

Research Progress of Mercury and Mineral Adsorption Behavior

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ABSTRACT

Thallium (Tl) and mercury (Hg), as heavy metal elements with significant biotoxicity, are typical environmental pollutants widely found in China and even globally. They are widely distributed in a variety of environmental media, such as water, atmosphere, soil, etc., and have the characteristics of persistence, bioaccumulation and amplification along the food chain/food web. Such characteristics lead to the continuous enrichment of Tl and Hg in living organisms, which constitutes a continuous and serious threat to the health of ecosystems and the safety of human beings. The aim of this paper is to systematically review the important progress of thallium and Hg pollution research in recent years, focusing on the main sources of pollution, spatial and temporal distribution characteristics in environmental media, key transport and transformation processes, potential hazards and toxicity effects on the ecosystem, as well as integrated soil and water environment management and pollution prevention strategies. Especially crucial, this paper focuses on the emerging research direction of adsorption and immobilization of Tl and Hg by natural mineral materials. Starting from the interaction mechanism between minerals and heavy metal ions, we will systematically summarize and review the latest research progresses at home and abroad in the use of natural minerals for Tl and Hg batch adsorption experiments, the in-depth analysis of adsorption mechanisms with the help of advanced instrumental characterization techniques (e.g., XPS, XRD, SEM-EDS, and spectroscopy, etc.), and the simulation of microscopic adsorption processes with the use of theoretical computational methods (e.g., density-functional-theoretic DFT). The latest research progress. This systematic review not only provides a solid foundation for the in-depth understanding of the scientific mechanisms of mineral interfaces regulating the environmental behavior of Tl and Hg, but also provides important theoretical support and practical guidance for the development of highly efficient, economical, and environmentally friendly remediation technologies based on natural minerals for heavy metal pollution.

KEYWORDS

ICP-MS; Drinking Water; Elemental Analysis

1. INTRODUCTION TO THALLIUM AND MERCURY AND THEIR ENVIRONMENTAL HAZARDS

Thallium (Tl) is a silver-white (or grayish-white), soft metallic element with significant biotoxicity. Its physical properties include a relatively high density (11.85 g/cm³), a low melting point (303.5°C), and a boiling point of 1457°C. Thallium exhibits both lithophilic (oxyphilic) and chalcophilic geochemical behaviors, which profoundly influence its distribution and occurrence states in the environment.

In aquatic environments, thallium primarily exists in two oxidation states: +1 (Tl(I)) and +3 (Tl(III)). However, under natural environmental conditions, Tl(III) has poor thermodynamic stability, and its environmental concentration is generally much lower than that of Tl(I). Therefore, in water bodies

and most environmental media, thallium predominantly exists as the relatively soluble and highly mobile Tl(I) species, whereas the more oxidizing, less soluble, and less mobile Tl(III) is only found under specific oxidizing conditions or at low concentrations. Thallium has two stable isotopes in nature: ^{203}Tl (abundance $\sim 29.5\%$) and ^{205}Tl (abundance $\sim 70.5\%$). [1]

The chalcophilic and lithophilic characteristics of thallium are core features of its environmental geochemical cycling. These properties lead to significant enrichment of thallium in sulfur-bearing minerals (such as sulfides) and certain oxygen-bearing minerals. For example, in pyrite (FeS_2) and manganese oxide minerals (e.g., MnO_2), thallium concentrations are often much higher than its background values in ordinary soils or sediments. Previous studies have revealed that thallium concentrations in certain pyrite and manganese oxide deposits can reach astonishing levels of 11,000 to 35,000 mg/kg, fully demonstrating the capacity of specific mineral phases as important environmental "sinks" for thallium. This enrichment phenomenon is mainly attributed to the strong adsorption of Tl(I) onto mineral surfaces or isomorphous substitution with cations in the mineral lattice. [2]

The toxic heavy metal Tl is a pollutant that poses a significant threat to all organisms, including humans, primarily due to its similarity to K (potassium), which causes organisms to absorb it as if it were potassium. Therefore, thallium can rapidly enter the human body through the respiratory tract, digestive tract, and other pathways, disrupting the stability of pyruvate kinase, ATPase, and ribosomes, thereby causing damage to the gastrointestinal tract, muscles, and nervous system. [3]

