Activation of periodate using ultrasonic waves and UV radiation for landfill leachate treatment

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Abstract
In the present work, saline leachate of the Bushehr coastal city (Iran) was purified using the ultraviolet/ultrasonication wave/periodate process. The initial TDS and TOC values of the leachate studied were 7390 mg/L and 975 mg/L, respectively. During the effect of various parameters on leachate purification, the experiments were optimized at pH 3, oxidizer concentration of 4 mM, and treatment time of 120 min. The initial BOD5/COD ratio of 0.66 was reduced to 0.42 at the end of the purification time (120 min). After leachate treatment under optimal conditions, the amount of BOD5, COD, and UV254 were 451.5 mg/L, 1072 mg/L, and 12.69 cm−1, respectively. Concentrations of heavy metals in crude leachate by ICP-OES were checked. Also, the concentration of organic compounds before and after purification was determined using GC-Mass. The leachate purification kinetics followed the first-order model using the designed method. Based on the COD factor, the system energy consumption for leachate treatment was calculated to be 11.4 kWh/m3. The results showed that the system explored (UV/US/IO₄⁻) can effectively purify high salinity waste leachate.

Keywords Leachate · Ultrasonication wave · Humic acids · UV254 · Organic compound

Introduction
About one billion tons of waste are annually generated, which is approximated to reach 2.2 billion tons per year by 2025. The landfill is one of the activities that is used for waste disposal and affects the ecosystem. Around 52%, 80%, 90%, and 95% of waste is landfilled in Korea, China, Poland, and Taiwan, respectively (Renou et al. 2008; Vaverková et al. 2018). In Iran, 10,370,798 tons of solid waste are annually produced, of which 8,666,000 tons are disposed in landfills. The level of leachate production in Iran, according to unofficial states of officials involved in waste management, is about 4000 m³/day without calculating the amount of precipitation. Waste leachate, which is a type of highly polluted wastewater, is considered as one of the major environmental problems (Pasalari et al. 2019; Sivakumar and Kumar 2017; Yaashikaa et al. 2020). The widespread pollution of soil, groundwater, and surface water by leachate cause many dangers. The variability of organic and inorganic pollutants as well as severe fluctuations in leachate discharge in different seasons have caused problems to treat this concentrated wastewater (Ghanbari et al. 2020; Tripathy and Kumar 2019). Thus, choosing an efficient treatment system to treat landfill leachate is still a challenge.

Conventional physicochemical and biological methods are ineffective and researchers are looking for other effective methods (Quan et al. 2020; Zhao et al. 2020). Typically, methods such as coagulation, precipitation (Tripathy and Kumar 2019; Tripathy et al. 2019), ammonia release (Huang et al. 2017), biological processes (Tripathy and Kumar 2019), and activated carbon-based adsorption, osmosis and nanofiltration (Iskander et al. 2018), and chemical oxidation process is used for purifying leachate. Not all of these methods are very effective for leachate treatment (Joshi and Gogate 2019). Advanced oxidation processes (Miklos et al. 2018) like ozone (Quan et al. 2020; Ranjbar Vakilabadi...
et al. 2017), Fenton (Gautam et al. 2019; Zhao et al. 2020), and persulfates (Poblete et al. 2019) have been proposed as a solution for treating complex wastewaters. Practice in the use of advanced oxidation technologies (AOTs) is the enhancement of the process by using oxidants and their activation processes (Abilarasu et al. 2021). Of course, the great success of these processes depends on the type of oxidant and the activation technique. Oxidants that have a higher activation capacity will have a more effective ability to create radicals (active components) (Du et al. 2019). Periodate is an oxidizer with a potential of +1.60 V. In the presence of ultrasonic waves or ultraviolet rays, periodate can be well activated and produced radicals (Du et al. 2019). Recently, periodate has been activated in polluted aquatic environments by some researchers. Choi et al. (Choi et al. 2018) and Bokare and Choi (Bokare and Choi 2015) have studied IO$_4^-$ to reduce organic pollution in an aquatic media. Du et al. (Du et al. 2019) have tested periodate oxidants to eliminate bisphenol A. The purification of perfluorocarboxylic acid using ultrasonic waves, UV, and periodate oxidizer was reported by researchers (Lee et al. 2016).

