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Removal of chemical oxygen demand from textile wastewater using a natural coagulant

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Abstract−A biomaterial was successfully synthesized from *Plantago ovata* by using an $FeCl_3$-induced crude extract (FCE). The potential of FCE to act as a natural coagulant was tested for the pretreatment of real textile wastewater. Tests were performed to evaluate the effects of FCE quantity, salt concentration, and wastewater pH on chemical oxygen demand (COD) reduction during a coagulation/flocculation process. Experimental results indicated that the wastewater could be effectively treated by using a coagulation/flocculation process, where the BOD_5/COD ratio of the effluent was improved to 0.48. A low coagulant dose, 1.5 mg/L, achieved a high COD removal percentage, 89%, at operational conditions of neutral pH and room temperature. The experimental data revealed that the maximum COD removal occurred at water pH<8. Increasing the salt promoted the COD removal. The settling and filterability characteristics of the sludge were also studied. Scanning electron microscopy and energy dispersive spectroscopy studies were conducted to determine the sludge structure and composition, respectively. Overall, FCE as an eco-friendly biomaterial was revealed to be a very efficient coagulant and a promising option for the removal of COD from wastewaters.

Keywords: Biomaterial, Coagulation, *Plantago ovata*, Pretreatment, Textile Wastewater

INTRODUCTION

The textile industry is one of the biggest users of water and complex chemicals such as azo dyes during textile processing at various processing stages. The unused materials from the textile processes are discharged as wastewater that is high in color, biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, temperature, turbidity, and toxic chemicals. The effluent from textile industries contains different types of dyes, and because of their high molecular weight and complex structures, they are resistant to photodegradation, biodegradation, and oxidizing agents [1]. The direct discharge of this wastewater into the water bodies affects the flora and fauna. The treatment methods of textile wastewater include activated carbon adsorption, oxidation, chemical coagulation/flocculation, electrochemical methods, and membrane techniques [2,3]. Among these available techniques, the process involving activated carbon is the most commonly used adsorption process. The major problem with activated carbon is that while bench tests may show excellent treatment performance, full-scale operation is fraught with severe problems, such as clogging and biofouling [2,4]. Dye house discharges are varied and insoluble dyes such as disperse, sulfur, and pigment dyes cannot be removed by carbon adsorption. Therefore, activated carbon is best preceded by a filter and used in conjunction with a coagulation step. The coagulation and flocculation process is a versatile method used either alone or combined with biological treatment to remove suspended solids, organic matters, and dyes from textile industry wastewater [5].

Many flocculants and coagulants are widely used in conventional wastewater treatment processes. These materials can be classified into inorganic coagulants (e.g., aluminum and ferric salts) and synthetic organic polymers (e.g., polyacryl amide derivatives and polyethylene imine). All of them are very efficient for the textile wastewater treatment [6]. The cost of achieving the desired level of wastewater quality mainly depends on the cost and the availability of coagulation agents. Aluminum salts are most widely used together with synthetic organic polymers in wastewater treatment. These coagulants are often expensive, and in many developing countries they have to be imported.

Moreover, inorganic coagulants are highly sensitive to wastewater pH, produce more sludge, and are possibly toxic for organisms. These are the main challenges of chemical flocculation/coagulation processes [7]. Furthermore, many researchers have related Alzheimer's disease to residual aluminum ions in water [8,9]. Moreover, as reported by Anastasakis et al. [10], the sludge formed at wastewater treatment plants during flocculation/coagulation with synthetic polymers has a limited potential for recycling because of the non-biodegradability of synthetic polymers. To make the flocculation/coagulation process attractive, novel low-cost coagulants with higher coagulation capability are required. This has led to an increasing research interest in the production of natural coagulants from renewable and cheaper precursors. Natural coagulants, mainly polysaccharides, are generally nontoxic and biodegradable [11], which is essential from a sustainability point of view.

Recently, the use of various types of chemical and natural coagulants for the treatment of textile wastewater has been reviewed by Verma et al. [6]. They addressed textile decolorization by natural coagulants and found that further study and a significant amount of work was still necessary before making any definitive conclusions regarding the capability of these coagulants for the removal of wastewater dyes. Furthermore, as mentioned by Verma et al. [6], the major

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disadvantage of natural coagulants is the production of sludge and relatively low treatment efficiency. Therefore, the production and extraction of the biomaterials, as a coagulant, is expensive, making it impractical for full-scale applications. For more attractive applications of natural coagulants, research to find a potential and cheap precursor is necessary.

