Removal of organics, suspended solids, and turbidity in a single sludge anoxic-aerobic biological process followed by slow sand filter

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The investigation reported in this paper is part of an ongoing research aimed at finding simplified wastewater treatment operations which can produce acceptable effluent quality with less cost and using processes less demanding for operating skills. A single sludge two stage anoxic-aerobic biological process followed by slow sand filter was operated in the laboratory on municipal raw wastewater directly fed to the anoxic zone. Two sizes of filter media and 3 filter bed depths were investigated. Performance evaluation of the biological process, the slow sand filter, and overall system for removal of BOD_5, COD, Total Suspended Solids, and Turbidity is presented in this paper. The biological process was very efficient in removing all four parameters. However, a high rate of nitrification coupled with moderate denitrification in this system resulted in substantial decrease in effluent alkalinity. Both filter media sizes gave excellent polishing of biological effluent with minor differences. Filter runs averaged 30 days for coarse media and 18 days for fine media. Increased filter bed depth resulted in minor performance improvement.

هذه الدراسة هي حلقة في أبحاث مستمرة تهدف إلى إيجاد عمليات مبسطة لمعالجة مياه الصرف الصحي للحصول على مياه ذات جودة مقبولة بتكلفة أقل وباستخدام عمليات لا تحتاج إلى مهارات عالية في التشغيل. لقد تم تشغيل محطة مصغرة تحوي عملية حيوية ذات مرحلتين إحداهما قليلة الأكسجين (لا هوائية) يليها عملية هوائية ثم مرشح رملي بطيء ، حيث يتم إدخال مياه الصرف الصحي الخام مباشرة على العملية اللاهوائية. و أستخدم في الدراسة مقاسين من حبات الرمل و ثلاث أعماق من المرشح. و تم تقييم العملية الحيوية و المرشح الرملي كل على حدة بالإضافة إلى تقييم العمليات مجتمعة في إزالة متطلب الأكسجين الحيوكيميائي و متطلب الأكسجين الكيميائي و المواد العالقة الكلية و العكارة. و كانت العمليات الحيوية ذات كفائة عالية في إزالة العناصر الأربعة المذكورة ، إلا أن المعدل العالي للنترجة و الذي تزامن مع معدل متوسط لعملية نزع النيتروجين أدى إلى إنخفاض كبير في القلوية للمياه المعالجة. وقد أعطى كل من مقاسي حبات الرمل المستخدمين نوعية جيدة من المياه المعالجة بإختلافات طفيفه. كما أن دورة الترشيح إستغرقت ٣٠ يوما للحبات الكبيرة و ١٨ يوما للحبات الصغيرة ، و لم تؤدي زيادة عمق المرشح إلى تحسينات جوهرية على الأداء.

Keywords: Organics, Suspended solids, Turbidity, Anoxic-aerobic process, Slow sand and filter

1. Introduction

Increased utilization of treated wastewater for many reuse applications and the implementation of more stringent effluent discharge requirements have resulted in more and more dependence on advanced wastewater treatment. Conventional secondary level treatment for organic and suspended solids removal has increasingly became the exception in many new wastewater treatment installations. Biological nitrification-denitrification for the removal of nitrogen is one of the advanced processes which received tremendous attention in both research and actual application for the past two to three decades [1]. In conventional activated sludge process, little nitrogen removal is generally accomplished. However, some biological denitrification processes can remove up to 95% of total nitrogen.

The single sludge nitrification-denitrification process is a process in which biodegradable material in the influent are utilized as an energy source for denitrification. Early developments of this process

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concentrated on the utilization of two reactors, one aerobic and one anoxic, followed by a clarifier. In the Wuhrmann process the influent is discharged first to the aerobic reactor, which is followed by the anoxic reactor [2]. In the Ludzack-Ettinger process, the influent is discharged first to the anoxic reactor that is partially separated from the following aerobic reactor, and clarifier under flow is recycled to the aerobic reactor [3]. The latter was later modified by completely separating the anoxic and aerobic reactors, recycling clarifier underflow to the anoxic zone, and providing an additional recycle from the aerobic to the anoxic reactor [4]. Since part of the flow leaving the aerobic reactor is not recycled to the anoxic reactor in the modified Ludzack-Ettinger process, complete denitrification can not be achieved. The Bardenpho process and its modifications combine the modified Ludzack-Ettinger process with the Wuhrmann process for complete denitrification [5,6,7].

