

Ultrasonication coupled electrochemical treatment of sugar industry wastewater: Optimization, and economic evaluation

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Abstract—This study demonstrates the optimization of treatment option, an integrated advanced-oxidation process (AOP) based approach where integration of two processes, ultrasonication (US) and electrocoagulation (EC), were applied for sugar industry wastewater (SIW) treatment. Experimental results confirm that the individual US and EC processes for SIW treatment are found to be inefficient, as only 16% COD removal (equivalent to COD removal: 268 mg/L) is achieved with US process in 20 min, while 68% COD removal (equivalent to COD removal: 1,142 mg/L) is achieved in 60 min operation time with EC process. Encouraging results were obtained after integration of US (10.6% COD removal in 20 min equivalent to COD removal from 1,680 mg/L to 1,502 mg/L) with EC (82% COD removal in 30 min equivalent to COD removal from 1,502 mg/L to 270 mg/L) process, which is collectively classified as ultrasonication-electrochemical (US+EC) process. Overall integration of US and EC process ultimately increased the COD removal up to ~84% (equivalent to COD removal from 1,680 mg/L to 270 mg/L) in comparatively shorter operating time (US+EC=30 min). Calorific value of sludge and scum obtained after EC treatment was determined as 3.69 and 2.87 MJ/kg, respectively. Treatment cost of sono-electrochemical is estimated based on 1 kg COD removal or 1 m³ wastewater as 1.40 or 1.974 \$, respectively, which is found on lower ends when compared with the many other available treatment technologies.

Keywords: Cost Analysis, COD Removal, Industrial Wastewater Treatment, Electrocoagulation, Sono-electrochemical, Sugar Industries Wastewater, Ultrasonication

INTRODUCTION

Agro industries produce an enormous amount of wastewater that contains high chemical oxygen demand (COD) [1]. Sugar industry wastewater (SIW) is brown with high COD, biological oxygen demand (BOD), organic and inorganic pollutant (melanin, lignin, glucose etc.), total dissolved solid (TDS) [2,3]. The sugar industry stands fourth in water consumption after the primary metal, chemical and pulp and paper industries [4,5]. The sugar industry generally generates 1 liter of wastewater for 1 kg of sugar production, which demands urgent attention for treatment before discharging [5]. Generally, conventional water remediation technologies like biodegradation [6,7], adsorption [8,9], membrane filtration [10,11], coagulation-flocculation [12,13], advanced oxidation processes such as ozone, photochemical, Fenton's, and electrochemical [14-17] are applied to remove COD, total organic carbon (TOC) and color from SIW. However, the single treatment approach is not found efficient to completely remove industrial wastewater organic load in terms of COD and even fails to achieve the effluent discharge norms of the Central Pollution Control Board (CPCB), New Delhi, India, [18,19]. As single treatment is not sufficient in the complete

mineralization of high organic content due to the presence of melanoidin, lignin, water soluble glucose derivatives. Among all available treatment technologies, biological and bio-membrane processes require long time, high initial investment, and less operating cost. Whereas, chemical/electrochemical treatments require less time, less initial investment, and considerable operating cost. Basically, biological treatment is recommended for high biodegradability index (BI) containing wastewater. But coupling of two processes may offer an effective treatment option to achieve CPCB norms (COD<250 mg/l) [20-22]. Therefore, the selection of the best wastewater treatment option may depend upon two criteria, such as economics and effective treatment, and their efficacy generally depends upon the recalcitrant characteristics of the pollutants.

Electrochemical (EC) treatment can be recommended for SIW treatment because of less chemical consumption, relatively fast mechanism to destabilize recalcitrant pollutants, ease of operation and need for less operating power [18]. The performance of EC treatment can also be improved by using a variety of pre-treatment methods. Strategies like thermal, wet air oxidation, and incineration require high temperature and pressure conditions, while anaerobic treatment requires longer time but is even inefficient to destabilize complex recalcitrant pollutants present in industrial wastewater [23-26]. Moreover, degradability of the pollutants can be enhanced by mechanical/chemical vibration. Pre-treatment methods, such as ultrasonication (US) [27,28] and aeration [29] are easy to operate

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and can be recommended for the primary COD reduction along with destabilizing the complex pollutants present in the SIW.

A substantial number of works have also been reported for the treatment of industrial wastewater using ultrasonication [30-32]. Ultrasound has increasingly emerged as a potential approach for wastewater treatment and sewage sludge management. In this approach, cavitation phenomena result in the generation of hydroxyl radicals by the utilization of sound energy in terms of mechanical and chemical vibration, which has ultimately attracted considerable attention for the degradation of recalcitrant compounds. During the ultrasonication process, the instantaneous collapse of air bubbles releases energy, and before dissipation of this energy in the bulk solution, provides activation energy for the degradation of the pollutants present in the wastewater [33]. Therefore, this approach is considered under the advanced oxidation process (AOP) domain. Recently, ultrasonic cavitation in synergy with advanced oxidation processes, has been reported for effective degradation of various organic compounds like cyclic or aromatic organic complexes, glucose, protein [34-37]. There are some limitations associated with this approach, such as the requirement of large hold-up volume, large time scale, and the high dissipation power for complete mineralization, which is not economically acceptable. So, US as single treatment option is not recommended for complete demineralization of industrial wastewater.