The ultrasound wave has been combined with many processes like Fenton to improve the removal rate of target pollutants. The ultrasonic system generates high-energy sound waves to reduce pollution by generating bubbles and hydroxyl radicals (Tripathy and Kumar 2017). Equations 1–3 show the mechanism of the reaction of periodate and ultrasonic waves.

\[
\text{IO}_4^- + \text{hv} \rightarrow \text{IO}_3^- + \text{O}^{\bullet\bullet}
\]

\[
\text{O}^{\bullet\bullet} + \text{H} \leftrightarrow \text{OH}^+
\]

\[
\text{OH}^- + \text{IO}_4^- \rightarrow \text{IO}_3^- + \text{OH}^-
\]

The basic mechanism of activation of iodine radical intermediates (IO$_3^-$ and IO$_4^-$) is based on electron transfer reactions or intramolecular reactions (Bendjama et al. 2018). UV radiation can reduce pollution directly or by creating radicals (from oxidizing substances such as potassium periodate) (Cui et al. 2016). Periodate can be stimulated and activated by UV radiation with a wavelength of < 300 nm to reduce organic contaminants. The following mechanism reveals that UV-photolysis of periodate can generate radicals.

\[
\text{IO}_4^- + \text{hv} \rightarrow \text{IO}_3^- + \text{O}^{\bullet\bullet}
\]

\[
\text{IO}_3^- + \text{IO}_3^- \rightarrow \text{IO}_4^- + \text{IO}_3^-
\]

We have little knowledge about the effectiveness of the UV/US/periodate system in different environments and therefore, it is necessary to clarify and develop this part. Bendjama et al. (Bendjama et al. 2018) evaluated the effectiveness of UV/IO$_4^-$ in the marine environment and Du et al. (Du et al. 2019) studied the effect of periodate on bisphenol A oxidation, and several researchers have also studied the influence of UV/IO$_4^-$ and US/IO$_4^-$ in certain waters. But so far, few studies have been reported on the treatment of landfill leachate, in particular, those with high TDS.

High concentrations of salt can be found in waste leachate, especially in coastal cities. Fish processing processes that require large amounts of sodium chloride, high groundwater level, and wastewater from oil and gas mines can be the reasons for the high concentration of salt in the waste leachate in these areas (Darvishmotevalli et al. 2019; Moredian et al. 2020). Leachate salinity changes the liquid ionic structure and the ions toxicity and consequently reduces the effective removal of COD (Galgal et al. 2014). Therefore, for the treatment of leachate containing high salt, either membrane methods (which are expensive) should be used or other methods should be developed.

The current investigation was done to purify landfill saline leachate of Bushehr port (a coastal city in southern Iran) by activating potassium periodate with ultrasound (US) waves and ultraviolet. In the treatment of saline leachate, the simultaneous utilization of UV and US to activate periodates remains unclear. Accordingly, the overall goal of this study was to purify the saline leachate using US/UV/IO$_4^-$ approach. The influence of leachate pH, treatment time, IO$_4^-$ dose, leachate content, UV output intensity, and synergistic impact of the developed method components were explored in depth. The reduction kinetics of saline leachate pollution and the amount of energy consumed by the explored process were investigated. Organic components of leachate were identified before and after treatment.

**Experimental**

**Materials**

Sodium periodate was purchased from the Merck Company (German). NaOH and HNO$_3$ were provided by Kimia Mavad, Iran. The leachate pH was set using NaOH or HNO$_3$ with a pH meter (Mettler Toledo, Switzerland).

**Sampling of landfill leachate**

Bushehr city is located on the northern shore of the Persian Gulf with a warm climate and a population of about 200,000 people. The average annual rainfall in Bushehr is about 220 mm. The garbage of this city is transferred to a landfill at a distance of 10 km. Waste is incompletely (non-engineered) landfilled, so waste leachate is collected in pits around the site. The landfill site (28° 52' 50.72" N, 50° 52'
34.05° E) is about 3 km from the sea. This landfill has been open since 2009. About 25 L of leachate was taken from the leachate pits and immediately transported to the laboratory. The leachate sample was first purified with a paper filter and then subjected to the desired tests.

**Experimental design**

A 25-cm long cylindrical stainless-steel reactor with a diameter of 5 cm equipped with a UV-C lamp (Philips, Germany, 6 watts) in the middle was prepared for the reaction. The distance from the wall of the lampstand to the wall of the reactor was about 1.7 cm. The exact amount of leachate (200 mL) was placed inside the reactor for reaction. The reactor was put diagonally inside a sonication device (Soltec model, Italy) with a capacity of 2.75 L and a frequency of 37 kHz. All tests were done in a closed reactor in different steps. In this investigation, the variables were included leachate pH (3–11), ultrasonication time (30–120 min), concentration of periodate (0.5–5 mM), and leachate concentration (25–100%) (Moradian et al. 2020; Ranjbar Vakilabadi et al. 2017; Vakilabadi et al. 2017). To optimize each variable, only one variable in each part of the experiment was considered and the rest of the variables were kept constant. In the study of the synergistic impact of the system components, each of the parameters was examined separately and together. To determine the oxidizing power of periodate alone, leachate was treated at 4 mM periodate and pH 3 without US and UV. Periodate oxidizer and ultrasonic device were not used for testing the effect of UV alone. The leachate was tested in the reactor for 120 min with the UVC lamp on. To observe the US effect, no UVC lamp and periodate oxidizer were used and the leachate was placed in the ultrasound bath only for 120 min. The laboratory temperature was between 23 ± 1 °C and all tests were done at this temperature. The temperature of the reactor was kept constant by the flow of water when placed in an ultrasonic device (Farhadi et al. 2020; Tavasol et al. 2021). All the experiments were performed with 3 replications.

