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Enhancement of Coagulation Flocculation Process Using Anionic Polymer for the Post Treatment of UASB Reactor Effluent

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This study was conducted for the treatment of up-flow anaerobic sludge blanket (UASB) reactor effluent by polymer assisted coagulation–flocculation process. The efficiency of alum, $FeCl_3$, and polyaluminum chloride (PAC) was observed alone and in coupled with anionic polymer (Synpol). The results revealed that $FeCl_3$ and PAC are efficient to remove 99% of turbidity, 83% of total suspended solids (TSS), 82% and 85% of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), respectively, and 99.5% removal of total coliforms (TC) and fecal coliforms (FC). The addition of anionic polymer to alum, $FeCl_3$, and PAC reduces the sludge volume upto 25%.

Keywords alum; anionic polymer (Synpol); coagulation-flocculation; ferric chloride; polyaluminium chloride; UASB reactor effluent

INTRODUCTION

The continuous increase in water demand due to the rapid growth of human population has resulted in the creation of strong interest in wastewater reuse for industrial and municipal water supply. Wastewater can become a feasible option as a water source after appropriate treatment. The high-rate anaerobic reactors used for treatment of domestic sewage are a consolidated technology in some warm-climate countries, especially in Brazil, Colombia, and India. Some of its merits presented in literature are a high degree of waste stabilization, low production of excess sludge, low nutrient requirements, no oxygen requirement, production of energy rich methane gas, and low operating and capital cost (1). The use of UASB technology for sewage treatment has been explored as a feasible option in many developing countries like Colombia, Indonesia, Brazil, China, and India (2). However, to meet the future effluent requirements of such countries, anaerobic effluents need to be improved (3). Therefore, posttreatment is being considered as a necessity. Combined with a proper posttreatment process, anaerobic treatment can provide a good quality effluent when treating domestic sewage.

Currently, UASB facilities in India are integrated with the pond system for posttreatment. However, due to low detention times, these ponds are found to be ineffective in the removal of pathogens, BOD and TSS. Nevertheless, several studies show that pathogenic microorganisms and BOD and TSS can be removed by various systems such as Aerated lagoons, Downflow Hanging Sponge (DHS), Rotating biological contractors, Trickling filters, and Biological aerated filters but at the expense of high-energy, operation, and maintenance requirements (4–7). Most of these processes require high energy and high capital cost and in addition to that, even the effluent quality is not in compliance with the standards for the disposal.

Coagulation-flocculation may be considered a promising posttreatment option in terms of effluent quality, cost-efficiency, and operational simplicity. Recent results on the use of physico-chemical processes for domestic wastewater have indicated that coagulation-flocculation can be an attractive alternative for post treatment of anaerobic reactor effluents (5,8–20). Different chemical coagulants, such as alum, lime, ferric chloride ($FeCl_3$), and PAC have been used worldwide in the treatment of wastewater. However, the main disadvantage with this system is its high chemical cost and sludge production. Therefore, it is not only necessary to overcome these problems but also to improve the process efficiency of coagulation-flocculation process to obtain good quality effluent and the rapid sedimentation of the formed flocs.

Several products like high molecular weight polymers have often been used as coagulant aids in chemically-assisted sedimentation of sewage solids to enhance the removal of suspended matters. Advantages of the polymers usage are—low dosage requirements; reduced coagulant doses, low sludge production; no pH adjustment required; bridging of many smaller particles by polymers; improved floc resistance to shear forces, etc. (18,21). According to

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Aguilar et al. (21), anionic polyacrylamide when added in combination with ferric sulphate or polyaluminium chloride led to a significant increase in the settling speed. In account to recent developments in polymers, it is now possible to use low coagulants dose, and achieve excellent COD, TSS, and BOD removal with more manageable levels of sludge production (11,12,17,18,20–24).

To the best of the authors knowledge, sufficient work has not been done in relation to the posttreatment of municipal UASB reactor effluent by coagulation-flocculation process with or without coagulant aid. Thus, the present study was carried out to investigate the efficiency of the three coagulants (alum, $FeCl_3$, and PAC) with and without the anionic polymer (Synpol) for the treatment of UASB reactor effluent and to select the appropriate coagulant-flocculant scheme with the technical analysis criteria. The determination of the proper coagulant type and dosage will not only improve the water characteristics, but also decrease the sludge volume and cost involved.

MATERIAL AND METHODS

Materials

A sewage treatment plant of 38 MLD capacity at the city of Saharanpur, Northern India, adopting the UASB Process was selected for regular monitoring. The wastewater samples were obtained from the outlet of the UASB reactor.

