Design of an Integrated Electrocoagulation-Microfiltration System for Community College Laboratory Experiments

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Abstract

In collaboration with faculty at NorthWest Arkansas Community College (NWACC) an integrated electrocoagulation-microfiltration (EC-MF) system was designed for use in laboratory experiments as a part of a National Science Foundation Research Experiences for Teachers (RET) program. Here, the two participants gained knowledge in the field of wastewater treatment by working with both graduate and undergraduate researchers to treat different types of wastewaters such as produced water and textile wastewater.

The EC-MF process was built at University of Arkansas (U of A) including five EC units with one MF cell. A custom-built polycarbonate batch EC reactor having dimensions of 7 cm x 11 cm x 14 cm with a total volume of 1078 cm^3 was used to conduct all the EC experiments. Five electrodes (aluminum) were fitted vertically inside the reactor with a 10 mm inter electrode distance. A DC power supply was connected to each EC reactor using a bipolar series (BPS) configuration. The current was tested in the range of 1 to 9.5 A, while the reaction time was in the range of 5 to 90 min. After each specified EC operating condition, sludge is formed and separated using MF. A custom-built MF cell was employed having a surface area of 33.75 cm^2. A commercially available polyethersulfone (PES) membrane having a porosity of 80.4%, 0.1 μm pore size and 43.7° air contact angle was used in all the MF experiments.

The participants were initially trained to use the laboratory scale EC unit at U of A by treating wastewater at different operating conditions. Then, they worked on using MF to further filter the EC treated water. A number of experiments were conducted using model and real wastewater to demonstrate visually the removal of contaminants from water by applying EC then MF. The set up was then transferred to NWACC where it was initially used as a demonstration experiment. Lesson was created to demonstrate the EC-MF experiments in class at NWACC.

Keywords

Wastewater treatment, electrocoagulation, microfiltration, membrane separations, water recycle, student paper

Introduction

Increase in water demand due to population growth, climate change, and uneven economic development including irrigation, urban supply, and hydropower has been considered as a growing problem in many countries [1]. An increase of about 55% in global water demand is expected by 2050. This is due to a significant increase in demand for water resulting from

industrialization (+400%), thermal electricity production (+140%), and domestic consumption (+130%) [2].

Treating and reusing wastewater in a wide range of applications, such as livestock or wildlife watering, hydraulic fracturing, irrigation and various industrial uses (e.g., dust control, power plant makeup water, fire control, and vehicle washing), can play an important role in reducing the water demand [3]. However, wastewater is very challenging to treat via conventional methods (e.g., coagulation, flocculation, sedimentation, centrifugation, oxidation, multistage flash distillation, and filtration) due the presence of a wide range of contaminants such as inorganic salts, suspended solids, organic carbon, heavy metals, nutrients, and pathogens [4].

The need for applying treatment trains is essential to meet the water discharge standards. Treatment trains may involve the integration of two or more-unit operations such as sedimentation or coagulation (preliminary treatment) with precipitation or flocculation (primary treatment). In addition, producing high quality water requires the integration of secondary treatment technologies such as biodegradation, filtration, or adsorption with tertiary treatment methods like oxidation or membrane filtration [5], [6].

Here, we focused on using the integrated EC-MF processes to treat different types of wastewaters such as produced water and textile wastewater. The EC unit was used as a primary treatment method to remove most of the total suspended solids (TSS) and insoluble organic compounds prior to MF [7]. Thus, using EC can help decreasing the fouling tendency of the membrane in MF.

The main goal in this work was for the two-community college faculty to gain knowledge in the field of wastewater treatment by working with both graduate and undergraduate researchers to treat different types of wastewaters as a part of the RET program. The work started by training the two RET participants in the use of a laboratory scale EC unit at U of A to treat wastewaters at different operating conditions. After that, both RET participants worked on using MF to further filter the EC treated water.

Five EC units with one MF cell was built and tested at U of A to make sure the integrated EC-MF process worked properly with no leaks. Then, the whole process was moved to NWACC to be established and tested by the RET participants. Most of the results presented here was obtained at U of A during the training and testing period. Due to the COVID 19 pandemic, we could not do more experiments at NWACC. The future plan is to conduct more experiments using synthesis textile wastewater at NWACC to demonstrate the removal of dyes in class.

