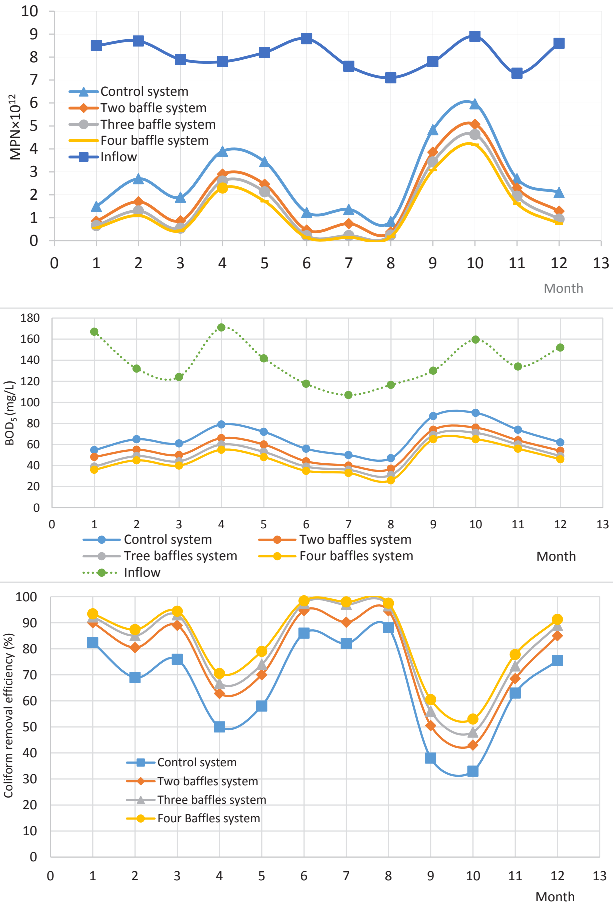

Figure 4. Effluent coliform (A), BOD_5 (B) and coliform removal efficiency (C) for systems.

Coliform removal efficiency

Figure 4C shows the efficiency of coliform removal in sampling duration. During the first phase, due to decrease in HRT, coliform removal decreased as well, except in the third month. This refers to the increased number of sunny hours and increased temperature as explained in Figure 3. Although they also increased in the fourth month, it seems it could not control the effect of decreased HRT. In the second phase duration, with increasing HRT, coliform removal increased. Although the changes in the 6th, 7th, and 8th months were slight, that indicates the increase in HRT and decrease in climatological parameters offset the effects of each other on coliform removal. As in the second phase, in the third phase duration, increased HRT resulted in increased coliform removal except in the 10th month. It seems that, according to Figure 3, a notable decrease in temperature and sunny hours caused coliform removal decreased in 10th month. Figure 4C, like Figure 4B, shows that increasing the number of baffles and the amount of fixed media improved coliform removal so that for the control, two-, three-, and four-baffle systems, the amounts were 67%, 77%, 81%, and 83%, respectively. In the baffled attached growth waste stabilization systems, factors such as filtration, adsorption, aggregate formation, and predators attributed to passive aerobic conditions and attached growth surface area may be responsible for the higher coliform removal rates observed (25,26).

Determination of coliform die-off coefficient (K_b)

Figure 5A shows K_{b20} for the first pond of all systems in the sampling duration. According to this figure, the average K_{b20} concentrations for the first pond of the control system in the first, second, and third phases were 0.11, 0.13, and 0.07 d^{-1}, respectively. This may be attributed to the climatological changes that occurred during sampling months; the warmest and coldest months belonged to the second and third phases, respectively, with average wastewater temperatures of 27˚C and 19˚C, respectively. This procedure happened for baffled systems too. Thus, the average of this coefficient in the 12-month period for the first pond of the control, two-, three-, and four-baffle systems was 0.11, 0.15, 0.16, and 0.18 d^{-1}, respectively. According to Figure 5B, the average K_{b20} concentrations for the second pond of the control system in the first, second, and third phases were 0.15, 0.24, and 0.23 d^{-1}, respectively. As with the first pond, increasing the number of baffles resulted in an increase in K_{b20} concentration. Concentrations in the control, 2-, 3-, and 4-baffle systems were 0.21, 0.26, 0.29, and 0.31 d^{-1}, respectively. Figure 6A shows the effect of the number of baffles on K_{b20} changes in the first pond of all systems. According to this figure, the maximum of this coefficient belongs to a flow of 1 m^3/d. It refers to the setting of the 6th month in this flow, which is the warmest month of the year and has the maximum climatological factors such as sunny hours (Figure 3). Also, the minimum concentration of K_{b20} occurred for a flow of 1.2 m^3/d. It may refers to minimum HRT that occurred by this flow, although one of the months that this flow entered the systems was fifth month that had maximum temperature and sunny hours like sixth month. So it seems the HRT (6-day) was insufficient and made it have minimum quantities of K_{b20}. In Figure 6B, the same flows have the maximum and minimum quantities of K_{b20} for second the ponds, too. According to Figure 6, adding two baffles make it grow at a notable rate, while its growth in the 3- and 4-baffle systems was at a lower rate than the 2-baffle system.