In this study, we attempt to use *Plantago ovata* as a low-cost, abundantly available, and renewable precursor for the production of coagulant for the removal of wastewater dye. We considered this plant (*P. ovata*) because it grows fast and is easily found in Iran. *P. ovata* is a small, annual plant with or without a very short stem covered with soft fiber, from the Plantaginaceae family, and its height ranges from 7 to 30 cm [12]. *P. ovata* seeds contain mucilage, protein, fixed oil, cellulose, and starch [13]. Interestingly, as it is clear from the existing literature [14-16], the efficiency of water or wastewater treatment by a natural coagulant is significantly influenced by the characteristics and the origin of the coagulant. Therefore, the method of extraction is aimed at improving the material's coagulation capability, thereby reducing the rate of coagulant consumption to reduce the cost of wastewater treatment and making it more cost-effective.

Several chemicals have been used in coagulant extraction, and the best extraction has been obtained in the presence of KCl or $NaNO_3$ [14,15], and NaCl [16]. However, the main challenge posed to these methods of coagulant extraction is their relatively low efficiency for treatment purposes and the formation of organic matter during the treatment process. The salts, which have a one-valance metal (Na^+ and K^+), are deposited in the internal structure and the pore of the coagulant, and may be useful for the coagulation/flocculation process. In this research, we used an innovative method. We used $FeCl_3$ during the purification of an extracted coagulant with the assumption that the Fe^{3+} ions are trapped in the structure of the biomaterial extracted from *P. ovata* and according to the Hardy-Schulze rule [16], this may improve the coagulation potential of the coagulant rather than K^+ and Na^+.

Therefore, the aim of this work is to evaluate the $FeCl_3$-induced crude extract (FCE) provided from *P. ovata* seed, as a novel coagulant, for the COD removal of dye from textile wastewater. The effect of different parameters, such as wastewater pH, FCE concentration, and salt concentration on the COD removal is studied. Moreover, the settling characteristics of the precipitated sludge and the filterability of the effluent after the treatment are investigated.

MATERIALS AND METHODS

1. Materials

Dry seeds of *P. ovata* were purchased from a local herb market and stored at room temperature. Ammonium acetate, hydrochloric acid, sodium hydroxide, ferric chloride, calcium chloride, and sodium chloride were supplied by Aldrich Co. and were of analytical grade. Ethanol (98%) and *CM-Sepharose* were purchased from Merck Co.

2. Extraction and Purification Processes of Coagulant from *P. ovata*

Extraction of the crude coagulant from *P. ovata* seed was carried out as follows:

- First, seeds were soaked in water for 1 day.
- The obtained gelatinous material was filtered and dried at 70 °C in an oven and then milled in a domestic blender (VARING).
- The powder was defatted by mixing with ethanol 98% using a magnetic stirrer for 60 min. Then, the supernatant was separated by centrifugation (3,500 rpm, 40 min), and the settled powder was dried in an oven (at 60 °C) overnight.
- The crude coagulant was extracted from the oil-free powder using ammonium acetate 10 mM in 5% w/w. The mixture was stirred for 50 min using a magnetic stirrer and the supernatant, namely the crude extract, was separated by centrifugation (3,500 rpm, 40 min).

Purification of the coagulant protein from the crude extract was performed as follows:

- *CM-Sepharose* ion exchange was equilibrated using a 10-mM ammonium acetate solution.
- Equilibrated *CM-Sepharose* ion exchange was added to the crude extract in 10% (v/v) proportion and mixed with a blade stirrer for 50 min.
- Finally, the absorbed coagulant protein was eluted by using different concentrations of the $FeCl_3$ solution.

The purification procedure was carried out directly first with 0.25-M $FeCl_3$ and then with 0.5-M $FeCl_3$ elution according to the basis of the ion-exchange processes [17,18]. In the first elution, proteins that presumably did not lead to a higher coagulation performance were removed as they just added dissolved organic matter in the treated wastewater. Consequently, the second elution produced a more purified coagulant as it contained only the active coagulant proteins. The elution stages were repeated three times in order to recover as much coagulant as possible.

