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Characterization and treatment of flour mills wastewater for reuse – a case study of Al-kausar Flour Mills, Pakistan

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ABSTRACT

Pakistan is increasingly confronted with shortage of fresh water resources, as annual per capita water availability has reduced to less than 1,000 m^3. Wastewater reclamation and reuse practices must be adopted to deal with the situation. For this purpose, small and medium scale industries can play a vital role. With this mind set, wastewater from Al-Kausar Flour Mills Islamabad (AFM), Pakistan was investigated using physico-chemical treatment options. Total water consumption of AFM is 74.1 m^3/d, and groundwater is being pumped for 8 h/d. Four experimental trains were tested using various combinations of pre-sedimentation, horizontal roughing filter, coagulation/flocculation/settling setup, and multi-media filtration. Ferric chloride and alum were used as coagulants. Results revealed that flour mill wastewater had high concentration of total suspended solids. Ferric chloride provided appreciable suspended solids removal in terms of turbidity. While, every option tested, removed over 98% of turbidity but option C, with 25 mg/L ferric chloride dosage, produced effluent fit for water reuse in the industry. It was also evaluated that AFM could save up to PKR 83,500.0 (US $800) in terms of energy cost and ground water volume of at least 1.6 ML per year.

Keywords: physico-chemical treatment; Horizontal flow roughing filters; Wastewater reuse; Coagulants; Flour mills; Wastewater treatment

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1. Introduction

Water assets in several regions and countries around the globe are expected to face unparalleled demands in coming decades because of ongoing population growth along with wrinkled distributions of water [1]. Water availability in Pakistan has reduced from 1,299 m^3 per capita in 1996 to less than 1,000 m^3 per capita in 2006. A further decrease in per capita availability of water to <700 m^3 has been forecasted till 2025 [2]. In contrast to global practices, there is no regulation of ground water pricing for industries in Pakistan. According to the Organisation of Economic Co-operation and Development, US $0.05 and 0.03/$m^3$ are charged to industries in Germany and Poland, respectively, as groundwater abstraction price [3]. Due to the current scenario of water availability in Pakistan, regulations for the pricing of water from industries need to be formulated and enforced. According to

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Water Sector Strategy (2002) issued by Ministry of Water and Power, Pakistan water consumption by industries was 1.452 billion cubic meter (BCM) per year in 2001 and it was estimated to be 2.268 BCM by the year 2025 [4]. Most of the fresh water resources of Pakistan are contaminated due to discharge of untreated municipal and industrial wastewater into natural streams. Total wastewater generation in Pakistan is 4.43 BCM, including 1.452 BCM originating from industrial sector [4]. Currently, large scale multinational industries are often interested in reusing their wastewater which requires advance, expensive, and sophisticated wastewater treatment technologies. Wastewater reuse technologies for different complex production processes have also been developed in recent years [5]. Small and medium enterprises (SMEs) having simple wastewater characteristics should be given priority for wastewater reclamation and reuse, as these generate major fraction of wastewater. Wastewater reuse opportunities are available in SMEs because industrial activities such as washing, cooling, and rinsing require just clean and pollution free water [6].

Flour mills are one of the small- to medium-scale industries with significant value, as wheat (the only raw material) is the leading food grain of Pakistan. A total of 915 flour mills are registered with The Pakistan Flour Mills Association having milling capacity of 77,275 MT/d [7]. According to Trade Development Authority of Pakistan, export of wheat flour was worth US $222.46 million for FY 2012–2013 and an increase of 4.34% was recorded as compared to FY 2011–2012 [8]. The production process of wheat flour varies depending on desired output. Generally, flour production involves cleaning and storage of wheat, washing and sorting, conditioning, gristing, milling, and packaging [9]. Wastewater primarily originates from washing of wheat containing wheat dust and straw. This study focused on characterization of flour mills wastewater and development of a cost effective physico-chemical treatment system for reuse of flour mills effluent.

2. Materials and methods

2.1. Sampling

Al-kausar Flour Mill (AFM) selected for this study is located in Islamabad Industrial Estate. AFM is ISO 9001:2008 certified facility with production capacity of 360 MT/d. Major products of AFM are wheat flour, special flour, pizza flour, bran, maida, and suji. Washing of wheat, which is the main source of wastewater, is carried out up to 8 h/d. Water is also used for washing of floors and personal consumption. Total water consumption in industry is 74.1 m^3/d. Water demand is being met through direct pumping of groundwater. Untreated wastewater is discharged directly in to Nallah Lai, a seasonal drain in the area.