Experimental Work

Figure 1 shows the experimental set up used in this work. A custom-built polycarbonate batch EC reactor having dimensions of 7 cm x 11 cm x 14 cm with a total volume of 1078 cm^3 was used to conduct all the EC experiments. Five aluminum electrodes were fitted vertically inside the reactor with a 10 mm inter electrode distance. A DC power supply was connected in a bipolar series (BPS) configuration to the first and last electrodes in the EC reactor.

The EC operating conditions was optimized by testing the effects of current, time, pH, and inter electrode distance on the removal efficiency of TSS, turbidity, and total organic carbon (TOC). The current was tested in the range of 1 to 9.5 A, while the reaction time was in the range of 5 to 90 min. In addition, three pH values (5, 7, and 9) with two inter electrode distance (5 mm and 10 mm) were tested with respect to removal efficiency of TOC and electrical energy consumption (EEC). After each of the specified EC operating conditions, the sludge formed is separated using MF

MF was conducted immediately after EC using a custom-built MF cell having a surface area of 33.75 cm^2. A commercially available PES membrane having a porosity of 80.4%, 0.1 μm pore size and 43.7° air contact angle was tested in all MF experiments. After conducting the EC experiment, the entire volume of the EC treated feed water (about 3 L) was placed in the MF feed tank. The feed was initially recirculated through the membrane module by means of a diaphragm pump (P800, King-Kong, Taiwan) while the permeate outlet was closed.

The MF operating conditions were as following: feed pressure of 110 kPa with permeate side pressure being atmospheric. Once steady state had been reached, the permeate outlet was opened and permeate was collected in the permeate tank. The permeate tank was placed on a computer-connected analytical balance (Mettler Toledo, Columbus, OH) to calculate the permeate flux based on the rate of permeate collection. A total recovery of 80% of the EC treated water was obtained when using the integrated EC-MF process. A cleaning cycles were applied after each MF experiment by circulating DI water for 1 hour prior to starting a new experiment.
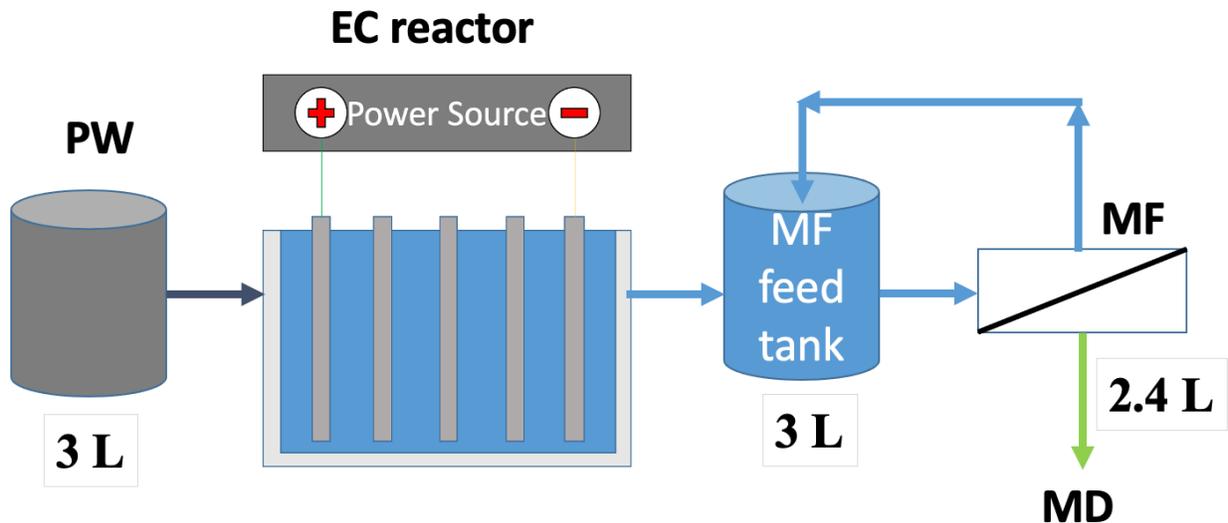

