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Article

Comparative Study of Microwave and Resistance Heating for the Efficient Thermal Desorption of Mineral Oil from Contaminated Soils

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Abstract: The contamination of soils by mineral oils presents a significant environmental challenge, particularly due to the widespread use of petroleum products in various industrial sectors. This study investigates the efficiency of microwave heating compared to conventional resistance heating for the thermal desorption of mineral oil from contaminated soils. Experimental results demonstrated that microwave heating offers superior performance in terms of pollutant removal efficiency, energy consumption, and preservation of soil's physical and chemical properties. The study further conducted a kinetic analysis of the desorption process, revealing that microwave heating follows a first-order kinetic model and requires lower activation energy than conventional methods. The findings suggest that microwave-assisted thermal desorption is a highly effective and energy-efficient technology for soil remediation, providing a potential alternative to conventional techniques. This research offers valuable insights into optimizing thermal desorption processes for environmental remediation, with implications for broader applications in soil treatment.

Keywords: microwave heating; thermal desorption; mineral oil contamination; soil remediation; kinetic analysis

1. Introduction

The contamination of soil by organic pollutants, particularly mineral oils, has emerged as a significant environmental issue, primarily due to the widespread use of petroleum products in industrial and agricultural activities. Polluted soils pose serious threats to ecosystems and human health, making the development of effective remediation technologies essential [1]. Among various remediation techniques, thermal desorption has proven to be an effective method for removing organic pollutants from soil [2,3]. This technique involves heating contaminated soil to volatilize the pollutants, which are then collected and treated [4].

Conventional thermal desorption methods, such as resistive heating, rely on external heat sources to raise the temperature of the soil [5]. However, these methods often suffer from inefficiencies, including uneven heating, extended treatment durations, and significant energy consumption [6]. Studies have shown that, compared to more advanced technologies, resistive heating tends to result in higher energy costs and lower pollutant removal efficiencies [7,8]. In contrast, microwave heating has emerged as a more effective alternative due to its ability to generate heat directly within the soil through the interaction of microwave energy with polar molecules such as water and organic compounds. This internal heating mechanism results in a more uniform temperature distribution and faster pollutant removal rates, making microwave heating a promising option for soil remediation [9]. Recent studies have shown that microwave heating not only reduces energy consumption but also significantly enhances the desorption efficiency of various organic pollutants, including hydrocarbons and volatile organic compounds (VOCs) [10–12]. For example, a

study by Tanaka et al. (2018) found that microwave-assisted thermal desorption improved the removal efficiency of heavy oil by 40% compared to traditional methods [13]. Similarly, research by Wang et al. (2020) highlighted the role of microwave heating in the rapid removal of hydrocarbons, particularly in soils with varying moisture content [14]. Despite the many advantages of microwave heating, its application in soil remediation is still limited by several challenges, including the optimization of operational parameters and a deeper understanding of the kinetics governing pollutant desorption [15–17]. Previous studies have emphasized the importance of better understanding the effects of factors such as heating time, temperature, and soil moisture content on the desorption process. For instance, Liu et al. (2020) suggested that optimizing these parameters could enhance the effectiveness of microwave-assisted soil remediation technologies when dealing with complex organic pollutants [18]. This study aims to address these challenges by systematically comparing the effectiveness of microwave heating and traditional resistive heating in the thermal desorption of mineral oil-contaminated soil. We focused on evaluating desorption efficiency under different heating conditions and analyzed the kinetics of the desorption process using a first-order kinetic model. The findings from this study are expected to provide valuable insights into optimizing microwave heating for soil remediation and may guide the development of more energy-efficient and effective strategies for the removal of organic pollutants.

2. Materials and Methods

2.1. Experimental Materials and Device

The soil used in the experiment was collected from an area contaminated by transformer oil (mineral oil) near a transformer at an electric power research institute in Hebei Province, China. The topsoil was sampled from a depth of 5-10 cm using the five-point sampling method. The relevant physical properties of the soil are shown in Table 1.