This study involved three coagulants and one coagulant aid. The coagulants chosen were Alum $[Al_2(SO_4)_3 \cdot 16 H_2O]$, $FeCl_3$ and PAC which are traditionally used in the coagulation-flocculation treatment of wastewater. The commercial anionic polyelectrolyte (SYNPOL 10) was chosen as the coagulant aid. Distilled water was used to prepare the feedstock solutions of all coagulants and flocculants.

Experimental Procedure

Jar tests were performed using the conventional jar apparatus which constituted of 6 standard 1 L glass beakers run at their full capacity. Different concentrations of the coagulants (25, 50, 70, 85, 100, 120, 180, 240, 300, 350, 400 $mg\,l^{-1}$) as well as the anionic polymer (0.1, 0.2, 0.4, 0.6, 0.8, 1.0 $mg\,l^{-1}$) were implemented in the process. The selected coagulant dosage (70, 120, 180, 240, 300 $mg\,l^{-1}$) was added to 1 L of the UASB reactor effluent and the solution was stirred for a period of 1 min at 200 rpm. At this moment the selected polymer dosage was added to the same solution that was followed by a rapid mixing of 1 min at 100 rpm and a slow mixing of 20 min at 20 rpm. In all the cases, pH of the solution remained unadjusted. The flocs formed were allowed to settle for 30 min. After settling, the turbidity, pH, COD, BOD, TSS, TC, and FC of the supernatant were determined. The remaining portion of the treated sample was used to determine the production of sludge volume. All parameters were determined according to the standard methods (25).

All the experiments were carried out only one time excepting those involving optimal conditions and the corresponding blanks, which were performed in duplicates.

RESULTS AND DISCUSSION

The physico-chemical and microbiological characteristics of the UASB reactor effluent are listed in Table 1.

Determination of the Optimal Coagulant Dose

Prior to the implementation of the polymer, experiments were carried out to determine the optimal coagulant dose. The optimum dose of a coagulant is defined as the value above which there is no significant increase in the removal efficiency with further addition of the coagulant (21). The effects of the coagulant doses were observed by comparing the residual turbidities of the treated samples. The performance of the three different coagulants with respect to turbidity removal is shown in Fig. 1, which plots the turbidity reduction vs. the coagulant dose and shows the enhancement in turbidity removal with the corresponding increase in coagulant doses.

In case of $FeCl_3$ and PAC, the minimum effluent turbidity was found to be 0.8 NTU at an optimum dose of 300 $mg\,l^{-1}$ (103.56 $mg\,l^{-1}$ as Fe^{3+} and 47.40 $mg\,l^{-1}$ as Al^{3+}, respectively). Similarly, in case of alum the minimum effluent turbidity observed was 1.1 NTU at an optimum dose of 300 $mg\,l^{-1}$ (25.70 $mg\,l^{-1}$ as Al^{3+}). Pinto Filho and Brandao (26) revealed that the alum doses ranging from 160 $mg\,l^{-1}$ to 240 $mg\,l^{-1}$ showed better results. No significant removal or slight removal of turbidity was observed at the higher coagulants doses (350 and 400 $mg\,l^{-1}$). No

TABLE 1
Characteristics of the UASB reactor effluent

Parameters	Values (average)
pH	7.1–7.8 (7.73)
Turbidity (NTU)	35–60 (56.5)
Alkalinity ($mg\,l^{-1}$)	367–450 (373)
TSS ($mg\,l^{-1}$)	65–110 (78)
COD ($mg\,l^{-1}$)	109–256 (120)
BOD ($mg\,l^{-1}$)	38–55 (48)
Total Coliforms (MPN/100 ml)	2.3×10^5–2.3×10^7 (4.3×10^5)
Fecal Coliforms (MPN/100 ml)	4.3×10^4–9.3×10^6 (2.1×10^5)