Figure 1. Diagram showing the combined EC-MF system

Results and Discussion

Raw produced water samples (PW 1 and PW 2) were sent to the Arkansas Water Resources Center, University of Arkansas (Fayetteville, AR) to be analyzed. Tables 1 shows the water quality parameters of PW 1 and PW 2, respectively, as received from the hydraulic

fracturing facility in terms of TDS, TOC, TSS as well as inorganic compounds. Both PWs were treated with chlorine dioxide at the hydraulic fracturing facility prior to receival. As can be seen the TDS is very high. Chlorine, calcium, magnesium potassium and sodium are the majority of the inorganic ions present. The TOC and TSS are 393 mg L^{-1} and 172.8 mg L^{-1} for PW 1 and 120.0 mg L^{-1} and 131 mg L^{-1} for PW 2, respectively. It is important to note that the quality of the PW in general is highly variable (highly impaired), and this will affect the efficiency of the treatment operations.

Table 1 shows characterization of raw produced water collected from different location in Texas.

Parameter	Unit	Raw PW 1	Raw PW 2
TDS	mg L-1	100822.8	245300
TOC	mg L-1	393	120
TSS	mg L-1	172.8	131
Turbidity	NTU's	178	6
pH	-----	7.3	6.7
Chloride	mg L-1	75382.8	156820
Sulfate	mg L-1	644.8	478
Iron	mg L-1	3.85	0.2
Boron	mg L-1	30.05	97
Calcium	mg L-1	1332.2	30500
Magnesium	mg L-1	210.54	5454
Manganese	mg L-1	0.21	0.1
Nickel	mg L-1	0.05	0.2
Potassium	mg L-1	1217	4331
Aluminium	mg L^{-1}	0.0	0
Sodium	mg L-1	46127.6	63600
Conductivity	µS/cm	157100	323400

The effects of current, time, pH, and inter electrode distance were investigated to optimize the operating conditions of the EC system. In this work, a range of current (1 to 9.5 A) at different reaction time (5, 20, 60, and 90 min) was studied to reach a high removal efficiency of TOC. We tested a 5 mm and 10 mm inter electrode distances.

Figure 2 shows the removal efficiency of TOC, TSS, and turbidity as a function of pH (5, 7, 9) and inter electrode distance (5 mm or 10 mm). It can be seen that a high removal efficiency of TSS and turbidity (more than 90 %) is achieved at different pH values, while the highest removal efficiency of TOC (58 %) is obtained at pH 7. By changing the pH from 5 to 9 there is no significant enhancement in the removal efficiency of TOC as shown in Figure 2.

The electrical energy consumption at different pH and inter electrode spacings is calculated as illustrated in Figure 2. At pH 7, the lowest electrical energy consumption is obtained about 5 KW h / m^3. Adjusting the pH to 5 or 9 can lead to increase in the electrical energy consumption as seen in Figure 2. The inter electrode distance has a significant effect on

the electrical energy consumption. Increasing the inter electrode distance from 5 to 10 mm can lead to a significant decrease in the electrical energy consumption as seen in Figure 2 (pH 5 from 30.2 to 18.8; pH 7 from 8.9 to 5; pH 9 from 48.7 to 24.8 KW h / m^3).

The effects of reaction time on the removal efficiency of TOC, TSS, and turbidity were also investigated in this work. A high removal efficiency of both TSS and turbidity was achieved at a variety of reaction times as shown in Figure 3. However, the highest removal efficiency of TOC (68%) was obtained at 90 min reaction time. Increasing the reaction time from 20 to 60 min can increase the removal efficiency of TOC from 55% to 67%, while increasing the time further to 90 min can lead to a slight increase in the removal efficiency of TOC to about 68%. As we can see, working at a reaction time more than 60 min is not practical due to the slight increase in removal efficiency with high electrical energy consumption. Further from a practical perspective it is too long for a laboratory exercise. The electrical energy consumption increased from 8.9 to 103 KW h / m^3 when increasing the reaction time from 20 to 60. At 90 min, the highest recorded electrical energy consumption is obtained about 217 KW h / m^3.

