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Investigation into the removal of persistent organic pollutants from soil using infrared thermal desorption apparatus

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Abstract

The rapid accumulation of electronic waste has led to severe soil contamination with persistent organic pollutants (POPs), particularly polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs), posing significant environmental and health risks. Consequently, this study developed and evaluated a vacuum-infrared thermal desorption system for the efficient remediation of POPs-contaminated soil. A comprehensive investigation was conducted to determine the critical operating factors governing the desorption process. The results identified temperature, pressure, and residence time as the dominant factors affecting POPs removal, whereas moisture content and particle size exhibited minimal influence. Furthermore, a second-order polynomial prediction model for POPs removal was established using response surface methodology based on a box-behnken design, achieving an R^2 of 0.9921. It is noteworthy that the synergistic interaction between high temperature (400 °C) and low pressure (100 Pa) significantly enhanced the contaminant removal rate of POPs to levels exceeding 90%. Moreover, an increase in heating rates substantially accelerated the removal of POPs independent of system pressure, progressing from a rapid initial spike to a subsequent phase of steady enhancement. Throughout this process, PBDEs consistently exhibited higher removal efficiencies than PCBs due to their lower thermal decomposition thresholds. In conclusion, these findings not only validate the feasibility of the integrated vacuum-infrared technology but also provide crucial theoretical guidance and technical support for the energy-efficient remediation of POPs-contaminated soil.

Keywords: Persistent organic pollutants; Thermal desorption; Removal; Soil remediation

1. Introduction

Persistent organic pollutants (POPs), mainly including polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs), are highly efficient flame retardants that have been extensively applied in industrial production, including furniture, textiles, and electronics, to ensure fire safety (Hites 2004; Montano et al. 2022; Negrete-Bolagay et al. 2021; Ogunkunle et al. 2026). Since these substances are not chemically bound to the materials, they are easily released into the environment, leading to increasing concentrations in recent years (Hu et al. 2010; Persoon et al. 2010; Venier et al. 2016; Zhang et al. 2014). Substantial evidence from toxicological studies indicates that PBDEs can impair the endocrine and reproductive systems, as well as induce cancer in animals (Darnerud 2003; Herbstman et al. 2010; Stapleton et al. 2011; Talsness et al. 2008). Furthermore, prenatal exposure to PBDEs has been associated with reduced birth weight and length in newborn males (Vizcaino et al. 2011). Similarly, studies have demonstrated that environmental exposure to PCBs causes a spectrum of diseases in humans, such as cancer, endocrine disorders, and neurobehavioral anomalies (Barrios et al. 2023; German et al. 2023; Montano et al. 2022). Notably, electronic waste (e-waste) recycling is currently considered a significant pathway for the entry of PBDEs and PCBs into the environment (Hites 2004; Khalid et al. 2021; Montano et al. 2022).

The status of China as a global manufacturing leader has contributed to its position as a major repository for electronic and electrical waste, subjecting the nation to pressures from both domestic sources and foreign imports (Chi et al. 2011; Shi et al. 2021; Song et al. 2013). Thus, this intensified activity has transformed areas like Guiyu Town, Shijiao Town, and Taizhou into major hubs for e-waste accumulation (Song and Li 2014). Monitoring data from these regions reveal significant contamination by toxic heavy metals and organic compounds in recycling sites and the surrounding

air, soil, and water environments. The unregulated processing of e-waste typically involves recovering gold and other valuable materials through rudimentary techniques, including open burning, melting, and acid leaching. Consequently, these anthropogenic activities discharge toxic heavy metals such as Cu, Cd, Pb, and Hg, severely leading to profound contamination of aquatic and terrestrial systems and the atmosphere.

In family-run workshops, e-waste is processed through informal dismantling techniques designed to recover Au, Co, Cu, and other electrical components. These activities lead to the release of substantial quantities of persistent POPs, during stacking, dismantling, and landfilling operations. The primary pollutants include PCBs associated with capacitors and converters, PBDEs derived from circuit boards, and highly toxic dioxins and furans produced by open wire incineration (Ghimire et al. 2019; Steliga et al. 2020; Yin et al. 2022). Due to their stable structures and resistance to degradation, these POPs exhibit carcinogenic, teratogenic, and mutagenic toxicities while possessing bioaccumulative properties (Xiang et al. 2020). This has resulted in severely excessive concentrations of PCBs and PBDEs in residential areas and farmlands adjacent to dismantling sites. Statistics indicate that the average PBDE concentrations in soil at e-waste dismantling sites in Qingyuan and Guiyu have reached 2909 ng/g and 3330 ng/g respectively. Furthermore, PBDE content in soil at e-waste incineration points has been reported to be 445 times higher than that found in urban soils in the UK (Sepúlveda et al. 2010; Ye et al. 2015). Therefore, the remediation of soil contaminated by e-waste is imperative. Various technologies have been developed for the removal and disposal of PCBs in soil, including landfilling, advanced microbial degradation strategies, solvent extraction, thermal desorption, and incineration (Wang et al. 2021; Widanapathirana et al. 2023). Among these options, thermal desorption is distinguished by its effectiveness in treating volatile and semi-volatile

compounds, including polycyclic aromatic hydrocarbons (PAHs), PCBs, dichlorodiphenyltrichloroethane (DDT), total petroleum hydrocarbons (TPH), and Hg. Thermal desorption treatment offers distinct advantages such as the ability to handle a wide range of contaminants, rapid processing speeds, high efficiency, operational safety, and minimal generation of secondary pollutants (Wang et al. 2021). As a result, this method has been widely utilized to remediate highly polluted localized regions and is frequently applied to sites requiring emergency treatment. To date, most research on the thermal treatment of contaminated soil has focused on high temperatures, usually operating between 350 °C and 600 °C, which effectively meet cleanup standards. This reliance presents a significant challenge: high temperatures necessitate excessive energy consumption, while the traditional heating mechanisms involved are hindered by slow heating rates and long cycle times, ultimately limiting the technical and economic efficiency of the process.