**Measurements**

All measurements were performed according to the standard methods. The COD and BOD₅ tests were done based on standard method# 5210 and ISO 5815–1: 203. TOC was measured with Shimadzu TOC-VCSN (Japan). UV absorption at 254 cm⁻¹ in the waste leachate was performed with a spectrometer (HACH DR5000, Germany). Concentrations of heavy metals were identified by ICP-OES (Agilent Varian Pro 710, Santa Clara, CA USA). Agilent 7890B gas chromatography device (Agilent, Palo Alto, CA, USA) was applied to identify organic compounds (Ahmed et al. 2022). First, the solution was completely condensed in the freezer. Then, it was diluted using methanol and injected into the device.

**Results and discussion**

**Properties of raw leachate**

Table 1 shows the composition of raw waste leachate taken from the Bushehr landfill. Concentrations of the components are largely depending on the site of the landfill, climate change, and waste sources. In general, the main characteristics of raw leachate were high organic matter and TDS above 7000 mg/L. Heavy metals in crude leachate may be due to aromatic hydrocarbons, phenolic compounds, halogenated hydrocarbons, pesticides, and pharmaceutical compounds. Heavy metals were measured in crude leachate and the results are shown in Table 1. Heavy metals such as Cd, Cr, Cu, Pb, Hg, and Zn can be problematic when combined

| Parameter          | Mean ± SD  |
|--------------------|------------|
| pH (unit of pH)    | 6.05 ± 0.21|
| EC (mS/cm)         | 11.370 ± 152|
| TDS (mg/L)         | 7390 ± 136 |
| BOD₅ (mg/L)        | 1630 ± 56  |
| COD (mg/L)         | 2450 ± 72  |
| BOD₅/COD           | 0.665      |
| TOC (mg/L)         | 980 ± 35   |
| UV₂₅₄ (nm)         | 79.8 ± 3.8 |
| N-ammonia (mg/L)   | 0.81 ± 0.20|
| Cd (mg/L)          | 0.002 ± 0.001|
| Pb (mg/L)          | 0.001 ± 0.0001 |
| Fe (mg/L)          | 209 ± 18   |
| Mn (mg/L)          | 9.59 ± 1.14|
| Cu (mg/L)          | 0.331 ± 0.08|
| Zn (mg/L)          | 0.299 ± 0.05|
| Ni (mg/L)          | 1.7 ± 0.12 |
| Na (mg/L)          | 920 ± 38   |
| B (mg/L)           | 1.55 ± 0.23|
| As (mg/L)          | 0.111 ± 0.02|
| Hg (mg/L)          | 0.001 ± 0.0001|
| Mg (mg/L)          | 438 ± 41   |
| Ca (mg/L)          | 1382 ± 106 |
| S (mg/L)           | 0.87 ± 0.13|
| Co (mg/L)          | 0.326 ± 0.10|
| Cr (mg/L)          | 0.139 ± 0.02|
| K (mg/L)           | 1082 ± 98  |
| V (mg/L)           | 0.013 ± 0.01|
| Al (mg/L)          | 0.001 ± 0.0001|
| Ag (mg/L)          | 0.001 ± 0.0001|
with high concentrations of organic matter in the leachate (Wei et al. 2019).

The pH of the crude leachate was 6.05 at the time of sampling. Usually, the pH range of the leachate is between 4.5 and 9 (Rani et al. 2020). The pH reflects that the leachate in this landfill is almost young (Grosser et al. 2019). Hydrogen cations and the production of bicarbonate ions affect the pH of the municipal waste disposal solution due to the separation of the effect of carbonic acid. Higher pH reduces heavy metals due to the production of deposits such as sulfides, carbonates, and hydroxides (Rani et al. 2020). TDS is an important parameter for waste leachate disposal in many countries. High concentrations of soluble and insoluble salts in leachate can damage physicochemical parameters of the receiving waters, which if entered without treatment will reduce water quality and photosynthesis. High leachate strength is reflected by the high TDS value (Rani et al. 2020).

