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Biological treatment of dairy wastewater using activated sludge

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ABSTRACT: The objective of the research was to evaluate the performance of a laboratory-scale biological treatment unit for dairy-industry wastewater and to determine the kinetic parameters for the activated sludge process. A laboratory-scale treatment unit comprising an aeration tank and final clarifier was used for this purpose. The treatment unit was operated continuously for three months by varying the hydraulic retention times from 2 to 12 days. The biological oxygen demand (BOD) of the influent and effluent and the mixed liquor suspended solids of the aeration tank were determined at various detention times to generate data for the kinetic coefficients. The kinetic coefficients k (maximum substrate utilization rate), K_s (half velocity constant), Y (cell yield coefficient), and K_d (decay coefficient) were found to be 4.46 day^{-1}, 534 mg/l, 0.714, and 0.038 day^{-1}, respectively, based on the BOD. These coefficients may be used for the design of activated sludge process facilities for dairy wastewater.

KEYWORDS: aerobic treatment, biological oxygen demand (BOD), chemical oxygen demand (COD), kinetic coefficients, dairy industry

INTRODUCTION

Dairy plants are considered as 'wet industry' because they consume large volumes of water, which is used for very diverse purposes. As a result, dairy plants discharge large volumes of wastewater[1]. Dairy is one of the expanding industrial sectors in Pakistan with currently about 17 units engaged in the production of various dairy products. Interestingly, the majority of the dairy plants with varying processing capacities are located near Lahore, which serves as the hub of this industry in Pakistan. The Pakistan dairy industry is the fifth largest dairy industry in the world, with dairy products forming part of traditional Pakistani diet[2]. The dairy industry, like most other agro-industries, generates wastewater characterized by high biological oxygen demand (BOD) and chemical oxygen demand (COD) due to their high organic content[3]. The discharge of the polluted water is the most significant contributor to the pollution of environment from the dairy industry in terms of both quality and quantity; contamination by the solid waste and waste gases are less serious[1]. The dairy-industry wastewater is primarily generated from the cleaning and washing operations in milk processing plants. It is estimated that about 2% of the total milk processed is wasted into drains[4]. Dairy wastewater differs widely both in quantity and quality depending on a given dairy-factory production characteristics. Many products in dairy factories are manufactured separately, thus pollutant contents in the dairy wastewater at a given time changes together with the application of another technological cycle of the processing line[5]. The dairy industry is one of the most polluting industries, not only in terms of the volume of effluent generated, but also in terms of its characteristics as well. It generates about 0.2–10 l of effluent per litre of processed milk[6].

Biological treatment processes offer a cost-effective method to remove organic compounds and nitrogen from the wastewater. Treatment designs are continually evolving to provide greater treatment efficiency, at a lower cost[7]. Biological wastewater treatment is the primary method of preparing food-processing wastewater flows for return to the environment. Increasing industry wastewater loads on existing plants and more stringent government discharge requirements have put considerable pressure on the food-processing industry to refine and understand better the design and management of biological wastewater treatment processes[8].

Dairy wastewater is generally treated using biological methods such as activated sludge process, aerated lagoons, trickling filters, sequencing batch reactor, upflow anaerobic sludge blanket reactor, anaerobic filters, etc[9]. Biological methods, like activated sludge process, are invariably employed for the

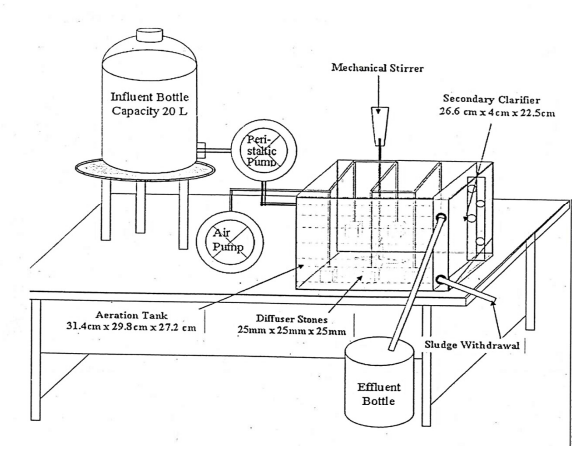

Fig. 1 Sketch of the laboratory-scale completely mixed continuous flow reactor.

secondary treatment of a large number of industrial wastewater. Knowledge of the microbial kinetics and determination of the kinetic coefficients for a particular wastewater are, therefore, imperative for the rational design of treatment facilities [10].