Mercury in nature mainly exists in three forms: elemental Hg (liquid or monatomic vapor), mercuric ion Hg(II) , and methylmercury (MeHg), which can interconvert through biotic and abiotic redox processes. Different mercury species have distinct chemical properties, bioavailability, and toxicity. Unlike Hg, Hg(II) is highly reactive and exhibits nephrotoxicity, hepatotoxicity, and immunotoxicity. Moreover, Hg(II) can react in the environment to form the more toxic methylmercury, which poses a great threat to human health. [4]

Major anthropogenic sources of Hg emissions in the environment include gold mining and fossil fuel combustion. Once mercury is deposited in aquatic environments, it undergoes redox reactions, forms complexes with ligands in the water, and adsorbs onto particles. It can also be methylated by microorganisms. The methylated form, MeHg , can be absorbed by organisms and undergoes bioaccumulation and biomagnification along the food chain, thereby exerting adverse effects on ecosystems and human health.

2. DISTRIBUTION OF THALLIUM AND MERCURY CONTENTS IN SOIL AND WATER BODIES

2.1. Distribution of Thallium

Thallium (Tl) concentrations in water are generally low. The abundance of thallium in seawater is $0.019\text{ }\mu\text{g/L}$, while in freshwater it ranges from 0.01 to $0.05\text{ }\mu\text{g/L}$. The concentration of thallium in drinking water is generally below the detectable level of $0.3\text{ }\mu\text{g/L}$ and is rarely higher than $1\text{ }\mu\text{g/L}$. The toxic concentration of thallium in water is $5\times 10^{-5}\text{ }\mu\text{g/L}$, and a concentration of $1\times 10^{-3}\text{ }\mu\text{g/L}$ of Tl can cause plant poisoning, thereby affecting agriculture. In unpolluted shallow groundwater, Tl concentrations range from $0.0077\text{ }\mu\text{g/L}$ to $0.437\text{ }\mu\text{g/L}$; in contaminated water bodies, Tl concentrations can be dozens or even hundreds of times higher than background levels.

The distribution of thallium in soil is heterogeneous worldwide. In natural background soils, the Tl content ranges from 0.01 to 3.0 mg/kg , with a median value of 0.2 mg/kg , generally not exceeding 1.0 mg/kg [5]. In surface soils of the United States, thallium content ranges from 0.2 to 2.8 mg/kg [6]; in French surface soils, it ranges from 0.13 to 1.54 mg/kg [7]. In China, the background range of thallium in soils is 0.29 – 1.17 mg/kg , with a median value of 0.58 mg/kg [7]. The distribution of Tl

contamination in China shows a trend of "lighter in the north and heavier in the south, lighter in the west and heavier in the east." Thallium in Jiangxi Province soils is significantly higher than in neighboring provinces, ranking the highest in the country. Although relatively lower compared to France and the United States, it still exceeds the global mean value.

2.2. Distribution of Mercury

Annual mercury emissions from anthropogenic activities are approximately 2,000–2,500 t/a [8-11], while natural processes contribute 1,000–5,500 t/a. Both pathways release substantial amounts of mercury into the atmosphere. Since the Industrial Revolution, anthropogenic activities have led to a 3- to 5-fold increase in global atmospheric mercury concentrations and deposition fluxes, with total mercury concentrations in surface seawater and soil increasing by approximately 2-fold and 3-fold, respectively [12-14].

In the soil survey report released by China in 2014, mercury has become one of the top three inorganic pollutants in terms of soil contamination in China. The Wanshan area in Guizhou Province, China, was once the largest mercury mining and refining center in the country. By 2001, the Wanshan area had produced approximately 22,000 tons of mercury and 6,000 tons of cinnabar (HgS). The mercury mass fraction in soils of this area reached 5.1–790 mg/kg [15]. Research by Zheng Dongmei et al. showed that the mercury mass fraction in surface soils of the non-ferrous metallurgical and chemical industrial zone in Huludao City ranged from 0.05 to 14.6 mg/kg. Yin Wei et al. reported that the average mercury mass fraction in urban soils of Guangzhou reached 0.614 mg/kg.

3. ENVIRONMENTAL SIGNIFICANCE OF THALLIUM AND MERCURY ADSORPTION ON MINERAL SURFACES

Both thallium (Tl) and mercury (Hg) are non-essential heavy metal elements in ecosystems, meaning that even at trace levels, their presence in the environment can exert significant toxic effects on organisms and ecosystems. Given their potential ecological and health risks, relevant environmental management agencies have significantly strengthened monitoring and control measures for Tl and Hg pollution in water bodies. However, in comparison, current understanding remains relatively limited regarding the speciation, release kinetics, and migration–transformation patterns of Tl and Hg in contaminated soils within the soil–water–biological system.