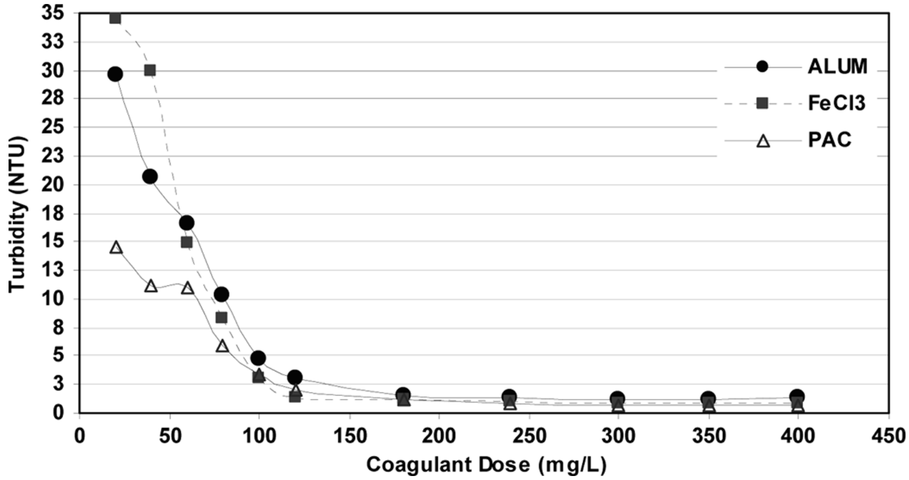

FIG. 1. Effect of different coagulant doses on Turbidity removal from UASB reactor effluent in jar test.

colloidal restabilization occurred for PAC and $FeCl_3$ at higher doses, while it was observed at higher alum doses ($>300\,mg\,l^{-1}$).

Variation in pH at Optimum Coagulant Doses

pH variation at the optimum doses of different coagulants is shown in Fig. 2. The pH reduction was observed greater in case of $FeCl_3$ in comparison to PAC. At the optimum doses of alum, $FeCl_3$, and PAC, the pH values were found to be 6.5, 5.8, and 6.95, respectively. The results revealed that taking into consideration the effluent pH discharge restrictions, PAC is a more useful coagulant. Basically, aluminium and iron-based coagulants form metal hydroxides when they coagulate. In effect, they fully hydrolyze to become 100% hydroxylated, releasing a hydrogen ion for each hydroxyl group (OH) acquired. The equations (1, 2, and 3) below depict this effect in terms of the overall hydrolysis of each trivalent metal present in the coagulant:

Alum Sulphate and Ferric Chloride

$$2Al^{3+} + 6H_2O \rightarrow 2Al(OH)_3 + 6H^+ \quad (1)$$

$$2Fe^{3+} + 6H_2O \rightarrow 2Fe(OH)_3 + 6H^+ \quad (2)$$

These reactions in turn lead to a decrease in the pH of the water as it become more acidic. Since PAC is already 65% hydroxylated (while alum sulphate and ferric chloride has near-zero hydroxylation), the magnitude of this pH drop is significantly lower.

PAC:

$$[Al_2(OH)_5]^+ + H_2O \rightarrow 2Al(OH)_5 + H^+ \quad (3)$$

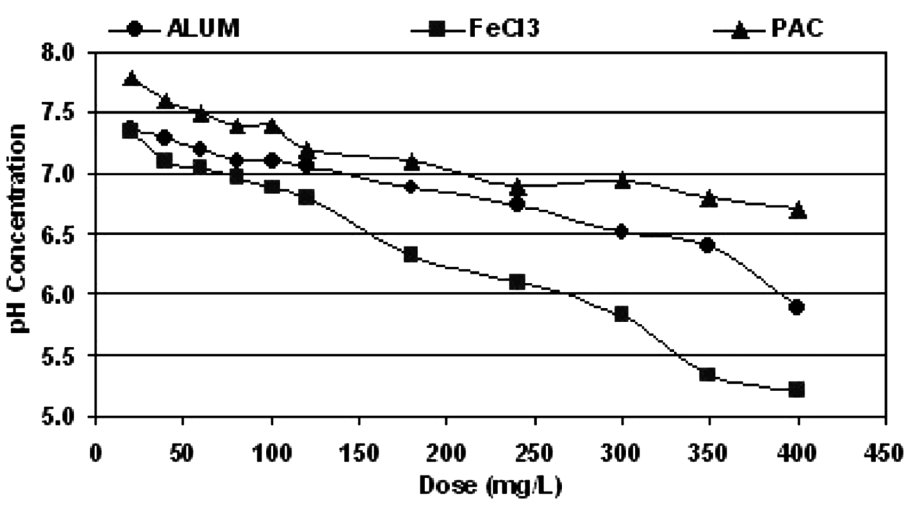

FIG. 2. Effect of different coagulant doses on the pH values in jar test.

Unlike aluminium hydroxide and ferric chloride, PAC forms a stable solution in water. As PAC is a highly basic and highly polymerized coagulant.