3. Source and Characteristics of Wastewater

A bulk of wastewater samples was obtained from a textile finishing industry located in the Yazd province, Iran, where reactive dyes are used for coloring cotton fabric. The samples were delivered to the laboratory within 2 h of being taken and tested within 1 day. The samples were kept at 4 °C without adding any chemicals.

The characteristics of wastewater that was collected from a textile plant and analyzed are presented in Table 1. The wastewater, consisting of both organic and inorganic substances, was slightly alkaline. Further, the BOD_5/COD ratio was 0.19, indicating the insufficiency of the biological process for the treatment of such wastewater.

Table 1. The characterizations of textile raw wastewater

Characteristic	Unit	Average value
COD	mg/L	642
Filtered COD	mg/L	176
BOD_5	mg/L	124
TSS	mg/L	128
Total phosphorous	mg/L	19
TKN	mg/L	17.8
NH_3-N	mg/L	2.7
Hardness	mg/L $CaCO_3$	195
Conductivity	μS/cm	1328
Chloride	mg/L	418
Color	Pt-Co	992
Cr^{+6}	mg/L	2.9
pH	-	6.9
Turbidity	NTU	113

4. Coagulation and Flocculation Procedure

Coagulation tests were carried out in a standard jar test apparatus (Phipps and Bird, Model 300). The jar test is the most widely applied method for evaluating and optimizing the coagulation/flocculation process. The textile wastewater (300 mL) was filled into the beakers (1 L), and the standard procedure for the jar test was performed at a constant room temperature of 24 °C. The standard procedure involved 1 min of rapid mixing (120 rpm) followed by 30 min of slow mixing (45 rpm) for flocculation. Then, the treated wastewater was allowed to settle for 1 h, and the supernatant sample was withdrawn for the analysis by using a syringe from approximately 2 cm below the liquid level. The supernatant obtained after 1 h of settling was subjected to a COD analysis. The initial pH of the wastewater was adjusted to the desired value by using 1-M NaOH or 1-M HCl and further correction of pH was not carried out during the experiments. The same coagulation test was conducted with no coagulant as a blank. The impact of wastewater pH, coagulant quantity, and salt concentration as variable parameters was evaluated in this research. All the experiments were conducted in duplicate to ensure the reproducibility of the results; the mean of these two measurements are presented herein. The COD removal efficiency (CRE) was calculated using Eq. (1)

$$\mathrm{CRE}(\%) = \frac{D_0 - D}{D_0} \times 100 \tag{1}$$

where D_0 and D represent the initial and final COD (mg/L) of wastewater, respectively.

5. Sludge Volume Index, Settling, and Filterability

The most common parameter, sludge volume index (SVI), was used for quantifying the settling characteristics of the coagulation/flocculation-generated sludge. SVI is defined as the volume occupied by 1 g of sludge after 30 min of settling time. The SVI was calculated using the following relation:

$$\mathrm{SVI} = \frac{h_{30}}{h_0 X_0} \times 1000 \tag{2}$$

where h_{30} denotes the height of sludge after 30 min of settling; h_0, the initial height of the slurry; and X_0, the initial solids concentration in the slurry.

The suspensions from the coagulation and flocculation process were mixed, and the resultant slurry was used for studying the settling and filterability characteristics of the sludge. The sludge sedimentation tests were performed using a 100-mL graduated glass cylinder (height: 150 mm). No stirring was done during the tests. The well-mixed slurry was homogenized before being poured into the glass cylinder and was allowed to remain under quiescent conditions. The position of the upper interface between a clear supernatant and the settling solids was considered to be a function of time. The frequency of the measurement of the interface height was chosen in accordance with the settling rate. The method proposed by Richardson et al. [19] was used for designing a continuous thickener based on a single batch sedimentation test. This method provided a conservative estimate with an inherent high safety limit because of the changing nature of the flocs and their settling and compression characteristics [20]. Such parameters as sedimentation velocity (u_c), concentration of solids at time t (C_t), concentration of solids required in the underflow (C_u), and the sedimentation flux were calculated. The value of u_c was found from the slope of the tangent at a given solid concentration at any time. The concentration of the sludge at time t was determined by using the following formula:

$$C = C_0 \frac{h_T}{h_t} \tag{3}$$

where h_T and h_t denote the total height and the height of suspension after time t, respectively, and C_0 represents the initial solid concentration (kg/m^3).