2.2. Wastewater characteristics

Analysis of wastewater samples were carried out for temperature, pH, conductivity, turbidity, biological oxygen demand (BOD_5), chemical oxygen demand, total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), sulfates, chlorides, total hardness, total alkalinity, and phosphates (P). All analyses was carried out in accordance with methods outlined in the standard methods for examination of water and wastewater [10].

2.3. Experimental setup

Pilot plant system (Fig. 1), designed for evaluation of cost effective option, comprised of constant head tank, sedimentation tank, horizontal flow roughing filter (HFRF) followed by coagulation, and flocculation. Arrangements for inline coagulation were also provided.

2.4. Jar test experiments

Two coagulants i.e. alum [$Al_2(SO_4)_3 \cdot 18H_2O$] and ferric chloride [$FeCl_3 \cdot 6H_2O$] were used for this study. Phipps and Bird (2011) jar test apparatus was used with six beakers of 1 L each to determine optimum coagulant dose. Rapid mixing at 120 rpm for 2 min, slow mixing at 25 rpm for 25 min, and settling for 90 min was used for each jar testing experiment. These operational conditions for jar tests were selected from published literature [11–13]. All samples were withdrawn from a fixed depth of 2 cm. Experimental work was performed in the following order.

2.4.1. Series A experiments

In series A, jar tests were conducted to determine the optimum coagulant dose. Dosage of alum varied from 0 to 800 mg/L and that of $FeCl_3$ from 0 to 400 mg/L. Residual turbidity was measured at each stage as the sole dependent variable.

2.4.2. Series B experiments

Series B experiments were conducted on wastewater that was pre-settled for 3 h. Treatment train in this case was pre-sedimentation (3 h), coagulation,

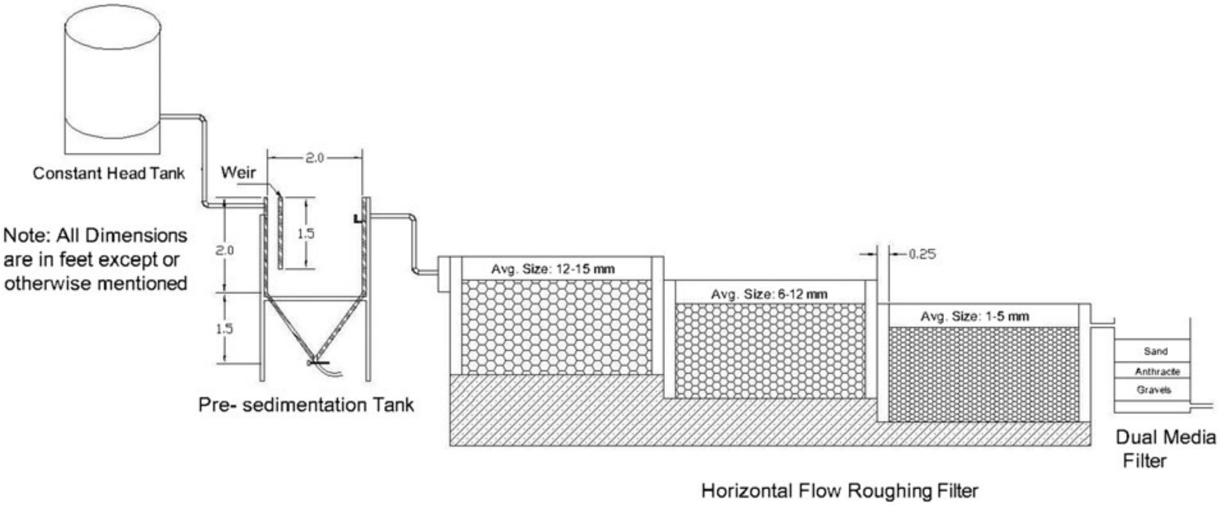

Fig. 1. Experimental setup.

flocculation, and sedimentation. Alum dose varied from 0 to 320 mg/L and ferric chloride varied from 0 to 100 mg/L. Residual turbidity was again measured, at all stages.

2.4.3. Series C experiments

Treatment train in series C experiments involved pre-sedimentation (3 h), HFRF, coagulation, flocculation, and sedimentation. HFRF, for this study, consisted of three identical compartments of 4´ × 1´ × 2.5´ size with filtration rate of 0.5 m/h. Multi-graded gravels of 12–15, 6–12, and 1–5 mm were used in first, second, and third compartment, respectively. Jar tests were performed on HFRF effluent samples drawn every three hours of operation to evaluate the effectiveness of this scheme.