To address prevalent remediation challenges, this study constructed a thermal desorption apparatus featuring an infrared heating source coupled with a constant pressure system. This configuration offered distinct advantages such as rapid heating capabilities, uniform thermal distribution, low thermal inertia, and enhanced economic feasibility. Initially, the critical factors governing the removal rate of POPs in soil were determined. Based on these key determinants, a prediction model for the removal efficiency of POPs was established. Moreover, the interactions among these variables were investigated using three-level response surface methodology (RSM). Ultimately, an investigation was performed to delineate the dependence of POPs removal efficiency on the heating rate during the thermal treatment of contaminated soil.

2. Materials and methods

2.1 Materials and reagents

A composite standard solution comprising a series of PCBs and PBDEs, specifically PCB28, PCB52, PCB101, PCB81, PCB77, PCB123, PCB118, PCB114, PCB153, PCB105, PCB138, PCB126, PCB167, PCB156, PCB157, PCB180, PCB169, PCB189, PBDE28, PBDE47, PBDE100, PBDE99, PBDE154, and PBDE153, was procured from Anpel-Trace Standard Technical Services Co. Ltd. and Cambridge Isotope Laboratories. Furthermore, individual standards of PBDE-3 and PBDE-15 were supplied by AccuStandard. Separate standards for PBDE-77 and PBDE-118 were also obtained from Cambridge Isotope Laboratories.

Given the spatial heterogeneity of POPs in naturally contaminated soils, laboratory-prepared samples were employed to ensure experimental reproducibility. The base soil was obtained from the 0-0.2 m surface layer in Wuhan, Hubei Province. Following the removal of organic residues and coarse materials, the matrix was naturally air-dried and sieved using a 23-mesh screen. The experimental samples were prepared by introducing 0.5 mL of PCBs (100 μg/mL) and 1 mL of PBDEs (50 μg/mL) standard solutions into a 50 g soil aliquot. The mixture was mechanically stirred to ensure homogeneity and aged in a fume hood for 24 h to yield a standardized contamination level of 1 ppm.

2.2 Experimental methods

Soil samples collected before and after thermal desorption were first pretreated via a sequential process consisting of microwave extraction, centrifugation with rotary evaporation, and concentration by nitrogen blowdown. Subsequently, the POPs levels were quantitatively measured by gas chromatography-mass spectrometry (GC-MS, 8860/5977B, Agilent, USA). Microwave-assisted extraction was conducted by combining the prepared sample with 20 mL of n-hexane and acetone mixed at a 1:1 volume ratio within an extraction vessel. The instrument adhered to a heating program where the temperature increased to 115 °C at a ramp rate of 10 °C/min and was maintained for 15

123 min. To ensure exhaustive extraction, this process was repeated four times, and the resulting
124 supernatants were pooled to obtain a total volume of 80 mL. The combined solution was centrifuged
125 at 2900 r/min for 5 min, and the supernatant was reduced to approximately 10 mL via rotary
126 evaporation. The concentrate was then transferred to a tube and further evaporated under a nitrogen
127 stream to a final volume of 2.5 mL. Prior to GC-MS detection, the sample was filtered through a 0.22
128 μm membrane into an injection vial.

129 Initially, the infrared thermal desorption device was constructed as depicted in Fig. 1 (Zheng et
130 al. 2026). The core configuration of this experimental system integrated several key elements,
131 predominantly featuring an electronic pressure gauge, an infrared heating furnace, and a vacuum
132 pump. In order to elucidate the impact of various factors on the removal rate of POPs from
133 contaminated soil, the effects of temperature, pressure, residence time, moisture content, and soil
134 particle size were examined. Subsequently, the influence of each individual factor was evaluated, and
135 the approximate ranges of the parameters were determined. The temperature was varied between 200
136 and 400 °C, the pressure between 100 and 101000 Pa, the residence time between 10 and 40 min, and
137 the moisture content between 10 and 30 wt%, while the soil particle size was classified into 23-60
138 mesh (250-700 μm), 100-150 mesh (100-150 μm), and 150-200 mesh (75-100 μm) for the subsequent
139 experiments. When analyzing the effect of a single parameter, the other parameters were held constant.
140 After identifying the most significant factors, 17 experimental combinations were designed following
141 the Box-Behnken experimental design method. The selected independent variables for further
142 investigation included temperatures of 200, 300, and 400 °C, pressures of 100, 505, and 101000 Pa,
143 and residence times of 10, 25, and 40 min. RSM was employed to fit a second-order polynomial
144 equation and develop a predictive model, thereby elucidating the interactions between the factors and

the target response. Finally, a series of experiments was designed to assess the influence of heating rates on POPs removal during thermal desorption. The control variables for these trials included a constant total heating time of 10 min and a steady terminal temperature of 400 °C. To comprehensively evaluate the targeted effect, the tests were systematically executed using predefined heating rates of 1 °C/s, 1.33 °C/s, 1.66 °C/s, 2 °C/s, 4 °C/s, 10 °C/s, and 40 °C/s.