Impact of leachate pH

The impact of pH on the reduction of contaminants using the UV/US/IO$_4^-$ process on waste leachate is shown in Fig. 1A. At acidic pHs, the increase in final pH, and at
alkaline pHs, the decrease in final pH is due to the amphoteric properties of the reaction solution (Tuzen et al. 2018). At acidic pH, the amount of UV$_{254}$ decreased compared to the amount in crude leachate, from 79.8 to 12.49 cm$^{-1}$ at pH 3. The value of the UV index indicates the amount of aromatic and unsaturated compounds such as phenolic, aniline, and benzoic. Due to their complex structure and continuous evolution over time, UV absorbers are highly resistant and can absorb them. Among these, humic acid has the highest UV absorption power (Iskander et al. 2018; Ozkantar et al. 2020). At pH 3, IO$_4$$^-\rightarrow$ attacks substances like humic, and blocks the absorption of UV rays. The reduction rate of UV$_{254}$ decreases gradually from pH 3 to 7 and does not decrease significantly at pH 9 to 11. Chadi et al. (Chadi et al. 2019a) have measured the removal of Toluidine blue (TB) using periodate from pH 3 to 11 and with increasing pH, the amount of pollutant removal increased. Bendjama et al. (Bendjama et al. 2018) have reported a decrease in chlorazol black in seawater in the acid range.

In Fig. 1B, with increasing pH from 3 to 11, the value of BOD$_5$, COD, and BOD$_5$/COD at the reactor output has increased. In other words, acidic pHs work better to purify this type of leachate. The decrease in BOD$_5$, COD, UV$_{245}$, and BOD$_5$/COD ratio at acidic pH is due to the predominance of IO$_4$$.^-\rightarrow$ While at alkaline pH, pHs of periodate as H$_2$I$_2$O$_{10}$ is observed (Bendjama et al. 2018). Another reduction factor in removal in alkaline media is the abstraction of free radicals by HCO$_3$$^-\rightarrow$ and CO$_3$$^{2-}$. At alkaline pH, CO$_2$ can be present in the form of HCO$_3$$^-\rightarrow$ and CO$_3$$^{2-}$. Both can react with O$^*$ and O$^{2-}$ to produce the CO$_3$$^{2-}$ radical which has less oxidant than OH$^*$. However, based on the following reactions (Eqs. 6–9), the reaction rate of OH$^*$ with CO$_3$$^{2-}$ is almost 46 times faster than that of with HCO$_3$$.^-\rightarrow$, which indicates the removal of hydroxyl radicals at pH above 10.

\[
\text{OH}^* + \text{HCO}_3^- \rightarrow \text{CO}_3^{2-} + \text{H}_2\text{O}
\]  
Eq. (6)

\[
\text{OH}^* + \text{CO}_3^- \rightarrow \text{CO}_3^{2-} + \text{OH}^-
\]  
Eq. (7)

\[
\text{O}_2^{2-} + \text{HCO}_3^- \rightarrow \text{CO}_3^{2-} + \text{HO}_2
\]  
Eq. (8)

\[
\text{O}_2^{2-} + \text{CO}_3^2^- \rightarrow \text{CO}_3^{2-} + \text{O}_2^{2-}
\]  
Eq. (9)

However, Eqs. 6–9 show that growing the pH level leads to a decrease in the content of active radicals in the solution and thus resulted in a decrease in the pollutant removal (Chadi et al. 2019a). According to Eqs. 1–5 and 10–18, periodate is activated by UV and US at acidic pH to form radicals and non-radicals such as OH, IO$_4$$^-\rightarrow$, IO$_3$$^-\rightarrow$, IO$_3$$^-\rightarrow$, H$_2$O$_2$, and O$_3$ (Bendjama et al. 2018; Chia et al. 2004; Lee et al. 2016; Shah et al. 2020).

\[
\text{OH}^* + \text{IO}_4^+ \rightarrow \text{OH}^- + \text{IO}_4^+
\]  
Eq. (10)

\[
\text{IO}_5^- + \text{OH}^* \rightarrow \text{HIO}_4^-
\]  
Eq. (11)

\[
2\text{OH}^- \rightarrow \text{H}_2\text{O}_2
\]  
Eq. (12)

\[
2\text{IO}_3^- \leftrightarrow \text{I}_2\text{O}_6
\]  
Eq. (13)

\[
\text{I}_2\text{O}_8 + \text{H}_2\text{O}_2 \rightarrow \text{IO}_3^- + \text{IO}_4^- + 2\text{H}^+ + \text{O}_2
\]  
Eq. (14)

\[
\text{I}_2\text{O}_6 + \text{H}_2\text{O} \rightarrow \text{IO}_3^- + \text{IO}_4^- + 2\text{H}^+
\]  
Eq. (15)

\[
\text{O}_2 + \text{O}(3\text{p}) \rightarrow \text{O}_3
\]  
Eq. (17)

\[
\text{O}_3 + \text{IO}_3^- \rightarrow \text{IO}_4^- + \text{O}_2
\]  
Eq. (18)

Activation of periodate and formation of strong oxidants (IO$_4$$^-\rightarrow$ and IO$_4$$^*$) as well as the reaction between IO$_4^-\rightarrow$ and OH$^-\rightarrow$ and the production of reactive oxygen species (O$_2^*$ and IO$_3^-\rightarrow$) according to the above equations are effective in eliminating pollutants at acidic pH (Chia et al. 2004; Choi et al. 2018).