2.4.4. Series D experiments

Series D experiments comprised of inline coagulation prior to sedimentation tank. Twenty five and ten percentage of the optimal dose, obtained in series A experiments were introduced one-by-one, at the outlet of the constant head tank. Treatment train involved inline coagulation, pre-sedimentation, and HFRF. Turbidity was measured at the outlet of HFRF.

Series A–D experiments were performed with the objective of determining the most effective and economical train in terms of coagulant type and dose, and treated water turbidity. To check the suitability of wastewater for reuse in industry, the final, series E experiments were conducted.

2.4.5. Series E

These experiments comprised of an additional component i.e. multimedia filter. Thus, the treatment train consisted of pre-sedimentation (3 h), HFRF, coagulation, flocculation, and multimedia filtration. To check the suitability of AFM effluent for industrial reuse, TSS, turbidity, and BOD$_5$ were measured at the outlet of multimedia filter after every 3 h for 24 h. Volume of multimedia filter was 4 ft^3 i.e. 1.6´ × 1.6´ × 1.5´ with hydraulic loading rate of 1.0 gallons per min per ft^2. Bed depth in the multimedia filter comprised of 150 mm sand (size 0.5–0.8 mm), 100 mm anthracite (size 1–1.5 mm), and 150 mm gravels (size 2–20 mm) to support sand and anthracite.

3. Results and discussion

3.1. Characterization of wastewater

Wastewater characteristics of AFM are given in Table 1, which indicates that BOD$_5$ is continuously within National Environmental Quality Standards [14]. Mean concentration of TSS and turbidity in raw water were 2,388 mg/L and 2,555.7 NTU, respectively. Further examination of experimental data were revealed to obtain useful relationship between major parameters as shown in Table 2. It can be seen in Table 2 that sufficient portion of TBOD$_5$ and TCOD was in the particulate form with mean values of 46 and 48%, respectively. The mean value of TCOD/TBOD$_5$ was 3.17 (serial No. 2), which appeared to indicate that a large portion of organic matter in AFM wastewater was non-biodegradable or very slowly

Table 1
Physical and chemical analysis of wastewater collected from AFM

Parameter[a]	N[b]	Min	Max	Mean ± SD	Pakistan NEQs for municipal and industrial effluents
Temperature (°C)	12	22.6	26	24.55 ± 1.16	40°C
pH	12	6.8	7.5	7.2 ± 0.17	6.0–9.0
Turbidity (NTU)	12	2,400	2,900	2,555.7 ± 108.2	Not given
Total five day biological oxygen demand ($TBOD_5$)	12	62.4	77.3	67.5 ± 1.3	80
Soluble BOD ($SBOD_5$)	12	27.5	45.3	36 ± 3.2	–
Total chemical oxygen demand (TCOD)	12	167.5	255.8	214.5 ± 36.7	150
Soluble chemical oxygen demand (SCOD)	12	90.2	137.4	110 ± 17.8	–
Total solids (TS)	12	3,680	4,460	3,975 ± 160.6	Not given
Total dissolved solids (TDS)	12	1,470	1,760	1,587 ± 83.87	3,500
Total Suspended solids (TSS)	12	2,210	2,700	2,388 ± 114.68	150
Total settleable solids (SS)	12	1,791	2,123	1,958.15 ± 144.5	–
Volatile suspended solids (VSS)	12	315.5	478.3	416.3 ± 56.4	–
Sulfates	12	30.78	48.6	32.87 ± 3.7	600
Chlorides	12	55	65	62 ± 2.7	1,000
Total Hardness (as $CaCO_3$)	12	298.5	321.7	305.8 ± 2.6	Not given
Total Alkalinity (as $CaCO_3$)	12	45	80	60.3 ± 4.8	Not given
Phosphates	12	0.07	1.375	0.534 ± 0.2	Not given

[a] All parameters except pH in mg/L if not specified.

[b] Number of samples.

Table 2
Relationships between major pollutant parameters

S. no.	Parameter/Relationship	Mean
1	Particulate BOD_5 (%$TBOD_5$)	46
2	$TCOD/TBOD_5$	3.17
3	TCOD/TSS	0.09
4	TDS/TS	0.4
5	SS/TSS	0.82
6	VSS/TSS	0.13

biodegradable [15]. Out of TS, on average, 40% were in the dissolved form (serial No. 4). Similarly, in case of TSS, 82% were settleable (serial No. 5) and 13% of TSS was volatile in nature (serial No. 6), on the basis of mean values. For industrial reuse, TSS and turbidity should be less than 30 mg/L and 2–5 NTU, respectively [16].