Through the use of the abovementioned values, the area of the sedimentation tank for any effluent flow rate can thus be calculated using the following formula [20]:

$$A = V_f C_0 \frac{(1/C) - (1/C_u)}{u_c} \tag{4}$$

where V_f denotes the volumetric flow rate of the effluent (m^3/s).

The filterability of the sludge was tested with a gravimetric filter (Whatman grade no. 1) having a pore size of approximately 11 μm supported over a ceramic Buchner funnel having an internal diameter of 93 mm (filter area: 6.793×10^3 m^2; the slurry was filled up to 60% volume of the funnel). The force balance for the gravity filtration using a filter paper on a Buchner funnel can be written in the form of a differential equation [21]:

$$\frac{\Delta t}{\Delta V} = \frac{\mu}{A_f \Delta P}\left(\frac{\alpha C V}{A_f} + R_m\right) \tag{5}$$

where Δt denotes the time interval of filtration (s); ΔV, the volume of the filtrate collected during Δt (m^3); V, the cumulative average volume of the filtrate collected up to the considered time interval (m^3); C, the concentration of solids in the wastewater (kg/m^3); α, the specific cake resistance (m/kg); μ, the viscosity of the filtrate (Pa s); ΔP, the pressure drop across the filter (Pa); A_f, the area of filtration (m^2); and R_m, the resistance of the filter medium (1/m) [22].

The volume of the filtrate collected in the graduated vertical cylinder was recorded at regular time intervals. The filtration phase was assumed to end when the experimental data in the Δt/ΔV versus V plot deviated from the initial linear plot. The linear plot was used for calculating the specific cake resistance. From the moment at which the liquid disappeared from the top surface of the cake formed, a certain desired dewatering time was allowed, and then, the cake was carefully removed, weighed, and dried at 105 °C in an oven until it attained a constant weight. The residue was expressed as the dry mass of solids in the slurry.

6. Analysis

The physical and chemical parameters of the wastewater were determined using Standard Methods [23]. The color in APHA platinum-cobalt (Pt-Co) units was measured by using an HACH-Dr-B model spectrophotometer. Turbidity was measured using a WTW TURB555IR turbidimeter (Germany). COD was measured by the standard method of potassium dichromate oxidation [23].

A scanning electron microscopy (SEM) image of the sludge produced after the coagulation/flocculation treatment was obtained using a scanning electron microscope (JSM-6390LV; Make: Jeol, Japan). An electron dispersive spectroscopy (EDAX) analysis was carried out to determine the elemental composition of the sludge and fresh FCE by using the FE-SEM (QUANTA 200 FEG). Fourier transform infrared (FTIR) spectra were recorded using a Nicolet FTIR

instrument (Model: Magna 550) with KBr phase in the range 400-4,000 cm^{-1} against KBr as the reference material.

The pH of the zero point charge (pH_{ZPC}) for FCE was determined. For this purpose, 50 mL of a 0.01-M NaCl solution was placed in a 100-mL Erlenmeyer flask. Then, the pH was adjusted to successive initial values between 2 and 12, by using either NaOH or HCl, and 2 mg of FCE was added to the solution. After a contact time of 24 h, the final pH was measured and plotted against the initial pH. The pH at which the curve crossed the line pH (final)=pH (initial) was considered to be the pH_{ZPC} of the FCE considered. The pH_{zpc} for FCE was determined to be 7.9.