Determination of Optimum Polyelectrolyte Dose

These experiments were performed with a fixed coagulant dose i.e., $300\,mg\,l^{-1}$ (optimum dose for each coagulant). The dose of anionic polymer varied from $0–1.0\,mg\,l^{-1}$ for the three coagulants studied. In order to determine the optimum dose of anionic polymer, the residual turbidity and COD of the treated effluent were taken into consideration (Table 2). Based on the observations, the turbidity and COD reduction was found to be optimum at polymer dose of $0.2\,mg\,l^{-1}$. A dose higher than $0.2\,mg\,l^{-1}$ did not instigate any better results.

Effect of Polymer Dose

Once the optimum coagulant-aid dose for each coagulant had been determined, experiments were performed in which varying doses of the coagulants i.e., between $70–300\,mg\,l^{-1}$ along with a fixed dose of anionic polymer ($0.2\,mg\,l^{-1}$) was added for treatment, in order to ascertain the effect of anionic polymer on the coagulation-flocculation process. The effect of polymer addition was observed on the removal of turbidity, TSS, BOD, COD, Fecal coliforms, and sludge volume.

Turbidity and Suspended Solids Removal

Figure 3, which plots the effect of polymer addition on turbidity removal, points to the substantial increase in the performance of each coagulant as the coagulant dose was increased. The addition of anionic polymer leads to a significant increase in efficiency. When the coagulants alone were used, the maximum turbidity reduction was achieved by PAC (98.58%) and $FeCl_3$ (98.48%) compared to a minimum by alum (97.91%) at optimum doses of $300\,mg\,l^{-1}$.

In case of polymer addition, the positive effect of using it was clearly observed for all the three coagulants. The reduction efficiency in the case of turbidity was improved over a 20% by the addition of anionic polymer together with alum. The other two coagulants, $FeCl_3$, and PAC also showed an improved performance of 25% and 30% turbidity reduction, respectively when used along with the polymer. In terms of turbidity, the removal efficiency was observed to be 98–99% for the coagulant dose of $180\,mg\,l^{-1}$. This indicates that lower quantities of alum, $FeCl_3$, and PAC are sufficient to obtain acceptable reduction in turbidity when used along with a specified dose of polymer. The performance of PAC + anionic polymer in terms of turbidity reduction was found to be the most efficient coagulant + flocculant system among the combinations investigated.

The removal efficiency of the system in terms of TSS, which is depicted in Fig. 3, shows a similar trend as in the case of turbidity. The efficiency with respect to TSS removal increases with the coagulant dose, although the improvement is not as good as in the case of the turbidity reduction. The suspended solids removal efficiency was found to be 78.46% with alum, 80% by $FeCl_3$, and 83.08% by PAC at the optimum doses of $300\,mg\,l^{-1}$. The use of anionic polymer with alum, $FeCl_3$, and PAC led to a significant increase in the TSS removal efficiency by 26.32%, 31.58% and 31.25%, respectively. The coagulant dose of $70\,mg\,l^{-1}$ (in case of all three coagulants) with $0.2\,mg\,l^{-1}$ dose of anionic polymer provided the effluent TSS of $<30\,mg\,l^{-1}$, which satisfies the effluent discharge standard (TSS: $50\,mg\,l^{-1}$) of National River Action Plans, Government of India.

BOD and COD Removal

Figure 4 shows the effect of polymer addition on the removal of BOD and COD. The result shows the improvement in BOD and COD reduction as the coagulant dose was increased. At the optimum doses, $FeCl_3$ and PAC exhibit high BOD (75%) and COD reductions (78%),

TABLE 2
Residual turbidity and COD of treated effluent using optimum dose ($300\,mg\,l^{-1}$) of Alum ($25.70\,mg\,l^{-1}$ as Al^{3+}), $FeCl_3$ ($103.56\,mg\,l^{-1}$ as Fe^{3+}) and PAC ($47.40\,mg\,l^{-1}$ as Al^{3+}) and different doses of anionic polymer as coagulant aid

		Dose of anionic polymer ($mg\,l^{-1}$)						
Coagulants	Parameters	0.0*	0.1	0.2	0.4	0.6	0.8	1.0
Alum	Turbidity	1.1	1.1	0.9	1.4	1.6	1.65	1.8
	COD	26.11	19.76	18.34	20.32	21.71	19.64	19.88
$FeCl_3$	Turbidity	0.8	1.0	0.5	0.8	0.7	0.6	0.85
	COD	22.44	19.87	16.75	18.54	18.36	19	18.24
PAC	Turbidity	0.75	0.52	0.5	0.63	0.86	0.98	1.10
	COD	21.44	18.24	15.6	16.45	16.15	19	17.45

*Only coagulant dose ($300\,mg\,l^{-1}$).