Granular media filters are utilized as an effective polishing step for secondary or tertiary effluents. Most filtration applications in wastewater employ rapid sand filters. Slow sand filtration is an old and reliable process which is still being extensively utilized for the purification of potable water. Such process is known to be simple, efficient, requires much less operational skills, , and economical; especially for communities where land is available at low cost. The application of slow sand filters for wastewater treatment has been investigated by several studies, dealing mostly with applications in the tertiary treatment level. Slow sand filtration was investigated as a tertiary step on trickling filter and activated sludge effluents [8]; on effluents from facultative and aerated lagoon systems [9,10]; and on effluent from an oxidation ditch biological system [11]. Others have reported comparative performances of slow sand filters for tertiary treatment of sewage effluents [12,13]. Results from slow sand filtration of secondary effluent revealed variable performance for removal of suspended solids, organics, and microorganisms. Such variable performance is dependant on media size, filtration rate, and influent quality. One investigation reported 90% removal of suspended solids, more than 65% removal of BOD, and over 95% removal of coliform bacteria with filter run lengths averaged 20 days at 3.5 m d^{-1} and 13 days at 7.0 md^{-1} filtration rate [8].

The investigation reported here is part of an ongoing research focussing on the search for simplified wastewater treatment operations which can produce good quality effluent with less cost and using processes less demanding for operating skills. Such topic is of high concern in developing countries where in many instances treatment costs are prohibitive and when complex systems are built, they are either not needed for the type of effluent or reuse practice or they are poorly operated due to lack of operating skills and/or funding. A single sludge anoxic-aerobic biological process followed by slow sand filter was selected in this investigation. The biological process is somewhat similar to the modified Ludzack-Ettinger process. In this paper, the results obtained for process performance in removal of BOD_5, COD, total suspended solids, and turbidity are discussed.

2. Materials and methods

The experimental set up used in this investigation is shown in fig 1. The system was operated in the laboratory at reasonably controlled conditions. The biological process consisted of a two stage anoxic-aerobic system. Raw wastewater was pumped at a flow rate of 55 $ml.min^{-1}$ from a completely mixed feed tank of 150 L volume to the anoxic zone which consisted of a 20 liter plastic reactor fitted with a slow mixer to keep contents in suspension. The effluent from the anoxic reactor moved by gravity to the aerobic reactor. The aeration-settling unit was fabricated from two plexiglass concentric cylinders. The inner cylinder, with an inside diameter of 14 cm, was continuously aerated using an air diffuser set at 20 cm above the bottom of the reactor, the volume reserved for sludge accumulation. Aerated water moved from the bottom of the reactor through the sludge zone and upward in the outside cylinder which had on inside diameter of 19 cm. The space between the two cylinders served as the settling zone. The total depth of this reactor, including sludge zone, was approximately 130 cm. Sludge was recirculated from the sludge zone to the anoxic reactor using a timed peristaltic pump.

Effluent from the biological process moved by gravity to the slow sand filter that was fabricated from a plexiglass cylinder of 14 cm inside diameter. Filter media consisted of sand typically used in tertiary filtration wastewater treatment plants. The total depth of filter media was 140 cm placed on top of a 15 cm layer of gravel support. Final effluent ports were set at media depths of 70, 100 and 130 cm.

Feed wastewater to the experimental plant was raw wastewater collected after the grit chambers of Riyadh, Saudi Arabia, main wastewater treatment plant (Al-Hayer South). Feed water was collected twice per week and stored in the laboratory refrigerator at 4 °C. The daily required volume of raw wastewater was taken out of the refrigerator and added to the feed tank at room temperature (23-25 °C).

The biological activity in the aerobic and anoxic reactors was started using mixed liquor seed collected from the aerobic and anoxic zones of Al-Hayer-North plant. Results reported here represent steady state operation of the experimental plant after approximately 50 days of equilibration and adjustment of plant variables. Continuous plant operating data and influent and effluent characteristics were recorded during two phases of operation.

The first phase represents data for 30 days of continuous operation using coarse sand filter media. The second phase represents data for another 30 days of continuous operation using fine sand filter media. The operating parameters of the biological process were kept as identical as possible during both phases. The filtration rate in both phases was almost identical at about 5 md^{-1}. Filtration cycle was terminated when the accumulation of solids in the filter top layer resulted in water level rise on filter top to about 10 cm from original level at the beginning of cycle. The filter media top layer (15 cm) was cleaned in place using water jet for about 5 min, then filter was put back into service.

Samples for plant control and performance evaluation were collected two to three times weekly and analyzed on the day of collection using standard procedures [14].