While at alkaline pH, it is unlikely that IO$_4^-\rightarrow$ as HIO$_6^{2-}\rightarrow$ will be present (Rani et al. 2020). Protons change the nature of ionic species in solution, affect the uptake of ions, and thus affect oxidation. When the pH is less than 7.5, IO$_4^-\rightarrow$ is the predominant species and at pH $>$ 7.5, most species become H$_2$I$_2$O$_{10}^{4-}\rightarrow$. The oxidation and reduction standard for the periodate-iodate pair decreases to +1.6 V in an acidic solution and +0.7 V in a base solution (Lee et al. 2016). Hamdaoui and Merouani (Hamdaoui and Merouani 2017) studied the effect of pH in the range of 2–8 with ultrasonic waves and showed that the presence of IO$_3^-\rightarrow$ strongly depends on reaction pH. In the Bokare and Choi study, pollutant degradation increased to pH 8.4 and then decreased (Bokare and Choi 2015).

**Impact of treatment time**

Figure 2A shows the amount of reduction of BOD$_5$, COD, and BOD$_5$/COD parameters at different times. With increasing purification time, the BOD$_5$ value decreased from 1325 mg/L in 30 min to 414 mg/L in 150 min. A similar trend was observed for the two parameters of COD and BOD$_5$/COD. The difference between 120 and 140 min in reducing pollution was not obvious. This indicates that after 120 min, the active radicals in the system are exhausted. The purification time reported by Hamdaoui and Merouani
According to Fig. 2B, the amount of $\text{UV}_{254}$ has decreased with increasing refining time. The amount of $\text{UV}_{254}$ for untreated leachate (79.8) was decreased to 12.49 and 11.61 after 120 and 150 min contact time, respectively. $\text{UV}_{254}$

(Hamdaoui and Merouani 2017) to remove dye using periodate was 140 min. Lee et al. (Lee et al. 2016) have degraded perfluorooctanoic acid using sonication and 4.5 mM periodate for 120 min.

Fig. 2 A, B Impact of purification time on the evaluated factors and C treatment process kinetics (pH: 3, $\text{IO}_{4}^{-}$ content: 4 mM, leachate content: 100%, intensity of UVC: 6 Watt)
indicates the organic matter content, including aromatic structures or unsaturated binary bonds. Humic substances are sensitive to UV and absorb it. Decreasing the intensity of UV$_{254}$ absorption during the oxidation reaction time may indicate the degradation of aromatic organic matter or even the formation of intermediates that have lower molecular weight. The intermediates materials can be observed by GC–MS (Jiang et al. 2017).

The first-order model was applied to describe the behavior of treatment kinetics (Fig. 2C). The equation of this model is expressed by Eq. 19:

$$\ln C_t / C_0 = k_1 t$$

In the equation, $k_1$ denotes the constant of the first-degree reaction (min$^{-1}$), $C_0$ is the initial concentration of leachate (mg/L), $C_t$ is the ultimate concentration of leachate (mg/L), and $t$ shows the treatment time (min). The result of the kinetic study, especially the value of $R^2$, shows the suitability of the equation for the desired system. Joshi-Gogate (Joshi and Gogate 2019) and Zhong et al. (Zhong et al. 2017) and da Costa et al. and Chia et al. (Chia et al. 2004; da Costa et al. 2018) also described leachate purification and COD removal by AOTs through the first-order equation. The $k_1$ parameter for COD removal in the UV/US/IO$_4^-$ system was obtained at 6.53×10$^3$ min$^{-1}$. Different values (79×10$^3$ min$^{-1}$—88×10$^3$ min$^{-1}$) have been reported by Joshi-Gogate (Joshi and Gogate 2019) for landfill leachate using different types of ultrasonic reactors combined with AOTs. In another study (da Costa et al. 2018), $k$ values were stated as 0.07 min$^{-1}$ ($R^2 = 0.91$), 0.03 min$^{-1}$ ($R^2 = 0.77$), and 0.03 min$^{-1}$ ($R^2 = 0.89$) for initial COD of 1000 mg/L, 2000 mg/L, and 3000 mg/L, respectively.