In recent years, tailings pond leakage accidents triggered by extreme climatic events (such as heavy rainfall and floods) or improper agricultural practices (such as soil acidification caused by excessive fertilization) have occurred frequently [16]. Such incidents directly result in severe contamination of farmland soils around mining areas with high concentrations of Tl, Hg, and other heavy metals, posing an imminent threat to agricultural product safety and regional ecological health. Therefore, in-depth investigation into the migration behavior and chemical transformation processes of Tl and Hg in complex environmental media (especially soil systems) has become a major urgent issue in the field of environmental science.

As typical heavy metal pollutants, Tl and Hg exhibit high persistence (long-term retention) and bioaccumulation in the environment. They can reside and continuously accumulate in soils and water bodies over extended periods, subsequently being absorbed by plant roots or entering animal bodies through other pathways. More critically, due to their low excretion rates and high bioaccumulation factors in organisms, Tl and Hg can be progressively transferred and significantly amplified (biomagnification effect) along the food chain (web). Ultimately, as the apex of the food chain, humans inevitably become the ultimate recipients of the accumulation and toxic effects of these harmful heavy metals, posing long-term and far-reaching risks to public health.

Understanding the emission pathways and migration–transformation patterns of mercury and thallium is fundamental to reducing their emissions and mitigating ecological and environmental risks. Currently, domestic and international scholars have conducted extensive research on the sources of mercury and thallium, their occurrence forms in soil, water, atmosphere, plants, animals, and various human tissues and organs, as well as their migration and transformation characteristics among rocks, soil, water, atmosphere, and changes in animal populations. However, research on the geochemical behavior of thallium and mercury still has significant limitations. At present, understanding of the enrichment mechanisms, migration and transformation patterns, toxicity pathways, and effects of thallium in supergene environments remains in its early stages. Studies on multi-media environmental models for mercury are mainly confined to aquatic environments. In addition to the atmosphere, water environments, and sediments, soil and plants are also indispensable environmental phases in the geochemical cycling of mercury [14].

Numerous minerals, such as montmorillonite, illite, kaolinite, and mackinawite, are abundantly present in soils and water environments on Earth. These minerals can effectively adsorb Tl and Hg in soil media. Investigating the adsorption of Tl and Hg on mineral surfaces can greatly aid in addressing environmental issues related to soils and water bodies. Moreover, adsorption methods are relatively cost-effective and can be readily applied to manage wastewater discharge from chemical plants and power plants. This approach holds significant environmental significance for addressing anthropogenic emissions of Tl and Hg.

4. BATCH ADSORPTION EXPERIMENTS AND INSTRUMENTAL CHARACTERIZATION OF THALLIUM AND MERCURY ADSORPTION ON MINERAL SURFACES

4.1. Research Progress on Batch Adsorption Experiments of Thallium and Mercury

Batch adsorption experiments of Tl and Hg are conducted under laboratory conditions by varying experimental parameters (pollutant concentration, temperature, pH value, etc.), with Tl and Hg quantitatively analyzed using XPS. Batch adsorption experiments primarily investigate the following aspects:

Adsorption Kinetics: During the adsorption process, adsorption and desorption occur simultaneously, and the rates of these two processes can fundamentally alter the adsorption capacity between the adsorbent and the adsorbate. Adsorption kinetics mainly studies the effects of various factors on chemical reaction rates and investigates the reaction mechanisms during chemical processes. It enables the practical application of thermodynamic calculations and correlates the relationships among macroscopic quantities in experimentally measured chemical reaction systems through empirical formulas.

Adsorption Isotherms: Adsorption isotherms refer to the curves that describe the relationship between solute concentrations in the two phases at the interface when the adsorption process reaches equilibrium at a given temperature. They are equilibrium curves reflecting the adsorption and desorption between the adsorbent and the adsorbate.

pH Adsorption Edges: pH adsorption edges refer to the variation in adsorption strength across different pH ranges. They primarily reflect changes in adsorption capacity caused by pH variations and are important parameters for determining whether an adsorbent can be applied in practical production.