The aim of the research presented in this work was to evaluate the performance of a laboratory-scale reactor to treat dairy wastewater and to determine the kinetic coefficients for the dairy-industry wastewater. The research was done under aerobic conditions and the kinetic coefficients were estimated on the basis of soluble biological oxygen demand (sBOD).

MATERIALS AND METHODS

A laboratory-scale reactor was used to determine the percentage removal efficiency of BOD, COD, SS, and kinetic coefficients. A completely mixed continuous flow reactor without recycle was used in this study (Fig. 1). The reactor was made of Perspex glass of 5 mm thickness. The wastewater to the reactor was fed using an influent glass bottle. A peristaltic pump was used to regulate the flow to achieve a particular hydraulic retention time. The capacity of the aeration tank was 25 l. Diffuser stones were used to supply air and were placed at the bottom of the aeration tank along the wall to maintain the dissolved oxygen (DO) level of 2.7 mg/l, which is suitable for the aerobic treatment [11]. A final clarifier followed the aeration tank with 2.4 l capacity. The depth of the aerator was 27.2 cm with a working volume of 25.45 l.

Wastewater samples for this study were collected from Nestle Milkpak, Shiekhupura Road, Lahore, Pakistan. Treatment facilities at the factory consist of primary and secondary treatment units. A primary unit includes fat traps, influent pit, grit chamber, and two balancing tanks with mechanical aerator. In the balancing tank, a part of recycle sludge is mixed and aeration is carried out, which results in some degradation of organic material present in the wastewater. Therefore, wastewater from the outlet of the balancing tank was not used for this study. So the sample was collected from the outlet of the fat trap.

Table 1 Detention times and flow rate of influent.

Hydraulic retention time (days)	Flow rate (l/day)
2	12.7
3	8.5
4	6.4
9	2.8
5	5.1
7	3.6
12	2.1

The laboratory-scale reactor was operated for about 90 days; by varying the hydraulic retention time of 2–12 days, the corresponding flow rates are in Table 1.

Before the start of the work, the reactor was seeded with the sludge taken from the secondary treatment unit of Nestle treatment plant for three days. The influent was subjected to settling in the effluent bottle. Due to lack of mechanical return sludge facility, the settled sludge was daily removed from the final clarifier in a beaker. The nitrogen (N) and phosphorus (P) requirements are based on the BOD of the wastewater, where a BOD: N: P of 100: 5: 1 is considered adequate [11]. In this study, the average value of BOD was 1520 mg/l. Thus the BOD: N: P for this wastewater came out to be 1520: 310: 3.3 or 100: 20: 0.22. These calculations show that sufficient amount of N was present in the wastewater. But the P was 0.22 as against the desirable value of 1. Hence it was deficient. The deficiency was met by adding a calculated amount of potassium di-hydrogen phosphate (KH_2PO_4) salt.

Flow, temperature, and pH values of the reactor were measured daily to ensure favourable environmental conditions in the reactor for biological treatment. Mixed liquor volatile suspended solids (MLVSS) in the reactor, COD, and BOD_5 of influent and effluent were measured thrice a week to determine kinetic coefficients. All the tests were performed according to the procedures laid down in the "Standard Methods" [12].

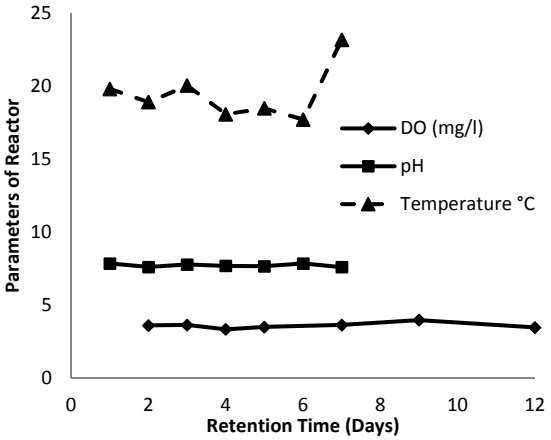

Fig. 2 Operating parameters of the reactor.