RESULTS AND DISCUSSION

1. Optimization of Coagulant Dosage

The coagulation process is generally a surface phenomenon; therefore, coagulation performance can significantly be affected by surface charge because of the mass of the coagulant. From an economic point of view, the optimization of coagulant dosage and the best-required mass of the coagulant for the scale-up and designing of large-scale equipment are necessary. Hence, the influence of FCE quantity on COD removal was considered at per original wastewater pH of 6.9 (Table 1), and the results are plotted in Fig. 1. The study range of the FCE dosage was 0.5-5 mg/L. The optimum FCE dosage was obtained as 1.5 mg/L. At the optimum coagulant dosage, the maximum COD removal efficiency was 89.3%. Fig. 1 makes two points. First, by increasing the FCE dose (up to 1.5 mg/L), we could increase the COD removal. This can be attributed to either the increase in the adsorptive surface due to an increase in FCE or the formation of flocs and acid anion complexes by electrostatic interaction. The complexes led to an enhancement of the removal of colloids. The second point made by Fig. 1 is the decrease in COD removal for FCE doses of more than 2 mg/L. With the addition of a relatively large dosage of the coagulant, the surface charge of the particles gets reversed because of the continued adsorption of the mono- and polynuclear hydrolysis species of the active group on the surface of FCE [6]. As the colloidal particles become positively charged, they cannot be removed by perikinetic flocculation.

A major advantage of the coagulation/flocculation of the textile wastewater by FCE is that the BOD_5/COD ratio was 0.19 for the original wastewater, which improved to 0.48 after treatment with FCE under optimum conditions. This shows that the biodegradability of the textile wastewater improves, and the pretreated textile wastewater can be subjected to a biological treatment.

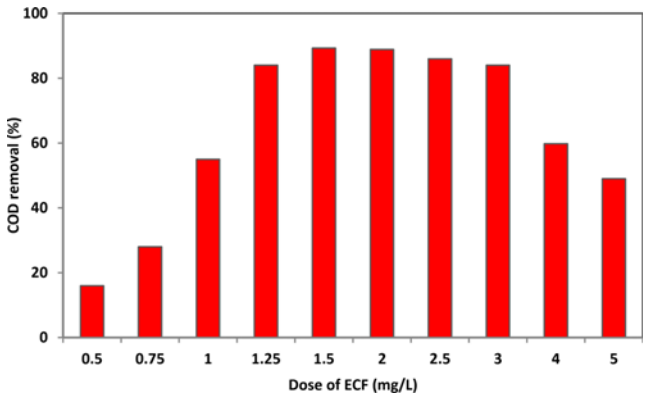

Fig. 1. Effects of FCE dose on COD removal (pH: 6.9).

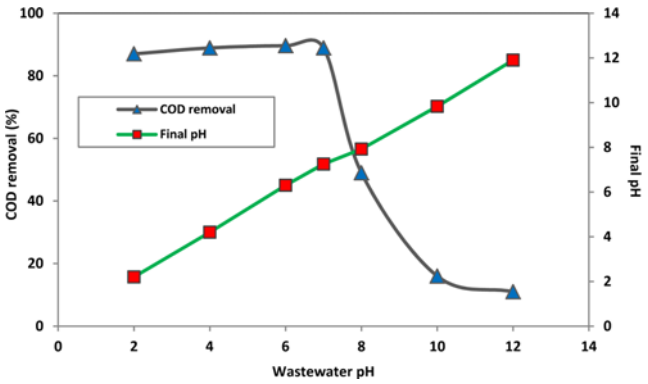

Fig. 2. Effects of wastewater pH on COD removal (FCE dose: 1.5 mg/L).

2. Effects of Wastewater pH on COD Removal

Since the pH of the wastewater affects the surface charge of the coagulants as well as the degree of the stabilization of the suspension [24], the effect of wastewater pH on the removal of COD by FCE was studied in the range of 2-12 and at an optimum FCE dose of 1.5 mg/L. The results of the pH effect on the COD removal are depicted in Fig. 2. This figure clearly shows that the removal of COD was highly influenced by the wastewater pH, as upon an increase in the wastewater pH from 2 to 6, the efficiency of COD removal increased from 87% to 89.6%. This phenomenon can be explained by the fact that the pH of the wastewater influences the surface charge of the FCE in the wastewater. Furthermore, the pH_{zpc} in the case of the FCE particles was determined to be 7.9; therefore, at less than pH_{zpc}, the surface of FCE is positive. Because the surface charge of an anionic dye is negative, an electrostatic attraction phenomenon can take place more easily as follows (Eq. (6)), thereby improving the turbidity removal at a wastewater pH of less than 8.

$$FCE^{+}+[Anionic_{dye}]^{-} \rightarrow FCE^{+}[Anionic_{dye}]\downarrow \quad (6)$$