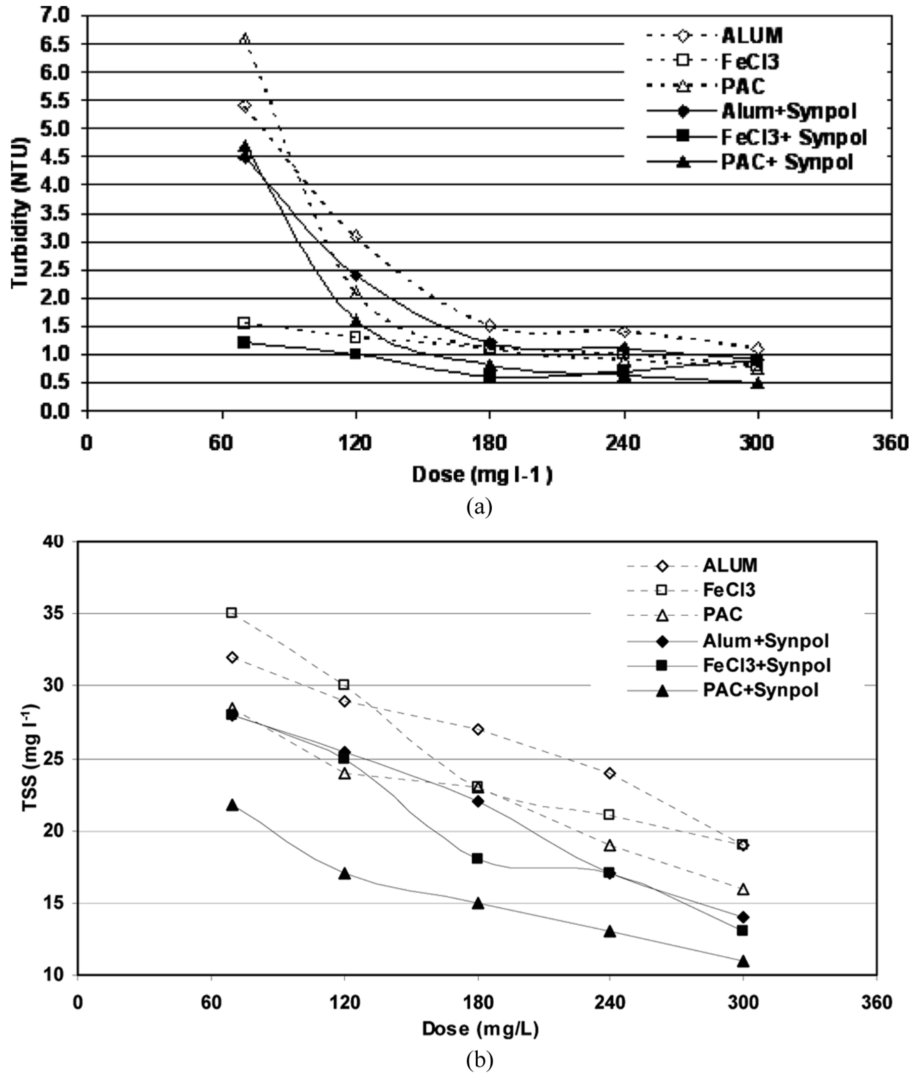

FIG. 3. Effect of anionic polymer aid on the Turbidity and SS removal.

whereas, alum shows a lower efficiency (70.45% and 74.40%, respectively). The addition of anionic polymer initiates a significant increase in BOD and COD reduction efficiency i.e., upto 30%. All three coagulants exhibited a good BOD and COD reduction efficiency (71–78%) even at lower doses (180 $mg\,l^{-1}$) when applied along with the anionic polymer. This also indicates that the use of anionic polymer decrease the required coagulant dose needed to obtain a satisfactory reduction in BOD and COD. Observably, PAC performs better than alum and $FeCl_3$ in the reduction of BOD and COD.

The coagulant-polymer combination of $70 + 0.2\,mg\,l^{-1}$ provides an effluent BOD and COD $<20\,mg\,l^{-1}$ and $<40\,mg\,l^{-1}$, respectively, which satisfy the effluent discharge standards (BOD: 30 $mg\,l^{-1}$ and COD: 100 $mg\,l^{-1}$) of Ministry of Environment and Forests, Government of India.