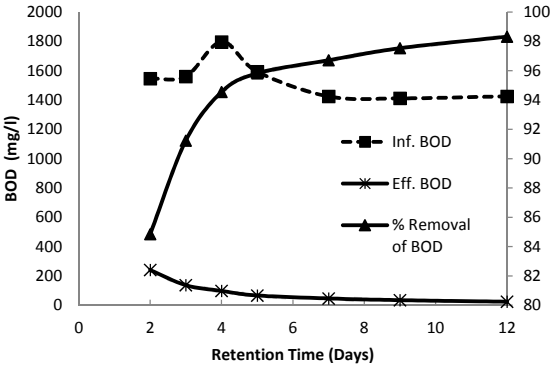

Fig. 3 Influent and effluent BOD at different hydraulic retention time.

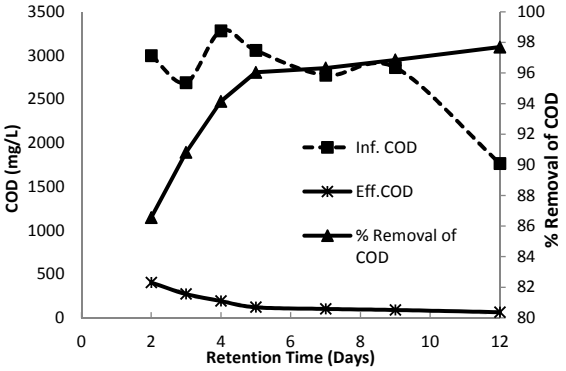

Fig. 4 Influent and effluent COD at different hydraulic retention time.

RESULTS AND DISCUSSION

The reactor during this study was monitored on a daily basis for four parameters, i.e., temperature, pH, DO, and mixed liquor suspended solids (MLSS). The first three parameters have a profound effect on biological growth and efficiency of biological treatment system [11] and the fourth parameter, i.e., MLSS was used to determine the kinetic coefficients. The values of these parameters are presented in Fig. 2.

The temperature of the reactor remained in a range of 16–24 °C. All the processes of growth are dependent on chemical reactions, and the temperature influences the rate of these chemical reactions. Thus the rate of microbial growth as well as total amount of growth can be affected by temperature.

The pH of the reactor during the study remained between 7.0 and 8.0 for most of the research period. Extremes of pH are fatal for most bacteria. The bacteria grow best when the pH is slightly on the acidic side. The optimum range for bacterial growth generally lies between 6.5 and 7.5 [13]. Activated sludge and aerated lagoons could be successfully operated when the pH was between 9 and 10.5 [11].

DO of the reactor remained between 3 mg/l and 4.2 mg/l for most of the study period. This value was ideal for the biological treatment systems working under aerobic conditions. The values of DO for the present study were above the minimum level of 2 mg/l which has been widely reported in the literature [11].

The treatment efficiency of the reactor in terms of BOD_5 and COD removal was studied at different detention times. It was noted that the process efficiency improved with increase in detention times. Thus the results indicate that the BOD and COD of the effluent at 5 days detention time were 66 mg/l and 121 mg/l, respectively. It shows that the BOD_5 and COD values met National Environmental Quality Standards (NEQS) limits of Pakistan, which is 80 mg/l for BOD and 150 mg/l for COD. The values of effluent SS were also within the limits of NEQS. So the activated sludge process operated at 5 days detention time shows good results for dairy wastewater as shown in Fig. 3, Fig. 4, and Fig. 5.

Fig. 6 reveals that a maximum removal efficiency of 96% was achieved at a detention time of 5 days for both BOD_5 and COD. The major change in percentage removal of SS is noted between a detention time of 5 and 7 days when it increased from 84% to 97%.

