Performance evaluation of various aerobic biological systems for the treatment of domestic wastewater at low temperatures

N. Sundaresan and L. Philip

ABSTRACT

Studies were undertaken on the performance evaluation of three different types of aerobic reactors, namely, activated sludge process, fluidized bed reactor and submerged bed reactor. Initially synthetic wastewater was used for stabilizing the system and later domestic wastewater of IIT Madras was used as the feed for the biological systems. The hydraulic retention time was maintained as 24 h. The seed sludge was collected from IIT Madras sewage treatment plant. The inlet COD to the reactors with synthetic wastewater was 1,000 ± 20 mg/L and with real wastewater, it was 150 to 350 mg/L. The performance of the reactors was evaluated based on the soluble COD and nitrogen removal efficiency. The pH, temperature, dissolved oxygen (DO) and mixed liquid suspended solid (MLSS) concentration were measured periodically. The reactors were acclimatized at 35°C in batch mode and changed to continuous mode at 30°C. After the systems attained its steady state at a particular temperature, the temperature was reduced from 35°C to 5°C stepwise, with each step of 5°C. The start-up time for submerged bed reactor was slightly more than fluidized and conventional activated sludge process.

The COD removal efficiency of the three reactors was higher with synthetic wastewaters as compared to actual domestic wastewater. Submerged bed reactor was more robust and efficient as compared to activated sludge and fluidized bed reactors. The COD removal efficiency of the reactors was relatively good until the operating temperature was maintained at 15°C or above. At 10°C, submerged bed reactor was able to achieve 40% COD removal efficiency whereas; the fluidized bed and conventional ASP reactors were showing only 20% COD removal efficiency. At 5°C, almost all the systems failed. Submerged bed reactor showed around 20% COD removal efficiency. However, this reactor was able to regain its 90% of original efficiency, once the temperature was raised to 10°C. At higher temperatures, the nitrification efficiency of the reactors was above 80–90%. As the temperature reduced the nitrification efficiency has reduced drastically. In summary, submerged bed reactors seems to be a better option for treating domestic wastewaters at low temperature regions.

Key words | biodegradation, biological treatment, cold climate, domestic wastewater, low temperature

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INTRODUCTION

Treatment of wastewater in cold climate regions is always being considered as greatest challenge for environmental engineers. Unlike the arid/semi arid regions, bio-degradation is very slow at cold climates due to the low activity of microbes. The climatic conditions inhibit enzyme-related bio-degradation action. Incineration and transport of waste

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from high altitude to arid/semi arid regions are the practiced options in environmentally sensitive areas like glaciers. Human habitations become essential in such places during war. For example, the Indian Army occupied the Siachen glacier – the world's highest battlefield.

Defense Research and Development Establishment (DRDE) in Gwalior has developed a new bacterial solution to keep the soldiers' makeshift loos clean. The bacterial cocktail can degrade human waste at low temperatures inside bio-digesters. Though these bio-digesters were widely installed in Siachen glacier, there remained certain difficulties like the large numbers of bio-digester required to fulfill the troop's deployment, requirement of more time for biodegradation and more complicated process. These problems may be partially taken care by aerobic processes.

There are a few reports available on the performance of aerobic biological systems under low temperatures. Stephenson *et al.* (1983) had conducted a pilot scale study to determine the effects of transient temperature reductions from 17.5°C to 12.5°C, 10°C, 7.5°C and 6°C at low and high influent metal concentrations on the biodegradation of nitrilo triacetic acid (NTA), $C_6H_9NO_6$. They presented that NTA biodegradation in the activated sludge pilot plant deteriorated below 10°C, as anticipated, and that this deterioration was pronounced below 7°C. Chapman (1990) reported the effect of higher temperature on an activated sludge process operated with extended aeration process. Lishman *et al.* (2000) studied the temperature effects on wastewater treatment under aerobic and anoxic conditions. They compared the bio-solids production rates for Sequential Batch Reactors (SBRs) achieving carbon removal under aerobic or anoxic conditions as a function of temperature (14°C and 20°C) and found that the small range of temperature change was not a significant factor. Lapara *et al.* (2001) studied the effect of temperature on the efficiency of soluble COD removal of a pharmaceutical wastewater. They have grown the culture at 30°C to 60°C with 5°C intervals in six batch bioreactors to elucidate the extend of soluble COD removal as a function of temperature. They had reported that the soluble COD removal in a given batch reactor declined by an average of 60 mg/L per°C as the temperature increased.

Osorio *et al.* (2002) conducted a study to determine the performance of a submerged biological aerated filter, composed of a double-layer bed at normal temperatures. They found that the elimination rates of the system were more than enough for effective removal of $TBOD_5$ and SS at relatively high loading rates. The maximum $TBOD_5$ and SS volumetric loads that can be applied, if effluent concentrations of under 20 mg $TBOD_5$/L and 25 mg SS/L are to be achieved, correspond to 4.87 kg $TBOD_5/m^3$/d and 3.0 kg SS/m^3/d, respectively. Morgan & Grant Allen (2003) analyzed the effects of temperature transient conditions on aerobic biological treatment of wastewater. They evaluated the effects of temperature variations on aerobic biological wastewater treatment with respect to treatment efficiency. The effects of controlled temperature shifts (from 35°C to 45°C and from 45°C to 35°C) and periodic temperature oscillations (from 31.5°C to 40°C, 6 day period, for 30 days) were assessed in 4 parallel, lab-scale sequential batch reactors (SBRs) that treated pulp and paper mill effluent. They found that the temperature upshifts (from 35°C to 45°C) had two major effects: a reduction (up to 20%) in soluble COD removal efficiency and an increase in effluent suspended solids (ESS) levels.

