



# Critical review of biochar for the removal of emerging inorganic pollutants from wastewater

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## ABSTRACT

Current research primarily focuses on emerging organic pollutants, with limited attention to emerging inorganic pollutants (EIPs). However, due to advances in detection technology and the escalating environmental and health challenges posed by pollution, there is a growing interest in treating waters contaminated with EIPs. This paper explores biochar characteristics and modification methods, encompassing physical, chemical, and biological approaches for adsorbing EIPs. It offers a comprehensive review of research advancements in employing biochar for EIPs remediation in water, outlines the adsorption mechanisms of EIPs by biochar, and presents an environmental and economic analysis. It can be concluded that using biochar for the adsorption of EIPs in wastewater exhibits promising potential. Nonetheless, it is noteworthy that certain EIPs like Au(III), Rh(III), Ir(III), Ru(III), Os(III), Sc(III), and Y(III), have not been extensively investigated regarding their adsorption onto biochar. This comprehensive review will catalyze further inquiry into the biochar-based adsorption of EIPs, addressing current research deficiencies and advancing the practical implementation of biochar as a potent substrate for EIP removal from wastewater streams.

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## 1. Introduction

Population expansion, industrialization, and evolving consumption patterns drive the escalating proliferation of emerging pollutants (EPs) in aquatic and terrestrial ecosystems [1]. The resilience of these pollutants to natural degradation processes, coupled with the direct and indirect risks they pose to human and animal health - through potable water, dermal exposure, and the food chain - presents significant challenges. Current research on EPs predominantly focuses more on emerging organic pollutants (EOPs), including endocrine disruptors, pharmaceuticals, personal care products,

perfluorinated compounds, polyfluoroalkyl substances, microplastics, and related compounds [2]. Conversely, emerging inorganic pollutants (EIPs) that include rare earth elements (REE) and noble elements (NE) have been relatively overlooked.

Recent progress in detection methodologies, in conjunction with rising levels of environmental contamination, has amplified research focus on EIPs [3]. Unlike conventional heavy metals such as mercury (Hg), zinc (Zn), chromium (Cr), cadmium (Cd), and palladium (Pd), EIPs have permeated the environment for extended periods, albeit at relatively low concentrations [4]. Their potential hazards have only recently received significant scrutiny [5].

Informed by pertinent research, our primary selection encompasses four categories of EIPs, namely: Precious metals [gold, silver, and platinum group metals (PGMs)], REE, radioactive elements,

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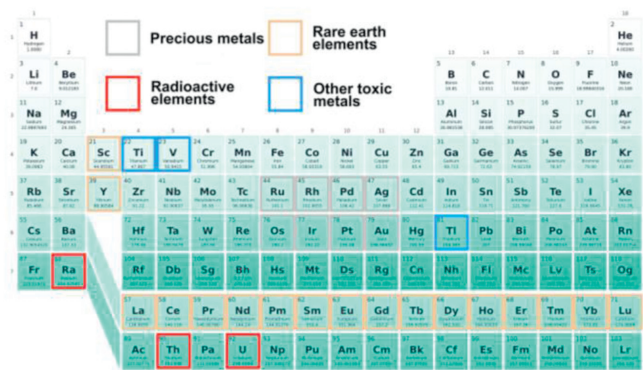


Fig. 1. Emergent inorganic pollutants and integral metals in multiple industries.

and other toxic metals (as depicted in Fig. 1) [3,5,6]. These EIPs are integral to advancing novel technologies across various sectors, including electric vehicles, energy storage (e.g., batteries), renewable energy, telecommunications, healthcare, defense technologies, agriculture, and aerospace [7]. In the extant literature, they are often designated as “key elements,” “crucial raw materials,” or “fundamental minerals” [7,8]. Within aqueous environments, they are typically manifested in the form of  $X^{n+}$  [7].

Presently, the prevailing techniques for removing EIPs from aqueous environments encompass solvent extraction, ion exchange, electrolysis, precipitation, membrane treatment, and adsorption [9–13]. A comparative analysis of these diverse EIP adsorption methods from water is presented in Table S1 (Supporting information) [11,14]. The adsorption technique boasts considerable merits, including straightforward operation, elevated efficiency, supply of a broad spectrum of adsorbents, and the capacity for concurrent multi-pollutant removal [6,15]. Owing to these attributes, adsorption has emerged as the technology of choice [16,17]. Optimal adsorbents should possess an expansive specific surface area (SSA), swift adsorption rate, low cost, and brief equilibrium time [18,19]. From this standpoint, biochar has surfaced as a proficient adsorbent amidst numerous novel functional materials employed in environmental applications, owing to its cost-effectiveness, plentiful material sources, and negligible ecological footprint [11].

When searching by *Web of Science* core collection, there was little or no literature on removing EIPs from wastewater using biochar before 2017. This study presents a comprehensive review of 105 scholarly articles published between 2017 and 2023 that focus on using biochar in treating EIPs. A keyword analysis was conducted using VOSviewer software (1.6.19), with the minimum keyword occurrence set at five, yielding a network map highlighting the most frequently used keywords within these studies, as il-

lustrated in Fig. S1 (Supporting information) [20]. The terms “adsorption,” “biochar,” and “adsorbent” emerged as key focal points. Fig. 2a delineates the annual publication count, which reveals an escalating trend in EIP-related research, particularly post-2019.

This study encapsulates the pertinent literature based on salient points. These points encompass raw materials, preparation and modification methods, metal ions, experimental conditions, adsorption models, isotherms and capacity, ionic strength and analysis experiments, desorption experiments, functional groups, adsorption types, and principles.

While research into using biochar for treating EPs has a considerable history, with numerous review articles published, the majority primarily focus on common EOPs (Fig. 2b) [3,5,21]. However, the effect of biochar on the adsorption and removal of EIPs from wastewater is still very lacking [3,22]. Given the potential application of biochar in the adsorption of these EIPs, it is essential to analyze its adsorption capabilities in wastewater treatment systematically [3,5]. Therefore, in this comprehensive review, we critically evaluate the adsorption performance of biochar on metal-based EIPs based on recent research publications. This analysis encompasses the following aspects: (1) An overview of the synthesis and preparation methods of biochar and biochar-based composite materials; (2) a thorough review of the literature related to the adsorption of EIPs by biochar; (3) an assessment of the mechanisms, economic impacts, and environmental implications of these substances adsorbed by biochar; (4) suggestions for future research directions in the field of EIPs using biochar.

## 2. Emerging inorganic pollutants (EIPs)

In the past few decades, EPs in aquatic environments have garnered attention from global research institutions, regulatory agencies, and the public [23,24]. The concept of EPs is not novel and has rapidly evolved [23,24]. The sources of EPs are diverse, stemming from various emission and disposal methods of pollutants [25]. Generally speaking, EPs can be categorized as EOPs and EIPs. EIPs are usually generated by human activities. Fig. 1 illustrates key contaminants (e.g., gold, palladium, lanthanum, thallium, and uranium) that are of particular concern to scientific researchers [5,26–29]. Fig. S2 (Supporting information) presents the potential sources and transfer of EIPs. Discharging wastewater from various industrial processes, including mining, light industry, energy production, and the chemical industry, typically results in the generation of EIPs [17,25]. Another significant source of EIPs is landfill leachate, particularly from electronic waste, which leads to the release of EIPs from soil through processes such as rainwater erosion [30–33]. The leachate is discharged directly or indirectly into water bodies, contributing to severe EIPs pollution in aquatic environments [31,32]. Additionally, domestic sewage can serve as a