3. Results and discussion

Table 1 illustrates the definition of parameters and symbols used in data presentation and gives a summary of mean system operating values during both phases of the investigation. During early operation of the experimental plant, slight sludge rising problems were encountered in the settling zone. It was realized that denitrification in the aerobic sludge zone was mainly the problem. It was decided then to increase sludge recirculation ratio from an original value of 0.8 to approximately 1.6, which reasonably corrected the problem. This value of sludge recirculation ratio was chosen as a compromise between controlling sludge rising in the clarification step and maintaining low dissolved oxygen in the anoxic zone.

System performance was evaluated based on systematic analysis of feed (RWW), effluent from the biological process (EBF), and final effluent from three filter depths (E70, E100, and E130).

3.1. Anoxic-aerobic-coarse media filter scheme

Summarized performance of the system using the coarse media slow sand filter is presented in table 2. There was a slight decrease in pH and a high reduction of total alkalinity in the biological treatment system. This is an indication of a high rate of nitrification in the aerobic reactor and relatively less effective denitrification in the anoxic step. Alkalinity was slightly increased in the slow sand filter, indicating possible denitrification in the filter, increasing with increased filter depth. Such reduction in effluent alkalinity may require, in some applications, the use of a more elaborate denitrification process, more extensive than the simple one utilized in this investigation.

The biological system removed on the average 90% of BOD_5 producing an effluent with 15 mgL^{-1} BOD_5. This was further reduced in the slow sand filter to an average of 2.8 mgL^{-1} after filtration at 100 cm bed depth, leading to an average overall BOD_5 removal of

98%. Increasing filter bed depth from 70 cm to 100 cm resulted in minor improvement of BOD_5 removal. COD removal in the biological system was slightly less than that for BOD_5, giving an average removal of 83% and an effluent COD of 51 mgL^{-1}. Removal of COD in the slow sand filter was also lower than for BOD_5, resulting in an average overall COD

Table 1
Definition of symbols and mean values of system operating parameters during the two phases

Parameter or symbol	Definition and units	Mean (S.D.)*	
		Biological + coarse media filter	Biological + fine media filter
Aeration zone			
DO	dissolved oxygen (mgL^{-1})	3.0 (1.1)	2.5 (0.3)
TSS	total suspended solids (mgL^{-1})	3418 (290)	3490 (325)
VSS	volatile suspended solids (mgL^{-1})	2500 (205)	2607 (152)
θ_A	hydraulic detention time based on influent flow rate (hr)	5.2 (0.1)	5.1 (0.2)
θ_C	sludge age based on aeration volume (day)	5.6 (1)	5.0 (1)
SVI	sludge volume index for aerated mixed liquor	191 (61)	198 (20)
Anoxic zone			
θ_{Anox}	hydraulic detention time based on influent flow rate (hr)	6 (0.2)	5.8 (0.3)
DO	dissolved oxygen (mgL^{-1})	0.5 (0.2)	0.5 (0.1)
R	sludge recirculation ratio related to influent flow rate	1.6 (0.2)	1.8 (0.3)
Settling zone			
T	detention time in settling (hr)	3.5 (0.2)	3.6 (0.2)
S.O.R.	surface overflow rate in settling (md^{-1})	8.0 (0.3)	7.6 (0.2)
Filter			
FR	filtration rate (md^{-1})	5.2 (0.3)	5.3 (0.3)
E	filter media effective size (mm)	2.41	1.3
U	filter media uniformity coefficient	1.54	1.46
FC	filtration cycle (day)	30	18
Samples			
RWW	raw wastewater (influent)		
EBF	effluent before filter		
E70	effluent at bed depth = 70 cm		
E100	effluent at bed depth = 100 cm		
E130	effluent at bed depth = 130 cm		

* Standard deviation

Table 2
Summarized performance of the anoxic – aerobic – coarse media filter system*

Parameter	RWW	EBF		E70			E100			E130		
		Conc.	% removal	Conc.	% removal in filter	% removal overall	Conc.	% removal in filter	% removal overall	Conc.	% removal in filter	% removal overall
pH	7.3 (0.3)	6.6 (0.4)	--	6.7 (0.3)	--	--	6.7 (0.3)	--	--	6.8 (0.3)	--	--
Alkalinity	282 (10)	18 (10)	--	24 (8)	--	--	25 (8)	--	--	28 (7)	--	--
BOD_5	144 (26)	15 (7)	90 (4)	3.8 (1.3)	71 (15)	97 (1)	2.8 (1.4)	80 (10)	98 (1)	2.4 (1.8)	84 (13)	98 (1)
COD	313 (56)	51 (10)	83 (6)	38 (10)	24 (18)	88 (3)	36 (9)	27 (19)	88 (3)	34 (9)	31 (17)	89 (3)
TSS	150 (39)	3.1 (1.5)	98 (1)	0.6 (0.7)	83 (19)	100 (0.5)	0.2 (0.4)	92 (16)	100 (0.4)	0.3 (0.6)	93 (15)	100 (0.4)
Turbidity	128 (37)	4.8 (2)	96 (2)	1.0 (0.3)	76 (12)	99 (0.4)	0.7 (0.2)	84 (7)	99 (0.5)	0.8 (0.3)	81 (6)	99 (0.5)

* All units of concentration are in (mgL^{-1}) except pH (units), turbidity (NTU), and % removal (%). Numbers given are mean values followed by standard deviation in parenthesis.