Apart from conventional activated sludge process, many other reactors are also being used for wastewater treatment. Reis *et al.* (1985) studied the performance of an aerobic submerged bed reactor applied to the treatment of a concentrated effluent. They concluded that the aerobic submerged bed reactor seems to be adequate for the treatment of concentrated wastewaters. For the effluent with COD concentrations of 3,000 – 3,500 mg/L, COD removal efficiencies in the range of 60 – 80% were obtained with hydraulic retention times of 10 – 16 h. Rosenberger *et al.* (2002) had investigated the reactor performance, process stability and the membrane capacity in a membrane bioreactor treating domestic sewage. They observed that the performance of membrane bioreactor was better than that of conventional sewage works and the COD reduction reached 95% at low F/M ratios and was extremely stable. Nitrification was complete and up to 82% of the total nitrogen could be denitrified. Kreuk *et al.* (2005) studied the formation of aerobic granules and conversion processes in an aerobic granular sludge reactor at moderate and low temperatures. They found that once a reactor is started up at higher temperatures it was possible to operate a stable aerobic granular sludge system at lower temperatures. Though there are a few studies on the temperature effect on activated sludge process, so far not much work has been carried out on the performance of various hybrid and high rate aerobic reactors under cold climates. Moreover, it is essential to develop a suitable bioreactor to treat the organic wastes in cold climate regions effectively and economically.

The main objective of the present study was to compare the performance of three aerobic biological systems namely activated sludge process working on extended aeration mode, fluidized bed reactor and a submerged bed reactor for treating domestic wastewater. The nitrification efficiency of the three systems was also monitored. Finally a management strategy based on treatment cost and reactor size was developed to design a proper waste treatment facility.

MATERIALS AND METHODS

Chemical

The chemicals used in the present study were procured from Ranbaxy Fine Chemicals Limited. New Delhi, India. All chemicals used were of analytical grade (AR). The glassware used for the anaerobic reactor was supplied by Schott Duran, Germany, and COD ampoules used were procured from Borosil, India. All glassware used in the study were cleaned properly using tap water followed by distilled water and dried in an oven at 105°C for 1 h.

Seed sludge

The seed sludge was collected from the aeration tank of an Activated Sludge Process in the sewage treatment plant at Indian Institute of Technology Madras, Chennai. Settled sludge was added to the reactor (50% of reactor volume, MLSS = 2,500 mg/L) for acclimatization. Acclimatization was conducted in a separate batch reactor (having a volume of 2 L), under aerobic environments. During acclimatization, the temperature was maintained at 35°C.

Wastewater

The composition of synthetic wastewater used in the present study is given in the Table 1. The synthetic media was composed in such a way that it imitates the domestic wastewater. Sewage collected from Indian Institute of Technology Madras, Chennai, after primary treatment, was used as the real wastewater. The composition of wastewater is given in Table 2.

Table 1 | Composition of synthetic Wastewater

Compound	Concentration
Dipotassium hydrogen phosphate	1,000 (mg/L)
Potassium dihydrogen phosphate	1,000 (mg/L)
Magnesium sulphate	120 (mg/L)
Cobalt chloride	36 (mg/L)
Ferric chloride	864 (mg/L)
Calcium chloride	600 (mg/L)
Urea	1,000 (mg/L)
Yeast extract	400 (mg/L)
Dextrose (carbon source)	1,000 (mg/L)

ANALYTICAL METHODS

Biochemical oxygen demand (BOD)

BOD of liquid samples was estimated as per *Standard Methods* (Ref. No. 5210 BioChemical Oxygen Demand, APHA 1998). 5-Day BOD test was conducted for estimating the BOD of the sample. Ten times diluted sample was taken in six bottles along with a blank.

Table 2 | Characteristics of domestic wastewater of IIT Madras, Chennai

Property	Quantity
Soluble COD, mg/L	150–350
Soluble BOD, mg/L	90–120
Total solids, mg/L	415
Total dissolved solids, mg/L	278
Dissolved volatile solids, mg/L	183
Dissolved fixed solids, mg/L	95
Total suspended solids, mg/L	137
Volatile suspended solids, mg/L	88
Fixed suspended solids, mg/L	49
pH	6–6.5
Dissolved oxygen, mg/L	Below 1
Total Kjeldahl Nitrogen, mg/L	10–30

Chemical oxygen demand (COD)

COD of liquid samples was estimated as per *Standard Methods* (Ref. No. 5220 Chemical Oxygen Demand, APHA 1998). Closed reflex method was followed. Digestion was carried out in a Hach COD digester (Model 45600, USA) fitted with temperature controller and timer.