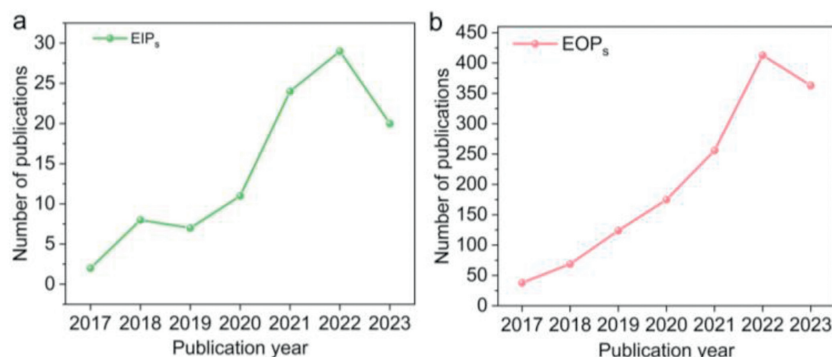


Fig. 2. Publication trends in biochar utilization for emerging inorganic pollutants treatment: (a) publication trends for emerging inorganic pollutants and (b) publication trends for EOPs.

source of EIPs [34]. Furthermore, other sources, including atmospheric transport, waste incineration, and transportation (*e.g.*, automobiles, diesel-powered vehicles, and aircraft), may contribute to the presence of EIPs. The EIPs in water bodies exhibit characteristics such as widespread sources, prolonged residence times, trace amounts, and challenging detection [5,26–28]. Moreover, they are prone to bioaccumulation along the food chain, leading to difficulties in detection and recovery after pollution events [35]. Furthermore, the persistence of EIPs in the environment can adversely affect human health, leading to damage to cell structures and impaired liver function, among other concerns [17,25,35].

The escalating presence of EIPs in the environment has emerged as a significant issue that necessitates urgent attention. EIPs, forming an integral part of essential high-tech applications and sustainable technologies, are indispensable to modern life [36]. In light of the burgeoning development of electronics, battery, automotive, and photovoltaic industries, a report indicates that approximately 5360 million tons of precious metals were globally produced in 2019 [36,37]. Furthermore, this report argues that the global production of precious metals will escalate to an estimated 7470 million tons by 2030 [37]. Another research reports that the global production of REE stood at 81 tons per annum in 2000, rose to 126 tons per annum in 2016, and surged to a staggering 280 tons per annum in 2021, representing a growth of over 100% in a mere span of five years [36]. The pressing need for EIP treatment is further underscored by their escalating concentrations in aquatic ecosystems. The sediment samples from Mystic Lake in Boston were analyzed by Rauch *et al.*, revealing that the concentration of palladium in samples collected between 1992 and 2022 was a staggering tenfold higher than those gathered between 1945 and 1974 [38]. Similarly, another study demonstrated that the concentrations of Gd in drinking water are increasing, posing a mounting concern for water treatment facilities [39].

The escalating extraction of EIPs and their subsequent utilization in manufacturing processes have been observed to lead to an amplified cumulative exposure to these elements in both human beings and the associated marine, freshwater, and terrestrial environments [40]. These persistent EIPs in the environment could potentially harm human health, notably impacting the central and peripheral nervous systems. The research conducted by Oladipo *et al.* underscored that elevated levels of exposure to EIPs can heighten the risk of cardiovascular, pulmonary, neurological, hepatic, and renal diseases, particularly among susceptible populations [41]. In addition, some previous studies have demonstrated that certain elements have the potential to disrupt biosynthetic pathways by inhibiting enzymatic activities, consequently affecting the functional dynamics of human cells [42,43]. Moreover, several EIP elements are employed in the production of various electronic devices such as televisions, computer and mobile phone screens, computer chips, magnets, and alloys, which could potentially augment the risks of human exposure.

Understanding information about the background concentrations of EIPs is crucial for ecological and human health risk assessments and disposal considerations [25]. Due to variations in detection locations, the content of EIPs also varies significantly [17,25,29]. It has been reported that mining activities are the primary input of EIPs into water systems. For example, Baotou, China, is one of the most significant mining areas in the world. A study has analyzed the EIP content in the Baotou section of the Yellow River in China, revealing that human activities enhance the enrichment of EIPs, with the highest REE reaching up to 3007  $\mu\text{g/L}$  [44]. Another study found uranium concentrations in surface water at the old Senhora das Fontes uranium mine in central Portugal as high as 83  $\mu\text{g/L}$  and uranium concentrations in groundwater as high as 116  $\mu\text{g/L}$  [45]. Similarly, the Sarcheshmeh mining area in Kerman, Iran, exhibits a similar phenomenon. Due to leaks, the

streams around this area show REEs at 934  $\mu\text{g/L}$  [46]. The increasing levels of EIPs in water may pose risks associated with water insecurity due to inadequate water sanitation conditions [25,35]. Therefore, regulatory standards should be formulated and implemented to control the occurrence of EIPs in water systems.

### 3. Preparation of pristine biochar and functionalized biochar

#### 3.1. Preparation of biochar

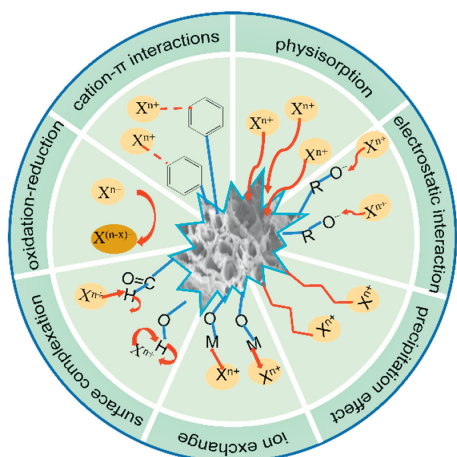
The physicochemical attributes of biochar are significantly influenced by the inherent properties of the raw materials (including the type of raw materials, biomass characteristics, and particle size) as well as the specific reaction conditions (such as pyrolysis temperature, duration, and heating rate) [22]. The primary constituents of biochar raw materials, namely cellulose, hemicellulose, and lignin, undergo progressive pyrolysis with increasing temperature [47]. Notably, at sub-700 °C temperatures, an elevation in temperature fosters the formation of porous structures, thereby augmenting the SSA [9,11,47]. This phenomenon can be attributed to the removal of volatile residues obstructing micropores at higher temperatures, thereby enhancing micropore volume and facilitating the adsorption of EIPs [11]. However, raising the temperature reduces the number of hydroxyl groups on the surface of biochar, causing a notable loss of negative surface charges [22]. Once the pyrolysis temperature > 700 °C, the mass loss of biochar slows down significantly. It is worth noting that there is an expression suggesting that low-temperature pyrolysis results in a higher proportion of micro/mesopores, while high-temperature pyrolysis tends to generate more macropores [9,48]. Typical operating conditions and carbon yields for different pyrolysis processes are provided in Table S2 (Supporting information) [49]. Despite these insights, accurately predicting biochar yield based on raw material characteristics and pyrolysis conditions remains challenging. It is gratifying that many researchers have begun using machine learning algorithms to predict biochar yield, nitrogen content, and SSA based on its raw material properties and reaction conditions [50,51]. An overview of the preparation of biochar is provided in Text S1 (Supporting information).

#### 3.2. Biochar modification methods

The surface functional groups of biochar play a critical role in its capacity to efficiently adsorb EIPs. Tailoring the attributes of biochar is typically necessitated by the demands of specific applications. The prevalent methods for such modifications encompass physical alterations (*e.g.*, gas activation and ball milling), chemical transformations (*e.g.*, acid-alkali modification, strong oxidant modification, inorganic loading, and organic loading), and biological modifications [9,11,49,52]. A thorough summary and comparison of these customary modification techniques are presented in Table S3 (Supporting information). An overview of the modification methods of biochar is provided in Text S2 (Supporting information).