3.2. *Results of series A–D experiments*

Figs. 2 and 3 illustrate results of series A experiments. It is clear that maximum turbidity removal was achieved at 650 mg/L of alum with residual turbidity of 25 NTU, and 250 mg/L of $FeCl_3$ with residual turbidity of 18 NTU. Ferric chloride demonstrated superior performance for initial turbidity removals. Minimum residual turbidity was still greater than 5 NTU required for reuse [16]. It was interesting to note that residual turbidity in the control jar reduced to less than 400 NTU just by mere mixing of high clayey suspension of wastewater.

Jar tests were conducted again on water samples drawn after the sedimentation of 3 h. Introduction of a sedimentation tank prior to coagulation resulted in far better quality. Figs. 4 and 5 represent the performance of alum and ferric chloride, respectively. Residual turbidity of 9.1 and 6.8 NTU was obtained for alum and ferric chloride, respectively.

Average turbidity after pre-sedimentation for 3 h was 519 NTU. To further reduce the waste water turbidity, HFRF was employed in series. Jar tests were carried out on HFRF effluent after every 3 h of operation as shown in Fig. 6, which indicated that optimum doses for alum and ferric chloride were 60 and 25 mg/L, respectively, i.e. over 90% reduction in coagulant for untreated wastewater. The performance of HFRF improved with the passage of time as shown by solid line in Fig. 6. The average turbidity at the outlet of HFRF reduced from 215 to 60 NTU and became almost constant after 20 h of HFRF operation i.e. filter ripening period. Similarly, the dosage of alum and ferric chloride dropped from 120 to 60 and 75 to 25 mg/L, respectively. Minimum residual turbidity of 6.1 and 5.2 NTU was attained by these experiments.

Next set of experiments were performed to evaluate the performance of both coagulants in the inline

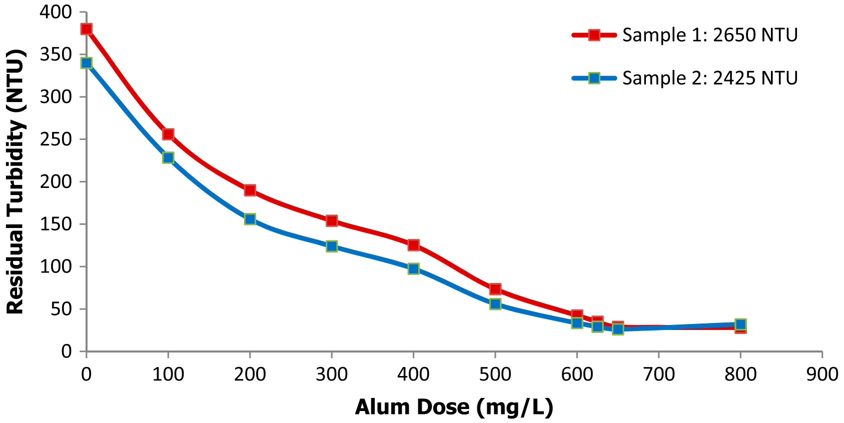

Fig. 2. Residual turbidity at different alum doses.

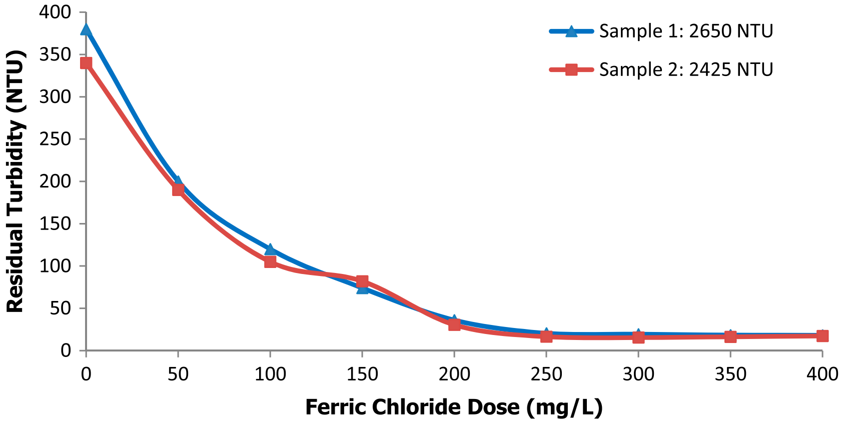

Fig. 3. Residual turbidity at different ferric chloride doses.