**Impact of periodate concentration**

As shown in Fig. 3A and Fig. 3B, the decrease in value of BOD$_5$, COD, and UV$_{254}$ increases with increasing periodate concentration. The majority of decontamination happened at periodate concentrations of 4 mM, which was almost identical to a concentration of 5 mM. Optimizing the ratio of periodate to organic matter is a vital factor in the landfill leachate treatment, as high content of IO$_4^-$ are likely to repel OH$^*$ and IO$_3^*$ radicals according to Eqs. 20 and 21 (Chadi et al. 2019a; Hamdaoui and Merouani 2017). High concentrations of periodate act as a free radical scavenger, thus, reducing the effective removal of contaminants in the system. In particular, IO$_4^-$ may cause the abduction of OH$^*$ and IO$_3^-$ in a higher degree reaction determined by the higher reaction rate (Eqs. 20 and 21: $k_{20}=(2–7)×10^8$ m$^{-1}$ s$^{-1}$ and $k_{21}=4.5×10^8$ m$^{-1}$ s$^{-1}$).

$$\text{OH}^* + \text{IO}_4^- \rightarrow \text{OH}^- + \text{IO}_4^*$$  \hspace{1cm} (20)

$$\text{IO}_5^- + \text{IO}_4^- \rightarrow \text{IO}_4^* + \text{IO}_3^-$ \hspace{1cm} (21)

Another possibility is the competitive reaction of the radicals with each other, which is described in the following equations.

$$\text{OH}^* + \text{OH}^* \rightarrow \text{H}_2\text{O}_2$$  \hspace{1cm} (22)

$$\text{IO}_5^- + \text{IO}_3^- \rightarrow \text{I}_2\text{O}_6$$  \hspace{1cm} (23)

$$\text{IO}_4^- + \text{IO}_4^- \rightarrow \text{I}_2\text{O}_4$$  \hspace{1cm} (24)

It seems that at high concentrations of periodate, which causes the production of more radicals (IO$_3^*$, IO$_4^*$, and OH$^*$), the radical–radical combination again has a higher reaction rate than the organic-radical reaction. Therefore, at higher periodate concentrations, a decrease in the removal of pollutants was observed. Chadi et al. (Chadi et al. 2019a) also examined periodate on resistant organic pollutants at five concentrations of 0.2, 0.5, 2, and 5 mM periodate. Removal of toluidine blue (TB) under optimal conditions at 5 mM IO$_4^-$, was reported at 98%, while at 10 mM it was reduced to 95%. The addition of more than 10 mM periodate for the decontamination process of Brilliant Blue R (Hamdaoui and Merouani 2017) has not reduced contaminant removal. Optimizing the ratio of periodate to organic matter is an essential issue in AOTs reactions. Bokare-Choi (Bokare and Choi 2015) positively assessed the effect of periodate concentration on the oxidation of furfuryl alcohol.
by increasing the periodate dose from 0.5 to 1 mM. When periodate increased over 1 mM, its removal effect on the pollutant slowly decreased. One explanation for this decrease may be the abdution of singlet oxygen by the remaining Periodate. Chia et al. reported a concentration of 4 mM periodate for the degradation of chlorophenol under the UV/IO₄⁻ process (Chia et al. 2004).

**Impact of leachate content**

High contents of organic matter affect the reduction of organic matter decomposition (Sharma et al. 2015). Also, the presence of mineral anions affects the system efficiency (Khan et al. 2017). The presence of CO₃⁻, HCO₃⁻, SO₄²⁻, and Cl⁻ anions are considered effective inhibitors of active radicals (Wang and Wang 2018). The purification rate was assessed by changing the leachate content. Figure 4A shows the amount of BOD₅ and COD for different leachate concentrations. With increasing leachate dilution, the amount of reduction of factors (due to the purification system) was more significant. Figure 4B shows the rate of UV₂₅⁴ reduction and the BOD₅/COD ratio at different leachate concentrations. The amount of UV₂₅⁴ was drastically reduced by the system developed, indicating that aromatic substances were affected in the leachate. The ratio of BOD₅/COD in 100% and 75% leachate concentrations was 0.42 and 0.41, respectively, while in concentrations of 50% and 25% leachate has reached 0.38 and 0.32, respectively. At higher concentrations, the reduction in contaminant removal may be due to the presence of mineral anions that are potentially in competition with free radicals (Chadi et al. 2019b). Saline leachate is a complex matrix containing a large number of known radical scavengers like Cl⁻ and SO₄²⁻. Concentrated leachate due to its dark color prevents the transfer of photons inside the reactor (Salmérón et al. 2020). Bendjama et al. have reduced Chlorazol black (CB) in two matrices of deionized water and seawater, a decrease in CB kinetics in deionized water was observed faster than in seawater (Bendjama et al. 2018).