However, the COD removal efficiency was maximized for a wastewater pH of 6, but we chose the pH value of 6.9, the original wastewater pH, for further experiments. The COD removal for pH 7 was 88.9%, a little less than the COD removal efficiency of 99.6% that was attained at pH 6. Because most of the textile wastewater is typically neutral [6], attaining maximum coagulation efficiency at around neutral pH is advantageous because the pH of wastewater does not need to be adjusted for efficient coagulation. Furthermore, the final pH of the solution at the end of each experiment was similar to the initial value (Fig. 2). Controlling the pH at an optimal value is critical to attaining maximum performance. However, the results indicate that the adjustment of wastewater pH during coagulation by FCE is unnecessary, which reduces the overall cost of treatment. The result is contradictory to the observation that higher pH values are optimal for other natural coagulants, *e.g.*, from *M. oleifera* [25], from *P. juliflora* and *C. latifaria* [26], from *C. angustifolia* [27] or common bean [28]. The contradictory reports can be explained by the differences in experimental conditions and the type and origin of the coagulant.

3. Effects of Salt Concentration

Wastewaters may have various concentrations of salts that influ-

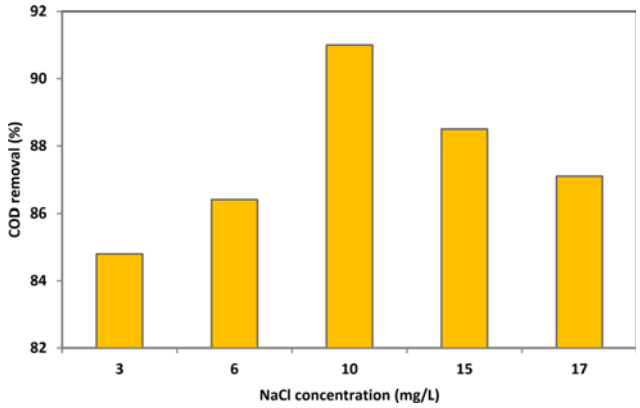

Fig. 3. Effects of salt content on COD removal (pH: 6.9, FCE dose: 1.5 mg/L).

enced the FCE performance for COD removal. Thus, in another attempt, the impact of water NaCl (3-17 mg/L) on COD removal efficiency was tested. The results of the salt effect on the COD removal by FCE are shown in Fig. 3. According to Fig. 3, COD removal was found to increase with an increase in the salt concentration of up to 10 mg/L. This implies that as the concentration of NaCl increased, more coagulant agent was dissolved in the wastewater. This phenomenon is known as the salting-in effect [29,30]. Since the FCE is a protein, when the salt concentration increases the solubility of the coagulant agent, FCE's concentration in the wastewater also increases. More FCE in solution means more coagulation activity, thus leading to a higher percentage removal of COD. Roussy et al. [29] and Hilal et al. [31] attributed the enhancement of coagulation in the presence of salts to the effect of double-layer compression. Edzwald and O'Melia [32] described that the double layer was compressed with an increase in the electrolyte concentration. Therefore, increasing the salt content would increase the destabilization of colloidal particles, improving their flocculation. Another observation from Fig. 3 is that for higher NaCl concentration, >10 mg/L, the percentage COD removal started to decrease. This was attributed to the salting-out effect whereby the solubility of FCE decreased with an increase in the salt concentration [29,30]. Further, as stated by Zhang et al. [33], the cationic ions can block negatively charged groups of the surface molecules, reducing electrostatic repulsion, and act as bridges between the functional groups of two adjacent molecules. These results agree with the results obtained by other researchers [34,35].

4. Sludge Volume Index, Settling, and Filtration

The SVI value for the FCE coagulation system at optimum conditions was calculated to be 167 mL/g. The low SVI value at the optimal FCE (1.5 mg/L) dosage without any coagulant aid was compared to the SVI values of the sludge obtained from the coagulation treatment with $FeCl_3$ (185 mL/g) [36]; this shows the potential of FCE for use in the coagulation/flocculation process.

Fig. 4 shows the settling characteristics of the sludge in the effluent treated with FCE. The addition of FCE (1.5 mg/L) at optimum dosage during a coagulation treatment considerably improves the settling characteristics of the sludge when compared to another coagulant [36]; however, the experimental conditions were different.