The data indicates that food to mass ratio (F/M) and removal efficiency were inversely proportional to each other and hence an increase in F/M ratio resulted in a decrease in efficiency. F/M ratio for the BOD in kg BOD (kg MLVSS)$^{-1}$ day^{-1} at various detention times with corresponding percentage removal efficiency are presented in Fig. 7. The range

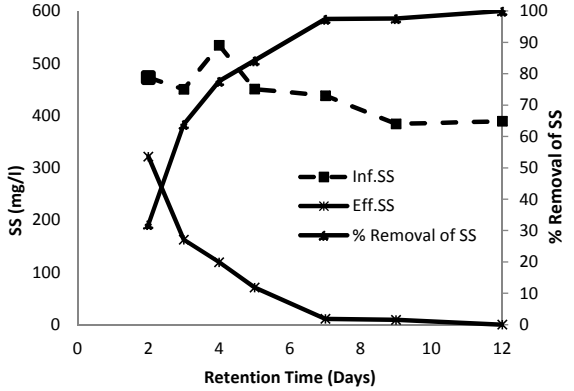

Fig. 5 Influent and effluent SS at different hydraulic retention time.

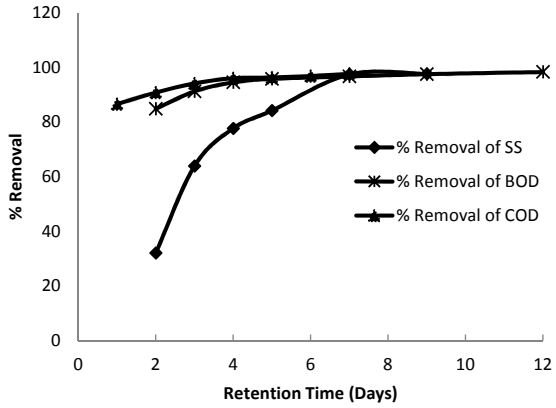

Fig. 6 Percent removal of SS, BOD, and COD at different hydraulic retention times.

of the F/M ratio for BOD was 0.21–0.98 kg BOD (kg MLVSS)$^{-1}$ day^{-1} corresponding to an efficiency of 98.3–84.5. These values can help the designers in the selection of an appropriate organic loading while targeting for the particular removal efficiency.

Metcalf & Eddy[13] reported that the values of the BOD F/M ratio vary from 0.04 g substrate (g biomass)$^{-1}$ day^{-1} for extended aeration processes to 1.0 g g^{-1} day^{-1} for high rate process and at detention times in the range of 5–7 days, the values range from 0.3–0.5 g BOD (g VSS)$^{-1}$ day^{-1}, respectively, for municipal wastewater with activated sludge system treatment[13]. The values of the present study are in line with these values.

Kinetic coefficients

Kinetic coefficients are usually determined through bench scale studies. For this purpose the bench scale completely mixed continuous flow reactor was

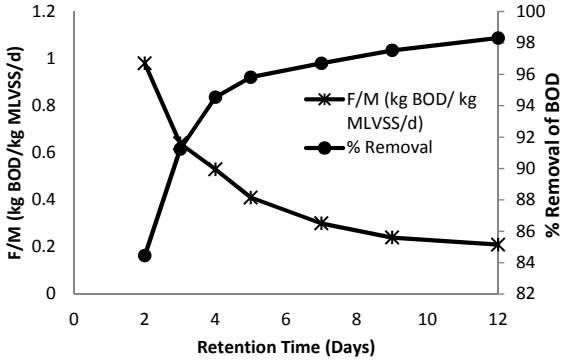

Fig. 7 Food to mass (F/M) ratio and removal efficiency of BOD.

Table 2 Mean values of data for kinetic coefficients.

θ_c (days)	S_0 (influent) (mg/l of sBOD)	S (effluent) (mg/l of sBOD)	X (MLSS) (mg/l of VSS)
2	1276 ± 26	98.0 ± 2.0	783 ± 22
3	1352 ± 38	77.3 ± 2.3	821 ± 26
4	1428 ± 26	52.7 ± 1.2	848 ± 14
5	1397 ± 12	42.3 ± 2.1	784 ± 13
7	1259 ± 26	30.7 ± 3.1	688 ± 17
9	1190 ± 16	25.7 ± 0.6	651 ± 23
12	1207 ± 13	22.3 ± 0.6	569 ± 15

Values are mean $\pm$ standard deviation.

operated for several hydraulic retention times, i.e., 2, 3, 4, 5, 7, 9, and 12 days. At each hydraulic retention time the data were collected at steady state conditions and mean values were determined for S_0 (initial substrate concentration expressed as BOD), S (substrate concentration), and X (biomass concentration). For each detention time three readings of each S_0, S, and X were taken, see Table 2. The mean of these values was used for the calculation of the kinetic coefficients.