Electrocoagulation (EC), as an example of an electrochemical approach, is widely used for the treatment of complex or high organic containing industrial wastewaters [2,38,39]. This method implies direct current (DC) source between the metal electrode (Iron, Aluminum) immersed in polluted wastewater. Metal ions release at electrode in the EC chamber as metal hydroxides, synergistically contributing to significant destruction of organic complexes in the form of CO_2 , H_2O , sludge and scum. Solid generated in the form of sludge and scum can be used as low-grade fuel [39-41]. From the above backdrop it appears that the combined approach involving ultrasonication and EC can be an alternative option for the treatment of SIW; however, it has not yet been investigated for SIW treatment. In addition, both US and EC come under the category of green technology applied for SIW treatment. Although, their effectiveness in wastewater treatment is limited due to the above limitations. Therefore, coupling these two processes could be a better alternative for treatment.

In this study, the integration of ultrasonication (US) with electrocoagulation (EC) method, termed as ultrasonication-electrochemical (US+EC) approach as an AOP, was applied for the SIW treatment. US is used at the primary stage followed by EC process. Overall, this study demonstrates the optimization of effective COD removal based on an economical assessment. Economical assessment study was performed to determine the minimum energy requirement for treatment, which is estimated based on electric energy consumed during EC and US process and electrode consumed in EC process. Treatment cost in the current study was also compared with some recent reported literature. In addition, scanning electron microscope-energy dispersive analysis (SEM-EDAX), Fourier transform infrared (FTIR) study of sludge and scum were performed to assess their utilization and disposal options.

Table 1. Properties of SIW

Chemical oxygen demand, COD (mg/L)	1,680±34
Biological oxygen demand, BOD (mg/L)	635±13
Initial pH	4.7±0.1
Total dissolved solid (mg/L)	330±7
Salinity (PSU)	0.32±0.01
Resistance ($\text{K}\Omega$)	1.52

MATERIAL AND METHODS

1. Materials

SIW was collected from local sugar mill of Gorakhpur, Uttar Pradesh, India. Random sampling at the inlet of wastewater treatment plant was used to collect the sample and stored in deep freeze at 4 °C for further experiments. The characteristics of SIW are given in Table 1.

Aluminum sheets were used as an electrode material and purchased from a local market of Gorakhpur, Uttar Pradesh, India. Chemicals sodium chloride (NaCl), sodium hydroxide (NaOH), hydrochloric acid (HCl), sulfuric acid (H_2SO_4), potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$), mercuric sulfate (HgSO_4), silver sulfate (Ag_2SO_4) of analytical grade were purchased from SD Fine chemicals, Mumbai, India for the experimental and solution preparation. Double distilled water with conductivity 0.45 $\mu\text{S}/\text{cm}$ was used throughout the experiment for dilution of wastewater and preparation of solution.

2. Treatment Process

A block diagram of the ultrasonication-electrochemical process is shown in Fig. 1(a), where the SIW was first pre-treated in the ultrasonic sonicator (Labman, LMUC-04, India) with maximum power 100 W and 40±3 Hz frequency, which was followed by EC treatment. The batch experimental setup is shown in Fig. 1(b).

Ultrasonicated reactor with 2.5 liter working volume was fed with SIW at ambient temperature (25 °C). Ultrasonication reactor was operated in ice water bath to maintain ambient temperature under batch mode conditions. Further, US treated SIW was treated in EC batch reactor. Fig. 1(a) depicts the process flow where two processes are integrated in batch mode. Fig. 1(b) shows the experimental setup of US and EC; the EC setup comprises 1 L working capacity of perspex glass. Four electrodes (dimension: 5 cm×4 cm×0.3 cm) were arranged in monopolar parallel connection. These electrodes were externally connected to a DC power supply (0-30 V, 0-5 Amp). The EC was operated at current density: 8.92 mA/cm^2 (1 A), electrode distance: 1.5 cm, NaCl concentration: 1 g/l, operating pH: 7 [18]. All the experiments were performed at room temperature, around 28±3 °C. Each experiment was repeated thrice at the same operating conditions and average values were reported. The treated effluent was sampled at a specified time interval of 10 min and centrifuged at 5,000 rpm for 5 min to determine the COD of sample. US treated SIW (left-over solution after sampling) was fed for next EC treatment. Scum was collected manually during EC performance, and at the end of each run whole treated wastewater was filtered by using vacuum filter paper (0.45 micron). Further, collected sludge and scum was dried in hot air oven overnight at 60-70 °C. Electrodes were cleaned by sandpaper followed by 5% HCl

