



# **Application of Radiofrequency for Decolorization, Floc Formation, and Microorganism Inactivation**

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**ABSTRACT:** The use of radio frequency for water and wastewater treatment is a topic that has not been extensively explored. In this study, the effect of a HydroFlow S38 device (HydroPath Holdigs) inducing 150 KHz radio frequency (RF) has been investigated, removing color, forming coagulant flocs and their sedimentation, and the removal of bacteria. Experiments were first conducted on synthetic samples, and then on landfill leachate from the Aradkooh waste processing and landfilling complex (Kahrizak) in Tehran, Iran. The results of the experiments showed that RF had little to no effect on de-coloring in the absence or presence of sodium hypochlorite. Also, the coagulation and flocculation of ferric chloride remained unaffected. However, the use of RF was shown to reduce the number of bacteria significantly. The inductance of RF alone, without any other aid or chemical/physical treatment, was able to reduce the bacterial count by 35%. These findings provide motivation for future research regarding the use of RF for bacteria inactivation.

**KEYWORDS:** Radio frequency treatment; floc settling; color removal; disinfection

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## **1. Introduction**

Landfill leachate (LFL) management is one of the main challenges at MSW landfill sites [1]. Leachate is the liquid that forms in the landfill and has both soluble and suspended solids in its composition [2]. Whenever the water content of the landfill exceeds its field capacity, whether due to the infiltration of external water into the landfill, compaction of the waste, or any other reason, the excess water flows through the waste and forms the leachate. Due to the variety of wastes in landfills, the composition of LFL is very complex and changeable, which creates treatment problems [3].

One of the concerns about LFL treatment is the existence of various contaminants, with concentrations varying from place to place and time to time [4]. Landfill age and waste composition are the two main factors that affect the LFL composition and concentration of contaminants [5]. Therefore, landfill sites are often categorized based on the age of the waste: young landfills (less than 5 years old), intermediate landfills (5 to 10 years old), and old landfills (more than 10 years old). Table 1 provides some characteristics of LFL according to the age of the landfill [6]. So far, several methods have been developed for LFL treatment [7], including physical treatment (such as adsorption [8] and filtration [9]), chemical treatment (such as chemical oxidation [10]) and biological treatment (such as using membrane bioreactors) [11]

and sequencing batch reactors [12]. Each of these methods has their own advantages and disadvantages, but none of them can treat LFL alone [13].

**Table 1.** Some leachate characteristics based on landfill age [14].

Parameters	Young	Intermediate	Old
Age (years)	<5	5-10	>10
pH	3-7	6-8	>7.5
COD (mg/l)	4000-90,000	1000-30,000	<3000
BOD (mg/l)	2000-50,000	500-15,000	<300
BOD/COD	0.5-1	0.1-0.5	<0.1
TOC/COD	<0.3	0.3-0.5	>0.5
Biodegradability	High	Medium	Low

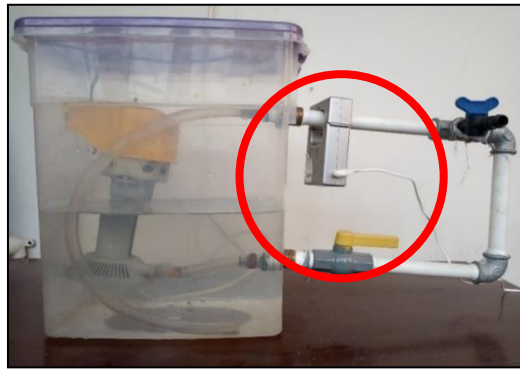
In the current study, the effect of radio-frequency (RF) inductance on LFL and some of its characteristics has been investigated. Using RF treatment can be considered a kind of physical treatment. In physical methods, in contrast to chemical methods, no chemicals will be added and no chemical reactions are expected; hence, physical methods can often be environmentally-friendly.

According to a review of the literature on treating fluids with RF, the most common areas of research appear to be prevention of fouling and scale formation in plumbing tubes and heat exchangers [15–18]; prevention of scale formation or corrosion of oilfield extraction wells [19], [20]; control and killing of bacterial biofilms [18], [21]; and treatment of dye-containing wastewater [22]. However, to the best of the authors' knowledge, the effect of RF inductance on LFL has not been studied yet. More specifically, this study has the following three objectives: (i) evaluate the effect of RF inductance on decolorization; (ii) evaluate the effect of RF inductance on coagulation and settling of coagulant flocs; and (iii) evaluate the effect of RF inductance on reduction of bacterial count.