The collected samples were first crushed using a crusher to remove large particles, then sieved through a 20-mesh sieve to eliminate stones, plant debris, and other impurities. After sieving, the soil was finely ground using a mortar and pestle and stored in brown glass bottles for later use.

Table 1. On site polluted soil parameters in a certain area of Hebei Province.

Water content (%)	Organic matter content ^a (%)	Petroleum hydrocarbon contaminant ^b (%)	Cation exchange capacity ^c (%)
11.22	6.74	9.76	6.27

^a HJ 615-2011. ^b HJ 1021-2019. ^c HJ 889-2017.

The experimental apparatus consists of a microwave source (microwave oven), soil reactor, power analyzer, temperature controller, temperature sensors, and subsequent pollutant collection devices. The microwave source is a modified household microwave oven (frequency: 2.45 GHz; maximum power: 1000 W). To meet the experimental requirements, the microwave cavity was modified by adding wave-absorbing materials to the inner walls to reduce reflection waves during the heating process. Two outlets were installed on the left side and the top of the cavity. One outlet is equipped with a fan to ventilate the interior of the microwave oven, facilitating better temperature regulation. The other outlet is connected to a pipeline leading to the reactor. Additionally, a series of gas collection devices were installed at this outlet to monitor the volume of evaporated gases during the soil heating process. The specific experimental setup is shown in Figure 1, where the blue represents the modified microwave heat source, the red represents the resistance heating device, and the yellow represents the temperature sensor (Weidmann OPTOCON fiber temperature measurement system), which is used to measure the internal temperature of the soil.

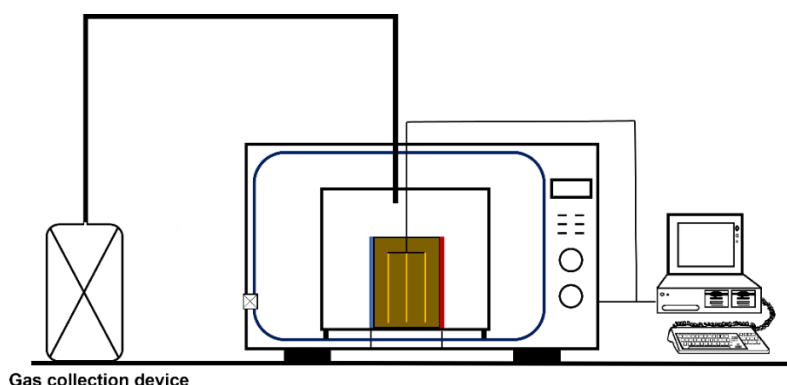


Figure 1. Experimental configuration of the microwave equipment.

2.2. Experimental Methods

2.2.1. Determination of Organic Matter Content

Determine the organic content using the *T 0151-1993* standard [19]. A soil sample of 0.1 g, previously ground, was weighed and placed into a hard glass test tube. To this, 10 mL of 0.075 mol·L⁻¹ K₂Cr₂O₇ standard solution was added. Eight test tubes, each containing the soil sample and the standard solution, were placed into a wire basket (with two blank test tubes as controls). The wire basket was then submerged in a paraffin oil bath preheated to 180°C, with the oil temperature maintained at 170°C. Timing began once the solution started boiling, and the test tubes were removed after 5 minutes. The content of each test tube was transferred into a 250 mL Erlenmeyer flask, and the test tubes were rinsed thoroughly with water to ensure the total solution volume in the flask reached 60 mL. Subsequently, 3 drops of phenanthroline indicator were added. The solution was titrated with a standard solution of ferrous sulfate until a color change from orange-yellow to blue-green and then to orange-red was observed. The volume of the ferrous sulfate solution used was recorded.

2.2.2. Determination of Cation Exchange Capacity (CEC) in Soil

Determination of cation exchange capacity using *HJ 889-2017* standard [20,21]. A 3.5 g homogenized soil sample was weighed and placed into a 100 mL centrifuge tube. Then, 50.0 mL of [Co(NH₃)₆]Cl₃ solution was added to the tube. The mixture was shaken at 20°C for 60 minutes using a shaker. After shaking, the tube was centrifuged at 4000 rpm for 10 minutes. The supernatant was collected into a colorimetric tube for subsequent analysis.