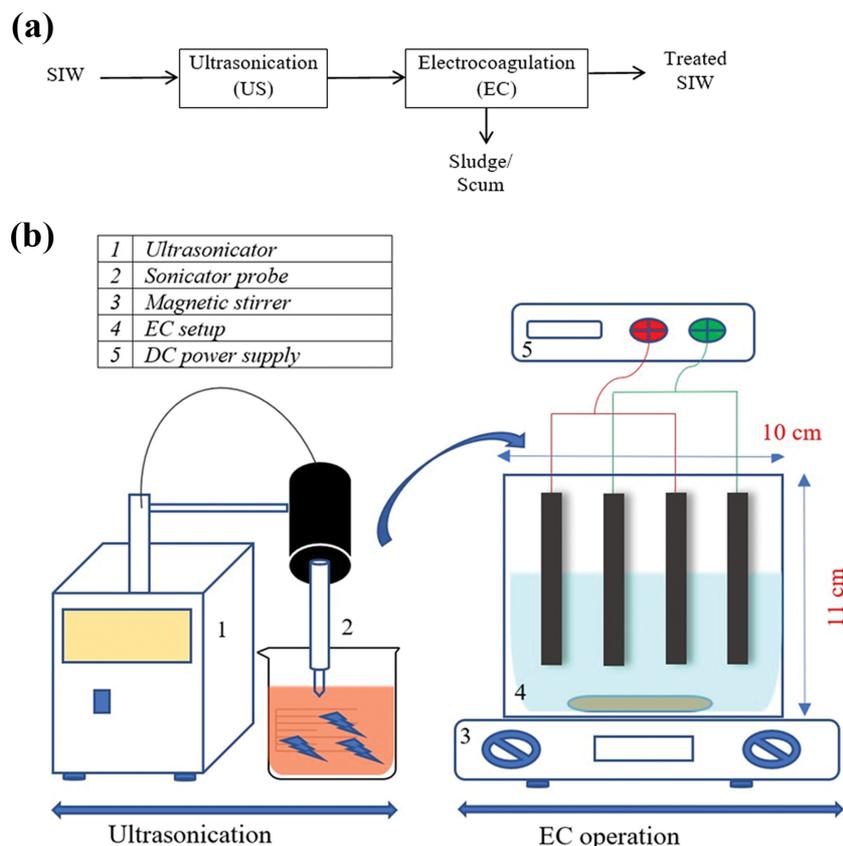


Fig. 1. (a) Block diagram of ultrasonication-electrochemical process, (b) schematic diagram of US+EC operation.

cleaning to use the same electrodes in multiple experiments. 1 N NaOH solution was used to change the pH of the wastewater.

FTIR (Nicolet 6700, USA) was used to detect the functional group present in the sludge and scum samples by using pellet technique. thermal gravimetric analysis TGA (EXSTAR, SII 6300 EXSTAR, Japan) was employed to study the thermal stability and calorific values of the materials. Field emission-scanning electron microscope (Fe-SEM) (QUANTA 200 FEG, FEI Netherlands) was utilized to study the surface morphology and EDAX study for the composition the sludge and scum. For COD measurement, a mixture of 3 ml SIW samples, 1.5 ml potassium di-chromate and 3.5 ml sulfuric acid solution was mixed and digested for 120 min at 150 °C in COD digester (Lovibond digester, United Kingdom). COD of the digested samples was determined by closed reflux method using LOVIBOND COD meter (MD 200, United Kingdom). The COD reduction was calculated by using Eq. (1).

$$\% \text{ COD reduction} = \frac{(K_1 - K_2)}{K_1} \times 100 \quad (1)$$

where K_1 is the COD of untreated wastewater and K_2 is the COD of treated wastewater, respectively.

Individual treatment of SIW by both process (US, and EC) was used to determine the optimum conditions of various process parameters. In US process the energy required for 1 kg COD removal and 1 m³ wastewater was determined based on variable US power input (40 to 100 W at regular interval of 10 W). All the EC pro-

cess was carried at inlet voltage supply of 11 V. US+EC was carried out at the optimum conditions of US and EC.

3. Economic Study

The cost for US+EC treatment process was calculated as per Eq. (2).

$$\begin{aligned} \text{US+EC treatment cost (\$/kg COD)} \\ = & \text{Energy cost for US+EC process (\$/kg COD)} \\ & + \text{Electrode material cost (\$/kg COD)} \\ & - \text{Energy cost recovered from sludge/scum (\$/kg COD)} \end{aligned} \quad (2)$$

Energy required in US+EC process for 1 kg COD removal was calculated as per Eq. (3).

$$\text{Energy consumed in US+EC process} = \frac{\frac{P_{US}t_{US}}{V_{US}} + \frac{V_{EC}I_{EC}t_{EC}}{V_{EC}}}{\text{CODR(Kg)}} \quad (3)$$

where, P_{US} (W) was the power required in US process, v_{US} was volume of US reactor (2.5 liter), v_{EC} was volume of EC reactor (1 liter), V_{EC} was the voltage applied in EC process (11 V), I_{EC} was current used in EC process (1 A), t_{US} and t_{EC} (sec) were the time consumed in US and EC process, respectively.

The electrode material cost was estimated by using Eq. (4)

$$\begin{aligned} \text{Electrode material cost (\$/kg COD)} \\ = & \text{Electrode price (\$/kg)} \times \text{Electrode dissolved (kg/kg COD)} \end{aligned} \quad (4)$$

The electrode dissolved was calculated as per Eq. (5)

$$\text{Electrode dissolved (kg/kg COD)} = \sum_{i=1}^{n=2} m_i c_i \quad (5)$$

where, m_1 and m_2 are mass (kg/Kg COD), and c_1 and c_2 are the Al composition (wt%, EDAX analysis) in sludge and scum, respectively.

Energy recovered from sludge/scum was determined by using Eq. (6).

$$\text{Energy recovered from sludge/scum (MJ/kg COD)} = \sum_{i=1}^{n=2} m_i E_i \quad (6)$$

where, E_1 and E_2 are the calorific value from differential thermal analysis (DTA analysis) in MJ/kg for sludge and scum, respectively.

RESULTS AND DISCUSSION

1. Ultrasonication

The effect of US power, 40-100 W (40-100% of maximum US power) on % COD removal and energy required for 1 kg COD removal is presented in Fig. 2(a) and (b), respectively.

Fig. 2(a) indicates that % COD removal increases with US power; only 13% COD removal was found at 40% input power and 22% COD removal at 100% input power in 60 min. However, the increment was found to be insignificant because COD removal at 100 W input power is ~1.7 times higher than that of 40 W US input power. Fig. 2(b) also indicates power consumed for 1 kg COD removal