### 4. Mechanisms of EIPs removal by biochar

Exploring the adsorption mechanisms of EIPs by biochar can provide a theoretical understanding of the influence of numerous factors and complex mechanisms. As shown in Fig. 3, physisorption, electrostatic interaction, precipitation effect, ion exchange, oxidation–reduction, surface complexation, and cation- $\pi$  interactions are identified as crucial adsorption mechanisms based on existing relevant literature [9,11,20,53,54]. The adsorption of EIPs by biochar involves the combination of multiple mechanisms instead



**Fig. 3.** Different adsorption mechanisms of emerging inorganic pollutants on the surface of biochar.

of relying on a single mechanism. The efficiency of EIPs ion adsorption by biochar primarily depends on its SSA, types, quantities of surface-active functional groups, and cation exchange capacity. Nevertheless, existing research is primarily qualitative, and there is a notable absence of comprehensive quantitative investigations into the adsorption mechanisms of metal ions. Table S4 (Supporting information) summarises quantitative studies conducted by various scholars investigating the adsorption mechanisms of metal ions on biochar through diverse methods. It can be seen from Table S4 (Supporting information) that most quantitative investigations indicate that the adsorption of metal ions by biochar is attributed to a combination of multiple mechanisms. Gaining insights into the individual contributions of these mechanisms to the adsorption of metal ions through qualitative and quantitative approaches is paramount in guiding the selection of optimal engineering solutions for EIPs ions wastewater adsorption. Based on the statistical findings of this study, 83.33% of research in related fields conforms to the Langmuir adsorption isotherm model, while 96.49% of the studied adsorption models adhere to the pseudo-second-order model. These results indicate that the dominant mechanism in biochar adsorption of EIPs is chemical adsorption involving a single layer.

#### 4.1. Physisorption

Physisorption is the phenomenon in which EIPs ions accumulate on the surface and within the pores of biochar without forming chemical bonds, typically due to van der Waals forces [11,49,55]. This process is primarily driven by intermolecular forces, resulting in a typically weak adsorption affinity and a reversible process [11]. Pore size, SSA, and volume are the primary influencing factors for physisorption. Various models have been employed to accurately describe the dominant type of adsorption observed, whether physical or chemical, typically including the *pseudo*-first-order and *pseudo*-second-order models. 96.49% of the research analyzed by this study adsorption models adhere to the *pseudo*-second-order model. The phenomenon suggests that most studies support the idea that physisorption is unlikely to be the primary adsorption mechanism for EIPs in biochar adsorption.

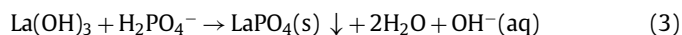
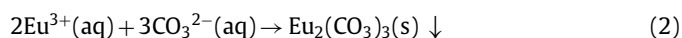
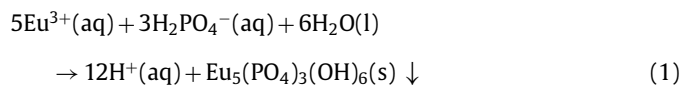
#### 4.2. Electrostatic interaction

Electrostatic interaction represents another pivotal mechanism for the adsorption of EIPs by biochar [56]. The strength of electrostatic interaction is intricately linked to several factors, including

the pH value of the solution, the oxidation state of heavy metals, ionic radius, and surface charge characteristics of biochar, including point of zero charge (PZC) [11]. Research has revealed a positive correlation between  $Q_{\max}$  and zeta potential ( $P < 0.05$ ), indicating that a more negative zeta potential likely enhances the strength of electrostatic interaction between biochar and U(VI) substances [57]. Out of the 105 literature studies analyzed in this research, experiments predominantly identified an optimal pH value below 7.0 for the electrostatic interaction-dominated adsorption process. One of the review literature points out that the lower pH during the adsorption process can not only provide a greater redox potential for EIPs ion reduction but also avoid the intensive electrostatic repulsion between EIPs ion and biochar when the initial pH is increased [58].

#### 4.3. Precipitation effect

Biochar typically contains soluble phosphates and carbonates, with  $\text{PO}_4^{3-}$  and  $\text{CO}_3^{2-}$ , capable of co-precipitating with metal ions in water to create relatively stable minerals [59–62]. The precipitation effect frequently synergizes with electrostatic attraction, ion exchange, and surface complexation. For instance, a study employed magnesia-embedded horse manure biochar to adsorb U(VI) from a solution [62]. Following the adsorption of U(VI) by biochar, deconvolution of XPS spectra showed a substantial 0.26 eV shift towards higher binding energy for pyrophosphate and phosphate, confirming the formation of stable precipitates involving U(VI) species and pyrophosphate or phosphate [62]. Furthermore, researchers employed Ca/Al-LDH and HAP@biochar to adsorption of Eu(III) in wastewater [60]. Observed precipitates encompass  $\text{Eu}_5(\text{PO}_4)_3(\text{OH})_6$  and  $\text{Eu}_2(\text{CO}_3)_3$  [60], with their respective formulas in Eqs. 1 and 2. Another review suggests that EIPs may form precipitates with phosphate on the surface of biochar, as indicated by Eq. 3 [35].



#### 4.4. Ion exchange

Ion exchange is the physical exchange between negatively charged groups on the surface of biochar and positively charged EIPs ions in the solution, primarily driven by Coulombic force [11]. The characteristics of ion exchange are low adsorption capacity and reversibility [9,11,52]. Nevertheless, as detailed in Section 5.3, ion exchange does not operate in isolation. For instance, Dong *et al.* have utilized Al(III) rich biochar to adsorb Eu(III) from wastewater [60]. Subsequent XPS analysis detected a notable reduction in the Al–O peak, suggesting a potential ion exchange between Al(III) and Eu(III) [60]. Similarly, researchers have employed Ca(II) enriched biochar to eliminate U(VI) from wastewater, and following U(VI) removal, the intensity of the Ca 2p peak diminishes, indicating a possible ion exchange between Ca(II) and U(VI) species throughout the adsorption process [63]. Ion exchange can occur between EIPs ion and porous materials featuring distinct functional groups, including hydroxyl and carboxyl groups. The efficiency of this mechanism hinges on the size of the adsorbed metal ions and the surface chemistry of the porous material [6].

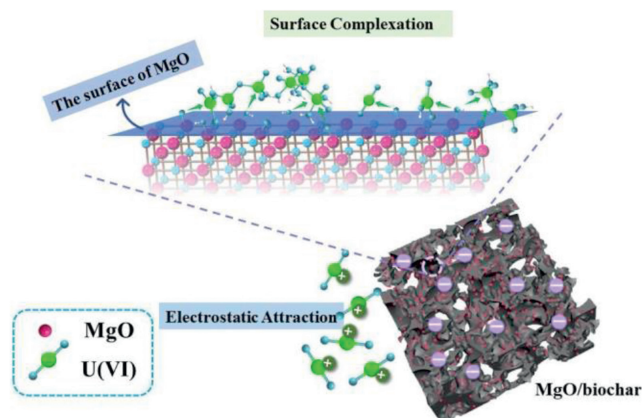


Fig. 4. MgO/biochar complexation with U(VI). Reprinted with permission [67]. Copyright 2022, Springer.

#### 4.5. Oxidation-reduction

The redox reaction involves altering the current forms of elements, primarily valence metal ions, to impact the chemical behavior of elements, migratory capacity, and bioavailability [6,11]. Numerous studies have substantiated redox reactions during biochar adsorption of metal ions. This phenomenon may be ascribed to the oxidation of specific functional groups within biochar, such as C–O and C=O to –COOH. In the preceding sections, as discussed, Section 5.1.1 elucidates the reduction of Au(III) to Au<sup>0</sup> mediated by biochar, given that Au<sup>0</sup> tends to precipitate more easily on the surface of biochar [64]. Similarly, Section 4.1.2 addresses the biochar-facilitated reduction of Ag(I) to Ag<sup>0</sup>[6]. Furthermore, redox reactions (U(VI) to U(IV)) can enhance the immobilization of U because U(IV) is more readily adsorbed.