For example, Chen Wanpeng et al. conducted batch adsorption experiments of thallium on goethite and hematite at a solid concentration of 10 g/L over a pH range of 5 to 12. These experiments examined the adsorption capacity of thallium as a function of concentration and pH conditions. The results demonstrated that when thallium adsorbs onto goethite and hematite surfaces, the effect of Tl

concentration on adsorption capacity is much smaller than that of pH; increasing pH enhances the adsorption capacity of the minerals. The experiments revealed that minerals generate more active functional groups under alkaline conditions. Fourier-transform infrared spectroscopy (FTIR) was employed to measure the dominant contributions of different functional groups to the adsorption process. XPS characterization confirmed that non-oxidative surface complexation adsorption is the primary adsorption mechanism occurring at the Tl(I)-iron/manganese secondary mineral interface. Furthermore, the Tl(III) content in the adsorption solution was very low, indicating that redox reactions between Tl(I) and the minerals have little influence on the Tl(I) adsorption process.

Martin L.A. et al. [17] conducted thallium adsorption experiments on illite and montmorillonite, primarily using Tl(I), which is widely present in the environment. The experiments adjusted solution pH and Eh values, with redox potentials measured on random samples using a Pt electrode (average value: 195.7 ± 4.3 mV at $T = 20.1^\circ\text{C}$) to ensure that experimental conditions remained within the above range. Under these conditions, Tl(I) was the only stable form of thallium, accounting for 95% of the total thallium species. In the experiments, HR-ICP-MS at low resolution was used to analyze solutions containing only stable isotopes at mass 205, with a ^{115}In (5 ppb) solution used as the internal standard. The montmorillonite and illite used in the experiments were sourced from the Loire region of France. They were ground, filtered, treated with hydrochloric acid for decarbonation and heating to remove calcite and dolomite, and then dispersed using sodium chloride solution. Centrifugation was performed before each step. Na^+ and Ca^{2+} were used as background cations in the experiments.

The experiments constructed adsorption isotherms for illite and montmorillonite, revealing that when Na^+ and Ca^{2+} are used as background cations, thallium exhibits an affinity for illite that is one order of magnitude higher than that for montmorillonite. By varying pH conditions, the experiments elucidated the curves of thallium adsorption on illite and montmorillonite as a function of pH and Tl concentration. The adsorption capacity was more strongly influenced by pH and Tl concentration on illite, whereas the effect on montmorillonite was relatively minor.

Yue Sun et al. conducted batch adsorption experiments of Hg(II) on mackinawite (FeS), finding that FeS achieved high removal efficiency (90%) for mercury across the pH range of 3–11. The experiments demonstrated that mackinawite has a larger specific surface area than pyrite, possessing more active adsorption sites and a richer porous system. The experiments revealed that the maximum Hg(II) adsorption capacity of mackinawite reached 769.2 mg/g, indicating the feasibility of using mackinawite for mercury removal from wastewater [18].

4.2. Research Progress on Instrumental Characterization of Thallium and Mercury Adsorption on Mineral Surfaces

Goethite and iron-manganese minerals were identified using mineralogical analysis (X-ray diffraction, XRD), while specific surface area (SSA) was measured via N_2 adsorption (BET- N_2). The mineral surface site density (DS) was determined by acid-base titration [16]. For instrumental characterization of mackinawite (FeS), the specific surface areas of FeS and pyrite measured by the N_2 -BET method were $100.05 \text{ m}^2/\text{g}$ and $13.02 \text{ m}^2/\text{g}$, respectively; the total pore volume and corresponding average pore diameter of FeS were $0.30 \text{ cm}^3/\text{g}$ and 9.59 nm , respectively [18].

Extensive research has been conducted on batch adsorption experiments of thallium and mercury, including adsorption onto montmorillonite, mackinawite (FeS), goethite, and others. However, due to the wide variety of soil minerals, many minerals remain unstudied, such as kaolinite for Tl and Hg adsorption, goethite for Hg adsorption, and so forth. For already studied systems, further investigation can be pursued by altering background cations, for example, replacing Na^+ and Ca^{2+} with Si^{4+} and Mn^{2+} . Additionally, many previous experimental methodologies can be adopted and applied to one's own experiments. Following Tl(I) and Hg(II) adsorption, minerals are analyzed to determine the binding states of Tl and Hg (X-ray photoelectron spectroscopy, XPS) and the speciation of functional groups on mineral surfaces (Fourier-transform infrared spectroscopy, FTIR) [16].