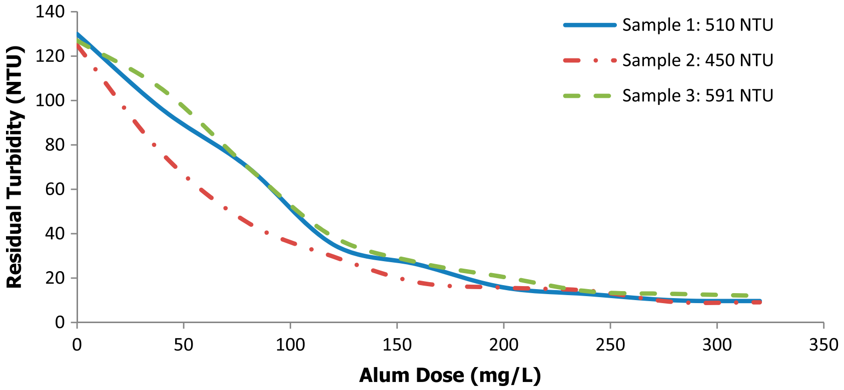

Fig. 4. Alum dose vs. residual turbidity after pre-sedimentation.

mode. The hypothesis was that in the presence of pre-sedimentation tank and HFRF, a fraction of the optimum dose determined on untreated wastewater (series A experiments) should do the trick.

The pilot plant was operated with 25 and 10% of the optimum coagulant dose as determined in series A experiments. For 25% of optimum dose, alum and ferric chloride doses of 162.5 and 62.5 mg/L were

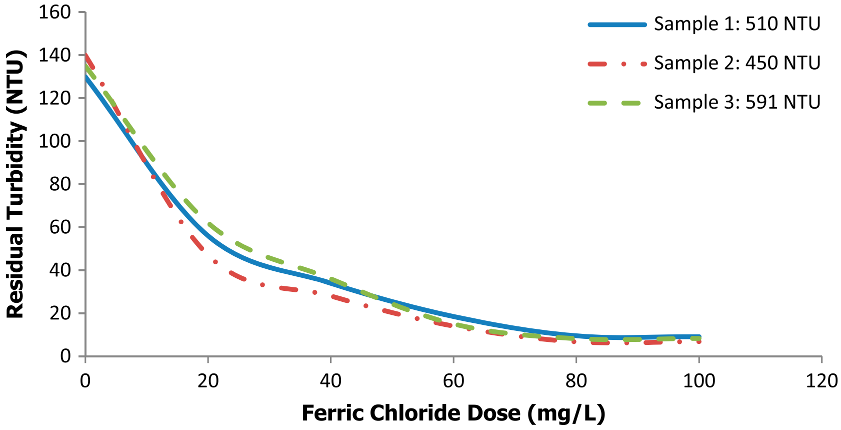

Fig. 5. Ferric chloride vs. residual turbidity after pre-sedimentation.

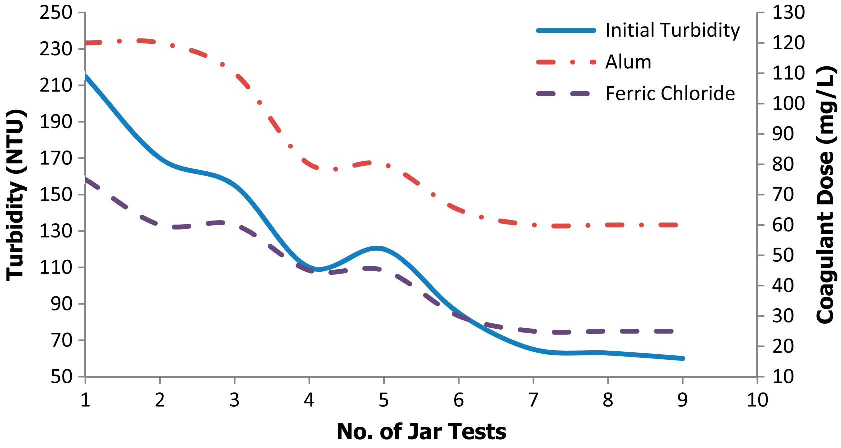

Fig. 6. Coagulant dose and turbidity reduction after sedimentation and HFRF.

used, respectively, for test duration of 24 h each. Turbidity of wastewater after HFRF was determined after every 3 h. Average raw water turbidity before pre-sedimentation was 2,432 NTU. The results for effluent turbidity are illustrated in Fig. 7. The residual turbidity after HFRF varied from 39 to 10.1 NTU for alum and 28.6 to 8.0 NTU for $FeCl_3$ as shown in Fig. 7. Increase in turbidity removal was observed with the passage of time and it became almost constant after 20 h with ferric chloride injected inline coagulation mode.