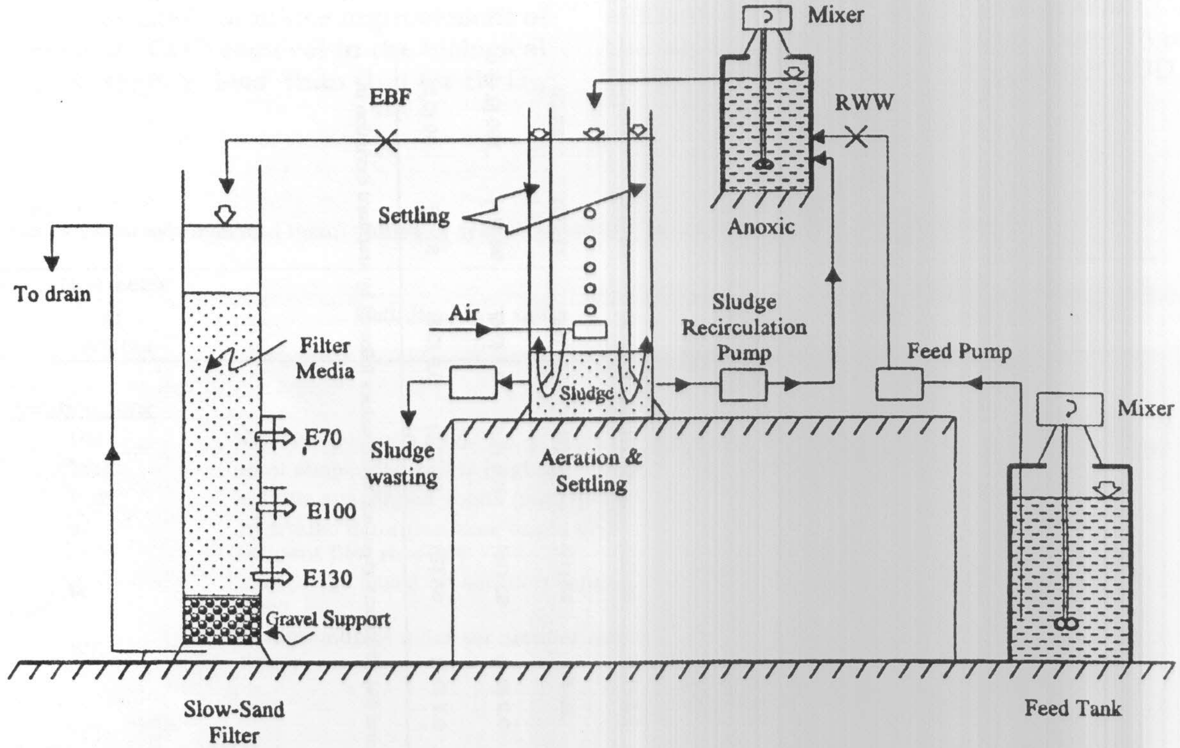

Fig. 1. Experimental set-up showing sampling points.

removal of 88% at 100 cm bed depth. Again, COD removal improvement with increased filter depth was only minimal. fig. 2 shows measured values of COD in the effluents from the biological system and from the coarse media slow sand filter.

Extremely high removals of TSS and Turbidity were obtained in the biological system, as shown in table 2, with average removals of 98% and 96%, respectively. Additional removals were also realized in the filtration step, which produced average effluent TSS and Turbidity of 0.2 mgL^{-1} and 0.7 NTU, respectively, at 100 cm bed depth. Such effluent levels amount to almost 100% removal of these two parameters. Measured values of TSS and turbidity in the effluent from the biological system and the coarse media slow sand filter are compared in fig. 3 and 4, respectively. Filtration cycles using the coarse media filter lasted for 30 days on the average before surface cleaning was required.

3.2. Anoxic-aerobic-fine media filter scheme

Summarized performance of the system using the fine media slow sand filter is presented in table 3. Generally, similar observations on pH and Alkalinity reduction as those seen in the first phase were obtained in the biological system during the second phase. Almost similar Alkalinity concentration was obtained in the final effluent from the filter. No increase in Alkalinity was observed in the filtration step, which eliminates the possibility of denitrification within the filter. This is probably due to presence of high dissolved oxygen level throughout the filter depth.