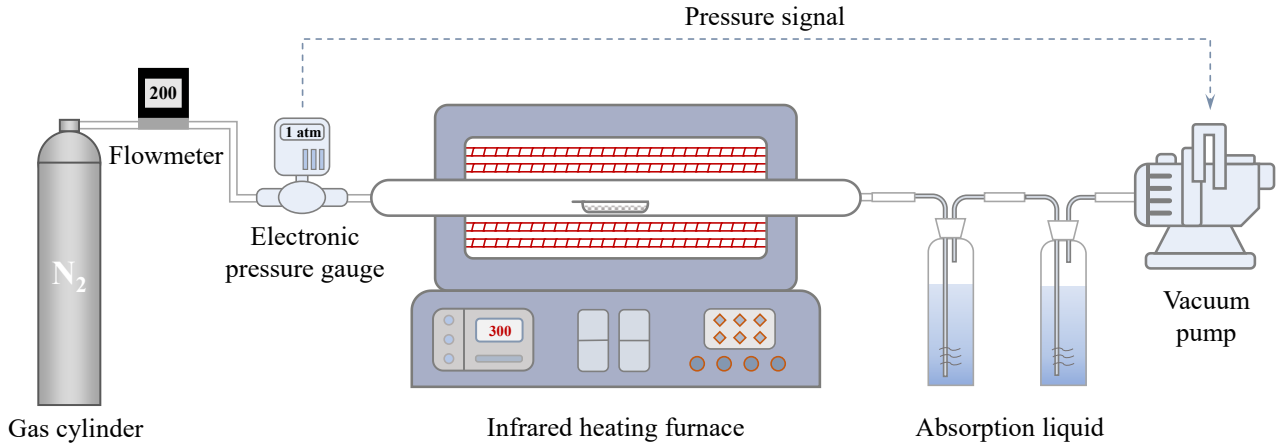


Fig. 1. Schematic diagram of the experimental apparatus utilized for infrared thermal desorption.

2.3 Analytical methods

The detection of POPs concentrations in the samples was carried out using GC-MS. The analysis utilized an Agilent DB-5MS chromatographic column (30 m × 250 μm × 0.25 μm). N_2 served as the carrier gas at a constant flow rate of 1 mL/min, and samples were introduced via splitless injection at 300 °C. The heating program commenced at 150 °C for 2 min, subsequently increased to 260 °C at 5 °C/min for 1.5 min, and finally reached 310 °C at 20 °C/min for 10 min. The ion source was EI, with the ion source temperature set to 230 °C, while the quadrupole and transfer line temperatures were set to 150 °C and 300 °C, respectively. In addition, a solvent delay of 5 min was implemented to avoid solvent interference. Full-scan spectra were recorded over 50 to 1000 amu, and SIM was employed to improve the specificity of compound analysis. The standard curves of 18 kinds of PCBs

and 6 kinds of PBDEs were prepared, with the concentration range of 0.1, 1, 2, 5, 10 mg/L.

To verify the reliability of the GC-MS analysis, the previously described procedure was used to analyze standard samples of PCBs and PBDEs. After five replicate injections, the retention times, qualifier ions, and quantifier ions for PCBs and PBDEs in soil are summarized in Table S1 and Table S2, while the corresponding calibration equations and correlation coefficients are provided in Table S3 and Table S4. Specifically, the quantitative ions for PCBs were monitored at 256, 292, 326, 360, and 394 m/z, whereas ions 246, 326, 404, and 484 were selected for PBDEs. The recovery rates of PCBs and PBDEs were calculated using the following equations:

$$\text{PCBs\%}=\frac{(M_{PCB28}+M_{PCB52}+M_{PCB101}+\ldots)-(m_{PCB28}+m_{PCB52}+m_{PCB101}+\ldots)}{(M_{PCB28}+M_{PCB52}+M_{PCB101}+\ldots)}\times 100\% \quad (1)$$

$$\text{PBDEs\%}=\frac{(M_{PBDE28}+M_{PBDE47}+M_{PBDE100}+\ldots)-(m_{PBDE28}+m_{PBDE47}+m_{PBDE100}+\ldots)}{(M_{PBDE28}+M_{PBDE47}+M_{PBDE100}+\ldots)}\times 100\% \quad (2)$$

The standard POPs-contaminated samples prepared in Section 2.2 were first pretreated and then quantified. The recovery rates of the pretreatment method were obtained by comparing the measured concentrations with the spiked concentrations, and the results are summarized in Table 1. The recovery rates of 18 PCBs congeners and 6 PBDEs congeners were within 65% to 120%, with relative standard deviations of 2.5% to 10%. Therefore, the pretreatment method satisfied the analytical requirements and demonstrated satisfactory repeatability.