Pathogens Removal

Coagulation results in the removal of particles and pathogens as well as organic matter. Pathogen removal is more important from the public health point of view when compared to the removal of organic matter (27). The removal of fecal coliforms by coagulants and coagulants + anionic polymer is illustrated in Fig. 5. The average concentration of TC and FC in UASB reactor effluent was found to be 7.5×10^5 and 4.3×10^5 MPN/100 ml, respectively. PAC and $FeCl_3$ were found capable of reducing the TC and FC numbers by 99%, whereas, alum exhibited a poor removal efficiency with respect to TC and FC i.e., only 97%, at their optimum doses. The addition of anionic polymer with the coagulants led to a significant improvement in the TC and FC removal efficiency increasing it by 60%.

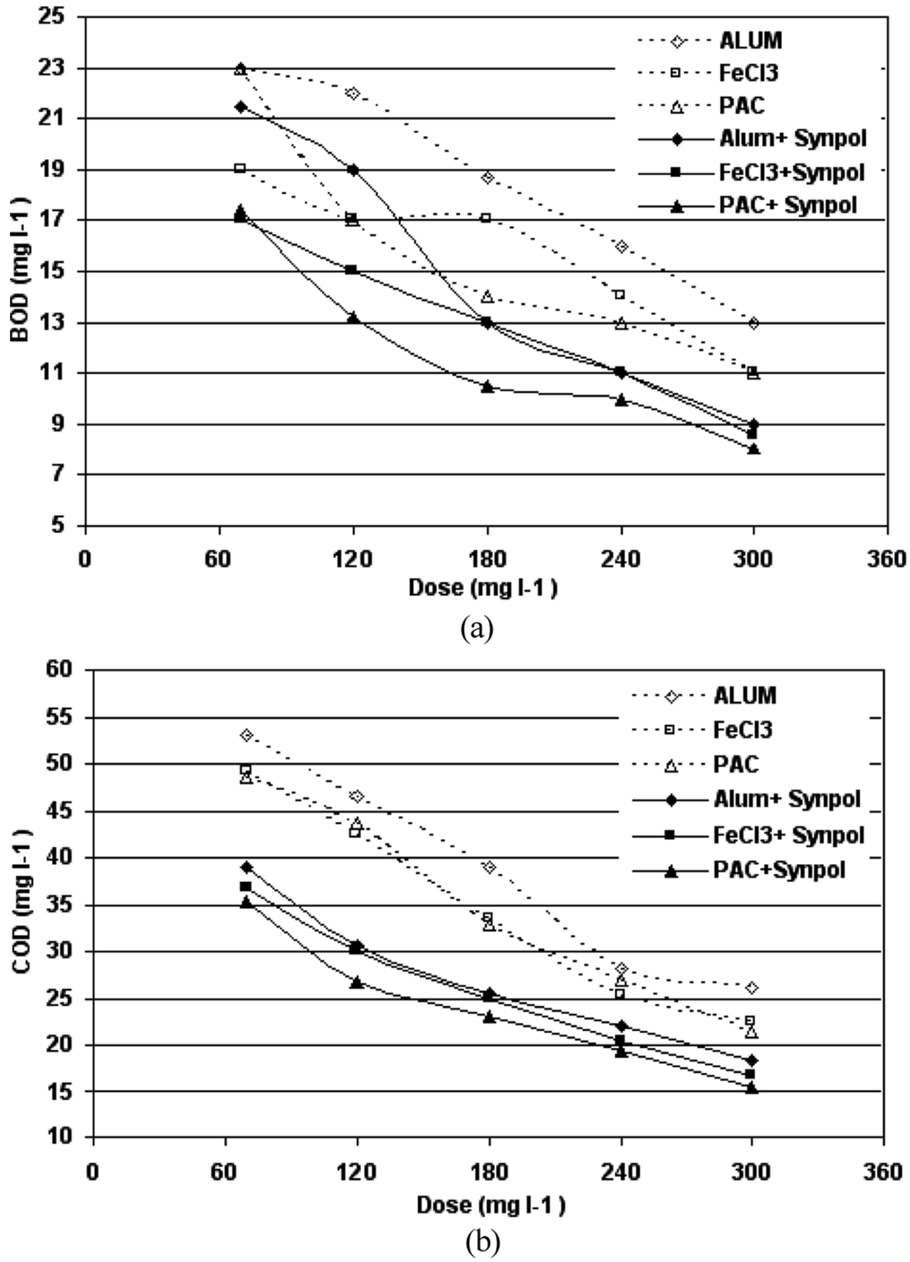

FIG. 4. Effect of anionic polymer aid on the BOD and COD removal.