The raw wastewater had higher levels of BOD_5, COD, TSS, and turbidity during this phase compared to the first phase. This is probably the reason for the differences in performance of the biological system in the two phases, and the overall improved performance in removal of all four parameters in the second phase.

The biological system showed higher average removals of BOD_5 (96%) compared to that in the first phase, producing an average effluent BOD_5 of 7.1 mgL^{-1}. The fine media slow sand filter showed less removals of BOD_5 than the coarse media filter. This is because most of BOD_5 was removed in the biological system and a lower concentration of BOD_5 was introduced to the filter. Similar observations were seen in COD, TSS, and Turbidity removals, and for the same reasons. Fig. 5 illustrates measured values of COD in the effluents from the biological system and the fine media slow sand filter.

The biological system produced final effluent with extremely low levels of TSS and Turbidity, with average removals of 98% for each parameter. Average TSS and Turbidity in the final effluent at 100 cm depth of the fine media slow sand filter were 2.5 mgL^{-1} and 0.9 NTU, respectively. This gives an overall removal of approximately 100% for each parameter. Measured values of TSS and Turbidity in the effluents from the biological system and the fine media slow sand filter are compared in figs. 6 and 7, respectively. Filtration cycle with the fine media filter was approximately 18 days.

The simple two stage anoxic-aerobic process applied in this investigation resulted in a high quality effluent of significantly low concentrations of BOD_5, COD, TSS, and Turbidity. Important features of this experimental system which contributed to better effluent quality include the provision in the settling zone of passing the aerated mixed liquor upward through the sludge zone. This has resulted in additional screening of effluent by removing suspended particles through contact with settled sludge. Another important feature is the use of a low surface overflow rate in settling, as shown in table 1, which reduced the possibility of extreme disturbance and resuspension of settled sludge. In this investigation, the slow sand filter was subjected to low levels of organic and suspended solids that, although resulted in excellent overall effluent quality, did not show significant removals within the filter.

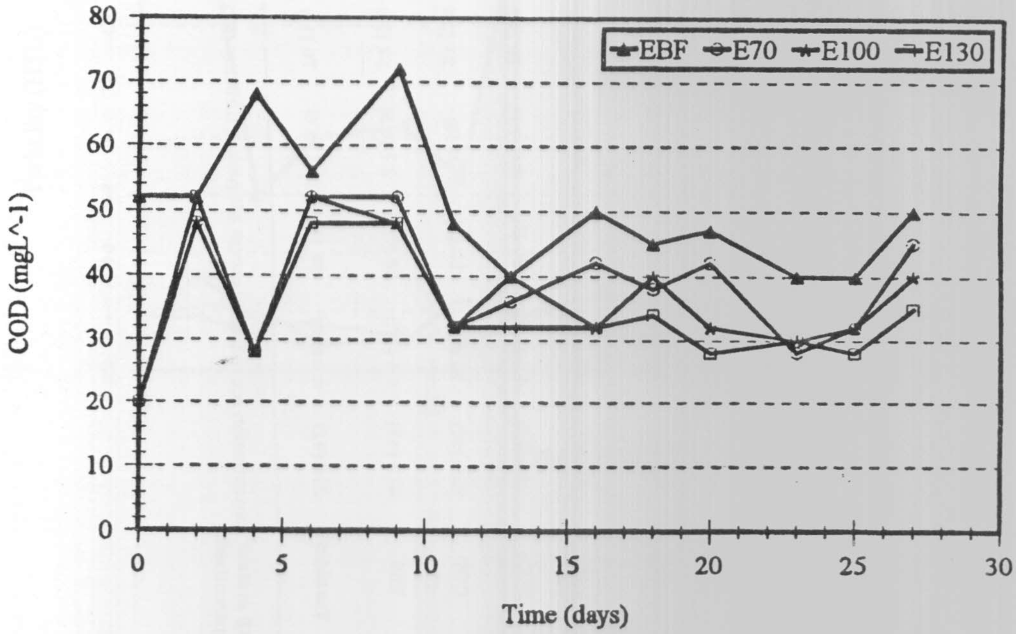

Fig. 2. COD removal in the coarse media slow sand filter.