177 Table 1. Recovery rates of spiked standard samples for PCBs and PBDEs.

POPs	Number	Name	Recovery rate%	RSD%
PCBs	1	2,4,4'-Tribromodiphenyl ether PBDE28	65	6
	2	2,2',4,4'-Tetrabromodiphenyl ether PBDE47	93	10
	3	2,2',4,4',6-Pentabromodiphenyl ether PBDE100	88	8
	4	2,2',4,4',5-Pentabromodiphenyl ether PBDE99	97	9
	5	2,2',4,4',5,6'-Hexabromodiphenyl ether PBDE154	105	6
	6	2,2',4,4',5,5'-Hexabromodiphenyl ether PBDE153	120	5
PBDEs	1	2,4,4'-Trichlorobiphenyl PCB 28	75	4.6
	2	2,2',5,5'-Tetrachlorobiphenyl PCB 52	86	5.7
	3	2,2',4,5,5'-Pentachlorobiphenyl PCB 101	76	4.9
	4	3,4,4',5-Tetrachlorobyl PCB 81	82	4.9
	5	3,3',4,4'-Tetrachlorobiphenyl PCB 77	86	5.6
	6	2',3,4,4',5-Pentachlorobiphenyl PCB 123	80	5.3
	7	2,3',4,4',5-Pentachlorobiphenyl PCB 118	82	5.2
	8	2,3,4,4',5-Pentachlorobyl PCB 114	80	5.0
	9	2,2',4,4',5,5'-Hxachlorobiphenyl PCB153	80	4.9
	10	2,3,3',4,4'-Pntachlorobyl PCB105	82	5.1
	11	2,2',3,4,4',5'-Hexachlorobiphenyl PCB138	80	4.6
	12	3,3',4,4',5-Pntachlorobyl PCB126	87	4.9
	13	2,3',4,4',5,5'- Hexachlorobiphenyl PCB167	82	4.8
	14	2,3,3',4,4',5-HexachlorobiphenylPCB156	96	5.9
	15	2,3,3',4,4',5'-HexachlorobiphenylPCB157	88	2.5
	16	2,2',3,4,4',5,5'-Heptachlorobiphenyl PCB180	84	3.8
	17	3,3',4,4',5,5'-HexachlorobiphenylPCB169	93	3.7
	18	2,3,3',4,4',5,5'- Heptachlorobiphenyl PCB189	92	4.2

178 **3. Results and Discussion**

179 **3.1 Identification of critical factors affecting POPs removal from contaminated soil**

To optimize the remediation process, this study investigated the impact of temperature, pressure, residence time, moisture content, and soil particle size on the removal rate of POPs from contaminated soil via the thermal desorption method. Three distinct levels were selected for each influencing factor in the subsequent experiments. The obtained POPs removal rates and the corresponding variability under each condition are depicted in Fig. 2.

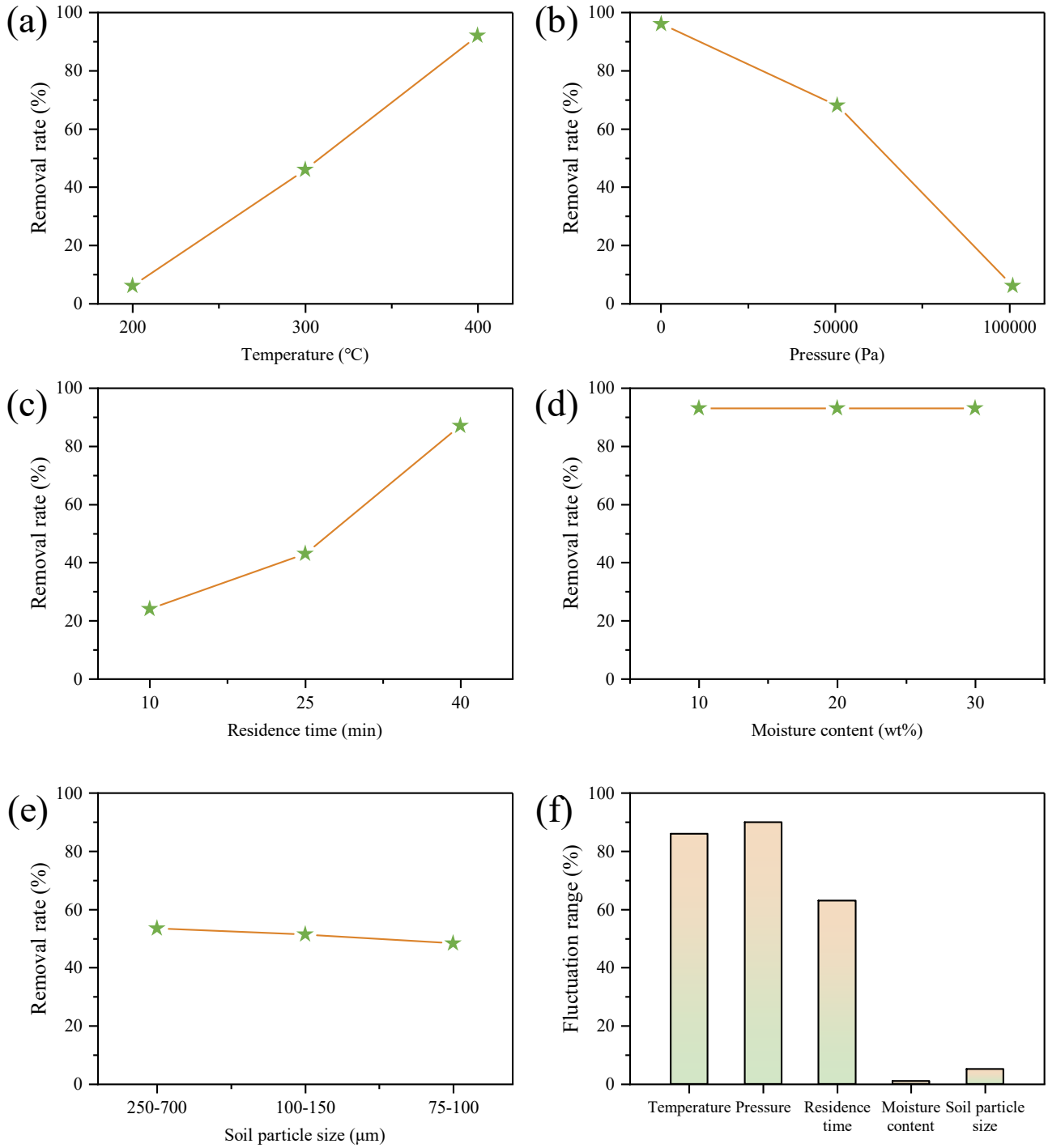


Fig. 2. Variation of POPs removal rates under different influencing factors: (a) temperature, (b) pressure, (c) residence time, (d) moisture content, (e) soil particle size, and (f) the fluctuation range of removal rate corresponding to each factor.