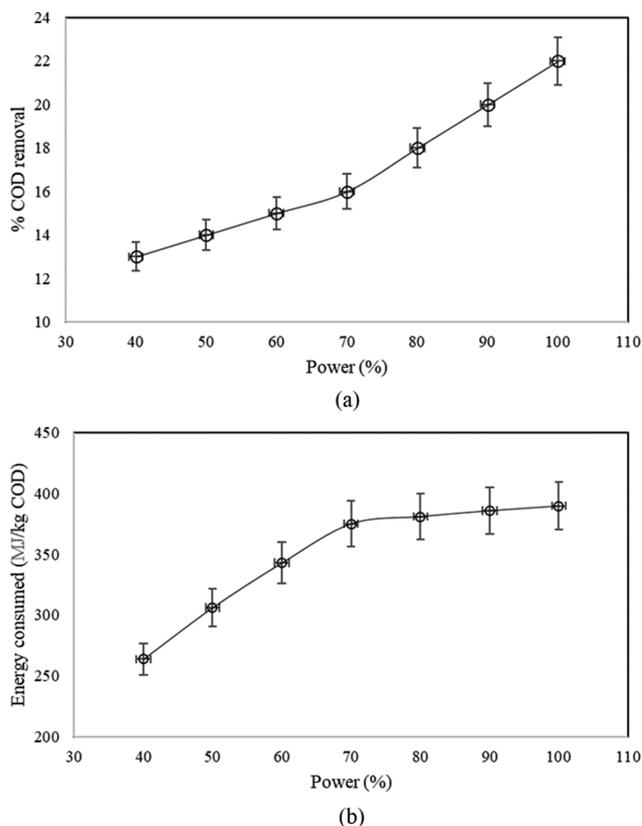


Fig. 2. Effect of US power on (a) % COD removal (b) energy required for 1 kg COD removal (Operating time=60 min; Initial COD: 1,680 mg/L).

also increases from 40% to 70% of US power inputs; thereafter, it becomes almost constant up to 100% power input. Lower input power generates waves with lower wavelength amplitude, which creates lower agitation in terms of mechanical and chemical agitation and reaction. When ultrasonic signals move in the polluted wastewater, microbubbles are generated, which move and burst in the liquid solution in a very short period. In this short period, the US process produces low and high-pressure waves within the solution, which leads to the creation and rapid collapse of small vacuum bubbles. These phenomena increase with input power supply of the US process [28]. A US input power of 70% is preferred for the further study for equipment safety purpose.

1-1. Optimization of Time for US Process

Effect of time on the COD removal and energy consumed for one kg COD removal is presented in Fig. 3(a) and (b), respectively.

Fig. 3(a) shows that the COD removal increases with increase in time, and it is showing a steep slope, which corresponds to the fast removal in initial treatment time of 25-30 min, although slow reduction of COD is noted as time proceeds. While energy required for 1 kg COD removal first decreases with time (20 min) then increases thereafter. So, based on energy needed for 1 kg COD removal, the minimum energy requirement is noted at time 20 min, and it is equivalent to 269 MJ/kg COD removal. At this time 10.6% COD removal is noted. Relatively fast initial COD removal is obvious in the initial time of US process, because lighter/degradable components such as light acid and sucrose of SIW are easily

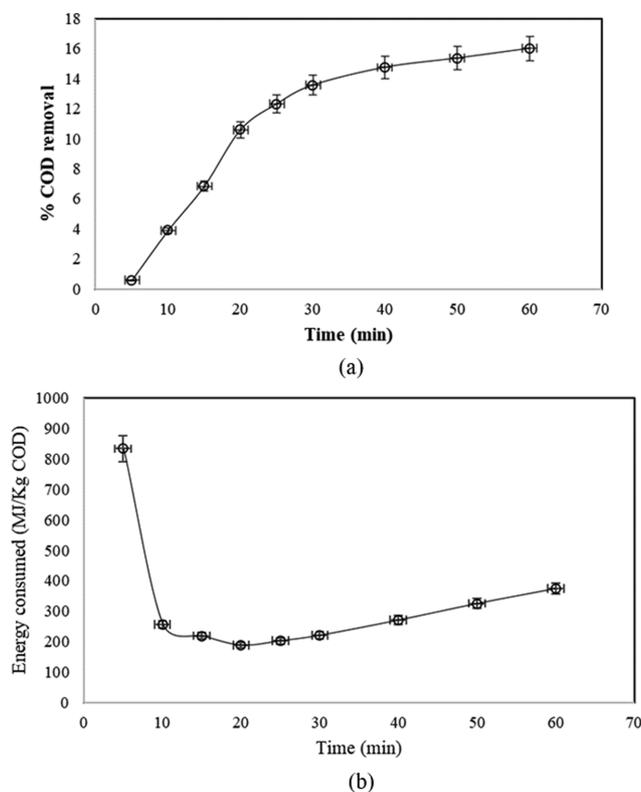


Fig. 3. (a) Effect of time on the COD removal, (b) Energy consumed for one kg COD removal (Input power: 70% of maximum US power).

degraded due to US vibration in the starting of treatment. Generated bubbles during US process collapse and are responsible for chemical (free radicals), thermal and mechanical effects (shear stress, collapse pressure, turbulence) [42]. In addition, the US process weakens complex structures such as protein and sugar [43,44] with time, which may ultimately be helpful in the destabilization of complexes compound present in SIW. Overall, during US treatment all the minerals are not demineralized completely, and longtime exposure of US process is not useful from energy input requirements; therefore, 20 min (minimum energy for kg COD removal) for US treatment is indicated for further study.

2. Effect of Time on EC, US, and US+EC Process for COD Removal

Effect of operating time for the treatment of SIW using US, EC and US+EC is shown in Fig. 4(a) for comparison purpose. COD of untreated and corresponding US, EC, and US+EC process treated SIW is presented in Fig. 4(b).