## 2. Materials and Methods

In this study, an S38-type HydroFlow (HF) device, developed by Hydropath Holdings, was used in order to induce RF into the liquid in the system. The HF device was generously provided to the research group by Radin Gostar Sina (rgspath.com), the producer's official representative in Iran. The working voltage of the HF is 1.2 V and it can easily be installed on any type of plastic or metal tube with a diameter of up to 1.25 inches (38 mm). The HF device is capable of generating and inducing RFs with frequencies between 120 and 200 kHz.

All of the experiments were carried out in a system composed of a 12 L container, circular plumbing, a semi-immersed pump, a flow-off button, and a sampling valve (Figure 1). By installing the HF on the plumbing and turning it on, RF will be induced into the circulating liquid in the system, and by comparing the characteristics of the liquid after treatment with the baseline scenario (absence of HF), the effect of RF inductance can be discerned. Circulating the liquid in the system ensures that all of the liquid has been subjected to the RF without any dead spots. Initially, the experiments were carried out on synthetic waste, followed by the treatment of LFL from the Aradkooh waste processing and landfill complex (Kahrizak).



**Figure 1.** The experimental setup used in this study. The HF device is shown with the red circle.

### 2.1. The effect of RF inductance on decolorization

A combination of tap water and black calligraphy ink was used as synthetic wastewater in decolorization experiments. Light absorption of the liquid in the visible wavelength range (400 to 700 nm) was used to measure any changes in the variation in dye concentration. For the first set of experiments, 7 L of tap water was mixed with 0.6 mL of black ink in the system. After turning the pump on, the solution circulated for 1 min in the system without induction. At that moment, a sample was taken from the solution as a representative of the baseline scenario. Then, the HF was turned on and the solution was exposed to RF for about 90 min. After 90 min, another sample was taken from the solution as a representative of the RF-aided scenario. Finally, the light absorption of both samples was measured with a DR5000 spectrophotometer and compared with each other.

In the second set of experiments, the effect of RF inductance on de-coloring in tandem with NaClO (5% purity) was investigated. The aim of this experiment was to see if RF inductance could enhance the decolorization performance of the bleaching chemical. In this experiment, a system with the ability to adjust dosing rate was used for the continuous injection of liquid NaClO. For the experiment, 7 L of solution with 0.35 ml of ink was allowed to circulate in the system for 1 minute. A sample was then taken before the NaClO solution was injected at a rate of 4 ml/s (240 ml/min). Samples were taken at 5-minute intervals. Next, the same procedure was repeated, but this time the HF was turned on during the experiment. Because of the high reactivity of NaClO, the taken samples were introduced to the spectrophotometer immediately after sampling. Here, in addition to measuring light absorption of the solution in the visible wavelength range, the 200 to 400 nm range was also investigated. It should be noted that measuring light absorption in the visible and UV ranges requires their own cells, as shown in Figure 2.



**Figure 2.** Cells for light absorption measurement with the spectrophotometer (left: UV cell, right: visible cell).

## 2.2. The effect of RF inductance on coagulant floc settling

In this part of the study, the possible effect of RF on  $\text{FeCl}_3$  (40% purity) floc formation and settling were investigated.  $\text{Ca(OH)}_2$  powder (95% purity) or NaOH (12.5% purity) were used to adjust the pH of the solution. The experiments were carried out at 3 different pH values of 5, 6 and 7.

First, 7 L of tap water was poured into the system and the pump was turned on. After one minute, a predetermined amount of  $\text{FeCl}_3$  was injected into the water. The resulting solution was circulated in the system for another 4 min. Then, the determined amount of alkaline material was added to the solution. The final solution was circulated in the system for 5 minutes. After that, the pump was turned off and the gradual sedimentation of suspended solids was recorded by a camera for 30 min. The same procedure was repeated with and without the HF device turned on. It should be noted that the depth and height of the container were graduated so that the thickness of the sludge blanket from the bottom of the container could be measured at any time. Tables 2 and 3 show the details of the conducted experiments.