![Fig 4](image-url) Impact of the leachate content on A BOD₅, COD, and B BOD₅/COD and UV₂₅⁴ during treatment by US/UV/IO₄⁻ (pH: 3, treatment time: 150 min, IO₄⁻ content: 4 mM, intensity of UVC: 6 Watt)
Impact of UVC power

Increasing the oxidation ability of $\text{IO}_4^-\text{ using light or rays is a useful method. Exposure to peridote with UV with wavelength < 266 nm or ultrasonic waves can cause radicals like }$ $\text{IO}_3^\ast$ and hydroxyl (Choi et al. 2018). $\text{IO}_3^\ast$ and $\text{IO}_4^\ast$ have been reported as the dominant mediators generated during photolysis and radiolysis of $\text{IO}_4^-\text{ and } \text{IO}_3^-\text{ in aqueous media (Eqs. 1–5) (Hamdaoui and Merouani 2017). To investigate how to reduce pollutants by UV rays, UVC lamps with voltages of 6, 15, and 25 watts were tested. According to Fig. 5A, the } \text{UV}_{254}\text{ absorption values after treatment of the leachate using 6 W, 9 W, and 25 W lamps were 12.49, 9.08, and 4.91, respectively. Also, according to Fig. 5B, the amount of } \text{BOD}_5\text{, } \text{COD}, \text{ and } \text{BOD}_5/\text{COD ratio was } 451 \text{ mg/L, } 1072 \text{ mg/L, and 0.42 for 6 W lamps; 279 mg/L, 701 mg/L, and 0.39 for 15 W lamp; and 235 mg/L, 611 mg/L, and 0.38 for 25 W lamp, respectively. Waste leachate is a complex structure and can absorb UV light. Different parts of aromatic substances such as phenolic, aniline, and benzoic absorb UV light. Among them, humic acid and then fulvic acid has the highest UV absorption power. Therefore, it has the greatest impact on reducing pollutants (Iskander et al. 2018). Reduction of pollutants with 25 W bulbs has been reported further, which can be due to the effect of ultraviolet rays on pollutants directly or indirectly due to photolysis and the formation of $\text{IO}_3^\ast$ and $\text{IO}_4^\ast$ free radicals. Because these radicals play a key role in reducing organic matter using photolysis, especially in the presence of hydroxyl radical scavengers (Hamdaoui and Merouani 2017). In environments with high TDS, the reduction of pollutant efficiency is due to the reduction of light reception, in which salts act as a light screen, and consequently, the amount of target pollutants decreases (Bendjama et al. 2018).

Impact of the system components

To observe the contribution of each system component alone or jointly, the synergy of system components was studied. During leachate treatment, UV rays, ultrasonic waves, and $\text{IO}_4^-$ were tested alone and together. Based on Fig. 6A, the UV$_{254}$ reduction had the “whole system > US alone > UV alone” trend. Accordingly, the synergistic impact of periodate/US/UV (entire system) is likely to further reduce the UV$_{254}$ index by 84%. Also, in Fig. 6B, the effect of the process components in ranked as “whole system > US alone > periodate > UV alone” in which BOD$_5$ reduction values was obtained 72% > 8.6% > 1.5% > 3%, respectively. Bendjama et al. (Bendjama et al. 2018) have reported the pollutant removal of 3% and 38% for periodate and UV alone. In Fig. 6C, the COD reduction values were examined alone and together. The effect of process components was seen in “whole system > US alone > UV alone > periodate.” The COD values were reported as 56% > 9.3% > 1.1% > 0.04%, respectively. In Fig. 6D, the BOD$_5$/COD ratio was stated as 0.42 for the whole system, 0.63 for US alone and periodate alone, and 0.65 for UV alone. Given the high effect of UV rays alone on waste leachate, ultraviolet rays can also directly destroy pollutants (Ghanbari and Moradi 2017). The high absorption of UV rays indicates that the waste leachate has a strong UV absorbing material. In addition, the direct photolysis by UV and the UV-based activation of free radicals are also effective in the reduction of leachate pollution by ultraviolet rays (Fang et al. 2017; Iskander et al. 2018).