5. THEORETICAL CALCULATIONS OF THALLIUM AND MERCURY ADSORPTION ON MINERAL SURFACES

A study on thallium adsorption onto Fe-Mn binary oxide-activated aluminosilicate was conducted. This paper primarily focused on batch adsorption experiments of thallium, with only a single adsorption energy calculation incorporated for theoretical purposes, aimed at verifying the comparison of adsorption capacity between FMAAM and activated aluminosilicate minerals for thallium.

A DFT study on thallium adsorption on silicene was carried out. In this work, DFT theoretical calculations for the adsorption of Tl, Pb, Bi, and other single molecules on silicene were performed using the Quantum ESPRESSO code. The calculations demonstrated strong bond interactions between Si and heavy atoms such as Tl, Pb, and Bi, resulting in relatively stable system structures. However, the paper did not provide an in-depth discussion of the chemical bond interactions between Si and Tl, instead focusing more on explaining s-orbital and p-orbital hybridization from the perspective of electronic band structure.

A DFT theoretical study on mercury adsorption on kaolinite (001) was conducted. Molecular models were constructed using Materials Studio (MS), and calculations were performed with the CASTEP module to investigate the adsorption mechanism of mercury on the kaolinite (001) surface. The study elucidated the bonding mechanism of mercury adsorption on minerals and the adsorption stability from an atomic-level perspective.

However, the theoretical calculations in this paper still have room for improvement. The kaolinite surfaces exposed to environmental interfaces primarily include the aluminum-oxygen octahedral (001) surface, the silicon-oxygen tetrahedral (00-1) surface, and the (010) surface. The study was not sufficiently comprehensive and did not integrate mercury adsorption experimental results, such as the adsorption efficiency of mercury on kaolinite. In comparison, a study using the VASP software package to calculate the adsorption mechanism of mercury on hematite also incorporated spectroscopic analysis methods such as XRD and XPS to enhance experimental reliability and compared the adsorption capacities of different hematite surfaces.

6. CONCLUSION AND OUTLOOK

This review systematically summarizes and critically evaluates the important findings of previous studies on batch adsorption experiments of mercury (Hg) and thallium (Tl), as well as theoretical calculations based on adsorption interfacial chemistry. Building upon the existing achievements, we further propose constructive recommendations for improvement in key aspects such as experimental design, condition control, and data analysis. These summaries and recommendations are intended to provide a solid theoretical foundation and practical reference for subsequent researchers conducting in-depth studies on Hg and Tl adsorption behavior, offering substantial guiding value.

Admittedly, in recent years, domestic and international scholars have carried out extensive work on the establishment of atmospheric emission inventories for Hg and Tl, as well as their migration and transformation patterns across multiple environmental media (water, soil, atmosphere, and biota), achieving fruitful results. However, it must be clearly recognized that the chemical behavior of Hg and Tl in the environment is extremely complex and highly dependent on environmental conditions, and numerous critical scientific questions still await further exploration.

The limitations of current research are primarily manifested in the following aspects:

Imbalance in research media: The vast majority of existing studies focus on aquatic environmental systems, while research on the environmental chemical behavior of Hg and Tl in other important

environmental media—such as soils, sediments, and atmospheric particulates—remains in its preliminary stages.

Insufficient depth in mercury speciation studies: For mercury, existing work has been excessively concentrated on elemental mercury (Hg(0)), while research on the adsorption behavior and transformation mechanisms of its highly toxic and mobile oxidized form (Hg(II)) and methylmercury (MeHg)—which exhibits strong bioaccumulation and neurotoxicity—remains relatively scarce. Experiments have investigated the effects of varying Tl concentrations and pH on iron-manganese minerals.

Weak foundational knowledge of thallium research: Compared to mercury, the overall foundation of environmental chemistry research on thallium is considerably weaker. In particular, systematic understanding of its occurrence speciation, migration and transformation pathways, and microscopic interfacial reaction mechanisms in complex environmental media remains very limited. Among these, theoretical studies on the adsorption and reaction mechanisms of Tl on environmental media (especially minerals) are particularly scarce.