As illustrated in Fig. 2(a-c), variations in temperature, pressure, and residence time resulted in significant changes in the removal rate of POPs. Specifically, when the temperature increased from 200 to 400 °C, the removal rate of POPs rose significantly from 6% to 92%. Similarly, a reduction in pressure from 101000 to 100 Pa enhanced the removal rate of POPs from 6% to 96%, while extending the residence time from 10 to 30 min increased the removal rate from 24% to 87%. The data presented in Fig. 2(f) further demonstrate that the fluctuation amplitudes for temperature, pressure, and residence time were 86%, 90%, and 63%, respectively, indicating that these three factors exert a strong influence on the removal rate of POPs. On the other hand, Fig. 2(d) and (e) show that the removal rate remained essentially constant when the moisture content rose from 10 to 30 wt%. Furthermore, the influence of particle size was found to be minor and complex, characterized by slight fluctuations without a distinct monotonic trend and insignificant differences between size intervals.

Overall, the impact of temperature, pressure, and residence time on the removal efficiency significantly outweighs that of particle size and moisture content. Variations in temperature, pressure, and residence time can induce significant changes in the removal rate of POPs from contaminated soil, whereas the impact of particle size and moisture content is relatively minor. Consequently, temperature, pressure, and residence time were selected as the critical factors for the subsequent thermal desorption experiments.

3.2 Model construction for the removal rate of POPs from contaminated soil

Based on the analysis in Section 3.1, temperature, pressure, and residence time were identified

as the primary factors affecting the removal of POPs from contaminated soil. Therefore, the combined influence of these factors was further investigated. For this investigation, the operating conditions were set within the ranges of 200-400 °C for temperature, 100-101000 Pa for pressure, and 10-30 min for residence time.

Response surface methodology (RSM) was utilized to elucidate the functional relationship between the influencing factors and the response values by fitting a second-order polynomial equation, which allowed for the optimization of the target parameters. In this investigation, the Box-Behnken design (BBD) was adopted to generate 17 experimental combinations to characterize the response surface. Table 2 provides the experimental matrix along with the corresponding results.

Table 2. Box-Behnken design matrix and results

Number	Temperature /℃	Residence time /min	Pressure /Pa	Removal rate /%
1	300	40	100	87
2	300	25	50550	58
3	200	25	100	96
4	200	25	101000	6
5	400	40	50550	88
6	200	10	50550	22
7	300	25	50550	43
8	300	10	101000	34
9	300	10	100	24
10	300	40	101000	46
11	300	25	50550	63
12	300	25	50550	68
13	300	25	50550	58
14	400	25	100	99
15	400	25	101000	92

16	400	10	50550	73
17	200	40	50550	68

Initially, the influence of temperature, pressure, and residence time was evaluated using the removal rate data from the experiments. Through multiple regression fitting, an empirical model was established to correlate the removal rate, *Y*, with the independent variables: temperature (X_1), residence time (X_2), and pressure (X_3). This relationship is mathematically represented by the following equation:

$$Y = 63.01 - 0.1987 \times X_1 + 3.185 \times X_2 - 0.0018 \times X_3 - 0.005167 \times X_1X_2 + 4.113 \times 10^{-6} \times X_1X_3 - 1.200 \times 10^{-5} \times X_2X_3 + 5.330 \times 10^{-4} \times X_1^2 - 3.405 \times 10^{-9} \times X_3^2 \quad (3)$$

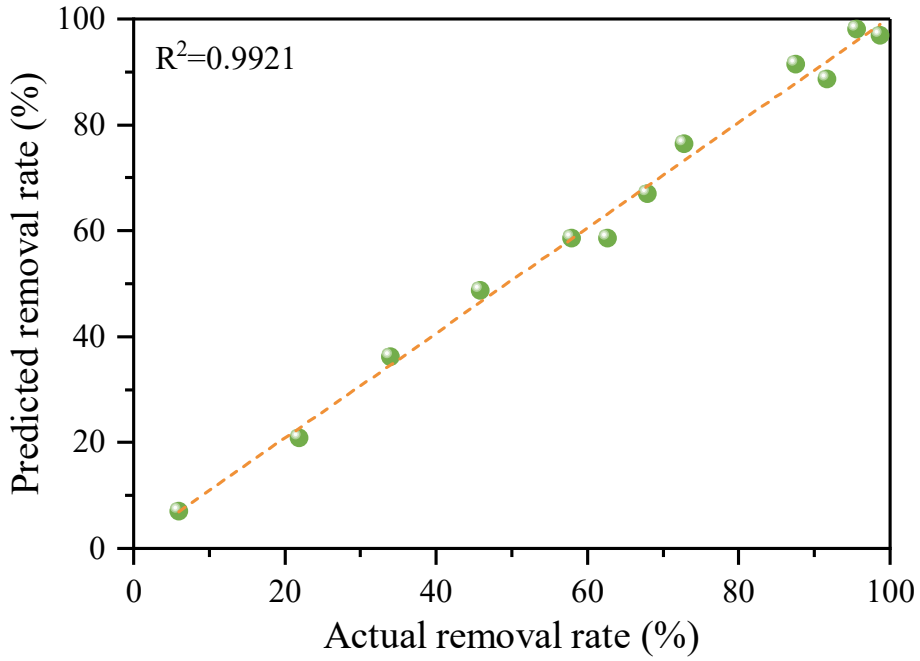
This established prediction model provides estimation of POPs removal rates by manipulating the desorption temperature, residence time, and pressure. Its validity was confirmed through an analysis of variance (ANOVA), summarized in Table 3. The analysis revealed that all model terms, excluding X_1^2, were significant with p-values below 0.005. The terms X_1, X_3 and the X_1X_3 interaction were exceptionally significant with p-values less than 0.0001, and the F-values were large, ranging from 5.37 to 201.47. These results collectively demonstrate the high significance and good fitting accuracy of the regression model.