Total Kjeldahl nitrogen (TKN)

TKN of liquid samples was estimated as per *Standard Methods* (Ref. No. 4500-N_{org} Macro-Kjeldahl Method, APHA 1998). To estimate Ammonia Nitrogen (NH_3-N), colorimetric method adopting a process known as Nesslerization was followed. This involves pretreatment to remove turbidity producing compounds and adding Nessler reagent (APHA 1998). Nitrate Nitrogen (NO_3-N) was estimated by ion chromatography analyses, as suggested in *Standard Methods* (APHA 1998). Dionex LC-20 Ion Chromatograph with ED-50 electrochemical detector and IP-25 isocratic pump was used for the analyses. The instrument was calibrated using two standard solutions containing 25 and 50 mg NO/L. The chromatograph was operated at a flow rate = 1.0 mL/min to obtain optimal peak detection. Samples were filtered before they were injected into the instrument, using Whattman 0.45 μm filters. A 12 mM NaOH eluent solution was used for isocratic elution of anions, and to frequently flush both the exchange column and the guard column for maximum precision. The samples were analysed for the pH, MLSS, MLVSS, and dissolved oxygen as per the methods described in APHA (1998).

EXPERIMENTAL METHODS

Reactor configuration and fabrication

Entire study was conducted in an incubator. The reactors were designed after considering the volume of the incubator, feed flow rate (HRT) and settling time. Three reactors were used in the present study, i) an extended aeration system, ii) a fluidized bed reactor and iii) a submerged bed reactor. All the reactors were of same size, shape and volume. The settling tank of the reactor was designed inside the aeration tank, which helped to achieve 100% recirculation without incurring any additional effort. The reactors were made up of fiber glass material. The schematic of the continuous system is shown in Figure 1a and b. The operating parameters of the bioreactors are presented in Table 3.

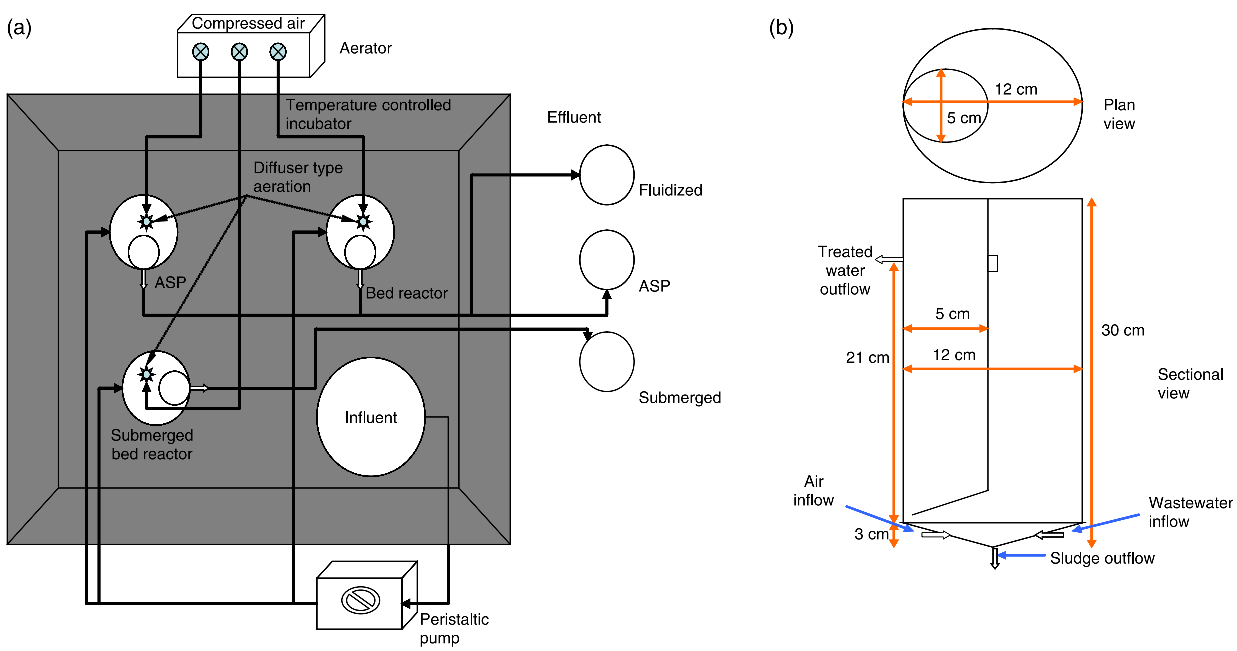

Figure 1 | a) Schematic of the experimental set-up, b) Cross sectional view of reactor.

Table 3 | Reactor details

Parameter	Quantity
Reactor	
Volume of bioreactor (L)	2
Volume of settling tank (L)	0.4
Recirculation ratio	1
Hydraulic retention time (h)	24
Start up condition	
Temperature range (°C)	35°C–5°C at 5°C interval
COD of feed (mg/L)	1,000
MLSS Conc (mg/L)	3,000–4,000
Wastage rate from recycle line (L/day)	Nil
pH	6.8–7.0
F:M ratio range	0.05–0.10

Startup of the reactor

The initial seed sludge collected from the aeration tank of an ASP in the sewage treatment plant at IIT, Madras, Chennai was acclimatized to the synthetic wastewater in the laboratory environment, in batch mode. 200 ml of seed sludge was added to 2 L of synthetic wastewater (Table 1) and the contents were aerated. Every day, 200 ml of reactor contents was wasted and 200 ml of fresh synthetic wastewater was added to the system. Mixed Liquid Suspended Solids (MLSS) concentration and residual COD were monitored continuously, until the system reached a steady state. The start-up of the reactor was done at 35°C. The temperature and feed composition of all the reactors were changed as per the schedule given in Table 4