The kinetic coefficients are of great importance for appropriate design of the bioreactors which are used for the treatment of wastewater. The basic two equations are used to mathematically describe the fundamental kinetics of the treatment that takes place as a result of microorganisms in biological treatment[13]:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{kSX}{(K_\mathrm{s} + S)},$$

$$\frac{\mathrm{d}X}{\mathrm{d}t} = Y\frac{\mathrm{d}S}{\mathrm{d}t} - K_\mathrm{d}X,$$

where X is mass of microorganisms, S is mass of organic matter used as food by the microorganisms (normally expressed as BOD), and Y is cell yield coefficient, the ratio of the mass of cells formed to

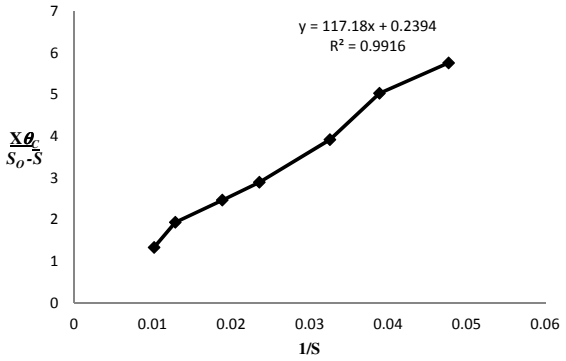

Fig. 8 Graph for k and K_s basis on sBOD.

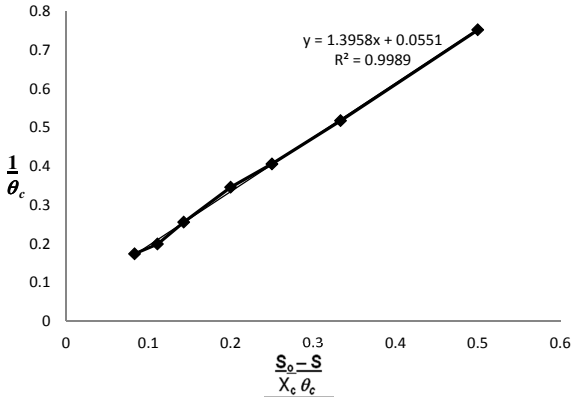

Fig. 9 Graph for Y and K_d basis on sBOD.

the mass of substrate consumed. K_d represents the proportion of the total mass of microorganisms that self degrades (endogenous respiration) per unit time, k is maximum rate of substrate utilization per unit mass of microorganisms, and K_s is half velocity constant, substrate concentration at one half of the maximum growth rate, mass per unit volume.

The following linearized equation as described by Metcalf & Eddy [13] was used to find k and K_s:

$$\frac{X\theta_\mathrm{c}}{S_0 - S} = \frac{K_\mathrm{s}}{k}\frac{1}{S} + \frac{1}{k},$$

where θ_c is mean cell residence time and S_0 is initial substrate concentration expressed as BOD.

By using the above equation, a graph was plotted with $1/S$ on the x-axis and $X\theta_\mathrm{c}/(S_0 - S)$ along the y-axis (Fig. 8). A linear regression line was fitted to the plotted data. The intercept on the y-axis and the slope of this line were used to find k and K_s. The equation of the fitted line is also shown on the graph in Fig. 8.

The following linearized equation was used to find Y and K_d [14]:

$$\frac{1}{\theta_\mathrm{c}} = \frac{S_0 - S}{X\theta_\mathrm{c}}Y - K_\mathrm{d}.$$

A graph was plotted with $1/\theta_\mathrm{c}$ along the y-axis and $(S_0 - S)/X\theta_\mathrm{c}$ along the x-axis. A linear regression line was fitted to the plotted data. The intercept on the y-axis and the slope of the line were used to find K_d and Y. The equation of the fitted line is also shown in the Fig. 9.

The values obtained for k, K_s, Y, and K_d from the graphs are 4.56 day^{-1}, 544.6 mg/l of sBOD, 0.713 mg VSS/mg sBOD, and 0.0381 day^{-1}, respectively.

The best efforts were made to find the values of these coefficients for dairy-product industry wastewater. Whatever data were found for domestic, fish manufacturing, and cheese are used for comparison with the results in Table 3. A brief discussion is done on each coefficient.