Table 3. Analysis of variance for the prediction model.

Item	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value	Significance
Model	8	10000.08	1250.01	78.7	< 0.0001	Significant
X_1	1	3200	3200	201.47	< 0.0001	
X_2	1	930.25	930.25	58.57	0.0006	
X_3	1	3040.13	3040.13	191.4	< 0.0001	
X_1X_2	1	240.25	240.25	15.13	0.0115	
X_1X_3	1	1722.25	1722.25	108.43	0.0001	

X_2X_3	1	114.08	114.08	7.18	0.0438	
X_1^2	1	85.33	85.33	5.37	0.0682	
X_3^2	1	225.33	225.33	14.19	0.0131	
Residual	5	79.42	15.88			
Lack of fit	2	60.67	30.33	4.85	0.1147	Not significant
Pure error	3	18.75	6.25		63	
Total variation value	13	10079.5			68	

231 The predictive performance of the model is presented in Fig. 3, which plots the predicted values
232 against the experimental removal rates. The analysis revealed a strong linear relationship with an R^2
233 value of 0.9921. This close correspondence between the predicted and actual values demonstrated the
234 high precision of the model. Thus, the model possessed significant credibility for practical
235 applications.



236

237 Fig. 3. Comparison between predicted values and experimental values.

3.3 The interactions between crucial factors for POPs removal using three-level RSM

Due to the simultaneous influence of multiple variables on POPs desorption, conventional two-dimensional plots fail to provide an intuitive visualization of the experimental results. Consequently, three-dimensional response surface plots were generated to characterize both the independent influence of each factor and their mutual interactions. During the assessment of the interaction between any two factors, the remaining factor was fixed at its intermediate level. The trends in desorption rate as a function of temperature and residence time are shown in Fig. 4. In Fig. 4(a), the 3D surface showed a steady increase, reflecting a consistent positive correlation with both variables. The similar slopes at the boundaries indicate that temperature and residence time contributed almost equally to the desorption rate. Analysis of the contour map in Fig. 4(b) revealed straight and uniformly dense contour lines. These graphical features confirmed that the interaction between temperature and residence time was weak and did not significantly alter the optimal conditions.

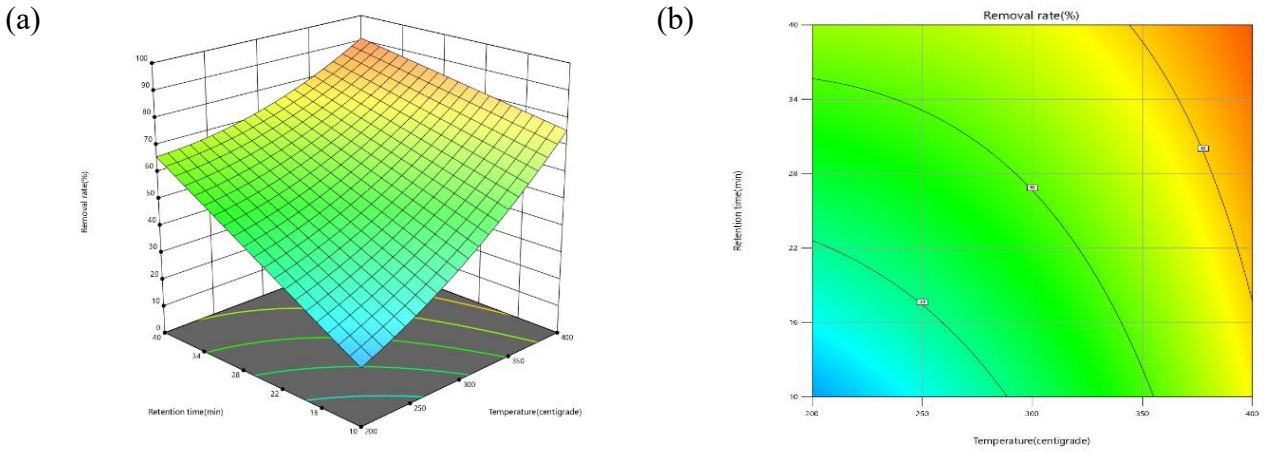


Fig. 4. The influence of temperature and residence time on POPs desorption rate: (a) 3D surface plot, (b) projected contour plot.