Figure 3 also shows the effect of inter electrode distance on both the removal efficiency and the electrical energy consumption. It can be seen that there is no significant change in the removal efficiency when increasing the inter electrode distance from 5 to 10 mm. However, a remarkable decrease was found in the electrical energy consumption if the inter electrode distance increased from 5 to 10 mm. Table 2 gives the conditions of each configuration used in Figure 2 and Figure 3

The TOC removal given in Table 3 shows the treatment of PW 2 using EC at a larger scale (5 L EC volume). As can be seen, the TOC removal increased from 17.9 % to 29.3 % as the current increased from 1 to 5 A. Higher currents and longer reaction times were investigated to obtain a high TOC removal. However, a small increase in TOC removal was observed when increasing the current above 8A for a reaction time of 20 min. On the other hand, a significant increase in power costs was obtained when increasing reaction time and current during EC. Consequently, all EC experiments used in MF (Table 3) consisted of treating PW 2 for 20 min using a current of 8 A. The TOC in the treated PW 2 that was the feed for MF was 64 mg L^{-1}.

The variation of permeate flux with time during MF is shown in Figure 4. Two repeat runs were obtained in this work. The initial flux was 28 L m^2 h^{-1} for the first run. After 320 min, the flux gradually decreased to 10 L m^2 h^{-1}. The deposition of flocs on the membrane surface was the main reason for flux decrease with time [8]. A very similar flux profile was obtained when the membrane was regenerated by simply recirculating the DI water for 1 hour and