**Table 2.** Experimental runs with 95% purity  $\text{Ca(OH)}_2$  used as the alkali for adjusting pH.

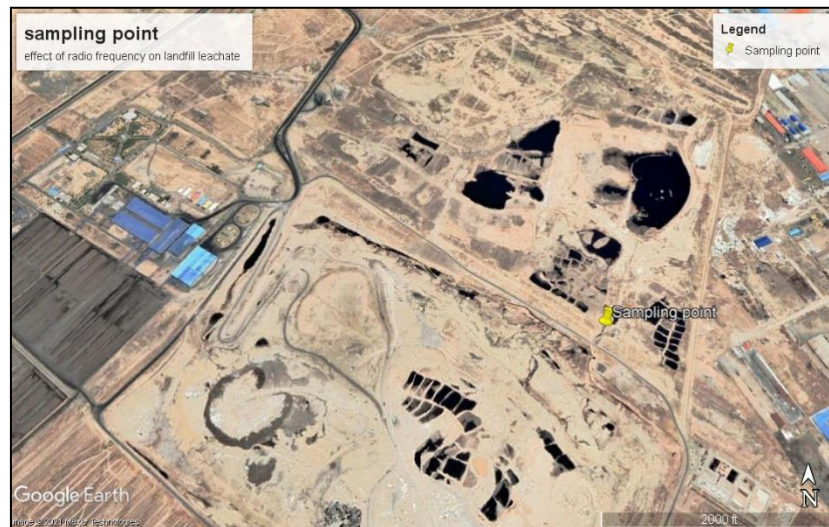
Materials	Water (L)	$\text{FeCl}_3$ (ml)	$\text{Ca(OH)}_2$ (g)	HF device	pH value
First Exp.	7	42	30	Off	7
	7	42	30	On	7
Second Exp.	7	42	25	Off	6.05
	7	42	25	On	6.05
Third Exp.	7	42	20	Off	5.2
	7	42	20	On	5.2
Forth Exp.	7	15	9	Off	7.6
	7	15	9	On	7.6
Fifth Exp.	7	15	8	Off	6.6
	7	15	8	On	6.6
Sixth Exp.	7	15	7	Off	5.5
	7	15	7	On	5.5

**Table 3.** Experimental runs with 12.5% purity NaOH used as the alkali for adjusting pH.

Materials	Water (L)	$\text{FeCl}_3$ (ml)	NaOH (ml)	HF device	pH value
First Exp.	7	15	30	Off	7
	7	15	30	On	7
Second Exp.	7	25	25	Off	6
	7	25	25	On	6
Third Exp.	7	20	20	Off	5
	7	20	20	On	5

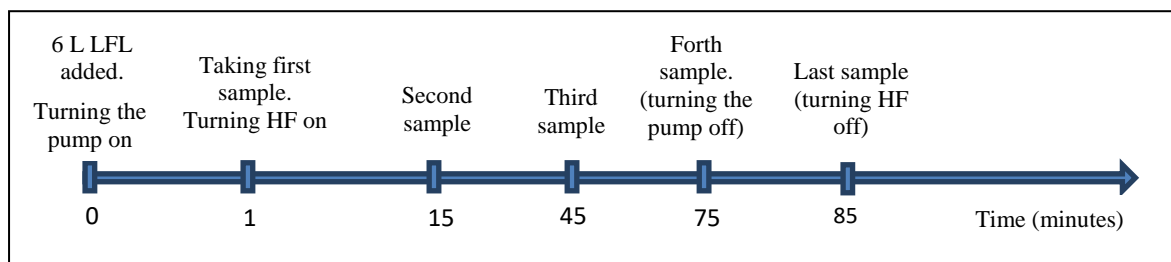
## 2.3. Landfill leachate sampling and experiments

After conducting experiments on synthetic wastewater, leachate was sampled from the Aradkooch waste processing and landfilling complex (Kahrizak), located in southern Tehran, Iran. Since one of the objectives of this study was to evaluate the effect of RF inductance on the bacterial community, samples were taken from young leachate with high bacterial activity. The coordinates of the sampling point were  $35^{\circ}27'42.6''$  latitude and  $51^{\circ}20'21.0''$  longitude (Figure 3). Leachate samples were stored in a refrigerator at  $4^{\circ}\text{C}$  as soon as possible in order to prevent decay, biological activity, or alteration in the properties as much as possible.