During the temperature experiment, 100 g of mineral oil-contaminated soil with known concentration and moisture content was taken after standing for 7 days. The sample was placed inside the experimental apparatus, and the soil was heated at a rate of 1°C per 5 minutes. When the temperature reached 50°C, the heating was maintained for 30 minutes before being stopped. After the apparatus cooled to room temperature, a 2 g soil sample was taken and placed in a headspace vial for analysis. For each temperature, three parallel samples were prepared, and the calculated average value was used as the result. To investigate the effect of time on organic matter desorption, the microwave power and the power of the resistance wire were adjusted to 1000 W during the experiment. The removal efficiency (*RE*) can be calculated using the following formula:

$$RE = \frac{X_0 - X_i}{X_i} \times 100\% \quad (1)$$

where X_0 represents the mass of the untreated soil (g), and X_i represents the mass of the soil after heat treatment (g).

3. Results and Discussion

3.1. The Effect of Temperature on Mineral Oil Removal Efficiency

The traditional heating method utilizes direct resistance heating. Through thermal radiation, the temperature of the soil layers near the resistance element rises first and then gradually conducts outward to the inner layers of the soil. This heating method causes excessively high temperatures near the heat source. Once heating is stopped, the heat near the source dissipates slowly, leading to significant temperature differences between the interior and exterior of the soil. As a result, the removal efficiency of pollutants in different soil locations varies considerably. Unlike conventional heating, microwaves rely on the high-frequency rotation of internal polar molecules, generating heat through friction. The internal temperature rises rapidly and is transmitted to the surface through polar molecules. Due to minimal influence from external temperatures, heat loss is reduced, resulting in more uniform heating and a faster temperature increase compared to traditional resistance heating [22,23].

Figure 2 shows the effect of different heating methods on the removal efficiency of pollutants for 100 g of contaminated soil under the conditions of a heating power of 1000 W, pollutant concentration of 9.76 wt%, and moisture content of 11.22 wt%, using temperature sensor data located in the middle of the soil reactor. As the temperature increases, the removal rates of mineral oil by microwave heating and conventional resistance heating both show an upward trend. When the temperature increases from 50°C to 300°C, the removal rate of mineral oil by microwave heating rises from 52.86% to 96.38%, while the removal rate by conventional resistance heating increases from 28.55% to 93.35%. The efficiency of microwave desorption is higher than that of resistance heating. Under the same power, due to differences in the heating mechanism, the soil temperature increase rate under microwave heating is faster than under conventional heating. This causes the energy absorbed by the mineral oil during microwave heating to be higher at the same temperature, resulting in a higher removal rate compared to conventional heating. As the heating temperature increases, the evaporation of moisture in the soil helps carry the mineral oil out, improving the removal rate of the oil. The increase in temperature also promotes the generation of hydroxyl radicals in the soil, which further aids in the decomposition of the mineral oil. When the temperature increases from 50°C to 150°C, the removal rate of mineral oil through conventional thermal desorption rises from 28.55% to 91.32%, while microwave heating increases the removal rate from 52.86% to 94.11%. This indicates that microwave heating achieves better pollutant removal even at lower temperatures. However, when the temperature increases from 200°C to 300°C, the degradation trends of mineral oil by both microwave and conventional resistance heating begin to plateau, with the removal rates stabilizing around 96% for microwave heating and 93% for conventional heating. The difference in removal rates between the two methods becomes smaller at higher temperatures. This is because water, as a polar molecule, largely evaporates once the temperature reaches a certain level, no longer playing a significant role in absorbing heat and facilitating pollutant removal. As a result, the removal rate of organic matter stabilizes compared to lower temperatures [24]. The moisture content in the soil after microwave thermal desorption is lower than that in soil treated with conventional resistance heating. This is because water, as a polar molecule, absorbs more microwave energy, resulting in a higher temperature in the microwave-treated soil system compared to the conventional heating system at the same temperature. Consequently, the evaporation of water molecules is greater with microwave heating. The water in the soil consists of free water and bound water, with the free water being the primary component that absorbs microwave energy and raises the system's temperature. As the temperature increases, the free water absorbs the microwave energy, heats up, and evaporates, leaving a small amount of bound water remaining in the soil. Therefore, as the temperature rises, the remaining moisture content in the soil gradually levels off. At higher temperatures, the organic pollutants in the soil undergo thermal decomposition, producing smaller molecules or secondary pollutants. These decomposition products may re-adsorb onto the soil surface. The adsorption sites where these molecules adhere remain stable even at elevated temperatures. As a result, further temperature increases do not significantly enhance the removal rate of pollutants, leading to a plateau in removal efficiency [25].