tested with a second batch of EC treated PW 2. The initial flux was 26 L m^2 h^{-1}. The result suggests that there is minimal irreversible fouling. The initial permeate flux could be regenerated over 10 runs. The result suggests that EC was effective at flocculating the organic compounds and particle matter that could plug the pores of the MF membrane. In addition, most of the flocs that had adhered on the membrane surface were removed after recirculating DI water for 1 hour.
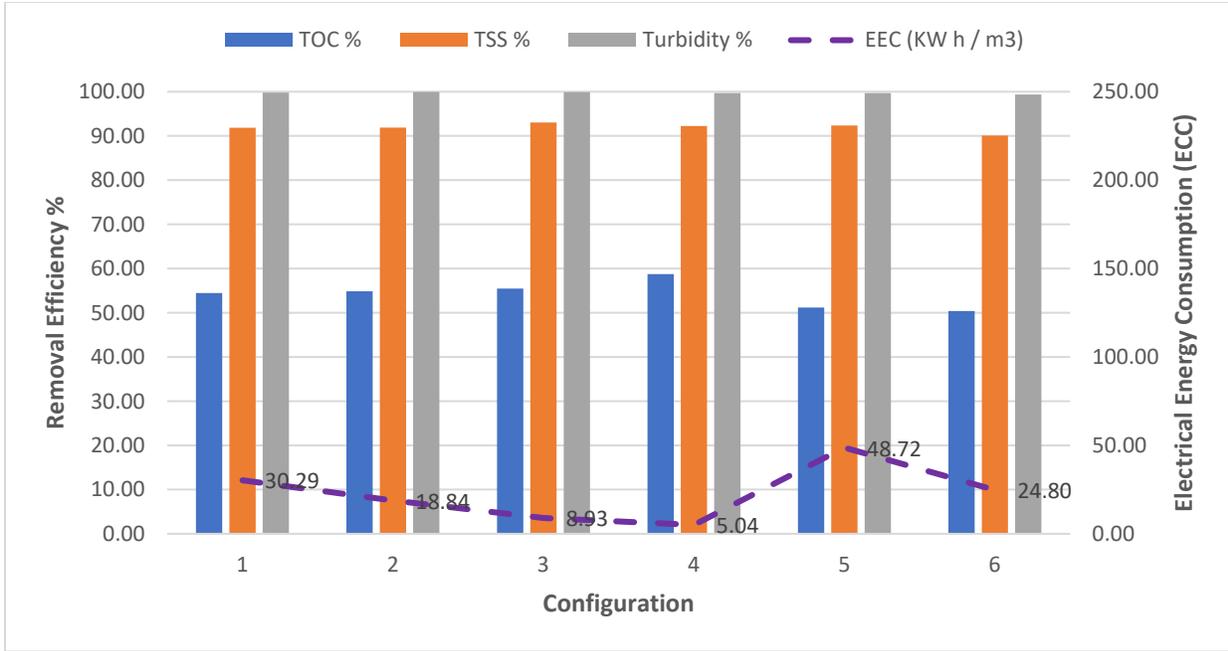
Figure 2. The removal efficiency of TOC, TSS, and turbidity as a function of pH and inter electrode distance (Table 2). The electrical energy consumption (EEC) is plotted using the secondary vertical axis
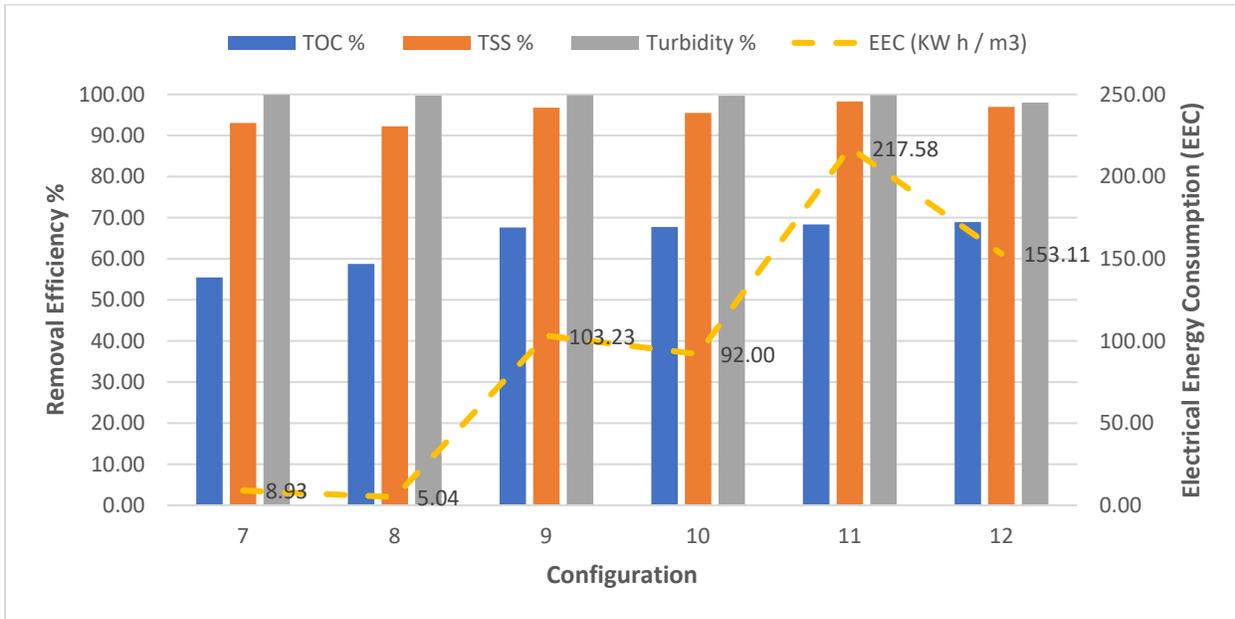

Figure 3. The removal efficiency of TOC, TSS, and turbidity as a function of time and inter electrode distance (Table 2). The electrical energy consumption (EEC) is plotted using the secondary vertical axis

Table 2. The conditions of each configuration in Figure 2 and Figure 3

Configuration	Conditions
1	PW 1, 8 A, 20 min, 5 mm, 6 Al, BPS, pH 5
2	PW 1, 8 A, 20 min, 10 mm, 3 Al, BPS, pH 5
3	PW 1, 8 A, 20 min, 5 mm, 6 Al, BPS, pH 7
4	PW 1, 8 A, 20 min, 10 mm, 3 Al, BPS, pH 7
5	PW 1, 8 A, 20 min, 5 mm, 6 Al, BPS, pH 9
6	PW 1, 8 A, 20 min, 10 mm, 3 Al, BPS, pH 9
7	PW 1, 8 A, 20 min, 5 mm, 6 Al, BPS, pH 7
8	PW 1, 8 A, 20 min, 10 mm, 3 Al, BPS, pH 7
9	PW 1, 8 A, 60 min, 5 mm, 6 Al, BPS, pH 7
10	PW 1, 8 A, 60 min, 10 mm, 3 Al, BPS, pH 7
11	PW 1, 8 A, 90 min, 5 mm, 6 Al, BPS, pH 7
12	PW 1, 8 A, 90 min, 10 mm, 3 Al, BPS, pH 7

Table 3. Percentage removal of TOC for different currents and reaction times using PW 2.