**Figure 3.** Landfill leachate sampling point (coordinates: 35°27'42.6" latitude and 51°20'21.0" longitude).

To begin the LFL treatment, 6 L of the sample were poured into the system and the pump was activated. After one minute, two samples were taken as a representative of the raw leachate, one for measuring bacterial count and one for measuring pH, EC, and color. The sample related to the bacterial count was immediately put in a bucket containing ice and water in order to stop further biological activity as much as possible. After one minute of turning the pump on, the HF device was also turned on. Subsequent samples were taken at 15 min, 45 min, and 75 min after turning the HF on. After 75 minutes, the pump was turned off while the HF was still on. Another sample was taken 10 minutes after turning the pump off to measure pH, EC, and color. Because of the strength of the color of the leachate, the samples were diluted 1:1 with distilled water so that the spectrophotometer could measure the light absorption without error. The experimental steps are shown in Figure 4.



**Figure 4.** Experimental steps to evaluate the effect of RF inductance on LFL.

The samples taken for measuring the bacterial count were prepared at four different dilution rates of 1:10, 1:100, 1:1000, and 1:10000 in accordance with a modification of the protocol described in the 9125 Heterotrophic Plate Count Method [23].

### 3. Results and Discussion

In the first round of de-coloring experiments, the RF inductance alone showed no effect whatsoever on the light absorption of the solution. The results of measuring the light absorption of the solution at various wavelengths by the spectrophotometer are shown in Table 4. As can be seen, no change has occurred with or without the HF device.

**Table 4.** Light absorption of ink solution before and after RF inductance

Wavelength (nm)	450	500	550	600	650
Absorption (baseline scenario)	1.773	1.653	1.548	1.451	1.361
Absorption after 90 min of RF inductance (RF-aided scenario)	1.772	1.656	1.549	1.454	1.365

That is why the second set of decolorization experiments were carried out, in order to test whether or not RF inductance could have any synergic effect with bleaching. Here, again, the use of the HF device did not lead to any substantial enhancement of color removal with NaClO. In other words, the value of light absorption by the solution was more or less the same in both the baseline and the RF-aided scenarios, for both the visible and UV wavelength range. The results for the visible range are displayed in Table 5.

**Table 5.** Detailed results of the adsorption of the solution during continuous injection of liquid NaClO for both the baseline and RF-aided (HF) scenarios, showing no significant difference between the two.

Wavelength (nm)		450		500		550		600		650	
Sample number	Time (min)	Baseline	HF	Baseline	HF	Baseline	HF	Baseline	HF	Baseline	HF
1	0	1.778	1.782	1.662	1.67	1.561	1.567	1.467	1.472	1.377	1.376
2	5	1.277	1.157	1.218	1.112	1.155	1.061	1.098	1.015	1.042	0.966
3	10	1.004	1.047	0.953	1.002	0.911	0.973	0.887	0.941	0.858	0.897
4	15	1.053	1.056	1.013	1.016	0.974	0.972	0.94	0.93	0.896	0.884
5	20	1.056	1.009	1.005	0.964	0.964	0.925	0.922	0.885	0.889	0.858
6	25	1.065	0.977	1.011	0.931	0.969	0.891	0.93	0.857	0.896	0.821
7	30	1.063	0.958	1.005	0.913	0.966	0.878	0.925	0.839	0.889	0.798

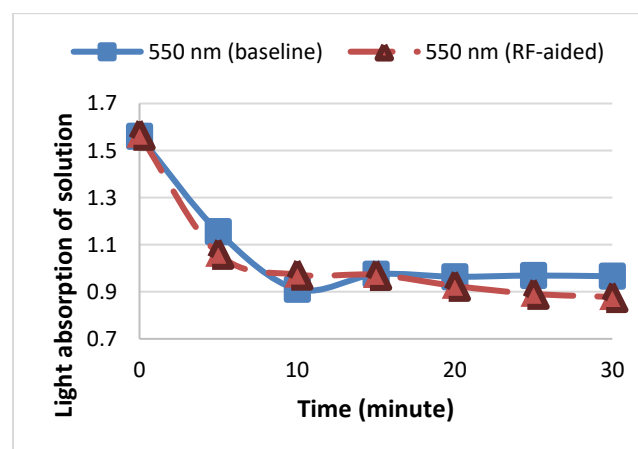
**Figure 5.** Visual comparison of changes in absorption of the water-ink solution, for baseline and RF-aided scenarios with continual injection of NaClO.