The sludge obtained from the coagulation treatment has to be

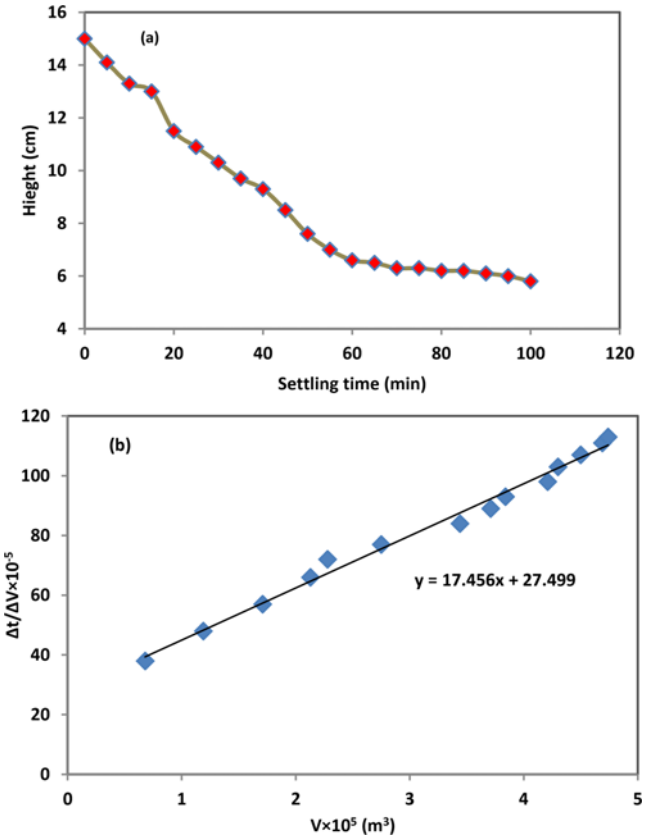

Fig. 4. (a) Settling characteristics of sludge in the treated effluent with FCE (b) Δt/ΔV as a function of filtrate volume for treated effluent with FCE.

dewatered before its disposal to reduce its volume and the moisture content. The dewatering can be carried out by filtration by using either a plate and frame filter or a rotary vacuum filter. Gravity filtration is generally used for generating and gathering experimental data in the laboratory. The filterability of the treated wastewater with 1.5 mg/L of FCE was tested by using a gravimetric filter. Assuming the change in the hydrostatic head to be negligible, and considering the gravity filtration to be a constant pressure filtration process, Eq. (5) gives a linear plot between Δt/ΔV and V for the treated effluent. The values of α and R_m can be obtained from the slope and

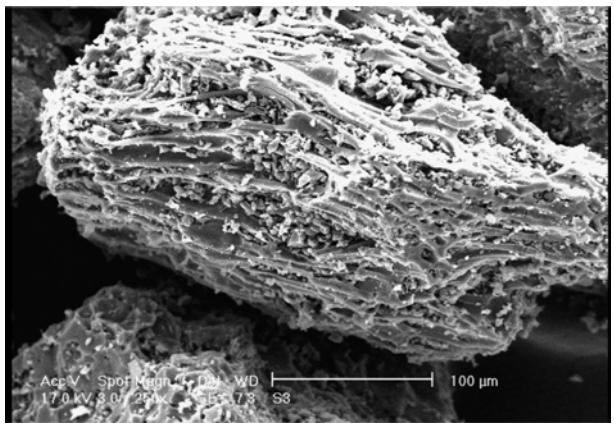

Fig. 5. The SEM image of FCE floc.

Table 2. Comparison the values of specific cake resistance (α) and resistance (R_m) for different types of sludge