Next, the pilot plant was operated with 10% of optimum alum and ferric chloride doses i.e. 65 and 25 mg/L for 24 h. Turbidity of effluent was determined after every 3 h. The results are shown in Fig. 8, which reveals that effluent turbidity dropped and varies from 85 to 30 NTU for alum and 39 to 9.2 NTU for ferric chloride.

From series D experiments, it can be concluded that ferric chloride was more efficient coagulant as compared to alum at 25% as well as 10% of optimum doses.

3.3. Comparison of options (A–D)

Chemical and economical viability of any treatment scheme especially for a reuse focus is extremely important. Chemical requirement along with influent and effluent turbidity for various options is give in Table 3. It can be concluded that option C with ferric chloride as coagulant is the best option as it requires less dosage for effective treatment of AFM effluent. Option D with 10–25% of the opted coagulant dose required less plant area but effluent turbidity is higher than 5 NTU.

Based on the doses of alum and ferric chloride found in this study, annual cost of chemicals for treatment of 1 m^3 of flour mills wastewater was evaluated. The cost (including shipping and handling) of alum and ferric chloride was US $0.43 and US $0.5 per kg, respectively. A cost comparison for all treatment options is shown in Fig. 9. It can be observed from Fig. 9 that option C is the most cost effective option with annual

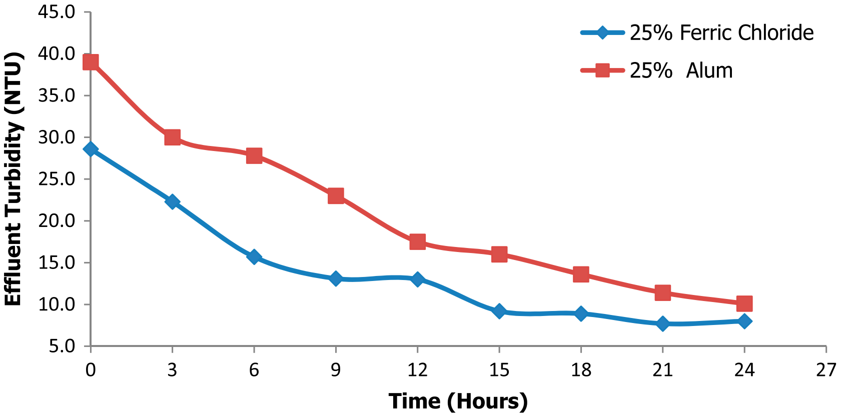

Fig. 7. Residual turbidity after inline coagulation with 25% dose and HFRF.

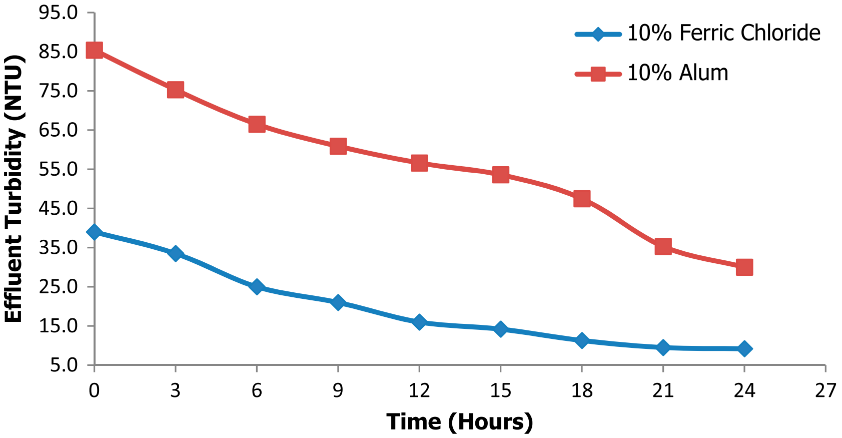

Fig. 8. Effluent turbidity for 10% of optimum ferric chloride and alum doses.