Discussion

In the current study, the average coliform removal efficiency

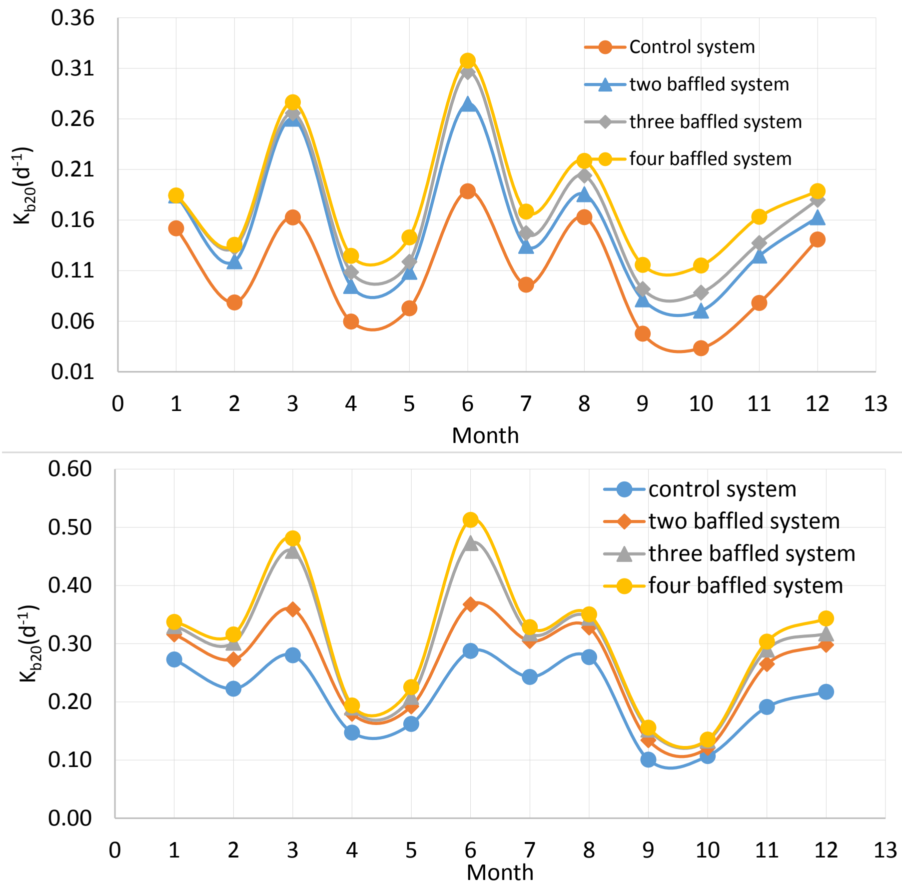

Figure 5. K_{b20} in first (A) and second (B) pond of each system in sampling duration.
Kb20: Coliform die-off coefficient in temperature of 20˚C

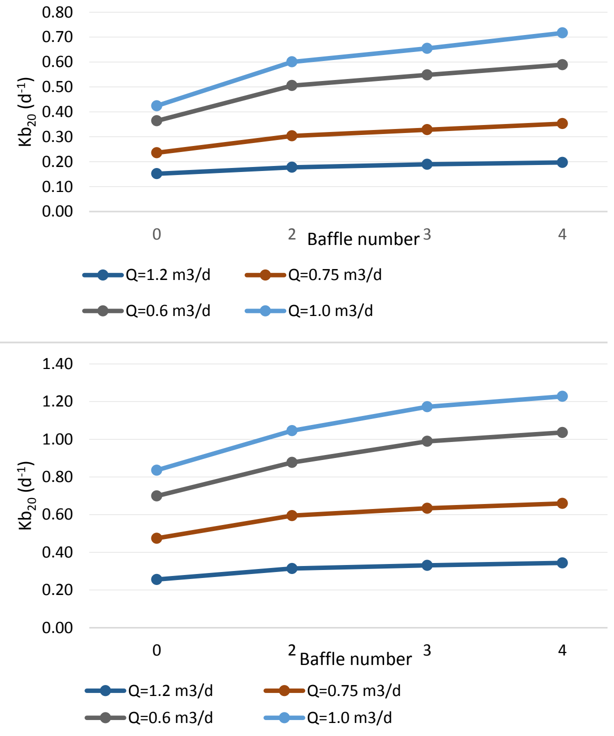

Figure 6. K_{b20} in first (A) and second (B) pond of systems in various flows and baffle numbers.
Kb20: Coliform die-off coefficient in temperature of 20˚C