Although fecal coliforms can be removed at a level of log 2.5 at the optimum coagulant-polymer dose, coagulation-flocculation alone is not sufficient to reduce the FC to a permissible limit (10^3 MPN/100 ml) for unrestricted irrigation. Therefore, the disinfection of the coagulated effluent is mandatory.

Disinfection by Chlorination

Chlorination is the most common method of wastewater disinfection. It is implemented worldwide for the disinfection of pathogens before the effluent is discharged into receiving streams, rivers or oceans. Chlorine is known to be effective in destroying a variety of bacteria, viruses, and protozoa, including *Salmonella, Shigella,* and *Vibrio cholera*. In our study, the effluent was chlorinated after the coagulation-flocculation processes. The clear supernatant was siphoned carefully and chlorine solution was added in the range of 1 to 5 $mg\,l^{-1}$ with a contact time of 30 minutes. A dose of 3 $mg\,l^{-1}$ eradicate the FC numbers from the sample, though a chlorine dose of 2 $mg\,l^{-1}$ can meet the effluent discharge standards of 10^3 MPN/100 ml as prescribed by WHO (28) for unrestricted irrigation.

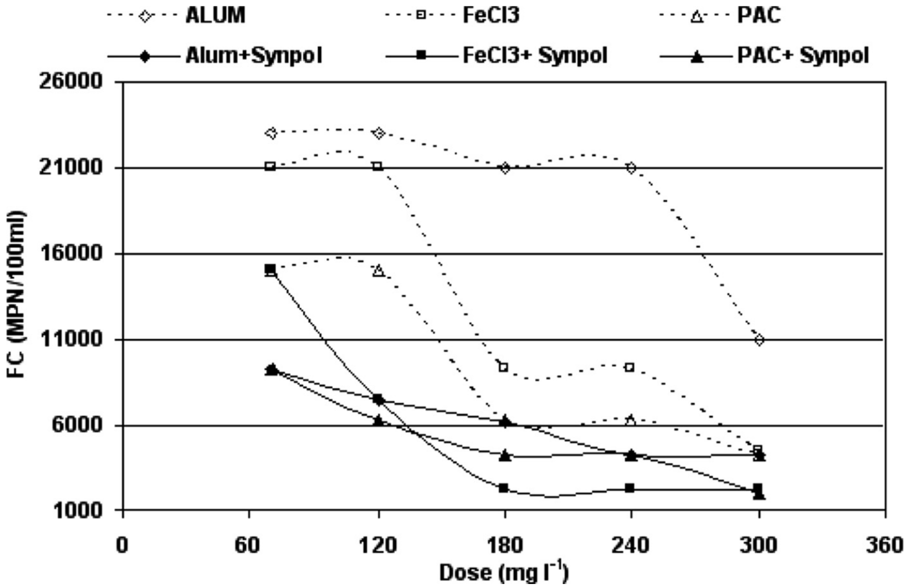

FIG. 5. Improvement in Fecal coliforms removal efficiency using anionic polymer as coagulant aid.

Sludge Production

After performing the jar test, the contents of the glass beakers were transferred to the imhoff cone of 1 (one) L capacity and the sludge production is determined by direct reading as ml of sludge settled/L of water treated. The results obtained for the optimum conditions are shown in Fig. 6. When the coagulants alone were used, a minimum volume of sludge was obtained with alum (40 $ml\,l^{-1}$) and $FeCl_3$ (55 ml l^{-1}), whereas, the maximum sludge volume was observed in case of PAC (140 $ml\,l^{-1}$). The addition of anionic polymer (Synpol) with alum, $FeCl_3$, and PAC led to a significant decrease (25%) in the volume of sludge. As shown in Fig. 6, the volume of sludge reduced from 140 $ml\,l^{-1}$ to 110 $ml\,l^{-1}$ when PAC acted together with the anionic polymer.

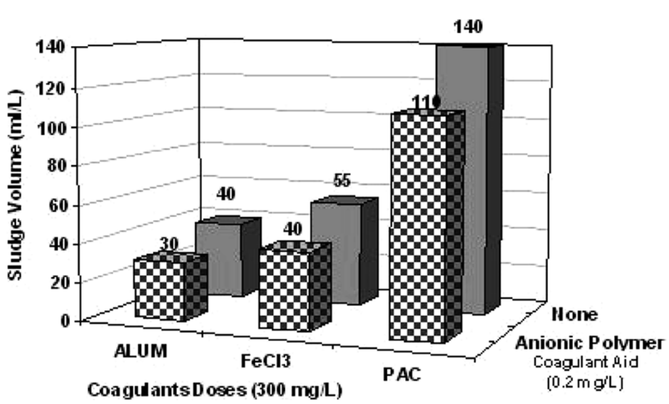

FIG. 6. Volume of sludge produced with different coagulants at optimum doses.