Table 3
Comparison of coagulant(s) doses, influent turbidity, and effluent turbidity for different options

Option(s)	*A*[a]	*B*[b]	*C*[c]	*D*[d]	
				25% of dose	10% of dose
Alum					
Optimum dose (mg/L)	650	250	60	162.5	65
Mean influent turbidity (NTU)	2,650	591	60–215	2,432	2,410
Minimum effluent turbidity (NTU)	25	9.1	6.1	10.1	30
Ferric chloride					
Optimum dose (mg/L)	250	80	25	62.5	25
Mean influent turbidity (NTU)	2,650	591	60–215	2,432	2,410
Minimum effluent turbidity (NTU)	18	6.8	5.2	8.0	9.2

[a] Coagulation + flocculation + sedimentation.

[b] Sedimentation + coagulation + flocculation + sedimentation.

[c] Sedimentation + HFRF + flocculation + sedimentation.

[d] Inline coagulation + sedimentation + HFRF.

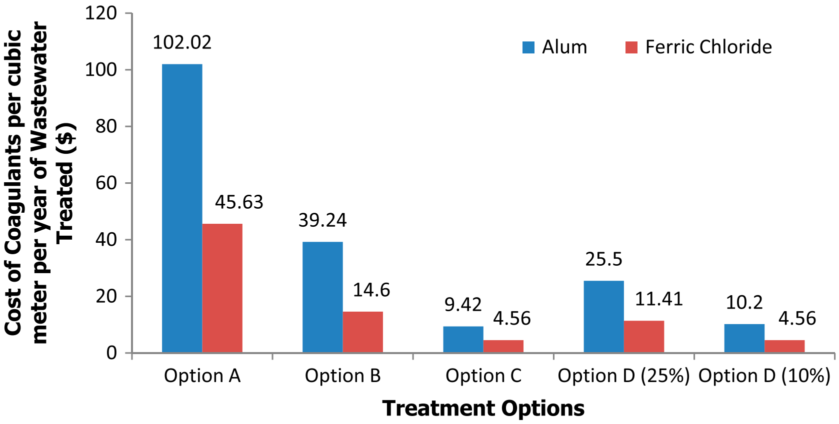

Fig. 9. Annual cost of coagulants to treat 1 m^3 of AFM wastewater for different options.

coagulant cost of US $9.42 and US $4.56/$m^3$ for alum and ferric chloride, respectively.

The cost of alum and ferric chloride in option C was almost 5–10 times less than option A and option B. For option D (25% of alum optimum dose or 10% of ferric chloride optimum dose), annual cost of alum and ferric chloride was US $25.50 and US $4.56/$m^3$, respectively. Both options, C and D (25% of alum optimum dose or 10% of ferric chloride optimum dose), were comparable in terms of cost effectiveness.

3.4. Series E experiments

Series C and D experiments were repeated with the addition of a multimedia filter at the end. Samples for turbidity, TSS, and BOD_5 were collected every three hours until 24 h. The results (Table 4) show that the treated AFM effluent met USEPA reuse standards for industrial applications. For Option C, average residual turbidity, TSS, and BOD_5 were observed to be 1.3 NTU, 2.4, and 8.7 mg/L with alum coagulant and 0.8 NTU, 1.5, and 5.7 mg/L with ferric chloride coagulant. For option D, average residual turbidity, TSS, and BOD_5 were observed to be 1.7 NTU, 2.9, and 8.5 mg/L with alum (25% of optimum dosage) as inline coagulant and 1.1 NTU, 1.8, and 11.34 mg/L with ferric chloride (10% of optimum dosage) as inline coagulant. It can also be evaluated from Table 4 that the quality of effluent with ferric chloride coagulant was better than alum coagulant. Final quality of treated effluent met the guidelines for industrial reuse as well as urban reuse (restricted and unrestricted), agricultural reuse (restricted and unrestricted), impoundment (restricted and unrestricted), groundwater replenishment, and environmental reuse guidelines [16].

3.5. Energy and water saving for AFM

Based on results and comparisons presented in this study, option C and option D were comparable and effluent quality was meeting guidelines for different water reuse categories. Option C was recommended,

Table 4
Turbidity, TSS, and BOD_5 at the outlet of rapid sand filter for selected options using both alum and ferric chloride

Parameters	N^a	Option C	Option D		USEPA reuse standards [16] Industrial reuse
			25%	10%	
Alum					
Average turbidity (NTU)	8	1.3 ± 0.3	1.7 ± 0.7	NA	2–5 NTU
Average TSS (mg/L)	8	2.4 ± 0.45	2.9 ± 1.2		>30 mg/L
BOD_5 (mg/L)	8	8.7 ± 1.45	8.5 ± 1.13		>30 mg/L
Ferric chloride					
Average turbidity (NTU)	8	0.8 ± 0.08	NA	1.1 ± 0.8	2–5 NTU
Average TSS (mg/L)	8	1.5 ± 0.35		1.8 ± 1.5	>30 mg/L
BOD_5 (mg/L)	8	5.7 ± 1.65		11.34 ± 1.9	>30 mg/L

[a] Number of samples.