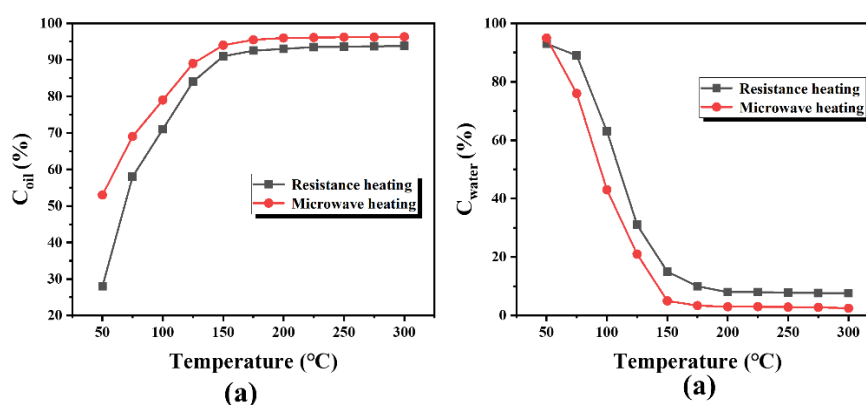


Figure 2. (a) Mineral oil removal rate under different heating methods. (b) Water content after heating.

3.2. The Effect of Heating Time on the Removal Rate of Mineral Oil Pollutants

Under the conditions of 1000 W power, 9.76 wt% pollutant concentration, and 11.22 wt% moisture content, 100 g of contaminated soil was taken for each experiment. Both resistance heating and microwave heating were used. Soil samples were taken every 5 minutes, and the concentration of mineral oil in the soil was measured using gas chromatography. By varying the heating time, the effect of heating duration on pollutant removal efficiency under different heating methods was investigated. The results are shown in Figure 3. As the heating time increased, the removal rate of mineral oil using microwave heating increased from 17.35% to 96.06%, while the removal rate using conventional resistance heating increased from 13.64% to 90.47%. The degradation of mineral oil by microwave heating was higher than that by conventional resistance heating. This difference is due to the distinct heating mechanisms of microwave and resistance heating. With the same pyrolysis time, the heating rate in the microwave chamber is faster than that in resistance heating, resulting in a more rapid temperature rise, which in turn enhances the removal rate of mineral oil. To further investigate this, a simple experiment was conducted. At the same power level, it took approximately 70.5 seconds for microwave heating to reach 100°C, which is 1/6 of the time required by conventional resistance heating. As the heating time continued to increase, the removal rates of mineral oil for both conventional and microwave heating began to plateau. The primary reason for this is that with prolonged heating, most of the mineral oil in the soil reaches its boiling point and evaporates. However, a small amount of mineral oil remains strongly adsorbed by soil colloids and organic matter. During microwave heating, polar molecules (such as water) absorb microwave energy and heat the soil. As the temperature rises, the number of polar molecules gradually decreases, leading to a reduction in the heating efficiency of the microwave, and thus the rate of pollutant removal slows down. Studies have shown that once the temperature reaches a certain threshold, the remaining polar molecules in the soil can no longer significantly increase the temperature, causing the pollutant removal rate to plateau [26].