#### 4.6. Surface complexation

Surface complexation refers to the formation of complexes between specific functional groups (e.g., carboxyl, hydroxyl, phenol, amine, and phosphoryl) containing elements (O, N, P, S) on the biochar surface and metal ions [11]. Essentially, surface complexation involves the creation of multiatomic structures (complexes) through precise metal-ligand interactions. This phenomenon may be attributed to the sharing of lone pair electrons between the metal and these functional groups [11,65]. For instance, X-ray photoelectron spectroscopy (XPS) deconvolution studies have demonstrated that, following Ag(I) adsorption, the C–O–C signal shifts from 285.22 eV to 285.81 eV [66]. This shift suggests that it may be attributed to the coordination of adsorbed Ag(I) with the oxygen atoms in C–O–C, which possesses lone pair electrons [66]. One possible reason is that donating lone pair electrons from oxygen atoms to coordinate with Ag(I) results in the migration of shared electron pairs towards oxygen, reducing electron density around the carbon atom. Furthermore, Chen *et al.* have demonstrated that MgO/biochar, enriched with surface oxygen-containing functional groups (e.g., ≡Mg–O–, ≡Mg–OH, and ≡MgO<sub>2</sub><sup>2–</sup>), can form complexes with U(VI), as depicted in Fig. 4 [67]. Modifying biochar to incorporate these functional groups, capable of readily forming complexes with metal ions, can significantly improve the adsorption efficiency of biochar for EIPs.

#### 4.7. Cation- $\pi$ interactions

Cation- $\pi$  interaction, a non-covalent molecular interaction, occurs between the surfaces of electron-rich  $\pi$  systems, such as compounds like C<sub>6</sub>H<sub>6</sub>, H<sub>2</sub>C=CH<sub>2</sub>, and similar  $\pi$  systems, and

cations like Na(I) and Au(III) [13,65]. However, the understanding of cation- $\pi$  interactions remains limited compared to hydrogen bonds. It is reported that the occurrence of an interaction between metal ions and aromatic carbons is termed cation- $\pi$  interaction [68–70]. Recent studies have suggested that nitrogen doping (N-doping) can enhance the polarization of  $\pi$  electrons on the carbon surface, increasing adsorption at electron-rich and electron-deficient sites [69,71]. Additionally, the literature of this study provided examples, including the study by Babu *et al.*, which discussed the presence of cation- $\pi$  interactions between aromatic compounds in biochar and Ag(I) [72]. Furthermore, Zhu *et al.* discovered that, during the adsorption of U(VI) from an aqueous solution using MoS<sub>2</sub>/BC composite material, no substantial shift in the aromatic C–H peak was evident in the FT-IR analysis [73]. However, a noticeable reduction in peak intensity strongly implied the participation of cation- $\pi$  bonding in the adsorption process [74]. Nevertheless, one comment pointed out that the discussion of cation- $\pi$  interactions did not account for the complexation involving transition metals (e.g., Ag<sup>+</sup>, Fe<sup>3+</sup>), benzene, and related  $\pi$  systems [74]. This is because transition metals and benzene (such as Ag<sup>+</sup> ⋯ C<sub>6</sub>H<sub>6</sub> structure) complexes as non-covalent interactions might be unreasonable [74]. In conclusion, further investigation is essential to comprehensively understand the cation- $\pi$  interaction mechanism.

### 5. Application of biochar in adsorption EIPs in wastewater

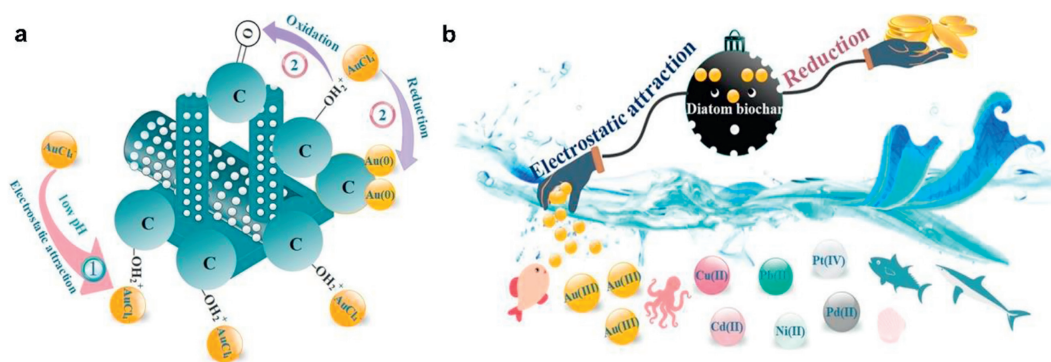
#### 5.1. Precious metals

Precious metals belong to a group of metallic chemical elements that are naturally occurring but rare in the crust of the earth [75]. They are distinguished by their high value, appealing physical appearance, and chemical stability, contributing to their substantial economic worth and effective preservation properties [76]. Apart from gold and silver, the category of precious metals typically encompasses six PGMs: ruthenium, rhodium, palladium, osmium, iridium, and platinum [14,75,76]. Among them, platinum holds the highest trading activity, ranking second only to gold and silver.

##### 5.1.1. Gold

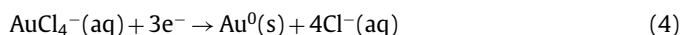
Gold plays a crucial role in the global economy as a precious metal [77]. Gold is extensively used in catalysts, sensors, jewelry, and other applications, leading to significant amounts of e-waste and gold-containing wastewater [78]. The above phenomenon poses a considerable risk to the environment and human health. However, the limited availability of natural gold reserves has resulted in substantial market demand. Consequently, there is an urgent need to develop technologies that enable the extraction, adsorption, and purification of gold from gold-containing wastewater.

Gold in aqueous environments typically exists as trivalent cations, with Au(III) displaying a pronounced affinity for oxygen-containing functional groups like hydroxyl and carboxylate [6,64,79]. Researchers have devised a diatomite biochar to facilitate the adsorption of gold from electroplating wastewater [64]. When the diatomite biochar is introduced to an Au(III) solution (as depicted in Fig. 5a), Au(III) is initially electrostatically drawn to the diatomite surface of the biochar [64]. Subsequently, the adsorbed Au(III) on the biochar surface undergoes electron reduction, forming Au<sup>0</sup>, while the hydroxyl groups in the diatomite biochar go through oxidation to form ketone groups. This reaction can be illustrated using Eqs. 4 and 5 [64]. Several studies have demonstrated that diatomite biochar exhibits a selective capacity for adsorbing Au(III) from electroplating wastewater, even in the presence of other coexisting metals (as indicated by the competitive

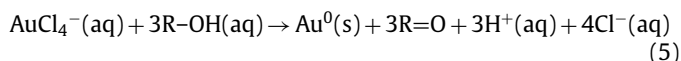


**Fig. 5.** Diatomite biochar-mediated gold adsorption from electroplating wastewater: Mechanism (a) and selective adsorption (b). Reprinted with permission [64]. Copyright 2023, ACS.

relationship depicted in Fig. 5b) [64]. Moreover, the adsorption efficiency for low concentrations of Au(III) remains exceptionally high, reaching 96.7% [64].



where the hydroxyl groups are simultaneously oxidized to carbonyl groups,

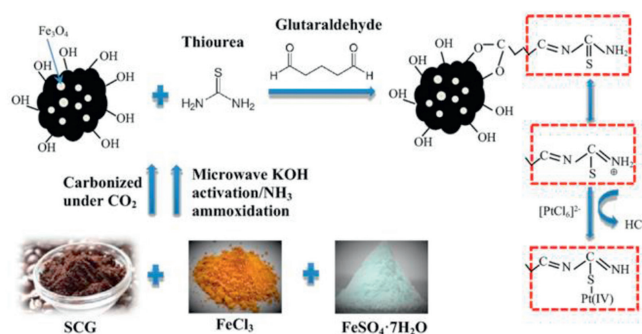


Doping biochar materials with N, O, S, and P have been shown to enhance their adsorption capacity for EIPs [11,79]. Consequently, biochar was developed from walnut shells and co-doped with boron and nitrogen [79]. This biochar exhibits a maximum adsorption capacity of 246.96 mg/g for Au(III) [79]. Research findings demonstrate that the adsorption kinetics by boron and nitrogen co-doped walnut shell biochar follow a quasi-two-level kinetic model concerning Au(III). In contrast to the adsorption of Pt(IV) and Pd(II), the adsorption of Au(III) by biochar is exothermic and spontaneous [64,79].