Maximum rate of substrate utilization (k)

k is the maximum rate of substrate utilization per unit mass of microorganisms. The value of k in this study came out to be 4.46 day^{-1} based on sBOD. The value of k for domestic wastewater is 5 g bsCOD (g VSS)$^{-1}$ day^{-1} and the value of k for cheese processing wastewater is 9.3 day^{-1}, showing that the maximum rate of substrate utilization is slightly less in the case of dairy-industry wastewater as compared to domestic and cheese processing wastewaters. The possible deviation may be due to the difference in the composition of the two wastewaters. As a matter of fact, the k value affects the volume of the reactor. The greater the value of k, the smaller will be the size of the reactor [11].

Half velocity constant (K_s)

K_s is the half velocity constant and is numerically equal to the substrate concentration. It is the maximum value at saturation concentration of growth limiting substrate. The value of K_s for this study came out to be 534.6 mg/l sBOD. The range of K_s for domestic wastewater lies between 25 and 100 mg/l BOD [13], for tannery wastewater K_s is 488 mg/l, and for cheesing processing it is 482.5 mg/l. A large value for K_s shows that the maximum specific yield of bacteria occurs at high substrate concentration in the case of dairy industry and other industrial wastewaters. Although K_s is one of the coefficients that are normally determined, yet it has no direct application in the process design. The only significance of K_s is more of a theoretical nature and gives an idea about change

Table 3 Kinetic Coefficient for Various Wastewaters.

Reference	k (day^{-1})	K_s (mg/l)	Y (mg VSS/mg BOD)	K_d (day^{-1})	Wastewater type
Metcalf & Eddy [13]	5	60	0.6	0.10	Municipal
Haydar and Aziz [15]	3.125	488	0.64	0.03	Tannery industry
Demirel et al [9]	9.3	482.5	0.20	0.25	Dairy (anaerobic treatment)
Bertola et al [16]	0.09[b]	0.006[c]	0.45[a]	0.024[b]	Potato industry
Gupta and Sharma [17]	0.216	56		0.068	Fertilizer industry

[a] g VSS/g COD.
[b] h^{-1}.
[c] g/l.

in specific growth rate of bacteria with a change in the concentration of growth limiting substrate [11].

Biomass yield (Y)

Y represents the biomass yield, i.e., how biomass is produced against substrate utilized. The value of Y recorded for this study came out to be 0.714 mg VSS/mg sBOD. The range of Y is 0.4–0.8 mg VSS/mg BOD for domestic wastewater and for cheese processing wastewater its value is 0.20 mg VSS/mg COD [9]. The significance of Y in process design is that it gives an estimate of the sludge produced as a result of wastewater treatment. The greater the value of Y, the greater will be the amount of sludge, and the size of sludge handling facility. Preliminary cost estimates for sludge handling can be found out once the size is known.

Endogenous decay coefficient (K_d)

K_d is the microbial decay coefficient and represents the biomass lost to endogenous respiration per unit of biomass per unit time and has the dimensions time^{-1}. For this study the value of K_d came out to be 0.038 day^{-1} on the basis of BOD. The decay coefficient for domestic wastewater fluctuates in the range of 0.06–0.1 g VSS (g VSS)$^{-1}$ day^{-1} and for cheese processing wastewater it is 0.25 day^{-1}. The lower value showed a lower bacterial decay rate in the case of dairy-industry wastewater.

The significance of K_d in process design is used when evaluating net sludge production in a treatment facility. Higher values of K_d reduce the net production of sludge. Although the effects are minimal, yet can be used to fine tune the size of sludge handling facilities resulting in some economic benefits in the cost reduction [11].

CONCLUSIONS

The activated sludge process is operated best at retention time of 5 days with BOD percentage removal efficiency of 95% for dairy wastewater. The treatment efficiency of the reactor in terms of BOD_5 and COD removals was studied at different retention times and is used for the large scale treatment plants. The values of kinetic coefficients based on soluble BOD are found to be k 4.46 day^{-1}, K_d 0.038 day^{-1}, K_s 534 mg/l sBOD, and Y 0.714 mg VSS/mg sBOD. The determination of these coefficients may be helpful in understanding the kinetics of substrate utilization and design of biological treatment facilities based on activated sludge process for dairy wastewater.

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