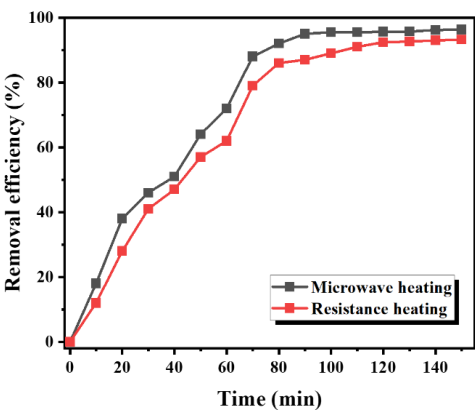


Figure 3. The influence of heating time on the removal rate of mineral oil.

3.3. Comparative Study on Soil Physical and Chemical Properties

Heat treatment causes changes in the physicochemical properties of soil, which can impact the potential for soil reuse. For instance, organic matter in the soil can degrade through volatilization, carbonization, and oxidation at excessively high temperatures. Soil adsorption of organic compounds mainly consists of mineral action and organic matter adsorption. A significant loss of organic matter can reduce the mobility and biodegradability of organic compounds in the environment, thereby decreasing the soil's self-purification capacity.

Table 2 shows the changes in organic matter content in soil after 30 minutes of pyrolysis at 1000 W using both conventional and microwave heating methods. In both heating methods, the soil experienced a loss of organic matter. This occurs because some of the mineral oil is adsorbed by the soil's organic matter and exists in the soil in this form. After 30 minutes of heating, the soil temperature rises, causing the desorption of the mineral oil. Furthermore, at higher temperatures after 30 minutes of heating, some organic components in the soil volatilize, leading to a reduction in organic matter content. Compared to conventional heating, microwave heating results in a smaller loss of organic matter. After conventional heating, the organic matter content in the soil sharply decreases from 6.74% to 1.88%, while after microwave heating, 4.04% of the organic matter remains. This difference is attributed to the higher degradation rate of mineral oil during microwave heating compared to conventional heating. During pyrolysis, mineral oil generates hydrocarbon compounds, which are also measured as organic carbon in organic carbon determinations [27]. Therefore, when heating organic-polluted soil, microwave heating retains more organic matter compared to conventional heating.

Table 2. Changes in soil organic matter content under conventional and microwave heating methods.

Soil Type	Mass (g)	Organic Matter Content (%)
Primitive soil	5.32	6.74
Soil after Ohmic Heating	4.21	1.88
Soil after Microwave Heating	3.54	4.04

Cation exchange capacity (CEC) is a crucial indicator of soil fertility and is significantly positively correlated with the integrated fertility index (IFI) of soil [28,29]. Therefore, studying the changes in CEC under microwave and conventional heating methods provides valuable guidance for the reuse of soil and the selection of degradation methods for organic-contaminated soils. The changes in soil CEC after conventional and microwave heating are shown in Table 3. After conventional heating, the soil's CEC decreased from 6.27 cmol·kg⁻¹ to 1.37 cmol·kg⁻¹. In contrast,

microwave heating resulted in a smaller reduction, with the CEC decreasing from 6.27 cmol·kg⁻¹ to 4.86 cmol·kg⁻¹. CEC in soil is positively correlated with the organic matter content. As the organic matter content decreases, the number of negative charges on soil colloids reduces, leading to a corresponding decline in CEC. Compared with conventional thermal desorption, microwave thermal desorption not only saves time but also causes less damage to soil fertility [30].

Table 3. Changes in soil cation exchange capacity under conventional and microwave heating.