Table 3
Summarized performance of the anoxic – aerobic – fine media filter system*

Parameter	RWW	EBF		E70			E100			E130		
		Conc.	% removal	Conc.	% removal in filter	% removal overall	Conc.	% removal in filter	% removal overall	Conc.	% removal in filter	% removal overall
pH	7.4 (0.17)	6.8 (0.2)	--	6.8 (0.2)	--	--	6.8 (0.2)	--	--	6.8 (0.1)	--	--
Alkalinity	250 (23)	34 (12)	--	33 (11)	--	--	33 (12)	-	--	34 (11)	--	--
BOD_5	186 (22)	7.1 (3.4)	96 (2)	4.6 (2.6)	38 (21)	97 (2)	3.6 (2.1)	51 (18)	98 (1)	4.4 (2.1)	41 (17)	98 (1)
COD	436 (37)	31 (10)	93 (2)	23 (5)	21 (23)	95 (2)	23 (6)	21 (22)	95 (2)	23 (6)	23 (21)	95 (2)
TSS	271 (47)	6.5 (1.5)	98 (0.7)	2.7 (1.5)	57 (22)	99 (0.7)	2.5 (1.1)	60 (16)	99 (0.6)	2.8 (1.7)	59 (22)	99 (0.6)
Turbidity	210 (42)	4.9 (1.2)	98 (1)	1.1 (0.4)	76 (11)	100 (0.5)	0.9 (0.2)	82 (6)	100 (0.4)	1.0 (0.3)	78 (9)	100 (0.5)

* All units of concentration are in (mgL^{-1}) except pH (units), turbidity (NTU), and % removal (%). Numbers given are mean values followed by standard deviation in parenthesis.

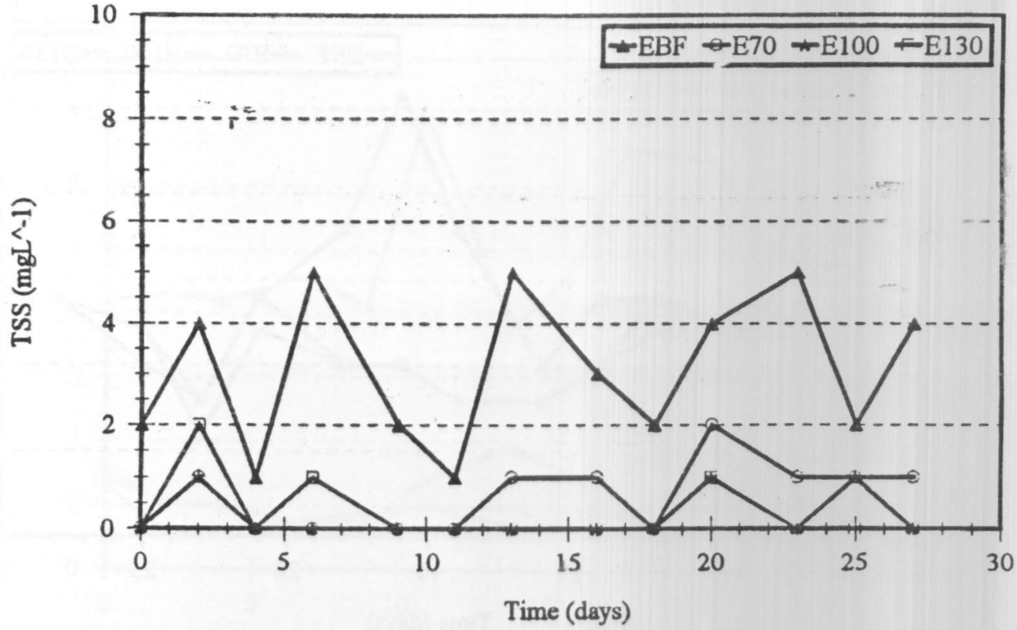

Fig. 3. TSS removal in the coarse media slow sand filter.