Fig. 4(a) and (b) show the comparative COD removal rate in the three different processes (US, EC and US+EC) adopted for SIW treatment in the current study, showing similar increasing trend of COD removal rate for all three processes. However, a sharp increment in COD removal is noticed and the maximum (82%) is achieved for US+EC in initial 30 min time, in comparison to EC and US process. SIW treatment via EC process shows 48 and 68% COD removal in the 30 and 60 min operation time, respectively, which is equivalent to COD removal from 1,680 mg/L to 873 mg/L in 30 min and 1,680 to 537 mg/L in 60 min operation. On the

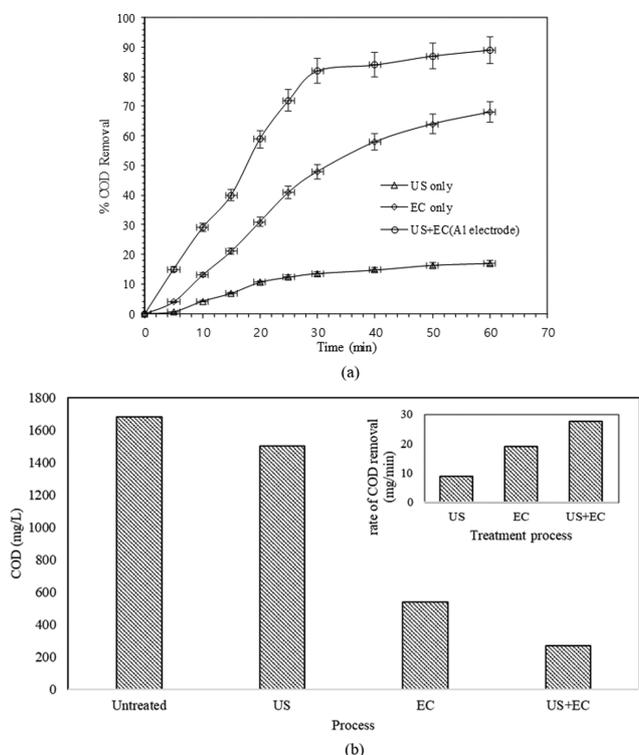


Fig. 4. (a) Effect of time on COD removal for US, EC, and US+EC process, (b) Effect of US (20 min), EC (60 min), and US (20 min)+EC (30 min) treatment for SIW treatment (initial COD 1,680 mg/L).

other hand, it is noteworthy that 20 min US treatment followed by EC treatment (US+EC) achieves steady state condition in 30 min. Important aspect about the ultrasonication-electrochemical process is that 20 min of US treatment insignificantly reduces the COD from 1,680 mg/L to 1,502 mg/L, which is further used as feed to EC batch process for higher COD removal. Fig. 4(a), indicates maximum 82% of COD reduction in 30 min, which is equivalent to COD reduction from 1,502 to 270 mg/L. The outlet COD in the SIW is close to the permissible limit (250 mg/L) prescribed by CPCB Delhi, India [45]. Individual EC for SIW treatment consumed higher time (60 min), while US treatment followed by EC treatment (US+EC) improved the COD removal in lesser time (30 min). It is also interesting that 20 min US treatment followed by 30 min EC operation indicates 82% of COD removal, which signifies that US pretreatment of SIW enhances the COD removal efficiency of EC process. It is also noted in literature that individual EC process for many industrial wastewaters, such as sugar/distillery industries, wastewater, paper industries, wastewater needs more time (~75-150 min) to achieve maximum COD removal [5, 18,38]. But in the current observation, by applying US process as primary treatment followed by EC treatment (US+EC) reduces the treatment time to 30 min. The higher performance of ultrasonication-electrochemical is probably due to the destabilization of the complex compounds of SIW by US process via exposure to the chemical, thermal, mechanical activities, and this destabilized complex is easily broken down via EC process. In addition, inset Fig. 4(b) compares the rate of COD removal as 8.9, 19.05 and 27.7 mg/min for US, EC and US+EC processes, respectively. So, by applying US as pretreatment process of SIW reduces the operating time of EC process and improves the COD reduction rate by 1.45 times in comparison with individual EC process. Therefore, these results indicate the current treatment methodology (US+EC) can be chosen for the treatment of the industrial effluents.

3. Effect of US Power Input on US+EC

Impact of US power input on overall treatment of SIW via US+EC process is shown in Fig. 5.

SIW is first treated with US process at five different input pow-

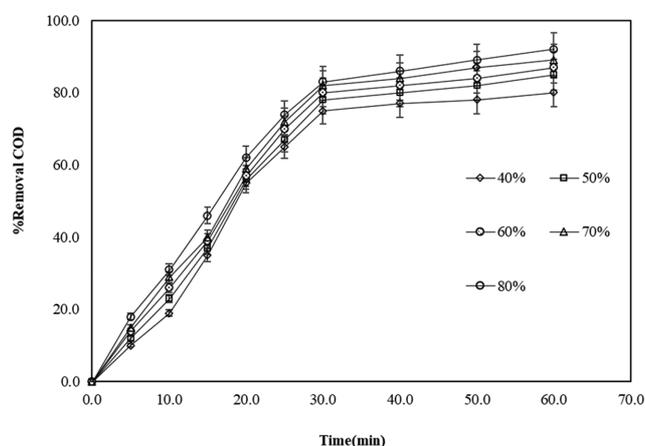


Fig. 5. Effect of US power input on COD removal in US+EC process (Current=1 A, Electrode distance=1.5 cm, NaCl conc.=1 g/l and voltage=11 V).