RESULTS AND DISCUSSION PERFORMANCE OF REACTORS

The reactors were acclimatized at 35°C in batch mode. Once the reactors reached steady state, they were operated in continuous mode at 30°C and 25°C with synthetic wastewater under aerobic condition. At 25°C, the feed was changed to primary treated domestic wastewater and the performances of the reactors were monitored in terms of COD, nitrate and ammonia removal. MLSS concentration of 2,500 to 3,000 mg/L was maintained in the reactors. Once the reactors reached steady state condition with respect to COD removal, temperature was changed 20°C. The step was followed at 15°C, 10°C and 5°C. The performance of the system under sudden change in temperature was also studied. The MLSS concentrations, DO, pH and temperature in the reactors were also monitored periodically.

COD removal at 35°C with synthetic wastewater

The COD removal efficiency in all the three reactors during startup period is presented in Figure 2. This stage; the reactors were operated in batch mode at a temperature of 35°C for 12 to 18 days until steady state in terms of COD removal efficiency was achieved. Immediately after starting the reactors with dextrose as the sole carbon source, COD removal efficiency was around 35% in both activated sludge process and fluidized bed reactors and 30% in submerged bed reactor. After 15 days of operation, the COD removal efficiency of submerged bed reactor reached 83% and activated sludge process and fluidized bed reactors reached

Table 4 | Schedule of operation of the bioreactor

Sl no	Days of operation	Temperature (°C)	Type of feed	HRT (h)	Mode of operation	COD range (mg/L)	Change of temperature
1	1–15	35	Synthetic feed	24	Batch	1000	After attaining steady state
2	16–32	30	Synthetic feed	24	Continuous	1000	After attaining steady state
3	32–47	25	Synthetic feed	24	Continuous	1000	After attaining steady state
4	48–65	25	Real wastewater	24	Continuous	150 to 350	After attaining steady state
5	66–86	20	Real wastewater	24	Continuous	150 to 350	After attaining steady state
6	87–101	15	Real wastewater	24	Continuous	150 to 350	After attaining steady state
7	102–118	10	Real wastewater	24	Continuous	150 to 350	After attaining steady state
8	119–132	5	Real wastewater	24	Continuous	150 to 350	After attaining steady state
9	133–146	10	Real wastewater	48	Continuous	150 to 350	After attaining steady state

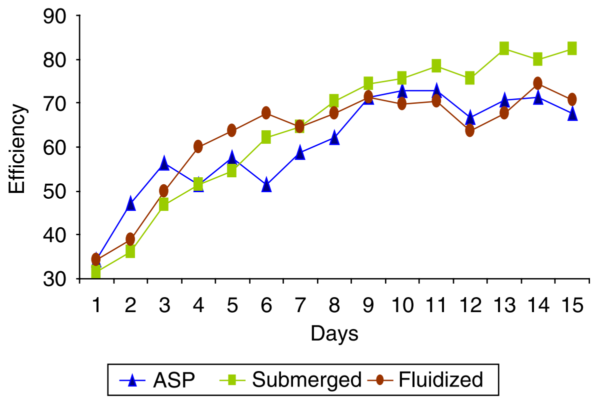

Figure 2 | COD removal efficiency of different reactors at 35°C with synthetic wastewater.

68% and 70%, respectively. During the earlier stages, the efficiency of the submerged bed reactor was less. This may be due to the low concentration of biomass on the submerged bed which took time to grow in number. Once the reactors maintained a constant COD removal efficiency, the system was converted into continuous mode operation and temperature was changed to 30°C for further study. The MLSS concentrations of the ASP and fluidized bed reactors were 3800 mg/L and 3700 mg/L, respectively.

COD removal at 30°C with synthetic wastewater

The reactors were operated in continuous mode with a Hydraulic Retention Time (HRT) of 24 h. COD removal efficiency of all the three reactors has been measured on daily basis and the results are presented in Figure 3. Submerged bed reactor has shown a uniform and steady

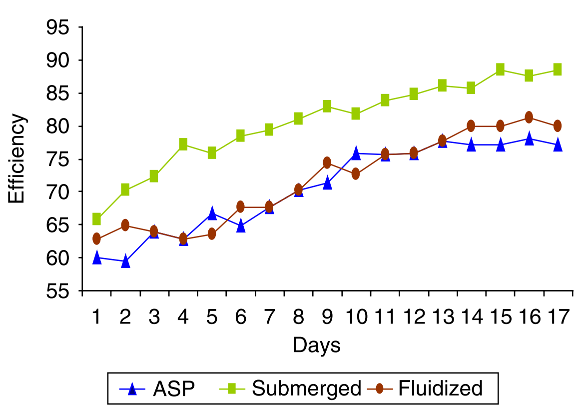

Figure 3 | COD removal efficiency of various reactors at 30°C with synthetic wastewater.

increase in efficiency and it attained 88% removal efficiency at steady state. However, the fluidized bed and ASP reactor attained a removal efficiency of only 79% and 76%, respectively at steady state.