Soil Type	CEC1 cmol/kg	CEC2 cmol/kg	CEC3 cmol/kg	Average cmol/kg
Primitive soil	6.32	6.21	6.24	6.27
Soil after Microwave Heating	3.98	3.34	4.04	3.79
Soil after Resistance Heating	1.36	1.43	1.33	1.37

3.4. Study on Desorption Kinetics

In the process of microwave thermal desorption of organic-contaminated soil, both heating temperature and time significantly affect the efficiency of desorption. As the temperature increases, the properties of the pollutants change. The soil, acting as an oxidation-reduction system, facilitates the thermal decomposition and oxidation of pollutants under varying temperatures. Prolonging the heating time allows for more complete degradation of pollutants, thereby improving the removal efficiency. In this section, a kinetic analysis of the thermal desorption process under different temperatures and durations is conducted. The reaction rate constant *k* and activation energy *E_a* are calculated to compare the ease of thermal desorption under different conditions and to explore the mechanisms behind pollutant removal [31–33].

For a single thermal desorption process, the reaction follows a first-order kinetic model. This model is commonly used to study the adsorption and desorption of organic compounds between solid-gas and solid-liquid phases in soil. In their research on low-temperature thermal desorption of organic-contaminated soil, Li et al. combined the kinetic model with the Arrhenius equation, finding that it better describes the dynamic changes of the pollutants [34]. The kinetic model primarily refers to the reaction rate constant *k* being linearly related to the concentration of one or two pollutants. The first-order kinetic model can be expressed as shown in Equation (2):

$$C_t = C_0 \cdot e^{-k_1 t} \tag{2}$$

where: *C_t* is the concentration of the organic compound remaining in the soil at a given time *t*, in mg·kg⁻¹. *t* is the heating time, in minutes. *C₀* is the initial concentration of the pollutant in the soil, in mg·kg⁻¹. *k₁* is the first-order reaction rate constant.

Taking the natural logarithm (ln) of both sides of the equation simplifies it to Equation (3)

$$\ln \frac{C_t}{C_0} = -k_1 t \tag{3}$$

By plotting the relationship between the thermal desorption time *t* and the ratio of concentrations *ln C_t/C₀*, the reaction rate constant *k* can be calculated. The slope of the linear plot represents the reaction rate constant *k₁*, as derived from the simplified first-order kinetic model.

Thermal desorption experiments were conducted at a pyrolysis temperature of 250°C using both microwave heating and resistance heating. The desorption of mineral oil was fitted to both first-order and second-order kinetic models for heating durations of 5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 35 min, 40 min, 45 min, 50 min, 55 min, and 60 min. Based on Equation (2), a plot was created, where the slope of the linear line represents the first-order reaction rate constant *k*. Figure 4 illustrates the first-order kinetic model fitting for the thermal desorption of mineral oil using both conventional and microwave heating. The rate constant *k* for microwave thermal desorption was determined to be 0.15706 min⁻¹, which is greater than the rate constant for conventional heating *k*=0.091 min⁻¹. This is attributed to the fact that water molecules, acting as polar molecules, absorb energy and rapidly evaporate in the microwave field, thereby accelerating the desorption of pollutants. This leads to

higher removal efficiency during microwave heating and allows the reaction rate constant k to remain relatively high across different temperatures. The higher k value for microwave heating indicates that microwave heating is more efficient in promoting pollutant desorption, further supporting the good fit of the first-order kinetic model under microwave heating conditions. Additionally, microwave heating can quickly reach the desired temperature within a shorter time and maintain stable temperature levels. This precise temperature control ensures that the reaction rate does not fluctuate significantly due to temperature variations, leading to a more accurate fit of the first-order kinetic model for the reaction rate constant k . In contrast, traditional resistance heating relies on thermal conduction, resulting in larger temperature fluctuations. These fluctuations cause greater variability in the reaction rate constant k across different regions, reducing the fitting accuracy of the kinetic model.