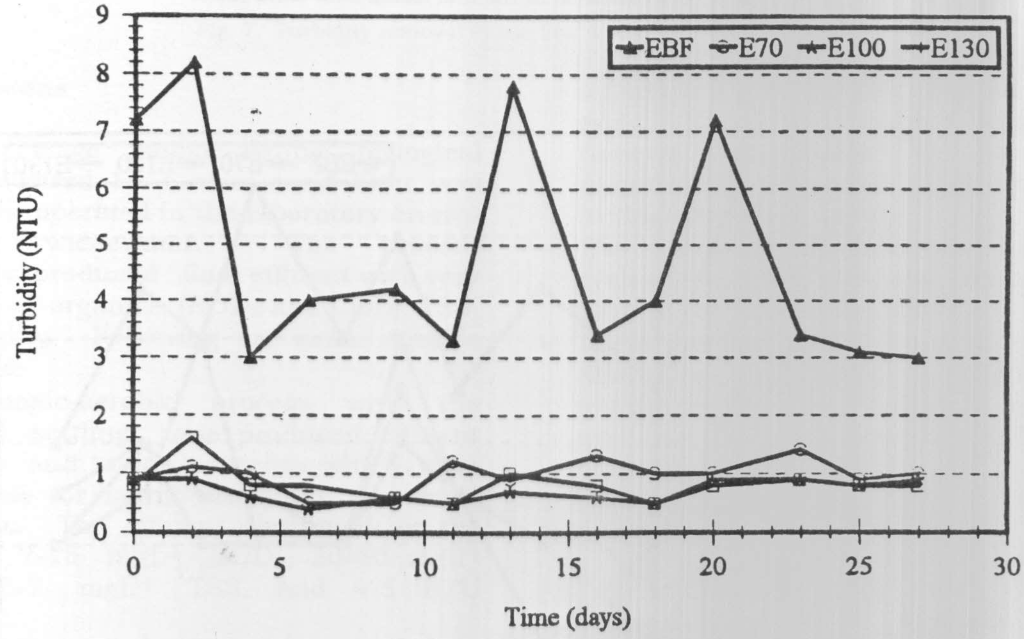

Fig. 4. Turbidity removal in the coarse media slow sand filter.

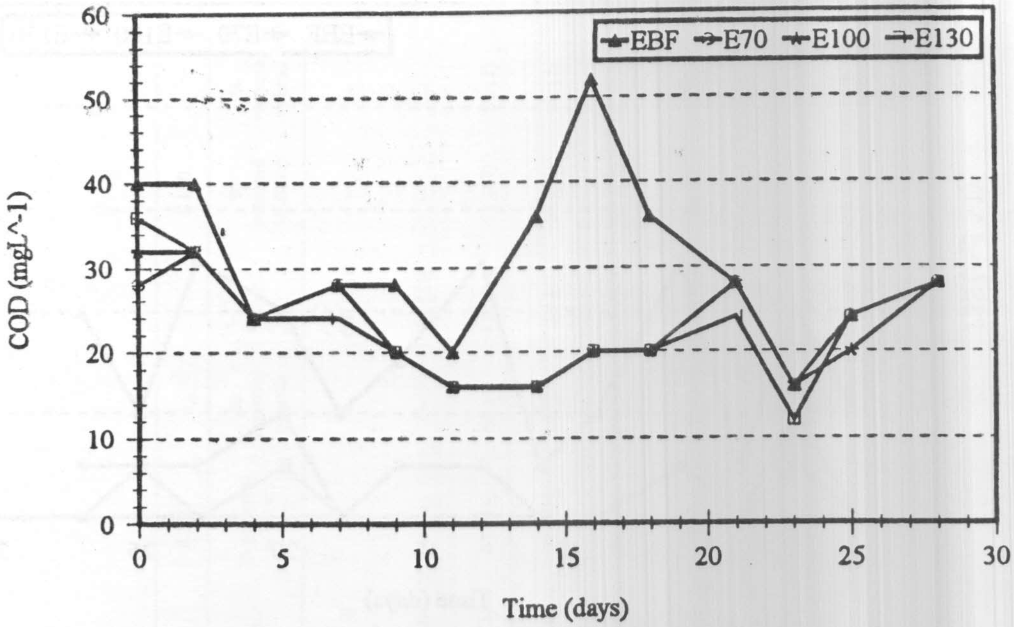

Fig. 5. COD removal in the fine media slow sand filter.