The MLSS concentration in fluidized and conventional ASP was 3,600 and 3,750 mg/L, respectively. After 17 days of operation the system was reached the steady state. At this stage, the temperature of the system was reduced to 25°C.

COD removal at 25°C with synthetic wastewater

The sudden reduction in temperature didn't affect the efficiency of the reactors significantly. The final COD removal efficiency at 25°C with synthetic feed was 84% for submerged bed reactor and 75% for other two reactors. The MLSS concentration in fluidized and conventional ASP was 3,550 and 3,500 mg/L, respectively. There was some washout of sludge in these reactors. This may be the reason for the decrease in performance of these reactors. After 15 days of operation, the system reached the steady state. During this period, the feed was changed to domestic wastewater and the temperature was maintained at 25°C.

PERFORMANCE OF AEROBIC REACTORS FED WITH REAL DOMESTIC WASTEWATER

COD removal at 25°C with domestic wastewater

The performance of the reactors after introducing the primary treated sewage is shown in Figure 4a and b. During this period, significant sludge wash-out took place in both fluidized bed and ASP reactors. The MLSS concentration reached as low as 1,300 mg/L. Fresh sludge was added twice to compensate the sludge wash-out. However, there was no significant adverse effect in the performance of submerged bed reactor. At steady state, COD removal efficiencies were 82% for submerged bed reactor, 65% for fluidized bed reactor and 52% for ASP. The disturbances in the system might have caused due to the very low concentration of influent COD (150–350 mg/L) and high fluctuations in the influent characteristics as compared to the synthetic wastewater.

During this period of operation, approximately 2,000 mg/L of MLSS was added twice to both fluidized

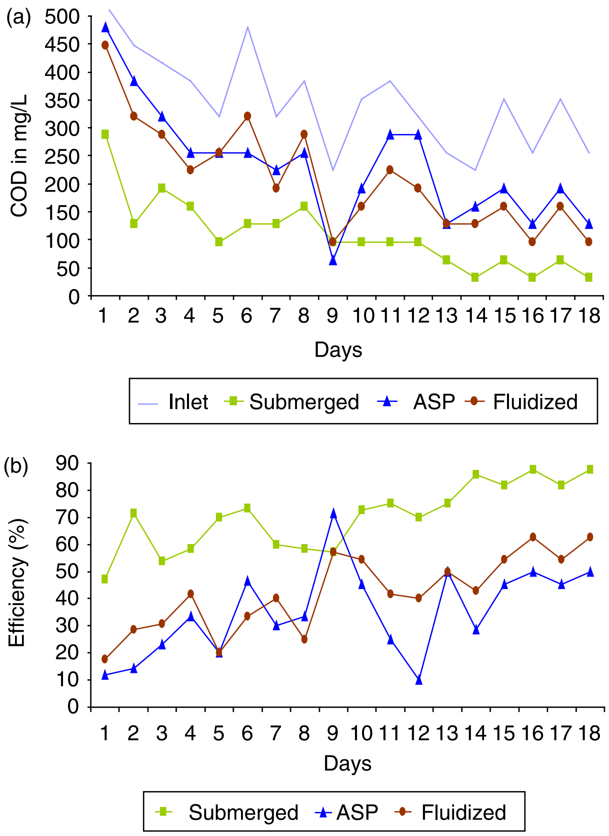

Figure 4 | a) Influent and effluent COD values of various reactors at 25°C with real wastewater, b) COD removal efficiency of various reactors at 25°C with real wastewater.

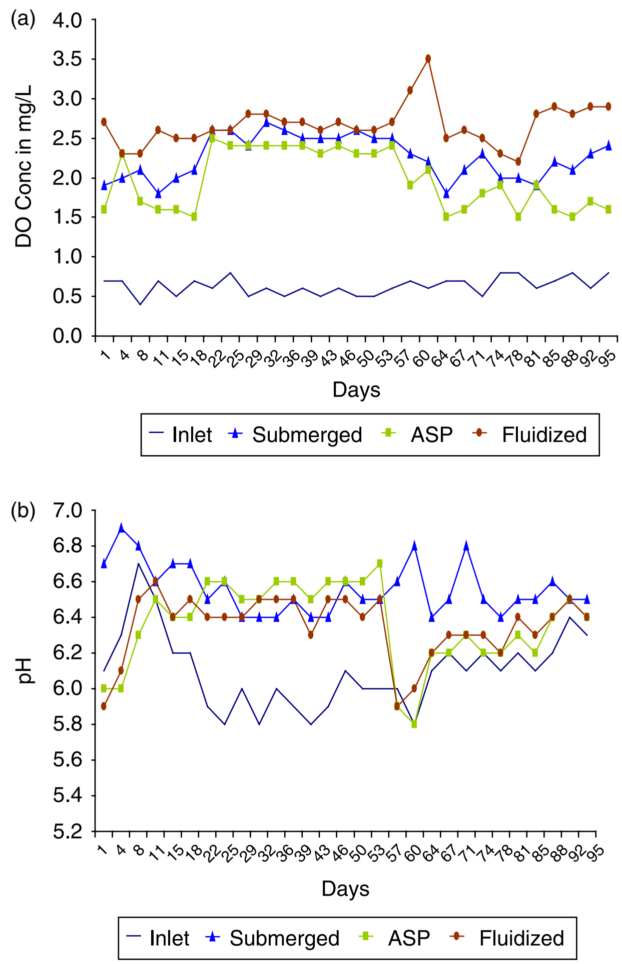

Figure 5 | a) Dissolved oxygen concentration profile in various reactors during operation, b) pH profile of various reactors during operation.

bed and ASP reactors for compensating the sludge losses due to wash-out. However, the MLSS concentration retained in fluidized bed and conventional ASP reactors was 1,600 and 1,300 mg/L, respectively.