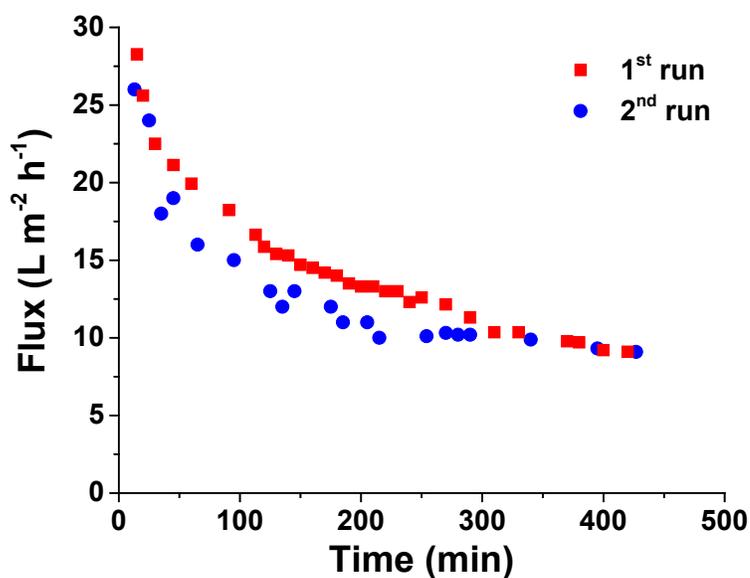| EC Operating Conditions	% TOC Removal
1 A, 5 min	17.9
5 A, 5 min	29.3
8 A, 20 min	46.4
9.5 A, 20 min	48.45