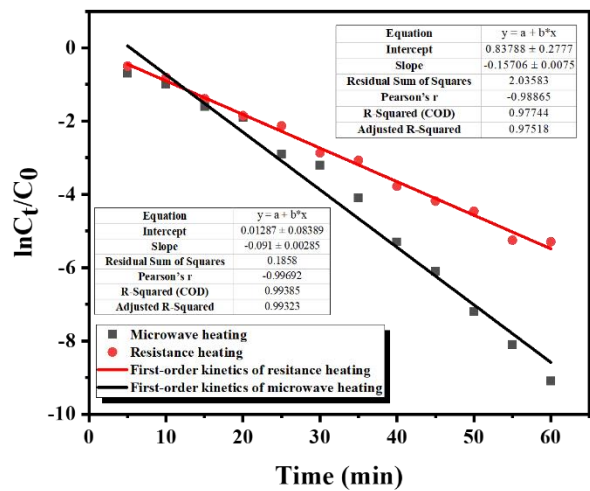


Figure 4. First-order dynamic fitting.

To further investigate the impact of heating temperature on the efficiency of mineral oil desorption using both microwave and conventional heating, the first-order kinetic model was employed, and the reaction activation energy was calculated using the Arrhenius equation [35]. The desorption experiments were conducted at pyrolysis temperatures of 200°C, 250°C, and 300°C, with heating durations of 10 minutes, 10 minutes, 30 minutes, and 40 minutes, respectively. Soil samples were taken to measure the residual mineral oil content, allowing for a comparison of the desorption efficiency under microwave and conventional resistance heating. Figure 5 presents the first-order kinetic model fitting results for the desorption of mineral oil under different temperatures for both heating methods. The fitting parameters are shown in Table 4.

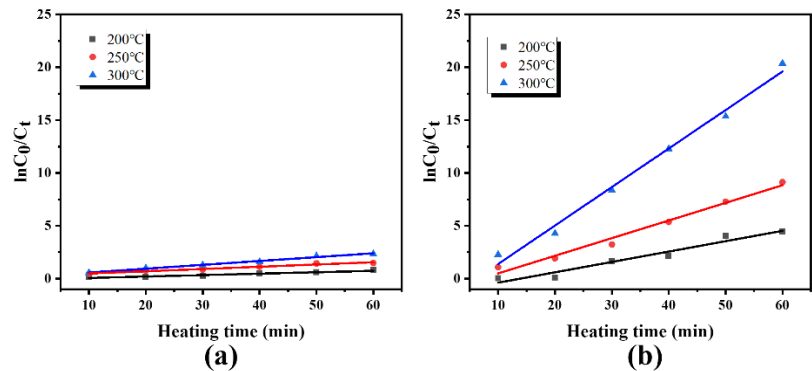


Figure 5. Conventional thermal desorption kinetics fitting at different temperatures. (a) Resistance heating. (b) Microwave heating.

Table 4. Parameters of first-order kinetic model for thermal desorption at different temperatures.

	200°C	250°C	300°C
K_{RH}	0.0135	0.0213	0.0364
R^2_{RH}	0.9403	0.9501	0.9483
K_{MH}	0.0982	0.1670	0.3645
R^2_{MH}	0.9618	0.9817	0.9819

As shown in Table 4, the correlation coefficient R^2 for microwave thermal desorption of mineral oil is consistently higher than that for resistance heating under the same conditions, indicating a better fitting effect for microwave heating. This is due to the uniformity of microwave heating, which results in more even volatilization of mineral oil from both the surface and deeper layers of the soil, leading to improved fitting accuracy. At the same heating temperatures, the k values for microwave desorption are consistently higher than those for conventional thermal desorption, suggesting that the reaction rate for microwave desorption is faster than that of conventional resistance heating. Furthermore, as the temperature increases, the k values for both heating methods increase, indicating that higher temperatures enhance the desorption efficiency of mineral oil. This is primarily because at temperatures above 200°C, the boiling point of mineral oil is reached, and the increase in temperature promotes more evaporation of water, which in turn increases the number of pollutants carried out of the soil. Experimental data shows that under microwave heating, the fitting coefficient R^2 is generally above 0.96, whereas for conventional heating, R^2 is typically lower. This demonstrates that under the same temperature conditions, the reaction rate constant k for microwave heating better fits the assumptions of the first-order kinetic model, which assumes a linear relationship between reaction rate and pollutant concentration. Theoretically, microwave heating reduces the dependence on heat conduction, resulting in more uniform temperature distribution. This decreases the variability in reaction rate and improves the fitting accuracy of the kinetic model.