The pH and dissolved oxygen content of the reactors were also monitored periodically and the results are presented in Figure 5a and b, respectively. It was noticed that there was not much of change in the pH of the systems. Dissolved oxygen concentration in all the reactors was in the range of 1.5–2.7 mg/L, which is the recommended concentration for activated sludge processes.

COD removal at 20°C with domestic wastewater

Submerged bed reactor has shown a uniform and steady COD removal efficiency and it attained 78% removal efficiency at steady state, when the reactor was operated at 20°C. However, the fluidized bed and ASP reactors attained only 68% and 71% removal efficiency, respectively at steady state. The COD removal efficiency of all the three reactors at 20°C is shown in Figure 6. The MLSS concentration in fluidized and conventional ASP was

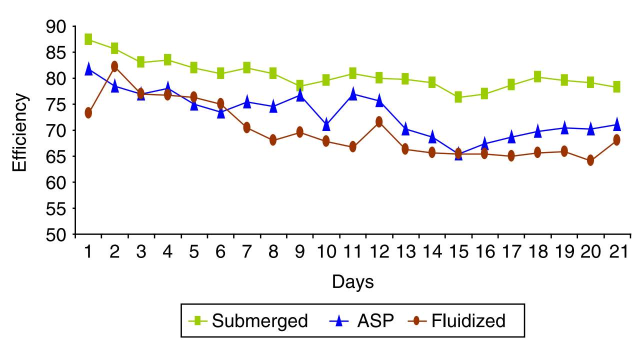

Figure 6 | COD removal efficiency of various reactors at 20°C while treating domestic wastewater.

1,850 and 2,000 mg/L, respectively. After 15 days of operation, the bio-systems attained steady state. The system temperature was changed to 15°C after 21 days of operation.

COD removal at 15°C with domestic wastewater

Submerged bed reactor has shown fluctuations in COD removal efficiency, when the operating temperature was reduced to 15°C, and it attained 74% COD removal efficiency at steady state. The fluidized bed and ASP reactors attained 63% and 67% removal efficiency, respectively at steady state. The MLSS concentration in fluidized and conventional ASP was 1,900 and 2,000 mg/L, respectively. No wash-out of sludge was observed while changing the temperature from 20°C to 15°C. However, the overall MLSS concentration in the system was less as compared to that at 25°C and 30°C. The reactors attained steady state after 15 days of operation, and the system temperature was changed to 10°C.

COD removal at 10°C with domestic wastewater

There was a steady decrease in COD removal efficiency in both submerged bed and fluidized bed reactors when the systems were operated at 10°C. At steady state, COD removal efficiencies of submerged and fluidized bed reactors were 39% and 23%, respectively. ASP reactor could achieve a maximum of 20% COD removal efficiency at this temperature. After 7th day of operation at 10°C, sudden drop in efficiency was observed in activated sludge process reactor. The COD removal efficiency of all the three reactors at 10°C is shown in Figure 7. The MLSS concentration in fluidized and conventional ASP was 1,200 and 1,150 mg/L, respectively. Moderate washing out of sludge was observed while changing the temperature from 15°C to 10°C in both the ASP and fluidized bed reactors. After 15 days of operation the operating temperature of the reactors was changed to 5°C.

COD removal at 5°C with domestic wastewater

Immediately after changing the temperature to 5°C, significant wash out of biomass was observed in both ASP and fluidized bed reactors. No biomass was retained in these reactors. Also the COD removal efficiencies of both the reactors became almost zero. However, submerged bed reactor was able to withstand the adverse condition though there was decrease in the COD removal efficiency.

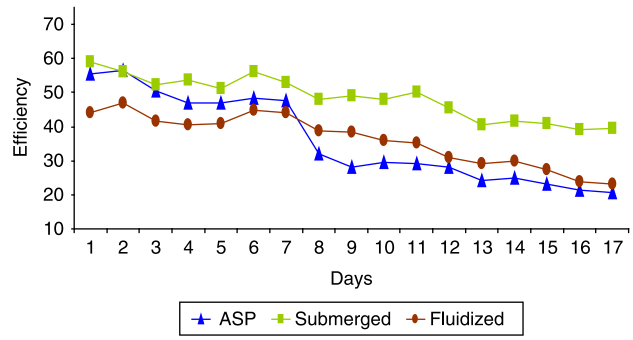

Figure 7 | COD removal efficiency of various reactors at 10°C while treating domestic wastewater.