This study has identified only two relevant studies published in the last five years that investigate using biochar for Au(III) adsorption, with maximum adsorption efficiencies of 443.00 and 246.96 mg/g, respectively [64,79]. There is a notable lack of additional literature in this specific domain.

### 5.1.2. Silver

Silver is the prevailing precious metal, extensively utilized across various domains, including electroplating, photography, household appliances, jewelry, non-ferrous metal smelting facilities, and electronic waste recycling facilities [53,66,80]. Additionally, it is increasingly utilized as a microbial inhibitor in textiles, serving as an antibacterial agent [81,82]. The toxicity of products containing silver nanoparticles results from Ag(I) release, constituting less than 10% of the total mass [72,83]. The World Health Organization (WHO) sets the permissible silver concentration in drinking water at 0.1 mg/L [66]. Nevertheless, numerous countries worldwide regularly confront environmental challenges from excessive silver discharge, manifesting as Ag(I) concentrations in various types of silver-containing wastewater ranging from several mg/L to several thousand mg/L [66]. Interestingly, biochar impregnated with Ag(I) exhibits potential utility in energy storage and antibacterial applications [84]. An overview of the research on the adsorption of silver using biochar is provided in Text S3 (Supporting information).



**Fig. 6.** Possible Pt(IV) adsorption mechanisms on biochar. Reprinted with permission [89]. Copyright 2021, Springer.

### 5.1.3. Platinum group metals (PGMs)

PGMs encompass ruthenium, rhodium, palladium, osmium, iridium, and platinum [54,85,86]. These elements share similar electronic configurations within the same energy level of the periodic table. Most of their outer shell electrons are primarily distributed in the s and d orbitals [54]. These elements share numerous characteristics, such as high density and weight, catalytic activity, corrosion resistance, a high melting point, and exceptional stability [87]. Besides, PGMs have extensive applications in various sectors, including automotive, electronics, petrochemicals, and aerospace, and are considered strategic resources. According to the "Global Platinum Group Metals Yearbook 2023", a deficit in global supply and demand for platinum, palladium, and rhodium is anticipated in 2023 [88]. This circumstance arises from many challenges encountered by South Africa and Russia, the two primary PGMs producing nations. Consequently, it is necessary to engage in the recycling and reutilization of PGMs.

Magnetic biochar modified with thiourea can selectively retrieve platinum from waste automotive catalyst solutions [89]. Under pH2 and at a temperature of 328K, the adsorbent exhibits a maximum adsorption capacity for Pt(IV) of approximately 42.8 mg/g [89]. Even after six cycles, the adsorption capacity remains consistently above 96.9%, signifying its substantial practical value [89]. The potential adsorption mechanism is depicted in Fig. 6, illustrating that within the biochar, -C=N and -OH functional groups can facilitate the reduction of Pt(IV) to Pt(II), sulfur can form coordination compounds with Pt atoms, and electrostatic attraction takes place between anions [e.g., (PtCl<sub>6</sub>)<sup>2-</sup>] and cations (biochar) under acidic conditions.

Besides adsorbing Au(III), boron and nitrogen co-doped biochar derived from walnut shells also display outstanding adsorption capabilities for Pt(IV) and Pd(II). The maximum adsorption capacity reaches 108.8 mg/g for Pt(IV) and 44.78 mg/g for Pd(II) [79].

The adsorption kinetics of metal ions onto the biochar conform to a pseudo-second-order kinetic model, and the equilibrium data of adsorption isotherms match well with the Langmuir isotherm model. These findings indicate a chemisorption mechanism between the biochar and precious metal ions [79].

Limited research has been conducted recently on the adsorption of PGMs from water using biochar. A limited number of publications in this field focus primarily on Pt(IV) and Pd(II) adsorption. However, compared to the research on the adsorption of PGMs by other porous materials, these studies lack scope and quantity.

### 5.2. Radioactive elements

Radioactive elements are chemical elements that exhibit radioactivity due to the instability of their atomic nuclei. The atomic nuclei of radioactive elements emit ionizing radiation, including electrons, alpha particles, as well as high-energy photons such as X-rays and gamma rays, and undergo decay to transform into other elements [90]. Examples of common radioactive elements comprise uranium (U), radium (Ra), and thorium (Th) [91,92].

As the primary fuel in modern nuclear power plants, uranium has become a potential environmental pollutant due to its biological toxicity and radioactivity [93]. Specifically, illegal/improper disposal of radioactive waste from uranium mining and processing seriously damages ecosystems [94]. Once released into the ecosystem, uranium exhibits toxicity to multiple organs, such as the lungs, liver, and kidneys, causing harmful effects on human health [95]. According to the WHO guidelines, the recommended limit for uranium in drinking water should be less than 30 µg/L [96,97]. Under such circumstances, effectively removing uranium from radioactive wastewater becomes an essential issue from both societal and environmental perspectives. Therefore, the design and synthesis of stable and efficient novel biochar adsorbents for removing radioactive uranium are essential. An overview of the studies of radioactive elements is provided in Text S4 (Supporting information).

### 5.3. Rare earth elements (REE)

REE, also known as rare earth metals, refer to the lanthanide series elements and the Group III scandium and yttrium [6]. They are a group of soft, silver-white sub-group elements. Despite being called REE, their abundance in the crust of the earth is higher than that of zinc and copper [98]. The name "rare earth" comes from the difficulty of enriching and separating these highly dispersed elements in the natural environment [98]. REE finds wide applications in manufacturing industries, such as filters, electronic components, hydrogen storage technology, artistic glass, steel modification agents, and batteries [60,98-100]. However, unfortunately, due to the emissions of industrial wastewater and leachate from waste disposal containing REE, they have caused severe environmental pollution and pose a serious threat to human health [99]. Hence, it is urgent to seek practical and effective methods for the adsorption of valuable REE.

Table S5 (Supporting information) illustrates various modification methods for enhancing the efficient adsorption of REE from aqueous solutions through biochar treatment. Most studies have concentrated on the concurrent adsorption of multiple types of REE. For example, the biochar modified with nZVI demonstrated remarkable adsorption concentrations of 12.66, 13.82, and 18.12 mg/g for La(III), Ce(III), and Nd(III), respectively, in wastewater [98]. Additionally, the combined characteristics of biochar and nZVI facilitated the separation of the spent adsorbent obtained following the adsorption of rare earth ions [98]. A separate study incorporated HAP and CaAl-LDH into biochar to enhance the Eu(III) adsorption in wastewater [60]. This composite material effectively

addressed the limitations of biochar and LDH, resulting in a remarkable maximum adsorption capacity of 714 mg/g for Eu(III) [60].

Although research on the adsorption of REE by biochar exists, it remains relatively inadequate compared to the extensive research conducted on the adsorption of REE by other porous materials, such as activated carbon. Moreover, future studies should address the prevalent scenario where REE frequently co-occurs with other metal ions in wastewater, particularly in contexts like mining wastewater. Consequently, the investigation of biochar with the capability to selectively adsorb rare earth ions holds paramount significance.

### 5.4. Other toxic metals

With the advancement of industrialization and improved detection levels, trace toxic EIPs, such as vanadium (V), titanium (Ti), and thallium (Tl), have raised concerns [101,102]. Many studies use biochar to adsorb these highly toxic EIPs, as shown in Table S6 (Supporting information). Tl is a highly toxic rare element classified as a significant pollutant by the USA Environmental Protection Agency [16,18]. The maximum allowable limit for thallium in drinking water is recommended to be 2.0 µg/L, with plans to further reduce it to 0.5 µg/L [16,18]. In aquatic systems, Tl is commonly present in the oxidation states of Tl(I) and Tl(III) [16,103]. Compared to Tl(III), Tl(I) exhibits more significant toxicity and mobility and is more challenging to adsorb [16,103]. Recently, a novel  $\alpha$ -FeOOH-modified biochar has demonstrated a noteworthy ability to efficiently adsorb Tl(I) from wastewater, exhibiting a maximum adsorption capacity of 4.375 mg/g [104].