Fig. 5 displays the combined impact of temperature and pressure on the desorption rate. Fig. 5(a) demonstrate that the desorption efficiency was maximized under conditions of elevated temperature and reduced pressure, which was driven by two primary mechanisms. Firstly, rising temperatures

intensify molecular thermal motion, making it easier for POPs to detach from soil particles. Secondly, low pressure creates a vacuum that not only extracts air trapped in soil pores but also reduces the partial pressure of POPs vapor, thus facilitating further desorption. The elliptical contour lines in Fig. 5(b) indicated a strong interaction between temperature and pressure. Specifically, under conditions of high temperature and low pressure, any reduction in temperature or increase in pressure led to a significant decrease in the desorption rate. This phenomenon is primarily attributed to the fact that POPs desorbed under negative pressure are simultaneously subjected to molecular thermal motion driven by temperature. Thus, the synergistic effect of temperature and pressure was crucial for optimal desorption. Moreover, the steep slopes at the boundaries of Fig. 5(a) underscored that both parameters exerted a significant influence on the overall removal rate.

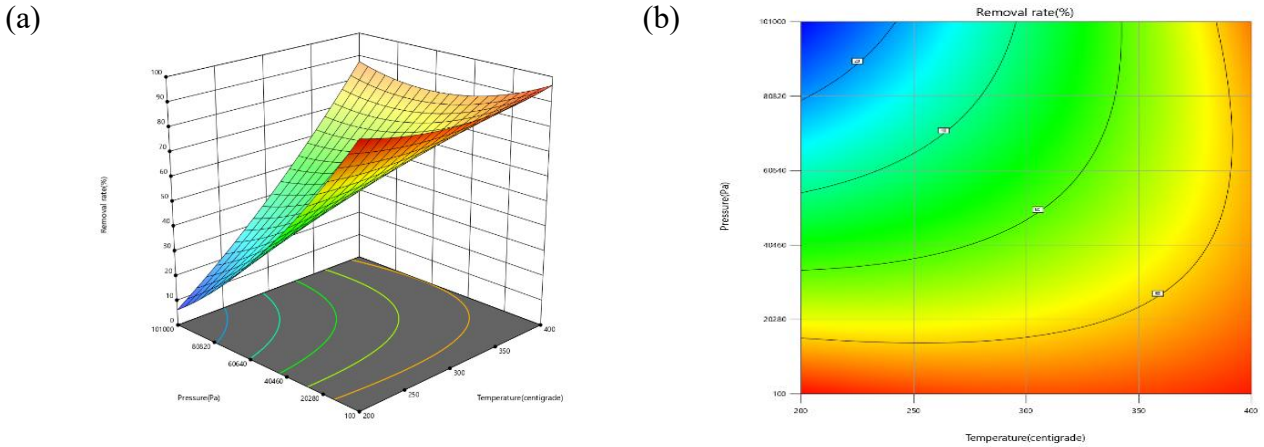


Fig. 5. The influence of pressure and temperature on POPs desorption rate: (a) 3D surface plot, (b) projected contour plot.

The similarity between Fig. 6 and Fig. 5 indicates that the combination of temperature and residence time had an impact on the desorption rate analogous to that of pressure and residence time. The experiment utilized an RTP photothermal furnace, where heat exchange occurred primarily through radiative heat transfer. Due to high heating efficiency, the sample reached the working temperature within 1 min. Consequently, the proportion of unsteady heat exchange was minimal

throughout the entire process, ensuring that the thermal desorption of POPs remained relatively stable. Therefore, both the temperature-residence time and pressure-residence time combinations exhibited weak interactions under working conditions, leading to a stable increase in the desorption rate.

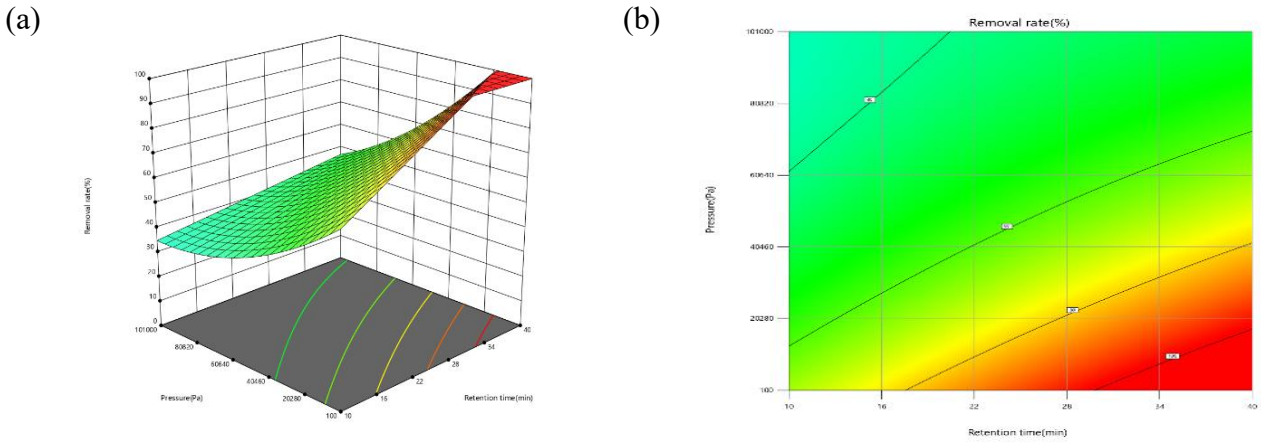


Fig. 6. The influence of pressure and residence time on POPs desorption rate: (a) 3D surface plot, (b) projected contour plot.

3.4 Effect of heating rate on the removal efficiency of POPs from contaminated soil

The impact of heating rates on the thermal desorption efficiency of POPs is detailed in Fig. 7. As illustrated in Fig. 7(a), the removal rates of both PCBs and PBDEs at normal pressure generally improved as the heating rate increased. Notably, a sharp surge in the removal rate occurred between 1 °C/s and 2 °C/s, while the progression shifted to a stable plateau between 2 °C/s and 40 °C/s. This specific trend was likely governed by the thermodynamic characteristics of the POPs, which predominantly have boiling points greater than 300 °C. During the initial thermal desorption phase below this temperature, the pollutants maintained strong thermal stability and remained adsorbed to the soil particles without undergoing thermal decomposition. Consequently, an adequate heating duration was essential, and the actual thermal desorption of POPs only commenced after a specific activation temperature was reached.