in facultative lagoons was studied and determined for the control system at an HRT of 6 to 12 days; it was 67% in a 12-month period. Pearson et al determined it as 84% for facultative lagoons. This increment may be attributable to different climatological conditions. The experimental ponds were constructed at the city of Campina Grande in northeastern Brazil which has a tropical climate, and the wastewater temperature remained constant at 25˚C during a 15-month period (15).

The results of this study confirm the findings of the research conducted by Al-Sa`ed et al. In his research, the efficiency of coliform removal in a 3-baffle facultative lagoon was reported as 69%, while in the 3-baffle system of the current study was 81%. The improvement observed in the current study may be due to the higher (L/W) ratio. Furthermore, the kind of fixed media applied in the current research had more specific area than that used in the study of Al-Sa`ed et al, and that caused more attached growth area and more coliform efficiency (19).

In the current study, increasing the number of baffles and the amount of fixed media resulted in coliform removal efficiency 14.7%, 21%, and 25% greater than that of the control system. Al-Sa`ed et al reported an efficiency of 8% that is explained by the differences in geometric dimensions and kind of fixed media. Moreover, the control system in the study of Al-Sa`ed et al had 3 baffles and no fixed media (19).

The results of this study are consistent with those of a study carried out by Mattamara and Puetpaiboon in which it was reported that increasing the number of baffles from 0 to 6 made coliform removal increase to 12% in a laboratory scale facultative lagoon and an HRT of 3 days (16).

Ouali et al studied a conventional activated sludge wastewater treatment plant followed by three maturation ponds (MP1, MP2, MP3) in which 2 baffles were introduced in the first maturation pond (MP1). The results showed that, because of the well-designed baffles, the removal efficiency of *Escherichia coli* increased from 69% to 82% (20).

According to the results of the current study, the average K_{b20} concentrations of the first ponds of the control system were 0.11 d^{-1} and increased 41.6%, 54.4%, and 69% in 2-, 3-, and 4-baffle systems, respectively. For the second pond of the control system, this amount was 0.21 d^{-1}, and the 2-, 3-, and 4-baffle systems had increments of 25.1%, 40.3%, and 74% greater than the control system. Thus, the setting of two baffles and fixed media packages in the ponds resulted in a significant increase in coliform removal efficiency, while in the 3- and 4-baffle systems increased at a lower rate than the 2-baffle system. Generally, coliform die-off coefficients were higher in the baffled systems than in the control system. The range of K_{b20} obtained in this study is consistent with a study of 186 pieces of data from facultative lagoons and supplementary stabilization ponds; K_{b20} concentrations were reported as 0.1-1 d^{-1} and 0.1-0.7 d^{-1} for primary and secondary facultative lagoons, respectively (6).

Conclusion

In this study, the efficiency of baffled attached growth WSPs in the removal of pathogens from primary sedimentation effluent was evaluated in the Choneibeh wastewater treatment plant of Ahvaz. The control system could decrease total coliform of settled wastewater to an average of 67% in an HRT of 6 to 12 days. However, this system requires other supplementary ponds to decrease this index to lower than the standard limit for agricultural usage or discharge to water resources. In addition, baffled attached growth ponds had higher efficiency compared with control ponds in coliform removal. The coliform die-off coefficient (K_b) was higher in the baffled attached growth system than in the control system, and increasing the number of baffles and amount of fixed media resulted in increased K_b as well. Moreover, by reducing the depth of the second pond rather than the first resulted in increased sunlight penetration, and K_b in the second pond was determined to be more than in the first pond. Thus, putting baffles and fixed media in facultative stabilization ponds improved the efficiency of pathogen removal due to the reduction in effects of short circuiting as well as increasing the attached growth area. This method can be used to upgrade the existing WSP, and investment and maintenance costs will be reduced since no additional land is required.

Authors' contributions

NM, BA, HS, and AT conceived and designed the study. BA and HS performed the literature search and wrote the manuscript. All authors participated in data acquisition, analysis, and interpretation. All authors critically reviewed, refined, and approved the manuscript.

Competing interests

The authors declare that they have no competing interests.

Ethical issues

The authors certify that all data collected during the study is presented in this manuscript, and no data from the study has been or will be published separately.

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