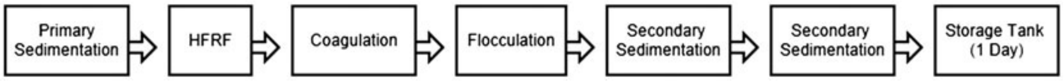

Fig. 10. Recommended schematics of proposed WWT&R plant for AFM effluent.

Table 5
Total water and energy savings from proposed wastewater reclamation option for AFM

Description	Current practices	Wastewater reclamation option	Savings
	(a)	(b)	(a–b)
Water consumption (m^3/d)	74.1	74.1	NA
Electricity charges (US $/year)	1,887.22	1,092.33[a]	749.89
Water abstraction charges (US $/year)	540.93	270.46[b]	270.47
Chemical cost (US $/year)	NA	266.76	−266.76
Total savings (US $/year)			798.59

[a] Include energy costs of chemical mixing in coagulation (24/7 basis) and GW pumping (4 h/d).

[b] Half of the current water consumption (74.1 m^3/d) i.e. 37.05 m^3/d will be pumped daily.

as option D would produce large quantity of sludge. This recommendation is supported by the fact that ferric chloride demonstrated better turbidity removal. Recommended schematic of wastewater treatment plant for AFM effluent is shown in Fig. 10.

Proposed wastewater treatment and reuse plant (WWT&R) would operate through gravity. Energy will be required in coagulation basin to mix ferric chloride coagulant. Power required to completely mix the coagulant dose is calculated using velocity gradient formula (Eq. (1)) [17].

$$P = G^2 \mu V \tag{1}$$

where G = velocity gradient (s^{-1}); μ = absolute viscosity of water (lb/s/ft^2); P = power imparted per unit volume of coagulation basin (lb/s/ft^2); V = volume of coagulation basin.

Velocity gradient of 700 s^{-1}, detention time of 60 s, and absolute viscosity of 2.73×10^{-5} lb/s/ft^2 were used for the calculation of power of motor. 0.036 HP motor will be required to completely mix the coagulant but 0.25 HP motor will be used, as motors less than 0.25 HP is not available in market. Cost of ferric chloride was already calculated as given in Fig. 9.

Due to the current scenario of water availability in Pakistan, regulations for the pricing of water for industries will have to be formed and enforced. For the purpose of comparison, US $0.02/$m^3$ is set as water abstraction price. AFM is using ground water, and daily water consumption is 74.1 m^3/d at pumping cost only. According to National Electricity Power Regulation Authority, electricity tariff for industries is Rs. 23/KW h [18]. Total water and energy savings after adopting the recommended wastewater reuse practices are given in Table 5 in comparison to the current practices which show that annual savings from energy charges and water abstraction will be US $749.89 and US $270.47 annually. If chemical cost of WWTP is met from the savings, the total savings by adopting wastewater treatment option will be US $798.59 per year i.e. PKR 83,500.

4. Conclusions

Following conclusions can be drawn from this study:

(1) AFM effluent can be used for various water reuse categories including industrial reuse as well as urban reuse (restricted and unrestricted), agricultural reuse (restricted and unrestricted), impoundment (restricted and unrestricted), groundwater replenishment, and environmental reuse. Apart from industrial reuse, groundwater replenishment is also recommended due to current situation of groundwater table at Islamabad, Pakistan.

(2) Ferric chloride was found to be more efficient coagulant to alum, and appreciable turbidity removal was achieved even at low dosage.

(3) Option C i.e. pre-sedimentation, HFRF, coagulation/flocculation, and dual media filtration provided the effluent quality better than plane groundwater being used for wheat washing.

(4) In case of space restrictions, option D involving inline coagulation with small coagulant dose, pre-sedimentation, HRFR, and dual media filtration can be adopted for slightly lower yet reusable quality of water.
(5) By employing wastewater reclamation practices, AFM could save up to US $800.0 (PKR 83,500.0) in energy bills and 1.6 ML of groundwater per year.

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