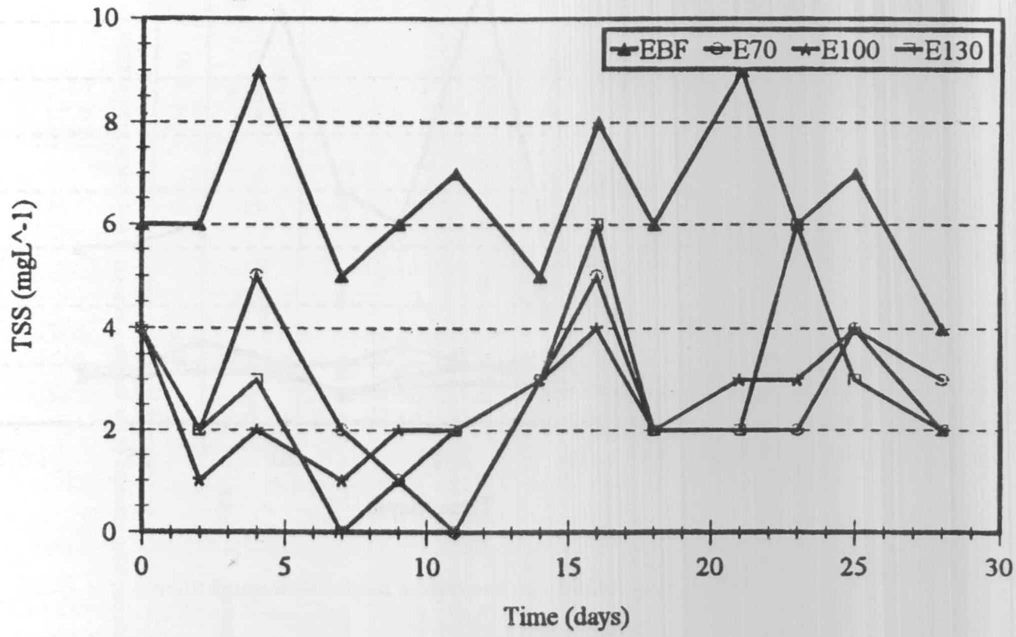

Fig. 6. TSS removal in the fine media slow sand filter.

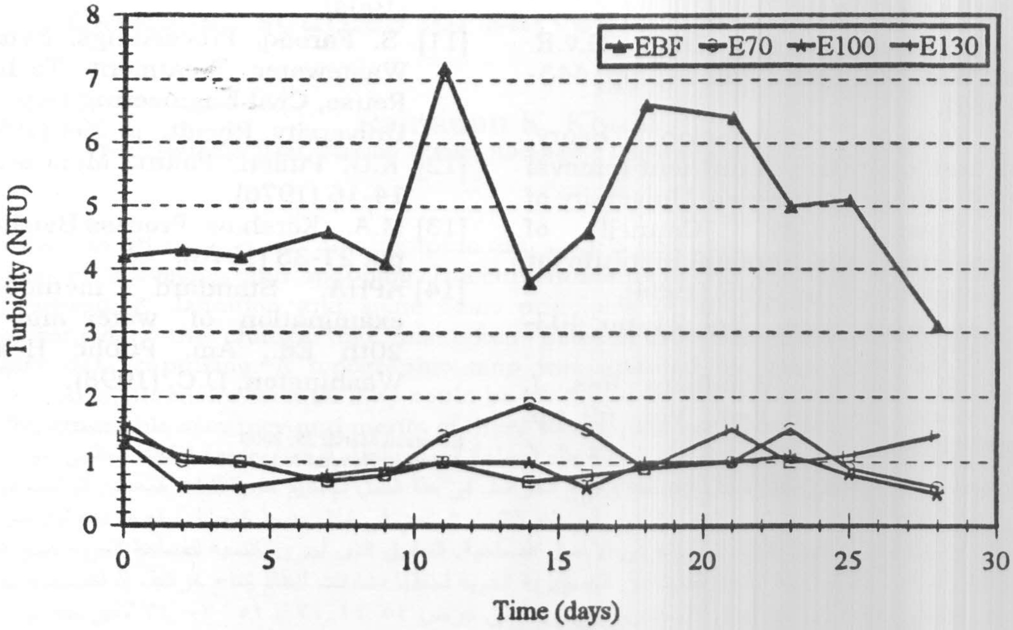

Fig. 7. Turbidity removal in the fine media slow sand filter.

4. Conclusions

A two stage anoxic-aerobic biological process followed by a slow sand filter was successfully operated in the laboratory on raw municipal wastewater. The process consistently produced final effluent with very low levels of organics (BOD_5 and COD), TSS, and turbidity. Following are some specific conclusions:

- The anoxic-aerobic process with the modified settling zone produced effluent organics and solids contents which were acceptable for many discharge and reuse purposes. The effluent contained on the average 7-15 mgL^{-1} BOD_5, 30-50 mgL^{-1} COD, 3-7 mgL^{-1} TSS, and 4-5 NTU turbidity.
- Passing the settled effluent through a slow sand filter further improved effluent quality producing a final effluent having on the average 3-4 mgL^{-1} BOD_5, 23-36 mgL^{-1} COD, 0.2-2.5 mgL^{-1} TSS, and 0.7-0.9 NTU.
- Both filter media sizes, coarse and fine, used in this investigation produced high quality effluent, with minor performance differences. Filter bed depths of 70, 100, and 130 cm gave almost similar overall removal efficiencies for the studied parameters, with very slight improvement in the longer bed depth.
- The coarse media filter gave longer filter cycles averaging 30 days compared to 18 days in the fine media filter.
- There was a substantial decrease in effluent Alkalinity, indicating a high rate of nitrification in the biological system that was not matched by a similar rate of denitrification.

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