Furthermore, under the same heating rate, the removal rate of PBEDs consistently exceeded that of PCBs. This phenomenon could be attributed to the lower thermal decomposition temperature of PBEDs compared to PCBs, which allowed the thermal degradation process to initiate at a lower temperature. Although the melting point of PBEDs is slightly higher than that of PCBs, which theoretically suggests a slower phase transition and soil desorption process for PBEDs, their total removal rate remained higher. This indicates that during the initial stage, the thermal decomposition of PBEDs was the dominant mechanism, whereas desorption played a secondary role. Additionally, the difference in removal rates between PBEDs and PCBs remained relatively constant, implying that their thermal desorption efficiencies became comparable at 400 °C. Notably, when applying a heating rate of 4 °C/s, the total removal rate of POPs exceeded 50%.

Additional experiments were conducted to determine the influence of heating rates at a low pressure of 50500 Pa on POPs removal efficiency. By comparing the outcomes in Fig. 7(b) with those in Fig. 7(a), it becomes evident that the general desorption pattern closely paralleled the trend observed under standard pressure. Specifically, there was a steeper increase in the desorption rate between 1 °C/s and 2 °C/s, whereas the rate of increase gradually diminished from 2 °C/s to 40 °C/s. Moreover, the desorption rate of PBDEs consistently exceeded that of PCBs throughout the process. This persistent difference indicates that the effects of heating rate and pressure on POPs thermal desorption were relatively independent. Similarly, when a heating rate of 4 °C/s was applied, the total desorption rate of POPs surpassed 50%.

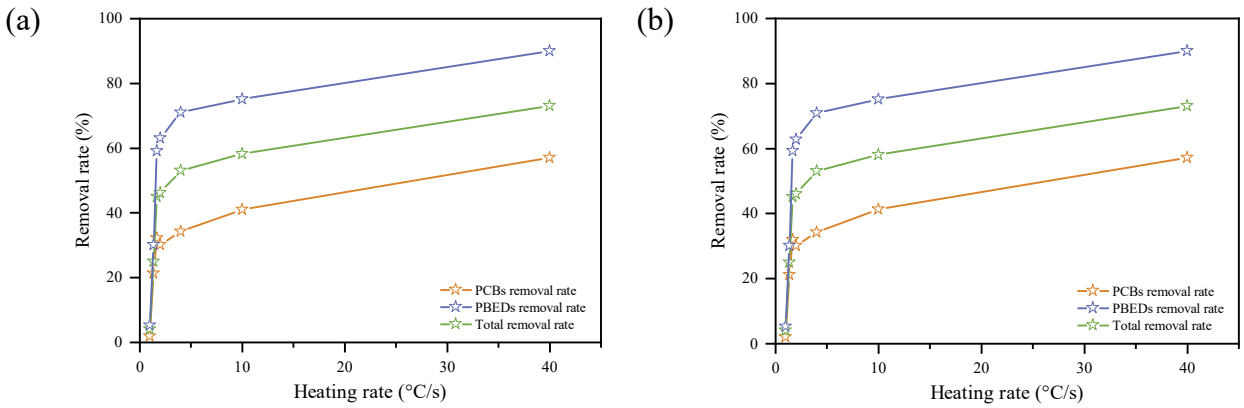


Fig. 7. The impact of heating rates on POP removal at distinct pressure levels: (a) 101000 Pa, (b) 50550 Pa.

4. Conclusions

This study elucidated the removal performance of POPs, specifically including PCBs and PBDEs, from contaminated soil using an infrared thermal desorption system coupled with vacuum control. Through a comprehensive parametric analysis, temperature, pressure, and residence time were identified as the dominant factors governing the desorption process of POPs, whereas moisture content and particle size exhibited limited influence. A second-order polynomial prediction model was established using RSM, which demonstrated high accuracy with an R^2 value of 0.9921 in forecasting removal rates of POPs under varying conditions. Specifically, a significant interaction was observed between temperature and pressure, where the coupling of high temperature at 400 °C and low pressure at 100 Pa yielded a synergistic effect that maximized the removal rate to over 90%. Additionally, the study highlighted the engineering superiority of infrared heating, which offered rapid thermal response and reduced energy dissipation compared to traditional conduction heating. Furthermore, higher heating rates significantly enhanced the initial thermal desorption efficiency of POPs independently of system pressure, with PBDEs consistently exhibiting higher removal rates than PCBs due to their lower thermal decomposition thresholds. These findings suggest that the

integrated vacuum-infrared technology presents a robust and energy-efficient method for the remediation of POPs-contaminated soil.

Availability of data and material

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests in this paper.

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Authors' contributions

Xinxin Li: Writing - original draft, Investigation, Methodology, Data curation, Formal analysis, Conceptualization. **Guangyuan Yang**: Writing - review & editing, Data curation, Formal analysis, Investigation. **Lu Ning**: Investigation, Methodology. **Kuang Sheng**: Investigation, Methodology, Formal analysis, Conceptualization. **Lei Han**: Supervision, Visualization, Methodology. **Chan Zou**: Supervision, Writing - review & editing. **Hongyun Hu:** Conceptualization, Funding acquisition, Project administration.

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