Figure 5 visually demonstrates that, during the first 10 minutes or so, the NaClO proceeds to react with the ink regardless of whether the HF device is on or off and the extent of reaction is more-or-less the same; at times however, the RF-aided system may have had a very slight impact. These findings are in line with previously reported findings by Dimitriou et al. (2017) who also found that RF inductance alone had no effect on decolorization of dye aqueous solution. Moreover, in that study, it was shown that the use of the RF device had a very slight synergic effect with ozonation of the solution [22]. Three commonly-used azo-reactive dyes (namely C.I. Reactive Yellow 84, C.I. Reactive Red 120 and C.I. Reactive Blue 198) were used in that study, and RF inductance showed a slight synergic effect with ozonation (5-10%

destruction of color) just in the first 15 min of experiment; while the values of color removal were almost the same in the remainder of the experiments [22].

In the UV range, no strong effect or difference could be observed between the baseline and RF-aided scenarios. This can be interpreted as no chemical reactions being affected by the presence of radio frequency inductance within the system. Following the observation that RF inductance was not successful at color removal, either in the presence or absence of an oxidizer, the study moved on to investigate the effect of RF inductance on coagulant floc formation and settling. The experiments were carried out as explained earlier, and after closely analyzing the recorded videos, it was concluded that RF inductance had no effect on coagulation or settling of the formed flocs. The results of these experiments are shown in Tables 6 and 7.

**Table 6.** Results of coagulant floc settling experiments using  $\text{FeCl}_3$  and  $\text{Ca(OH)}_2$ .

Exp. number	Water (L)	$\text{FeCl}_3$ (ml)	$\text{Ca(OH)}_2$ (g)	pH of solution	Did flocs form and settle?	Did RF inductance have any effects?
1	7	42	30	7	Yes	No
2	7	42	25	6.05	Yes	No
3	7	42	20	5.2	No	No
4	7	15	9	7.6	Yes	No
5	7	15	8	6.6	Yes	No
6	7	15	7	5.5	No	No

**Table 7.** Results of coagulant floc settling experiments using  $\text{FeCl}_3$  and  $\text{NaOH}$ .

Exp. number	Water (L)	$\text{FeCl}_3$ (ml)	$\text{NaOH}$ (ml)	pH of solution	Did flocs form and settle?	Did RF inductance have any effects?
1	7	15	30	7	Yes	No
2	7	15	25	6	Yes	No
3	7	15	20	5	No	No

In fact, two deductions were made after analyzing the recorded videos:

1. The rate of sedimentation of the suspended flocs in both scenarios (HF on or off) was the same, and the height of the sludge blanket from the bottom of the system container was equal at corresponding times.
2. The RF inductance was not able to alter the shape or texture of the  $\text{FeCl}_3$  flocs. More specifically, it did not break down flocs when they formed, nor did it help the formation of flocs when the conditions were not conducive to their formation.

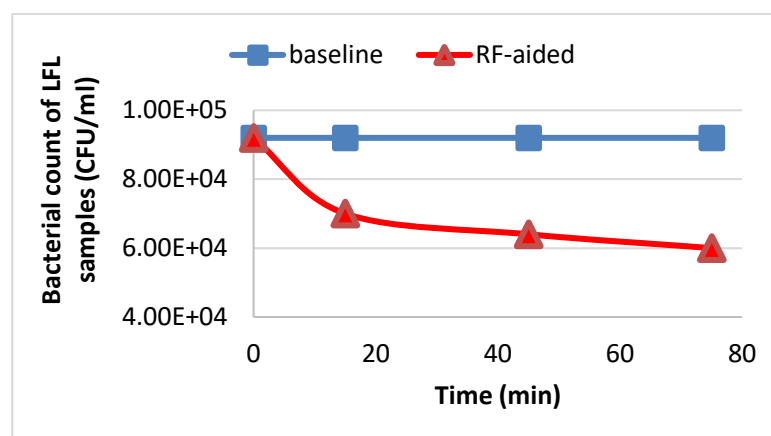
Although it has been claimed in the HF patents that the HF device has effects on flocculation and can improve the settling rate of flocs [24], in this study, no effect was observed. This could be because only one type of coagulation was used (ferric chloride) in this study. In future studies, the effect of the HF on other flocs such as polyaluminum chloride could be explored. In addition, in the current study, the coagulant was used alone without the existence of suspended particles in the system. In other words, the coagulant was allowed to form flocs with itself. In systems where other solid particles exist, the interface between the coagulant and the suspended matter might be affected by the HF. After acknowledging that the use of the RF did not exhibit any suitable effects on color removal or floc formation, the study proceeded to test the effects of the HF device on leachate samples. Similar to the initial experiments on synthetic wastewater, RF inductance showed no effect on decolorization of leachate. However, results indicated that RF inductance can significantly reduce the bacterial count of the LFL. Table 8

shows the result of the bacterial count of samples taken at various times with and without the HF device. Evidently, the use of the HF device leads to a marked reduction in bacteria.