By fitting the thermal desorption kinetics of microwave and conventional heating methods using the Arrhenius equation, the activation energy E_a for mineral oil desorption at different temperatures was calculated. As shown in Figure 6, the activation energy for microwave desorption of mineral oil is 29.36 J/mol, while for conventional resistance heating, it is 22.42 J/mol. The activation energy for microwave thermal desorption of mineral oil is higher than that of conventional thermal desorption, indicating that microwave energy provides a higher energy density at the same pyrolysis temperature. Microwave heating directly affects polar molecules, such as the polar components or impurities within the mineral oil. Microwaves induce molecular polarization and changes in dipole moments, thereby enhancing interactions between molecules [36]. This process may require more energy to overcome the molecular attractions, resulting in higher activation energy under microwave heating [37,38]. Additionally, microwave heating involves more complex molecular excitation mechanisms, including non-thermal effects, polarization, and enhanced intermolecular forces, which demand more energy to overcome these barriers [39]. The higher activation energy associated with microwave heating also suggests a stronger direct interaction between the microwaves and the material, offering greater reaction selectivity. At the same time, due to localized heating effects, microwave heating can still maintain a relatively high reaction rate, making it an efficient heating method.

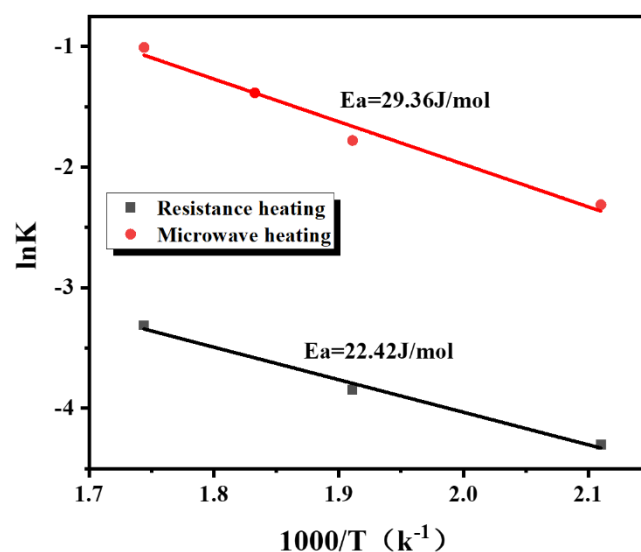


Figure 6. Arrhenius equation diagrams under different heating methods.

4. Conclusion

This study systematically compared the effectiveness of microwave heating and conventional resistance heating in the thermal desorption of mineral oil from contaminated soils. The results demonstrated that microwave heating significantly outperforms conventional resistance heating in terms of desorption efficiency, energy consumption, and the preservation of soil's physical and chemical properties. Specifically, microwave heating achieved higher removal rates of mineral oil at lower temperatures and shorter durations, owing to its more uniform and rapid internal heating mechanism. Moreover, the kinetic analysis confirmed that the desorption process under microwave heating aligns well with a first-order kinetic model, indicating its efficiency in accelerating the pollutant removal process. Furthermore, the study highlighted the advantages of microwave heating in reducing the activation energy required for desorption, thus offering a more energy-efficient alternative for soil remediation. The findings also revealed that microwave heating causes less degradation to the soil's organic matter content and cation exchange capacity (CEC), thereby preserving the soil's fertility and its potential for reuse after treatment. In conclusion, microwave-assisted thermal desorption presents a promising and superior alternative to conventional methods for the remediation of mineral oil-contaminated soils. Future research should focus on optimizing operational parameters and further exploring the long-term environmental impacts of this technology to enhance its applicability and effectiveness in diverse contaminated sites.

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