Response of reactors to sudden changes in temperatures

After 14 days of operation, the system temperature was again changed from 5°C to 10°C. The HRT of the systems were maintained as 24 h. Also 2,500 mg/L of fresh biomass which was well acclimatized at 10°C, was added to both ASP and fluidized bed reactors. However, the fresh sludge was not able to acquaint with the reactors. Moderate washing out of sludge was observed in the ASP and fluidized bed reactors. The submerged bed reactor was able to regain 90% of its earlier performance in just four days of operation. Both fluidized and ASP reactors were attained 18% and 10% respectively, at steady state. This clearly shows that submerged bed reactor was able to withstand the sudden changes in temperatures. The overall performance of the reactors in terms of COD removal efficiency is shown in Figure 8

Nitrogen balance

The influent total Kjeldahl nitrogen concentration was in the range of 10 to 30 mg/L and ammoniacal nitrogen concentration was in the range of 10 to 25 mg/L. The effluents also had 3 to 4 mg/L of ammoniacal nitrogen,

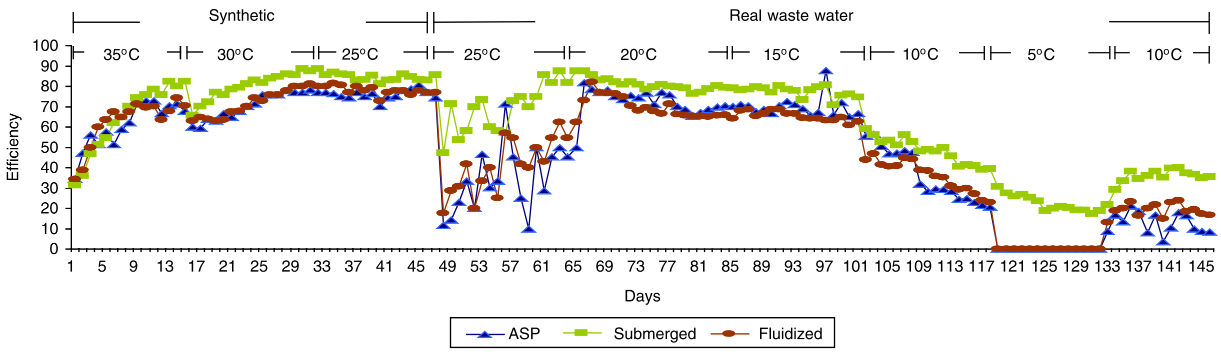

Figure 8 | Overall COD removal efficiency of various reactors at different operating conditions.

which shows that the nitrification in the system was not complete.

The effluent NO_3-N present in the system at various temperatures is given in Figure 9. The influent had negligible amount of NO_3-N. However, the NO_3-N concentration of the effluents was in the range of 10 to 35 mg/L, which is moderately higher than the discharge standards of 10 to 20 mg/L of NO_3-N. These figures clearly indicate that significant amount of nitrification took place in the system. At 25°C, approximately 80 to 90% of nitrification occurred in all the three reactors. However, the nitrification efficiency slightly reduced to 70 to 80% during 20°C and 15°C. Nitrification efficiency of the reactors reduced significantly at 10°C as compared to that at 20°C.

Benefit–cost analysis

The C++ program was used to carry out the benefit–cost analysis of the developed process. It is capable of designing the system at various temperatures. Also the provision was given to carry out the rough cost estimate of the process. By providing the detailed construction, maintenance and operation cost involved in the system, the exact estimate can be done.

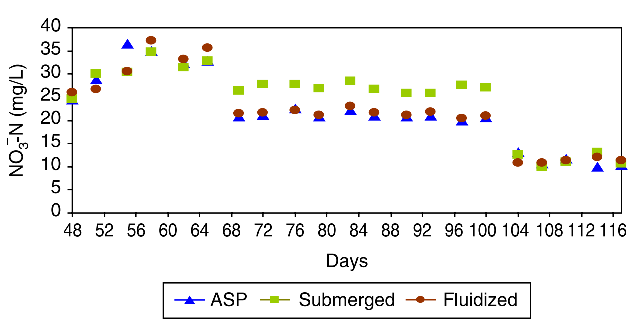

Figure 9 | Nitrate-N concentration in the effluent of different reactors.

Two systems (extended aeration and activated sludge process) were selected for the analysis. The input data like flow rate, BOD, COD, biomass concentration, decay rate etc were maintained as same for both the system. Then the design and estimation was carried out by setting the temperature at 10°C and 5°C. The cost involved for the system at 5°C is approximately 1.2 to 1.5 times higher than that at 10°C. The cost involved for rising the temperature of the system by 1°C was manually calculated as Rs 10/m^3/day. By applying appropriate correction to bio-kinetic parameters, one can find out the time required to achieve the required treatment efficiency in different biological reactors for a given temperature. Once the required HRT is known for a given temperature, the reactor size and cost of construction can be calculated. By increasing the temperature, the change in HRT and reduction in construction and operation cost can be found out. The sum of construction and operation cost along with the cost involved for rising temperature will give the actual cost of the system. By comparing these two costs, one can optimize the operating conditions in such a way that the total cost will be minimized. Here one point should be noted. Once the influent temperature is rose to a particular level, there is no need to supply heat energy to maintain the temperature provided; the heat lost from the reactor is minimized. Biological reactions are exothermic and they generate lot of heat energy. This concept is demonstrated in the following section. The bio-kinetic parameters calculated for different temperatures are presented in Table 5. The kinetic parameter '*K*' value is obtained by using the