**Table 8.** Bacterial count of leachate samples, comparison of baseline and RF-aided scenarios.

pH	Time (minutes)	Number of bacterial colonies in one ml of LFL (CFU/ml)	
		Baseline scenario	RF-aided scenario
7.7	15	$9.2 \times 10^4$	$7 \times 10^4$
	45	$9.2 \times 10^4$	$6.4 \times 10^4$
	75	$9.2 \times 10^4$	$6 \times 10^4$

As shown in Table 8, the number of bacterial colonies in the untreated leachate was  $9.2 \times 10^4$  CFU/ml and remained the same if the HF device was off, regardless of the amount of time it circulated in the system. However, by using the RF induction on the leachate, the number of bacterial colonies in the leachate decreased to 7104 and then to 6.4104 and 6104 CFU/ml after 15, 45, and 75 min, respectively. As a result, RF inductance could decrease the bacterial community by a quarter in the first 15 minutes and by about 35% depending on the induction duration. The results are visually shown in Figure 6. Based on the physical function of the HF device, the possible reason for the decrease in bacterial count can be speculated. By turning the HF on, RFs are induced in the liquid circulating in the system. RF waves rapidly oscillate from positive to negative with a mean voltage of zero. Thus, this oscillation can create zones in which the bacteria (cell bodies) in the water are alternatively positively and negatively charged. When particles such as bacteria or other suspended particles in the water have acquired a charge, water molecules adjacent to a bacterium orient and position themselves in such a way that a layer of water surrounds the bacterium. The result is that the cell membrane of the bacterium is subjected to osmotic pressure depending on the different concentrations of solute inside and outside of the membrane, which will eventually cause rupture of the membrane and the death of the bacterium [24].



**Figure 6.** Changes in bacterial count during experiments on LFL, comparison of baseline and RF-aided scenarios.

Similar findings were reported in the study of Kim et al. (2011) when direct RF electric fields were applied to cooling water circulating in a heat exchanger. The RF electric field (3.5 MHz) could control bio-fouling (near-zero fouling level) while maintaining a bacterial count under targeted values of 10,000 CFU/ml and 100,000 CFU/ml in the bulk water and sessile samples,



respectively [18]. Caubet et al. (2004) also found that radio frequency alternating electric current (10 MHz) inductance can reduce the bacterial count of a solution. In that study, it was found that radio frequency inductance can enhance antibiotic efficacy against bacterial biofilm. This effect was like the traditional “bioelectric effect”, in which direct electricity current is applied to medical wastewater in order to enhance antibiotic efficacy; while radio frequency inductance has no direct contact with the wastewater [21] and is thus safer. By analyzing the results, it can be seen that in the first 15 min of the experiment, 24% of the bacterial community was killed; while, in the following 60 min, only an additional 11% was added to the previous number. This hints at the idea that perhaps the marginal benefit of using RF for bacteria removal shrinks with longer residence times. Such findings will have to be further investigated and corroborated.

#### 4. Conclusions

In the present study, the effects of RF inductance on decolorization, coagulation and sedimentation of flocs, and bacterial count were investigated. A HydroFlow-S38 device (HydroPath Holdings) was used to induce radio frequencies in liquid within the system. Results of the experiments on synthetic wastewater showed that RF inductance had no significant effect on the decolorization of the liquid. When used alongside an oxidant (NaClO), again, the presence of the RF device had no sizable effect. These experiments were followed by an investigation of whether or not the RF device could have an impact on ferric chloride floc formation and settling. Using video recordings of floc formation and settlement at various pH levels, again, no visible differences could be observed when the RF device was used (compared to baseline tests without the RF). The volume of sludge forming from flocculation also showed no change. Finally, experiments were conducted on LFL samples collected from the Aradkooch waste processing and landfilling complex. Although RF did not aid LFL decolorization, it had a significant effect on the sample bacterial count. The number of bacterial colonies per ml of LFL decreased from  $9.2 \times 10^4$  CFU for untreated leachate to  $7 \times 10^4$ ,  $6.4 \times 10^4$  and  $6 \times 10^4$  CFU/ml, after 15, 45, and 75 min of RF inductance.

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#### Competing Interest

All authors declared no competing interest.

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