TABLE 3
Chemical cost involved for anionic polymer assisted coagulation-flocculation (coagulant and alum, $FeCl_3$ and PAC) process

Coagulant	Dose ($mg\,l^{-1}$)	Coagulant only: Rs.*/ m^3	Coagulant only: BOD reduction (%)	Coagulant + Anionic polyelectrolyte ($0.2\,mg\,l^{-1}$): Rs./ m^3	Coagulant + Anionic polyelectrolyte ($0.2\,mg\,l^{-1}$): BOD reduction (%)
Alum	70	0.77	47.73	0.79	51.14
	120	1.32	50.00	1.34	56.82
	180	1.98	57.50	2.00	70.45
	240	2.64	63.64	2.66	75.00
	300	3.30	70.45	3.32	79.55
$FeCl_3$	70	0.77	56.82	0.79	61.39
	120	1.32	61.36	1.34	65.91
	180	1.98	61.36	2.00	70.45
	240	2.64	68.18	2.66	75.00
	300	3.30	75.00	3.32	80.68
PAC	70	1.54	47.73	1.56	60.36
	120	2.64	61.36	2.66	70.00
	180	3.96	68.18	3.98	76.14
	240	5.28	70.45	5.30	77.27
	300	6.60	75.00	6.62	81.82

*1 $ = 40 Rs.

The generated sludge can be recycled back to the inlet of UASB, whereas, the effect of alum and $FeCl_3$ sludge on anaerobic activity can be the subject of further examination. The alum sludge produced may also be reused as a coagulant in primary sewage treatment, because the alum sludge contains a large portion of insoluble aluminum hydroxides that can be utilized. It will ease the burden of water treatment works relating to sludge treatment and disposal.

Cost Comparison of Coagulation-Flocculation Process

The determination of the appropriate coagulant type and dosage will not only improve the resulting water characteristics, but also decrease the cost of treatment. Table 3 illustrates the optimal dose for each coagulant, and also gives an account of the cost involved in the process.

Of the three coagulants studied the cheapest is alum and $FeCl_3$. The use of anionic polyelectrolyte had little effect on this cost but improved the coagulation-flocculation process, leading to a significant improvement in the removal of organic as well as microbiological pollutant and reduced the volume of sludge produced. It is important to point out that the optimal coagulation dose can be reduced with the use of anionic polyelectrolyte as a coagulant aid, thus decreasing the treatment cost.

CONCLUSIONS

Based on the observations, the following conclusions can be drawn:

1. The use of anionic polymer leads to a significant improvement in TSS removal of 26% with alum and almost 32% with $FeCl_3$ and PAC.
2. All the three coagulants was observed to reduced BOD and COD upto 78% even at a low coagulant dose of $180\,mg\,l^{-1}$ coupled with $0.2\,mg\,l^{-1}$ dose of anionic polymer. This shows that the use of anionic polymer reduced the dose of coagulants required to obtain a satisfactory removal of BOD and COD.
3. More than 99% fecal coliforms was removed effectively by coagulant aided settling process at optimum conditions.
4. Concerning public health, coagulation-flocculation alone is not sufficient to reduce the fecal coliforms concentration to a permissible limit (10^3 MPN/100 ml) for unrestricted irrigation. Thus, it would be necessary to disinfect the coagulated effluent. It was observed that a chlorine dose of $1–2\,mg\,l^{-1}$ can reduce the fecal coliforms to less than 10^3 MPN/100 ml from the coagulated effluent.
5. The treatment of UASB reactor effluent using coagulants dose of $180\,mg\,l^{-1}$ with $0.2\,mg\,l^{-1}$ dose of anionic polymer is most suitable to produce an effluent that can be utilized for various purposes such as food crop irrigation, groundwater recharge, recreational impoundments, toilet flushing by dual plumbing system, car washing, dust suppression, landscaping, and also in the recovery of a part of the cost involved. However, $70\,mg\,l^{-1}$ coagulant dose of PAC and $FeCl_3$ with $0.2\,mg\,l^{-1}$ of anionic polymer aid was found enough to satisfying the effluent discharge standards of BOD ($30\,mg\,l^{-1}$) and SS ($100\,mg\,l^{-1}$).
6. The addition of the anionic polymer along with alum, $FeCl_3$ and PAC leads to a significant decrease (25%) in the volume of sludge.

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