The innovative contributions of this review are as follows: To achieve an in-depth elucidation of the adsorption mechanisms of Hg and Tl on mineral surfaces, this study innovatively integrates experimental and theoretical simulation approaches. On the one hand, we have meticulously designed a series of batch adsorption experiments; on the other hand, we employ the first-principles density functional theory (DFT) computational software VASP (Vienna Ab-initio Simulation Package) to conduct high-precision theoretical calculations of the adsorption configurations, binding energies, and electronic structures of Hg and Tl on typical mineral surfaces. This research strategy, which integrates experimental characterization with theoretical calculations for mutual validation and deep fusion, aims to reveal the microscopic essence of adsorption processes at the atomic/molecular level and fill existing knowledge gaps. We anticipate that this work will not only deepen the scientific understanding of the environmental behavior of Hg and Tl but also provide critical theoretical support for the development of efficient heavy metal pollution control and remediation technologies, thereby making tangible contributions to addressing the severe environmental challenges posed by Tl and Hg and safeguarding ecological security and human health.

REFERENCES

- [1] Belzile N, Chen Y-W. Thallium in the environment: A critical review focused on natural waters, soils, sediments and airborne particles[J]. *Applied Geochemistry*, 2017, 84: 218-243.
- [2] Zhou T F, Fan Y, Yuan F, et al. A preliminary geological and geochemical study of the Xiangquan thallium deposit, eastern China: the world's first thallium-only mine[J]. *Mineralogy and Petrology*, 2005, 85(3-4): 243-251.
- [3] Wei X, Wang J, She J, et al. Thallium geochemical fractionation and migration in Tl-As rich soils: The key controls[J]. *Science of The Total Environment*, 2021, 784: 146995.
- [4] Driscoll C T, Mason R P, Chan H M, et al. Mercury as a global pollutant: sources, pathways, and effects[J]. *Environmental science & technology*, 2013, 47(10): 4967-4983.
- [5] Fergusson J E, Prucha F P. The heavy elements: chemistry, environmental impact and health effects[M]. Oxford: Pergamon press, 1990.
- [6] Smith I C, Carson B L. Trace metals in the environment[J]. 1977.
- [7] Tremel A, Masson P, Sterckeman T, et al. Thallium in French agrosystems—I. Thallium contents in arable soils[J]. *Environmental Pollution*, 1997, 95(3): 293-302.
- [8] Outridge P M, Mason R P, Wang F, et al. Updated global and oceanic mercury budgets for the United Nations Global Mercury Assessment 2018[J]. *Environmental science & technology*, 2018, 52(20): 11466-11477.
- [9] Pirrone N, Cinnirella S, Feng X, et al. Global mercury emissions to the atmosphere from
- [10] anthropogenic and natural sources[J]. *Atmospheric Chemistry and Physics*, 2010, 10(13): 5951-5964.
- [11] Pacyna E G, Pacyna J M, Steenhuisen F, et al. Global anthropogenic mercury emission inventory for 2000[J]. *Atmospheric environment*, 2006, 40(22): 4048-4063.

- [12] Streets D G, Hao J, Wu Y, et al. Anthropogenic mercury emissions in China[J]. *Atmospheric environment*, 2005, 39(40): 7789-7806.
- [13] Zhongming Z, Linong L, Xiaona Y, et al. Global Mercury Assessment 2013: Sources, emissions, releases, and environmental transport[J]. 2013.
- [14] Cooke C A, Martinez-Cortizas A, Bindler R, et al. Environmental archives of atmospheric Hg deposition—A review[J]. *Science of the Total Environment*, 2020, 709: 134800.
- [15] Biester H, Bindler R, Martinez-Cortizas A, et al. Modeling the past atmospheric deposition of mercury using natural archives[J]. *Environmental science & technology*, 2007, 41(14): 4851-4860.
- [16] Qiu G, Feng X, Wang S, et al. Mercury and methylmercury in riparian soil, sediments, mine-waste calcines, and moss from abandoned Hg mines in east Guizhou province, southwestern China[J]. *Applied Geochemistry*, 2005, 20(3): 627-638.
- [17] Chen W, Huangfu X, Xiong J, et al. Retention of thallium (I) on goethite, hematite, and manganite: Quantitative insights and mechanistic study[J]. *Water Research*, 2022, 221: 118836.
- [18] Martin L A, Wissocq A, Benedetti M F, et al. Thallium (Tl) sorption onto illite and smectite: Implications for Tl mobility in the environment[J]. *Geochimica et Cosmochimica Acta*, 2018, 230: 1-16.
- [19] Sun Y, Lv D, Zhou J, et al. Adsorption of mercury (II) from aqueous solutions using FeS and pyrite: a comparative study[J]. *Chemosphere*, 2017, 185: 452-461