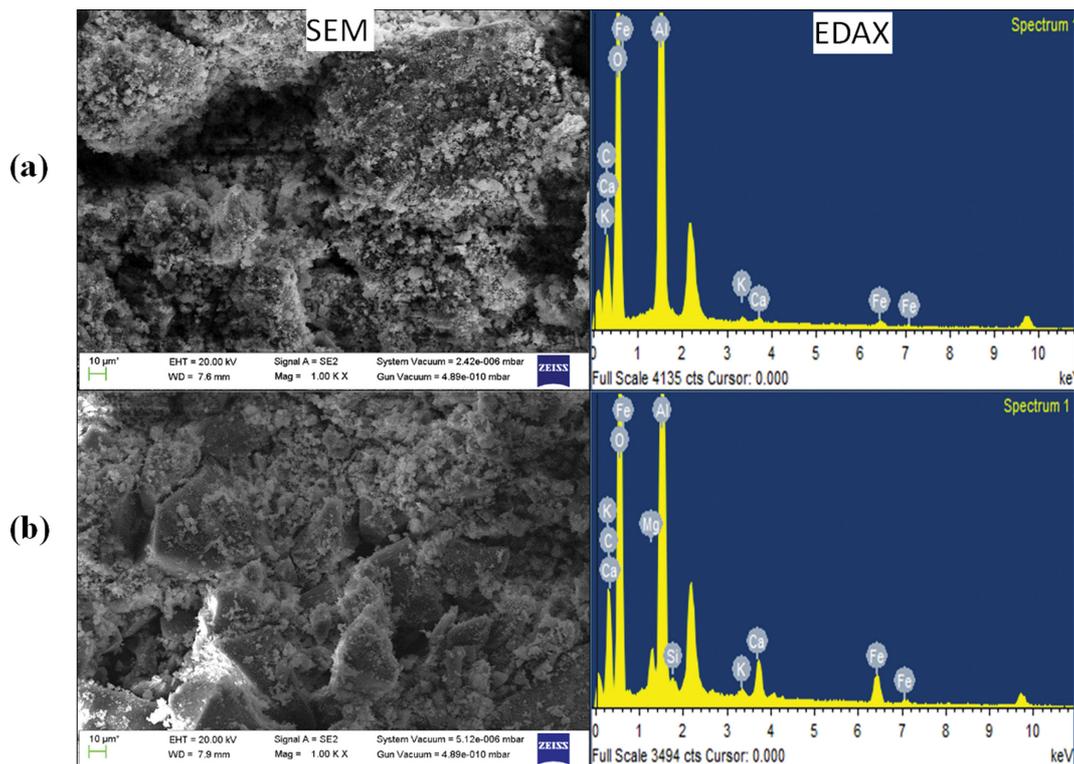


Fig. 6. SEM image and elemental distribution during EC process (a) scum, (b) sludge.

ers of 40, 50, 60, 70, 80% (40, 50, 60, 70, 80 W) for 20 min operating time, respectively. Further, these US treated SIW are further treated in the EC reactor for 60 min. It is noted that 75, 78, 82, 82, 83% COD removal during EC treatment of US pretreated SIW at 40, 50, 60, 70, 80% power, respectively, achieved in the first 30 min; after that only 5-9% of increment is noted in next 30 min; therefore 30 operation time is sufficient to achieve maximum COD removal. Moreover, also noted is that the % COD removal of EC process increases with the input power during US pretreatment process. It is obvious because the destabilization of complex organics of SIW increases with input power due to higher vibration at higher power input during US [44,46]. In addition, sharp reduction in COD is noted with 30 min for EC treatment of US treated SIW, which is much less in comparison to the treatment time required for SIW treatment using EC process [39,47]. The EC treatment process follows the sweep and bridge coagulation mechanism during pollutant removal from SIW. The effect of these mechanisms increases because impurities of SIW ionized during

US process along with breakup of these impurities due to physical and chemical changes. So, rate of pollutant removal marginally increases with input power in the US, which is followed by EC process for the treatment of SIW.

4. Sludge and Scum Management

4-1. SEM EDAX

Fig. 6(a) and (b) show the surface morphology along with elemental distribution of the scum and sludge generated during sono-

Table 2. Elemental composition of sludge/scum generated in US+ EC process

	Sludge (wt%)	Scum (wt%)
SN	Al	Al
C	19.49	20.41
O	64.03	65.96
Al	10.92	12.73
Ca, Fe, K, Si, Mg	5.57	0.90

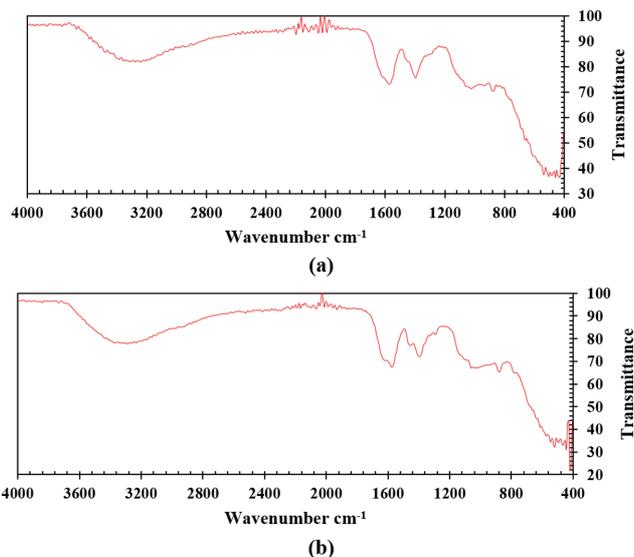


Fig. 7. FTIR pattern of (a) scum (b) sludge generated during EC process.

electrochemical process.

Fig. 6 indicates that sludge is coarser in comparison to scum, which is probably due to accumulation of heavy and coarse particles in the bottom of the EC reactor, while scum consists of lighter components with smaller size accumulated at the upper surface of reactor. The elemental composition of sludge and scum after EC process is presented in Table 2.