Figure 4. Variation of MF permeate flux with time

The experimental system was set up at NWACC. The electrocoagulation sub-system was used as a laboratory exercise prior to the COVID-19 pandemic. Figure 5 shows the first cohort of students running the experiment. It is expected the two subsystems will be run by two different laboratory groups simultaneously in spring 2022. Based on the experiences of the first cohort of students a list of pedagogical goals will be prepared prior to spring 2022. The student learning outcomes will be assessed at the end of spring 2022 and compared with the pedagogical goals we developed prior to conducting the experiments.
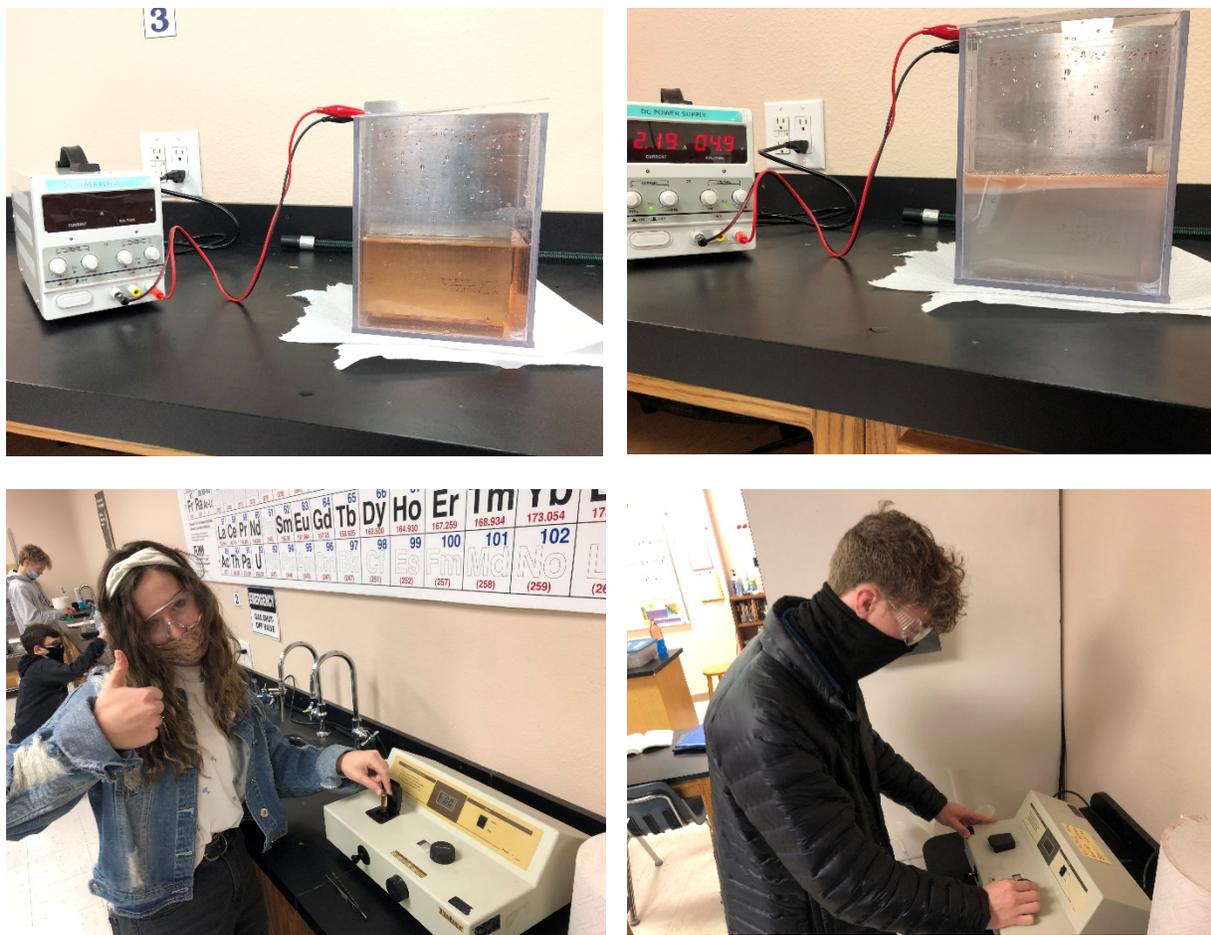

Figure 5 First cohort of students at NWACC using the electrocoagulation sub-system as a laboratory exercise.

Conclusion

The EC-MF system was designed and tested by the two faculty from NWACC at the U of A. The goal of this work was to provide knowledge and train the two RTE participants on conducting laboratory experiments by working with both graduate and undergraduate researchers to treat different types of wastewaters. After testing the integrated EC-MF system at U of A, the whole process was moved to NWACC to be used as a part of the experimental lesson given in the class.

Several EC parameters such as current, time, pH, and inter electrode distance were tested to obtain a high removal efficiency of TSS, turbidity, and TOC. It is clear that increasing the current from 1 to 8 A and the reaction time from 5 to 20 min can provide a good removal efficiency of TSS, TOC, and turbidity. However, increasing the reaction time further to 90 min can lead to slight increase in the TOC removal.

The effect of pH and inter electrode distance was not significant on the removal efficiency of TSS, TOC, and turbidity. On the other hand, the effect of inter electrode distance on the electrical energy consumption was remarkable. A significant decrease was found in the electrical energy consumption if the inter electrode distance increased from 5 to 10 mm.

The integrated EC-MF process showed that EC can lead to significant decrease in the TSS and turbidity with adequate reduction in the TOC, while MF can efficiently remove the particulate matter generated by EC. The ability to clean and recover the MF membrane by simply recirculating the DI water for 1 hour indicates that there is minimal irreversible fouling. The experimental set up was established to simultaneously allow two groups of students to work on the EC and MF sub-systems. Thus, the two groups will collaborate while conducting their individual group experiments. We will analyze the success of this experimental unit over the next year as a number of students groups complete their experiments.

Acknowledgements

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University of Minnesota	USA	Chemical Engineering	Doctor of Philosophy, 1992
Thesis: The Best Hollow Fiber Module			