Table 5 | Bio-kinetic parameters of the developed processes

Sl no	Temp (°C)	Type of feed	K (asp)	K (sub)	K (flu)	HRT (hrs) ASP	SUB	Fluid
1	35	Synthetic WW	0.052	0.067	0.057	36.344	28.290	33.525
2	30	Synthetic WW	0.063	0.087	0.070	29.958	21.896	27.199
3	25	Synthetic WW	0.062	0.073	0.062	30.849	25.817	30.849
4	25	Real WW	–	0.071	–	–	26.708	–
5	20	Real WW	0.051	0.066	0.045	37.344	28.691	42.309
6	15	Real WW	0.044	0.060	0.039	43.114	31.823	48.526
7	10	Real WW	0.010	0.021	0.011	189.083	92.113	165.907
8	5	Real WW	0.001	0.009	0.001	1897.462	210.829	1897.462
9	10	Real WW	0.004	0.018	0.008	500.495	106.519	238.313

experimental results. Later, the HRT of the system is estimated by assuming the influent BOD concentration as 250 mg/L and effluent BOD concentration as 30 mg/L

The comparison of the cost involved on the developed activated sludge process and submerged bed process were tabulated in Tables 6 and 7. The cost of construction is taken as a one time investment, which includes the approximate cost involved from planning to commission of the reactors, whereas the cost of energy required for elevating the temperature was a recurring cost which was calculated annually. Though the cost required for elevating the temperature is very high and recurring nature, it will be advisable to raise the temperature to meet the desired discharge standards rather than increasing the HRT of the system. At low temperatures, the biological activity is almost negligible. Hence, by increasing the HRT to any level will not affect the COD removal efficiency of the system. A continuously heated building is not necessary to maintain treatment efficiency. Operator comfort and convenience are the only justifications for such energy inputs. If the incoming sewage is 10°C or warmer there is sufficient heat in the liquid to sustain a protected treatment process. Also the biological reactions are exothermic in nature, which will supplement the reactor liquid temperature. A standby heat source and emergency power are recommended for extended power failures and other emergencies.

Table 6 | Cost comparison of the developed ASP process

Sl no	Influent temp (°C)	Reactor temp (°C)	*K* value for ASP process (1/hr)	HRT (hrs)	Cost Approx. cost of construction (lakh)	Approx.cost of energy reqd (lakh/year)	Total cost (lakh/year)
1	35	35	0.052	36.344	378.59	0.00	378.59
2	30	30	0.063	29.958	312.06	0.00	312.06
3	25	25	0.062	30.849	321.34	0.00	321.34
4	20	20	0.051	37.344	389.00	0.00	389.00
5	15	15	0.044	43.114	449.11	0.00	449.11
6	10	10	0.010	189.083	1969.61	0.00	1969.61
7	10	15	0.044	43.114	449.11	327.85	776.95
8	5	5	0.001	1897.462	19765.23	0.00	19765.23
9	5	10	0.010	189.0829	1969.61	1437.82	3407.43
10	5	15	0.044	43.114	449.11	655.70	1104.80

Table 7 | Cost comparison of the developed submerged bed process

					Cost		
Sl no	Influent temp (°C)	Reactor temp (°C)	For Submerged bed process (1/hr)	HRT (hrs)	Approx. cost of construction (lakh)	Approx. cost of energy reqd (lakh/year)	Total cost (lakh/year)
1	35	35	0.067	28.290	306.47	0.00	306.47
2	30	30	0.087	21.896	237.20	0.00	237.20
3	25	25	0.073	25.817	279.69	0.00	279.69
4	20	20	0.066	28.691	310.81	0.00	310.81
5	15	15	0.060	31.823	344.75	0.00	344.75
6	10	10	0.021	92.113	997.89	0.00	997.89
7	10	15	0.060	31.823	344.75	241.99	586.74
8	5	5	0.009	210.829	2283.98	0.00	2283.98
9	5	10	0.021	92.113	997.89	700.44	1698.32
10	5	15	0.060	31.823	344.75	483.98	828.73

CONCLUSIONS

Studies were undertaken on the performance evaluation of three different types of aerobic reactors, namely, activated sludge process, fluidized bed reactor and submerged bed reactor under different temperatures starting from 35°C to 5°C. Initially synthetic wastewater was used for stabilizing the system and later domestic wastewater of IIT Madras was used as the feed for the biological systems. From the study results, following conclusions can be drawn.

- The start-up time for submerged bed reactor was slightly more than fluidized and conventional activated sludge process.
- The COD removal efficiency of the three reactors was higher with synthetic wastewaters as compared to actual domestic wastewater.
- The submerged bed reactor was more robust and efficient compared to activated sludge and fluidized bed reactors.
- The COD removal efficiency of the reactors was relatively good until the operating temperature was maintained at 15°C or above.
- At 10°C, submerged bed reactor was able to achieve 40% COD removal efficiency whereas; the fluidized bed and conventional ASP reactors were showing only 20% COD removal efficiency.
- At 5°C, almost all the systems failed. The submerged bed reactor showed around 20% COD removal efficiency. However, this reactor was able to regain its 90% of original efficiency, once the temperature was raised to 10°C
- At higher temperatures, the nitrification efficiency of the reactors was above 80–90%. As the temperature reduced the nitrification efficiency has reduced drastically.
- In summary, submerged bed reactors seems to be a better option for treating domestic wastewaters at low temperature regions.

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