V, a transition metal, finds extensive use in industrial manufacturing [18,105-110]. Elevated V concentrations can inhibit plant growth and pose risks of paralysis to the respiratory, nervous, digestive, cardiovascular, and hepatic systems [108,109]. While V can exist in various oxidation states in water, including V(II), V(III), V(IV), and V(V), the prevalent form is V(V) [109]. Previous research has demonstrated the efficacy of modified biochar in efficiently removing elevated concentrations of V(V). In one study, red mud-modified biochar demonstrated selective V(V) adsorption characteristics, boasting a maximum adsorption capacity of 16.45 mg/g [109].

## 6. Economic impacts and environmental implications

Biochar is considered a renewable resource among bio-based materials. Large-scale biochar production can yield economic advantages. From an economic perspective, employing biochar for EIPs adsorption offers several advantages, including potential income generation for farmers, lower costs compared to alternative adsorbents like activated carbon, and the ability to recycle and reuse metal elements. Nonetheless, specific considerations must be given to various synthesis chains of biochar when evaluating economic factors. One research has underscored the necessity for biochar costs to encompass a broad spectrum of operating expenses, including but not limited to production, maintenance, feedstock, transportation, labor, and distribution costs [111]. At present, there exist no substantial industrial biochar markets that provide access to biochar pricing and costing data, thereby limiting the potential for comprehensive financial estimates. The cost of purchasing raw materials may vary depending on the type and origin of the raw materials. According to reports, in developed countries such as Europe and the USA, the raw material procurement cost of biochar ranges from \$6.71 to \$110 per ton [111]. Another study has developed a biochar enterprise budgeting tool based on Excel [112]. It points out that the biochar company baseline budget includes mobile pyrolysis units, pretreatment equipment, trans-

portation, and water tank storage facilities [112,113]. Variable costs of the biochar company include fuel, oil and lubricants, labor, and miscellaneous costs [112,113]. Besides, it has been shown that for biochar companies, there is a 90% probability that biochar production costs will range between \$571 and \$1455 per ton [112]. For biochar users, sensitivity analysis showed that biochar price is the largest factor affecting biochar production profitability and demand. However, biochar prices are highly volatile. A recent review statistically analyzed the price of biochar, with prices ranging from \$17.15 to \$2710 per ton or even \$0 per ton [114]. Two other reviews indicate high biochar prices (\$250–300 per ton) and (\$120–\$200 per ton), respectively [115,116].

Biochar offers several environmental benefits. Firstly, it can mitigate carbon emissions from uncontrolled (open) burning of biomass. Secondly, biochar is effective in wastewater treatment as it adsorbs toxic substances. Moreover, biochar can serve as a catalyst or gas adsorbent once it has undergone adsorption. Nevertheless, it is crucial to recognize that biochar may retain specific metals or organic pollutants, potentially posing risks to human health and the environment.

## 7. Potential development directions of biochar for adsorption of EIPs

Enrichment of metal ion types and concentration reduction experiment: Insufficient research has been conducted to explore the capacity and mechanisms of biochar for adsorbing certain EIPs, including titanium, rhodium, iridium, ruthenium, osmium, and specific lanthanide metals. Furthermore, significant technical challenges persist when attempting adsorption under low-concentration conditions. Consequently, additional research is imperative to investigate biochar adsorption capacity and mechanisms concerning these EIPs, especially under low concentrations experienced in wastewater streams.

Intelligent biochar design: Employ artificial intelligence, specifically machine learning, to design and screen more environmentally friendly, efficient, and cost-effective biochar. By integrating machine learning algorithms with experimental predictions, we can ascertain the adsorption capacity of biochar for EIPs present in wastewater. Attain the goal of fully automating the design process and advancing the development of industrial-scale biochar adsorption devices.

Cost analysis and modification of biochar: Further cost analyses of diverse modification methods are imperative. Furthermore, integrating distinct modification techniques continues to represent a future development trend. For instance, this includes combining biochar materials with microorganisms (such as immobilized microorganisms on biochar and biochar-based biofilters) and developing biochar-based two-dimensional membranes, among other possibilities.

Conduct in-depth research on complex adsorption mechanisms: While numerous studies have examined adsorption mechanisms, most have focused on single-component systems. The comprehension of adsorption mechanisms has predominantly been qualitative, with a limited presence of quantitative analysis. The forthcoming development trend entails conducting quantitative analyses of diverse adsorption principles, particularly within complex adsorption mechanisms of co-contaminant systems.

Conduct full-scale wastewater experiments: Presently, the majority of research is centered on laboratory simulations. While adsorption competition experiments have been undertaken, the composition of natural wastewater is considerably more intricate. Further investigations into the adsorption of Real-time wastewater are warranted.

Treatment of residuals after or during the adsorption process: Specific ions may become released through the ion exchange dur-

ing adsorption, potentially leading to secondary pollution. Subsequent treatment of used biochar is essential after adsorbing EIPs. For example, biochar that has adsorbed Ag(I) exhibits promising prospects for applications in energy storage and antibacterial domains. Besides, after adsorbing EIPs, biochar could catalyze persulfate as the catalyst to degrade organic pollutants. Moreover, biochar with adsorbed EIPs can adsorb other gases, such as CO<sub>2</sub> and SO<sub>2</sub>.

## 8. Conclusions

This review comprehensively evaluates the latest applications of biochar in adsorbing EIPs. The review concludes that biochar has significant potential for removing EIPs in wastewater, but significant research gaps also exist. The adsorption capacity of unmodified biochar is limited. Biochar can be modified (organic loading, inorganic loading, and biological modification) to increase the number and type of surface functional groups and the SSA, thereby improving the adsorption capacity for EIPs. Although there have been preliminary studies on the adsorption of certain EIPs by biochar (such as Ag(I) and U(VI)), compared with activated carbon, there are still certain EIPs like Au(III), Rh(III), Ir(III), Ru(III), Os(III), Sc(III), and Y(III), have not been extensively investigated. When discussing the adsorption mechanism, this study found that the adsorption of EIPs by biochar mainly involves physisorption, electrostatic interaction, precipitation effect, ion exchange, oxidation–reduction, surface complexation, and cation- $\pi$  interactions. The high cost and secondary pollution risk of biochar hinders its widespread application. Therefore, there is an urgent need to develop cost-effective, efficient, and environmentally friendly biochars. Besides, further research is needed to address the challenges of biochar application, including developing efficient modification technologies and mitigating secondary pollution during adsorption. These efforts are crucial to achieving the adsorption of EIPs via biochar.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Chong Liu:** Methodology, Project administration, Resources, Software. **Nanthi Bolan:** Writing – original draft, Writing – review & editing. **Anushka Upamali Rajapaksha:** Writing – original draft, Writing – review & editing. **Hailong Wang:** Writing – original draft, Writing – review & editing. **Paramasivan Balasubramanian:** Writing – original draft, Writing – review & editing. **Pengyan Zhang:** Writing – review & editing. **Xuan Cuong Nguyen:** Writing – original draft, Writing – review & editing. **Fayong Li:** Writing – original draft, Writing – review & editing.