Source of wastewater	Type of sludge	α (m/kg)	R_m (1/m)	Ref.
Domestic	Activated sludge	$(4\text{-}12)\times10^{13}$	–	37
	Biodigester sludge	$(3\text{-}30)\times10^{13}$	–	
	Conditioned digested sludge	$(2\text{-}20)\times10^{11}$	–	
	Conditioned primary sludge	$(3\text{-}10)\times10^{11}$	–	
Pulp and paper	Without any additive	6.8×10^{11}	8.9×10^{8}	22
	With NaCl as additive	3.2×10^{11}	2.3×10^{9}	
	With PAA as additive	4.6×10^{11}	2.9×10^{9}	
Pulp and paper	Thermochemical and Electrochemical sludge	(102.8-272.2)	$(0.69\text{-}4.84)\times10^{5}$	20
Petrochemical	$FeCl_3$	2.49×10^{11}	1.23×10^{5}	36
	$FeCl_3$+C-PAA	1.14×10^{10}	3.8×10^{5}	36
Textile	FCE	1.75×10^{11}	2.7×10^{5}	This work

the intercept of the plot shown in Fig. 5 as 1.75×10^{11} m/kg and 2.7×10^{5} 1/m, respectively. Smaller values of á in comparison with other studies (see Table 2) show an improvement in the filtration characteristics of the sludge produced by FCE. The specific cake resistance for the coagulant-treated wastewater is found to be in the lower range of the values given in Table 2. This indicates that the sludge from the coagulant-treated wastewater has better filterability than the domestic sludge and pulp and paper precipitation sludge [20,22,37].

5. SEM Micrographs, EDAX, and FTIR Analysis

From the SEM micrographs (Fig. 5), it is clear that the flocs produced after the treatment of textile wastewater with FCE are hard and sturdy. The honeycomb-like structure, with small colloidal particles entrapped in it, might indicate the contribution of the sweep flocculation mechanism for the removal of colloidal particles in the wastewater mixture. The chemical composition of the sludge and fresh FCE is given in Table 3. Among various elements, carbon was found to be dominant in the sludge as indicated by the COD removal. The FTIR spectra of FCE shown in Fig. 6 indicate several main peaks at 3,410, 2,920, 1,604, and 1,000 cm^{-1} on the spectra, which corresponds to -OH groups, -CH groups, C=O bands, and $-OCH_3$ groups [38]. These active groups on the surface of FCE may be involved in COD removal from textile wastewater.

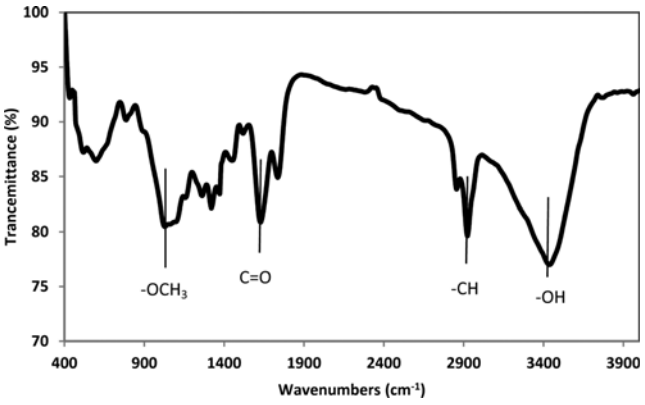

Fig. 6. FTIR spectra of fresh FCE.

Table 3. The EDAX analysis of the fresh FCE and FCE sludge

Element (wt%)	Value	
	Fresh FCE	FCE sludge
C	27.13	55.34
N	0.72	0.93
O	0.33	0.507
S	2.98	3.85
Al	1.70	4.72
P	0.22	0.31
Fe	4.64	5.12
Na	8.09	16.26
Cl	3.06	11.61
Cr	-	0.23

CONCLUSIONS

This study briefly indicated the following:

- FCE was found to be an effective coagulant with a COD removal efficiency of approximately 89%.
- The optimum dose of FCE for coagulation was 1.5 mg/L.
- Maximum COD removal was achieved at wastewater pH<8.
- Wastewater salinity content affected the COD reduction by FCE.
- The coagulation/flocculation process improved the BOD_5/COD ratio to 0.48, implying that the biological treatability of the textile wastewater was promoted.
- FCE produced sludge with good settling characteristics.
- The SVI of the sludge obtained from the treatment at optimal conditions with FCE was found to be 167 mL/g.
- EDAX analyses of the sludge revealed that the maximum removal of COD from textile wastewater was obtained with the use of FCE as a coagulant.

The results demonstrated that FCE could be effectively employed in textile wastewater treatment. However, practically all experimental runs took place under lab-scale conditions. The application to pilot and full-scale systems and a cost analysis are the necessary steps for the eventual application of FCE.

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