In the ultrasound system alone, the main mechanism for the growth and collapse of microbubbles in the liquid is the result of an unusual environmental reaction inside and near the bubble. Due to the frequency generation in the range of 20–10,000 kHz, the phenomenon of cavitation occurs, which causes the decomposition of water vapors of oxygen molecules and volatile organic compounds and can exist in the gas phase. The ultrasonic waves (US) can also cause the formation of free radicals individually (Hamdaoui and Merouani 2017; Lee et al. 2016; Miklos et al. 2018; Tripathy et al. 2019). Hamdaoui and Merouani have studied color removal using sonication and periodate alone (Hamdaoui and Merouani 2017). Effective reduction of color in the environment was reported using the joint of periodate and US. The impact of “periodate + US” on an effective process system for reducing perfluorocarboxylic in wastewater sample was also reported (Lee et al. 2016).

Fig. 5 Impact of UV intensity on A UV$_{254}$ and B BOD$_5$, COD, and BOD$_5$/COD after treatment by the developed system (pH: 3, treatment time: 150 min, $\text{IO}_4^-$ content: 4 mM, leachate content: 100%)
Identification of organic compounds after leachate treatment

Figure 7 shows the identified organic components in the raw and treated leachate. In crude leachate, the wide range of high peak heights indicates the existence of different types of organic and effective materials and their relatively high concentration. After treatment of the leachate using UV/US/IO₄⁻, the number of peaks was reduced and the peaks were also lowered. Substances like cyclotrisiloxane/hexamethyle with 55% content in crude leachate after refining have reached about 49% and substances like decamethyl have been reported to be about 5%. Cyclohexa siloxane do decamethyl at 18.1 mg/L and cyclotriadecan and phenolmethyl were among the three major molecules observed after treatment of waste leachate (Quan et al. 2020). As expected, phthalates had a high concentration, accounting for 3.75% of waste leachate. Phthalate compounds have also been frequently reported in raw leachate. Four phthalate compounds ranged from 200 mg/L butyl benzyl phthalate to 4900 mg/L di isobutyl phthalate as measured and reported by Ruiz-Delgado et al. (Ruiz-Delgado et al. 2020). Waste composition, age of waste, climatic, and geographical characteristics are factors that affect the compounds in waste leachate (Zhao et al. 2020).

Energy consumption

AOTs need the energy to remove pollutants from water solutions. Determining the electricity consumption in each method can be very fruitful. EE/O based on kWh/m³ is the amount of electrical energy required to reduce the concentration of pollutants by 1 time per 1m³ of contaminated water. The energy consumption per order (EE/O) is computed using the following formula:

\[
\frac{EE}{O} = \frac{P \times t \times 1000}{V \times 60 \times \log(C_0/C_f)}
\]  

(25)

In this formula, \( P \) denotes process electrical input power (kW), \( t \) implies the treatment time (min), \( V \) is treated leachate volume (L), \( C_0 \) and \( C_f \) are concentrations of inlet and purified leachate.

Specific energy consumption (SEC) is calculated according to the following formula:

\[
\text{SEC} = \frac{\sum P \times t}{(C_0 - C_f) \times V}
\]  

(26)

According to the calculations, the electrical energy for COD removal was attained at 11.42 kWh/m³ and SEC was obtained at 0.02 W-hours for each mg of the removed COD. According to Miklos et al.’s studies (Miklos et al. 2018), the energy consumption of the developed system in the group of
1–100 kWh/m³, is in the appropriate range. Liu et al. (Liu et al. 2019) reported the obtained electrical energy values for each removal period between 26 and 88 kWh. Also, values of 0.03–0.04 kWh/m³ were obtained to remove COD and humic acid by processes performed by many researchers (Lak et al. 2018; Liu et al. 2019; Lu et al. 2018; Miklos et al. 2018; Poblete and Pérez 2020).

Conclusions

In this investigation, saline waste leachate (TDS > 7300 mg/L) was purified by the UV/US/IO₄⁻ process. It was found that under optimum conditions (pH 3, IO₄⁻ content: 4 mM, treatment time: 120 min), the COD quantity was decreased from 2450 to 1072 mg/L. After leachate treatment by the developed system, the quantity of BOD₅, BOD₅/COD ratio, and UV₂₅₄ has also reduced from 1630 mg/L, 0.66, and 79.8 cm⁻¹ to 451.5 mg/L, 0.42, and 12.49 cm⁻¹, respectively. The acidic conditions of the leachate were beneficial for obtaining better purification efficiency. The synergistic study showed that the advanced oxidation process based on IO₄⁻ oxidizer, US waves, and UV ray is effective for purifying waste leachate with the high salinity in the coastal cities like Bushehr (Iran). The amount of consumed energy in the studied system was about 11 kWh/m³, which makes it economical for full-scale application.

Author contribution F. Moradian: formal analysis, methodology, writing—original draft. B. Ramavandi: supervision, conceptualization, writing—review and editing. N Jaafarzadeh: conceptualization, methodology. E. Kouhgardi: conceptualization, methodology.

Data availability The datasets used in this study are available from the corresponding author on reasonable request.
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