Table 2 illustrates the elemental composition 19.49 and 20.41%

C, 64.03 and 65.96% O, 10.92 and 12.73% Al in the sludge and scum generated during EC process, respectively. Carbon (C) content in scum is slightly higher than sludge due to presence of lighter component based on C in the scum as well as presence of some inert material in the sludge [48]. Attachment of oxygen with carbon, Al and other impurities also confirms that oxygen composition in heavier compound-based oxides is lower, which is responsible for higher oxygen in scum in comparison with sludge [49]. In

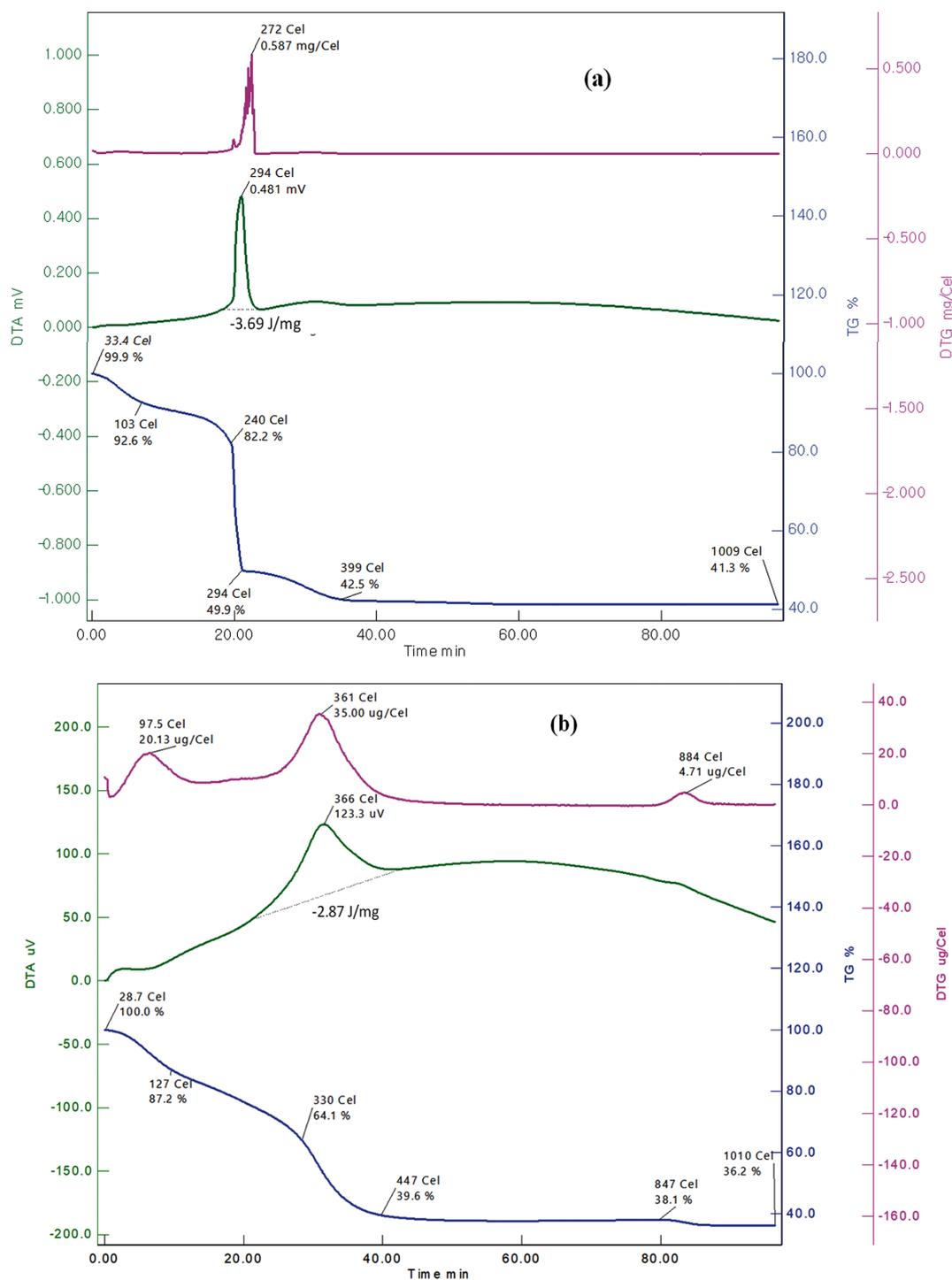


Fig. 8. TGA, DTA, and DTG analysis of (a) Scum, (b) Sludge generated during EC process.

Table 3. Treatment cost calculating parameters

S. No.	Parameters	Unit	Value	Ref
1	Sludge formed	kg/kg COD	0.826	
2	Scum formed	kg/kg COD	0.406	
3	Calorific value of Sludge	MJ/kg	2.870	
4	Calorific value of Scum	MJ/kg	3.690	
5	Electrode (Al) dissolved	kg/kg COD	0.150	
6	Energy from sludge	MJ/kg COD	2.370	
7	Energy from scum	MJ/kg COD	1.500	
8	Electrical energy for US (20 min) and EC (30 min) process	MJ/kg COD	51.920	
9	Aluminum electrode price	\$/kg	2.840	[53]
10	Electricity price	\$/kWh	0.075	[54]
Overall treatment cost		\$/kg COD	1.400	

addition, Al is a lighter metal in comparison to many metals such as SS and Cu and it is predominant in floc during EC process, while other heavy metals are separated in terms of sludge during EC process. So, sludge shows lower Al and higher other metals composition in comparison to scum [38].

4-2. FTIR Analysis

FTIR analysis of sludge and scum was done between the range 400–4,000 cm^{-1} wavenumber to determine the functional group present in the sample and is presented in Fig. 7(a) and 7(b), respectively.