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## Supplementary materials

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## References

- [1] A. Abdelfattah, S.S. Ali, H. Ramadan, et al., *Environ. Sci. Ecotechnol.* 13 (2023) 100205.
- [2] R. Al-Tohamy, S.S. Ali, F. Li, et al., *Ecotoxic. Environ. Safe* 231 (2022) 113160.
- [3] S. Dubey, C.W. Chen, D. Haldar, et al., *Environ. Pollut.* 317 (2023) 120840.
- [4] R. Roy, S. Samanta, S. Pandit, et al., *Appl. Biochem. Biotechnol.* 196 (2023) 1712–1751.
- [5] J. Singh, P. Yadav, V. Mishra, Chapter 11—Low-cost bio-adsorbent for emerging inorganic pollutants, in: P. Devi, P. Singh, S.K. Kansal (Eds.), *Inorganic Pollutants in Water*, Elsevier, 2020, pp. 205–220.
- [6] S. Iftikhar, G. Heidari, N. Amanat, et al., *Environ. Chem. Lett.* 20 (2022) 3697–3746.
- [7] X. Wang, J. Feng, Y. Cai, et al., *Sci. Total Environ.* 708 (2020) 134575.
- [8] C.J. Rhodes, *Sci. Prog.* 102 (2019) 304–350.
- [9] Y. Li, H. Yu, L. Liu, H. Yu, J. Hazard. Mater. 420 (2021) 126655.
- [10] C. Liu, Q. Xu, X. Hu, et al., *ACS Omega* 5 (2020) 29333–29341.
- [11] B. Qiu, X. Tao, H. Wang, et al., *J. Anal. Appl. Pyrolysis* 155 (2021) 105081.
- [12] C. Liu, X. Hu, Q. Xu, et al., *Arabian J. Chem.* 14 (2021) 102971.
- [13] A.Y. Li, H. Deng, Y.H. Jiang, et al., *Langmuir* 36 (2020) 9160–9174.
- [14] N. Das, *Hydrometallurgy* 103 (2010) 180–189.
- [15] S. Dhaka, R. Kumar, A. Deep, et al., *Coord. Chem. Rev.* 380 (2019) 330–352.
- [16] M. Haris, M. Usman, F. Su, et al., *Chem. Eng. J.* 434 (2022) 134842.
- [17] N.A.A. Qasem, R.H. Mohammed, D.U. Lawal, *npj Clean. Water* 4 (2021) 36.
- [18] J. Bąk, S. Gustaw, D. Kołodziejka, *Chem. Eng. J.* 470 (2023) 144309.
- [19] K. Chen, D. Ma, H. Yu, et al., *Chemosphere* 291 (2022) 132721.
- [20] C. Liu, G. Crini, L.D. Wilson, et al., *Environ. Pollut.* 348 (2024) 123815.
- [21] A.A. Al-Raad, M.M. Hanafiah, *J. Environ. Manag.* 300 (2021) 113696.
- [22] Y. Liu, Z. Weng, B. Han, et al., *J. Clean. Prod.* 421 (2023) 138495.
- [23] D.J. Lapworth, N. Baran, M.E. Stuart, R.S. Ward, *Environ. Pollut.* 163 (2012) 287–303.
- [24] L.B. Barber, 1.13—Emerging contaminants emerging contaminants, in: S. Ahuja (Ed.), *Comprehensive Water Quality and Purification*, Elsevier, Waltham, 2014, pp. 245–266.
- [25] M. Adeel, J.Y. Lee, M. Zain, et al., *Environ. Int.* 127 (2019) 785–800.
- [26] S. Singh, K.L. Wasewar, S.K. Kansal, Chapter 10—Low-cost adsorbents for removal of inorganic impurities from wastewater, in: P. Devi, P. Singh, S.K. Kansal (Eds.), *Inorganic Pollutants in Water*, Elsevier, 2020, pp. 173–203.
- [27] P. Verma, J.K. Ratan, Chapter 5—Assessment of the negative effects of various inorganic water pollutants on the biosphere—An overview, in: P. Devi, P. Singh, S.K. Kansal (Eds.), *Inorganic Pollutants in Water*, Elsevier, 2020, pp. 73–96.
- [28] M. Kumar, P. Borah, P. Devi, Chapter 3—Priority and emerging pollutants in water, in: P. Devi, P. Singh, S.K. Kansal (Eds.), *Inorganic Pollutants in Water*, Elsevier, 2020, pp. 33–49.
- [29] G. Heltai, Z. Györi, I. Fekete, et al., *Microchem. J.* 136 (2018) 85–93.
- [30] M. Hussein, K. Yoneda, Z. Mohd-Zaki, et al., *Chemosphere* 267 (2021) 128874.
- [31] L.S. Ankit, V. Kumar, et al., *Environ. Technol. Innov.* 24 (2021) 102049.
- [32] E. Spalvins, B. Dubey, T. Townsend, *Environ. Sci. Technol.* 42 (2008) 7452–7458.
- [33] Y. Li, J.B. Richardson, R. Mark Bricka, et al., *Waste Manag.* 29 (2009) 2147–2150.
- [34] P.C. Nagajyoti, K.D. Lee, T.V.M. Sreekanth, *Environ. Chem. Lett.* 8 (2010) 199–216.
- [35] A. Kunhikrishnan, M.A. Rahman, D. Lamb, et al., *Chemosphere* 286 (2022) 131661.
- [36] P. Neira, A. Romero-Freire, M.D. Basallote, et al., *Front. Mar. Sci.* 9 (2022) 920405.
- [37] A. Taghvaie Nakhjiri, H. Sanaeepour, A. Ebadi Amooghin, M.M.A. Shirazi, *Desalination* 527 (2022) 115510.
- [38] S. Rauch, H.F. Hemond, B. Peucker-Ehrenbrink, *Environ. Sci. Technol.* 38 (2003) 396–402.
- [39] R. Brünjes, T. Hofmann, *Water Res.* 182 (2020) 115966.
- [40] G. Pagano, M. Guida, F. Tommasi, R. Oral, *Ecotox. Environ. Safe.* 115 (2015) 40–48.
- [41] H.J. Oladipo, Y.A. Tajudeen, E.O. Taiwo, et al., *Challenges* 14 (2023) 20.
- [42] R.M. Pallares, D. Faulkner, D.D. An, et al., *Proc. Natl. Acad. Sci. U. S. A.* 118 (2021) e2025952118.
- [43] R.M. Pallares, D.D. An, S. Hébert, et al., *ACS Omega* 7 (2022) 34412–34419.
- [44] J. He, C.W. Lü, H.X. Xue, et al., *Environ. Geochem. Health* 32 (2010) 45–58.
- [45] A.M.R. Neiva, P.C.S. de Carvalho, I.M.H.R. Antunes, et al., *Geochemistry* 75 (2015) 345–356.
- [46] R. Sharifi, F. Moore, B. Keshavarzi, *Geochemistry* 73 (2013) 509–517.
- [47] D. Chen, K. Cen, X. Zhuang, et al., *Combust. Flame* 242 (2022) 112142.
- [48] Y. Yang, C. Sun, Q. Huang, J. Yan, *Chemosphere* 291 (2022) 132702.
- [49] K. Qian, A. Kumar, H. Zhang, et al., *Renew. Sustain. Energy Rev.* 42 (2015) 1055–1064.
- [50] L. Leng, L. Yang, X. Lei, et al., *Biochar* 4 (2022) 63.
- [51] H. Li, Z. Ai, L. Yang, et al., *Bioresour. Technol.* 369 (2023) 128417.
- [52] Z. Liu, Z. Xu, L. Xu, et al., *Carbon Res.* 1 (2022) 8.
- [53] B. Li, J. Gong, J. Fang, et al., *Environ. Sci. Pollut. Res.* 28 (2021) 1061–1071.
- [54] D. Bao, *Resour. Policy* 68 (2020) 101772.
- [55] H.N. Tran, F. Tomul, N. Thi, H. Ha, et al., *J. Hazard. Mater.* 394 (2020) 122255.
- [56] L. Wang, Y. Wang, F. Ma, et al., *Sci. Total Environ.* 668 (2019) 1298–1309.
- [57] L. Han, E. Zhang, Y. Yang, et al., *J. Clean. Prod.* 264 (2020) 121542.
- [58] M. Chen, F. He, D. Hu, et al., *Chem. Eng. J.* 381 (2020) 122739.
- [59] T. Zhao, Y. Yao, D. Li, et al., *Sci. Total Environ.* 640–641 (2018) 73–79.
- [60] L. Dong, S. Li, Y. Jin, et al., *Appl. Surf. Sci.* 567 (2021) 150794.
- [61] A. Tomczyk, Z. Sokołowska, P. Boguta, *Fuel* 278 (2020) 118168.
- [62] B. Zheng, J. Liao, L. Ding, et al., *J. Environ. Chem. Eng.* 9 (2021) 106897.
- [63] W. Ahmed, A. Núñez-Delgado, S. Mehmood, et al., *Environ. Res.* 201 (2021) 111518.
- [64] L. Wang, J. Li, G. Zhong, et al., *ACS ES&T Water* 3 (2023) 1395–1405.
- [65] M. Qiu, L. Liu, Q. Ling, et al., *Biochar* 4 (2022) 19.
- [66] S. Zhang, Y. Ji, J. Dang, et al., *Sci. Total Environ.* 668 (2019) 115–123.
- [67] W. Chen, J. Feng, S. Liu, et al., *Chem. Eng. Res. Des.* 180 (2022) 391–401.
- [68] T. Islam, Y. Li, H. Cheng, *Sustainability* 13 (2021) 9932.
- [69] X. Yang, Y. Wan, Y. Zheng, et al., *Chem. Eng. J.* 366 (2019) 608–621.
- [70] A. Kumar, T. Bhattacharya, W.A. Shaikh, et al., *Curr. Pollut. Rep.* 8 (2022) 519–555.
- [71] W. Yu, F. Lian, G. Cui, Z. Liu, *Chemosphere* 193 (2018) 8–16.
- [72] A. Naga Babu, D. Srinivasa Reddy, G.V. Krishna Mohan, et al., *Biomass Convers. Biorefin.* 13 (2023) 10065–10084.
- [73] K. Zhu, H. Xian, L. Peng, et al., *J. Radioanal. Nucl. Chem.* 332 (2023) 1743–1754.
- [74] J.C. Ma, D.A. Dougherty, *Chem. Rev.* 97 (1997) 1303–1324.
- [75] Y. Andrés, C. Gérente, Removal of rare earth elements and precious metal species by biosorption, in: P. Kotrbá, M. Macková, T. Macek (Eds.), *Microbial Biosorption of Metals*, Springer Netherlands, Dordrecht, 2011, pp. 179–196.
- [76] M. Azharuddin, G.H. Zhu, D. Das, et al., *Chem. Commun.* 55 (2019) 6964–6996.
- [77] T. Dinh, S. Goutte, D.K. Nguyen, T. Walther, *J. Commod. Mark.* 28 (2022) 100242.
- [78] M. Huy Do, G. Tien Nguyen, U. Dong Thach, et al., *Miner. Eng.* 191 (2023) 107977.
- [79] Z. Wang, X. Xu, S. Ma, et al., *J. Environ. Chem. Eng.* 9 (2021) 106288.
- [80] M.A. Islam, M.I. Parvin, T.K. Dada, et al., *Biomass Convers. Biorefin.* 14 (2024) 28007–28021.
- [81] R. Gulati, S. Sharma, R.K. Sharma, *Polym. Bull.* 79 (2022) 5747–5771.
- [82] M.A. El-Bendary, S.S. Afifi, M.E. Moharam, et al., *Prepar. Biochem. Biotechnol.* 51 (2020) 54–68.
- [83] J. Fabrega, S.R. Fawcett, J.C. Renshaw, J.R. Lead, *Environ. Sci. Technol.* 43 (2009) 7285–7290.
- [84] Y. Zhou, B. Gao, A.R. Zimmerman, X. Cao, *Chemosphere* 117 (2014) 801–805.
- [85] R. Panda, M.K. Jha, D.D. Pathak, et al., Commercial processes for the extraction of platinum group metals (PGMs), in: H. Kim, B. Westrom, S. Alam, T. Ouchi, G. Azimi, N.R. Neelameggham, et al. (Eds.), *Rare Metal Technology 2018*, Springer International Publishing, Cham, 2018, pp. 119–130.
- [86] C. O'Connor, T. Alexandrova, *Minerals* 11 (2021) 54.
- [87] A. Ostovari Moghaddam, E.A. Trofimov, *J. Alloys Compd.* 851 (2021) 156838.
- [88] P. Li, Q. Liu, P. Zhou, Y. Li, *Front. Energy Res.* 11 (2023) 033220.
- [89] S.Y. Lo, W. Dianbudiyanto, S.H. Liu, *Sci. Rep.* 11 (2021) 19281.
- [90] P.K. Gupta, Radiation and radioactive materials, in: P.K. Gupta (Ed.), *Problem Solving Questions in Toxicology: A Study Guide for the Board and other Examinations*, Springer International Publishing, Cham, 2020, pp. 241–251.
- [91] M. Albayari, M.K. Nazal, F.I. Khalili, et al., *J. Radioanal. Nucl. Chem.* 328 (2021) 669–678.
- [92] Y. Sun, N. Yuan, Y. Ge, et al., *Sep. Purif. Technol.* 294 (2022) 121158.
- [93] V. Natarajan, M. Karunanidhi, B. Raja, *Environ. Sci. Pollut. Res.* 27 (2020) 29812–29823.
- [94] B.M. Jun, H.K. Lee, S. Park, T.J. Kim, *Sep. Purif. Technol.* 278 (2021) 119675.
- [95] M. Ma, R. Wang, L. Xu, et al., *Environ. Int.* 145 (2020) 106107.
- [96] M. Prasad, G.A. Kumar, S.K. Sahoo, R.C. Ramola, *J. Radioanal. Nucl. Chem.* 319 (2019) 13–21.
- [97] V. Duggal, S. Sharma, A. Singh, *Groundw. Sustain. Dev.* 13 (2021) 100577.
- [98] D. Kołodziejka, J. Bąk, M. Majdańska, D. Fila, *J. Rare Earths* 36 (2018) 1212–1220.
- [99] Q. Zhao, Y. Wang, Z. Xu, Z. Yu, *Environ. Sci. Pollut. Res.* 28 (2021) 47024–47034.
- [100] S. Li, L. Dong, Z. Wei, et al., *J. Environ. Sci.* 96 (2020) 127–137.
- [101] X. Ren, H. Feng, M. Zhao, et al., *Int. J. Environ. Res. Public Health* 20 (2023) 3829.
- [102] E. Hanus-Fajerska, A. Wiszniewska, I. Kamińska, *Plants* 10 (2021) 1110.
- [103] F. Fang, S. Liu, W. Yuan, et al., *Sep. Purif. Technol.* 312 (2023) 123294.
- [104] J. Liu, Y. Liu, Y. Shen, et al., *Sep. Purif. Technol.* 306 (2023) 122532.
- [105] C. Fan, N. Chen, J. Qin, et al., *Colloids Surf. A* 599 (2020) 124882.
- [106] B. Ghanim, T.F. O'Dwyer, J.J. Leahy, et al., *J. Environ. Chem. Eng.* 8 (2020) 104176.
- [107] J. Kończyk, K. Kluziak, D. Kołodziejka, *J. Environ. Manag.* 313 (2022) 114958.
- [108] K. Rong, X. Li, Q. Yang, et al., *J. Ind. Eng. Chem.* 120 (2023) 170–181.
- [109] B. Ghanim, J.G. Murnane, L. O'Donoghue, et al., *J. Water Process Eng.* 33 (2020) 101076.
- [110] B. Wu, J. Ifthikar, D.T. Oyekunle, et al., *Sci. Total Environ.* 789 (2021) 148031.
- [111] M.B. Ahmed, J.L. Zhou, H.H. Ngo, W. Guo, *Biomass Bioenergy* 84 (2016) 76–86.
- [112] M. Nematian, C. Keske, J.N. Ng'ombe, *Waste Manage.* 135 (2021) 467–477.
- [113] E. Struhs, A. Mirkouei, Y. You, A. Mohajeri, *Appl. Energy* 279 (2020) 115782.
- [114] L. Campion, M. Bekchanova, R. Malina, T. Kuppens, *J. Clean. Prod.* 408 (2023) 137138.
- [115] L. Xia, W. Chen, B. Lu, et al., *Renew. Sustain. Energy Rev.* 175 (2023) 113145.
- [116] G. Kwon, A. Bhatnagar, H. Wang, et al., *J. Hazard. Mater.* 400 (2020) 123242.