The nature of FTIR peaks for both sludge and scum is similar, except some intensity variation between the wavenumber 2,000–2,400 cm^{-1} and 400–600 cm^{-1} . Generally -OH, -C=O and -C-H peaks are found between the wavenumbers 2,000–2,400 cm^{-1} [50], which is predominant in case of scum (from O composition from EDAX analysis). While peaks at lower wavenumbers are mainly due to the presence of heavy metals, which are predominant in the sludge [51]. In addition, peaks between wavenumber 1,300–1,500 cm^{-1} are due to C-H bending (in CH_3 groups)/aromatic -C=C stretching vibrations [52].

4-3. TGA/DTG/DTA Analysis

Sludge and scum are analyzed to determine their thermal stability and calorific value as these are key characteristics of fuel. The TGA, DTA, and DTG analyses of scum and sludge are represented in Fig. 8(a) and (b), respectively.

The thermal stability of waste (sludge and scum) is determined from slopes, calculated from the weight reduction versus time/temperature, which directly relates to the decomposition temperature of their various functional groups and various oxides of the scum/sludge. DTG analysis states the temperature range at which maximum weight loss takes place. The nature of the reaction (endothermic/exothermic) is also described by DTA analysis. TGA analysis describes weight loss of scum as 57.4% up to temperature 399 °C, while sludge loses 60.3% of its weight up to 447 °C. The weight loss in the temperature range of 25–200 °C is mainly due to loss of water moisture, and in the low molecular weight compounds in the range of 500–1,000 °C there is 1–4% of weight loss for scum and sludge. DTA analysis suggests that the calorific value of sludge and scum is 2.87 and 3.69 MJ/kg, respectively. So, sludge and scum can be used as low-grade solid fuel [40,41]. TGA analysis states that maximum rate of mass loss is 0.587 $\text{mg}/^\circ\text{C}$ at 272 °C and maxi-

imum rate of mass loss is 0.035 $\text{mg}/^\circ\text{C}$ at 361 °C. There are two other temperatures, 97.5 and 884 °C, for sludge where the rate of weight loss is 0.02013 and 0.00471 $\text{mg}/^\circ\text{C}$, respectively. These data clearly indicate sludge contains both lighter and complex combusting substances, and scum is mainly composed of lighter components.

5. Cost Analysis

The costs required for the treatment of SIW with consideration of different parameters are presented in Table 3.

The current treatment cost is calculated at optimum condition of US+EC process. Here, based on energy consumed for 1 kg COD removal study, 20 min and 30-min optimum time for US and EC process are considered for overall treatment cost calculation. Overall, 1.40 USD (\$) is required for 1 kg COD removal with current integrated US and EC process.

COMPARATIVE STUDY

The feasibility of the current study on the economic basis is compared based on treatment cost of industrial wastewater for 1 kg COD removal in Table 4.

Current comparative study indicates the treatment cost required for 1 kg COD removal or 1 m^3 of wastewater is less in comparison to some recent literature. In addition, by applying US process as a primary treatment process, EC process requires less time (30 min). Overall, the total operating time for simultaneous US and EC process can be performed within 30 min. So, during industrial application, simultaneous use of US and EC process, industrial wastewater may be treated in shorter time. Overall, the efficacy of the current system can also be increased by modifying reactor design and materials used.

CONCLUSION

The present study proposes a simultaneous combined treatment process as the US+EC approach can be a good choice for SIW treatment. Experimental results indicated that the US process as primary treatment can be used to destabilize the complex pollutants present in wastewater along with marginal changes in COD removal (10.6% in 20 min). In contrast, application of EC treatment for post-US treated SIW, requires less treatment time with higher

Table 4. Cost comparison of current study with various studies in the literature

S. N.	Type of wastewater	Process	Initial load	Result	Treatment cost (\$/kg COD)	Treatment cost (\$/m ³)	Time (min)	Ref
1	Real dyehouse wastewater	Continuous EC	COD- 1,940-2,060 mg/L; TOC- 520-450 mg/L	85% COD removal (Fe electrode)	7.28	1.562	80	[55]
				77% COD removal (Al electrode)	14.25	1.851	80	
2	Petrochemical wastewater	UV/hydrogen peroxide, UV/persulfate and UV/percarbonate	COD- 950±50 mg/L; BOD- 190±10 mg/L	70% COD removal	22.96	-	60	[56]
3	Molasses wastewater	EC	COD- 4,150 mg/L	54% COD removal	38.91	-	210	[57]
5	Coking wastewater	Aeration assisted electrochemical oxidation process	COD- 6,600 mg/L; TOC- 1,990 mg/L	99.8% COD removal	8.60	52.10	480	[58]
6	Landfill leachate treatment	Ozone and ozone/hydrogen peroxide system	COD- 5,230 mg/L BOD- 500 mg/L	48% COD removal	2.30	-	60	[59]
7	Metal working wastewaters	Continuous EC	COD- 17,312 mg/L TOC- 3,155 mg/L	75.1-94.8% COD removal (Fe electrode)	7.73-1.41	3.58-3.85	EC=40, retention time=70	[60]
				68.0-87.0% COD removal (Al electrode)	3.34-1.11	4.34-4.88	EC=40, retention time=70	
8	Sugar industry wastewater	US+EC	COD- 1,680 mg/L	82% COD removal	1.40	1.974	30	Current study

COD removal efficiency and lower treatment cost compared to the EC process. Current study recommends that the US+EC treatment process requires 1.40 \$/kg COD removal or 1.974 \$/m³, which is much less or comparable in comparison to most of the reported processes, including some recent literature. In addition, simultaneous US and EC process can be performed in 30 min, which is much less than in the available recent literature. So, in continuous performance the reported result can be achieved in 30 min. Overall energy recovery from waste can be enhanced by using US treatment followed by energy generating processes for high organic loading wastewater process.

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