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# REVIEW

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# Amidoxime-based materials for uranium recovery and removal

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Resources and the environment are two eternal themes of social development. Nuclear energy, a green source with high energy density, can greatly alleviate the pressure of the energy crisis in today's society. To guarantee the long-term sufficient supply of nuclear fuel, mining seawater uranium is imperative. Meanwhile, the great threats of uranium to ecological security and human health make the removal of uranium from the environment urgent. To achieve these ends, a large number of materials with specific functions have been born as a result. Among them, amidoxime-based materials serve as one of the most promising candidates and are the main tool used for uranium extraction from aqueous systems owing to their special affinity for uranium. However, there is still huge room for improvement in amidoxime-based materials in terms of their economic efficiency and performance. In this paper, we provide a comprehensive review of amidoxime-based materials for uranium recovery and removal, including synthesis strategies, characterization and types of amidoxime-based materials, the factors that influence uranium extraction, and the binding mechanisms between amidoxime ligands and uranyl ions, as well as the cost drivers in applications. Meanwhile, the shortcomings of current research as well as future development directions and research hotspots are also pointed out. Based on the in-depth analysis of the currently available literature, a demand-oriented strategy for fabricating a new generation of amidoxime-based adsorbents was proposed, and means to enhance the adsorbent performance were discussed with regards to four aspects, including adsorption capacity, selectivity, kinetics and regenerability. This paper aims to provide guidance for the purposeful design of novel amidoxime-based materials, and to provide advice on circumventing unfavorable factors and solving the technical problems relating to uranium recovery and removal.

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compounds and heavy metals and environmental impact assessment.

### 1. Introduction

Population growth, environmental pollution, and energy shortages are the three major global problems facing modern society. Energy and environmental issues, in particular, pose a great obstacle to the development of human society.<sup>1,2</sup> Fossil fuel, represented by coal and oil, as traditional energy resources, will be eliminated within 100 years,<sup>3</sup> not only because they are unclean and are the chief cause of many environmental problems comprising global warming and ozone depletion, but also because they are non-renewable and will eventually be exhausted with increasing demand.<sup>4</sup> Nuclear power generation is considered as the best alternative to meet the needs of the growing population.<sup>4,5</sup> During the period 2000 to 2013, nuclear power accounted for approximately 20% of electricity generation in the U.S. and 13% worldwide.<sup>6</sup>

Uranium, the main nuclear element, is increasingly needed.7 The main source of uranium fuel around the world by far is terrestrial uraninite.8 However, the conventional global uranium reserves (7.6 million tons) may be exhausted in a century.9,10 Increasing attention has thus been paid to the ocean since mining uranium from seawater was first proposed 50 years ago.<sup>11</sup> The total uranium reserves in seawater are nearly a thousand times the identified terrestrial supply,12 reaching 4.5 billion metric tons,13 which provides the possibility of solving the current energy crisis and guaranteeing future uranium resources.14 Besides, the lower environmental impact and fewer processing steps make this strategy more exciting.12,15 Therefore, uranium extraction from seawater is listed as one of the seven chemical separations that can change the world.<sup>16</sup> However, the ultra-low concentration (*ca.* 3.3 ppb),<sup>13</sup> the stable forms of  $(Ca_2UO_2(CO_3)_3(aq)^{17,18}$  or  $[UO_2(CO_3)_3]^{4-}$  (ref. 19)), the extremely complex system of the seawater environment (with almost all naturally occurring elements,12 as partly shown in Table 1), and the immense volume of seawater<sup>20</sup> make it strategically important to develop high-performance adsorbents to achieve in situ seawater uranium extraction.<sup>21</sup> Consequently, a large number of research teams from different organizations,

including the Japan Atomic Energy Agency (JAEA),<sup>22-26</sup> Oak Ridge National Laboratory (ORNL),<sup>27-29</sup> Pacific Northwest National Laboratory (PNNL),<sup>30-32</sup> Lawrence Berkeley National Laboratory (LBNL)<sup>10,18,19</sup> as well as universities in America,<sup>30,33-35</sup> Japan,<sup>33,36-38</sup> South Korea,<sup>39</sup> Thailand<sup>40</sup> and China,<sup>41-43</sup> have been attempting to design and develop advanced deployable adsorbents to this end since the mid-1960s.<sup>44</sup>

Despite uranium species being a limited precious strategic source for nuclear energy generation, their presence in undesirable places poses an enormous threat to ecological safety and human health owing to their long-lived radionuclides and toxicity.<sup>34,45</sup> As reported, uranium and its compounds entering the body can be deposited in the lungs and may move to the kidney through the blood flow, resulting in progressive or irreversible damage and to and failure of organs, and even direct death.46-48 It is considered one of the most dangerous heavy metals in the environment.49,50 It is thus an urgent requirement to dispose of uranium-contaminated water safely and effectively.<sup>51</sup> According to the U.S. Environmental Protection Agency (EPA) standards, the maximum permissible concentration for uranium in drinking water is 30  $\mu$ g L<sup>-1</sup>.<sup>52</sup> In the guidelines from Australia, Canada and the World Health Organization (WHO), the values are 20, 20, and 9  $\mu$ g L<sup>-1</sup>, respectively.53,54 Based on Gilman's study, the maximum tolerable uranium intake regulated by the WHO is 0.6  $\mu$ g kg<sup>-1</sup> of body weight per day.55 Uranium contaminants in the environment are mainly derived from nuclear industrial effluents and mining wastewater,<sup>56</sup> which also serve as promising pools of uranium.<sup>57,58</sup> In other words, uranium separation from wastewater can improve the aquatic environment, while the obtained uranium can once again be an important source of nuclear fuel.59

Adsorption is highly recognized as an efficient, inexpensive and easy-to-use method for uranium capture.<sup>13,22</sup> Commonly used adsorption materials can be roughly divided into inorganic adsorbents (such as metal oxides,<sup>60</sup> clay minerals,<sup>61,62</sup> and layered metal sulfides<sup>34,63</sup>), organic adsorbents (such as chitosan,<sup>64</sup> bio-wastes,<sup>65,66</sup> synthetic polymers<sup>67</sup>). Inorganic



toring and control technology.

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500 peer-reviewed papers with more than 50204 citations and a H factor of 96 (according to the ESI database updated as of 9 May 2019) and is a named inventor of more than 300 issued patents.

Table 1 Concentrations of selected elements in seawater

	Concentration in seawa	ater		Concentration in seawater		
Element	$\mathrm{mg}~\mathrm{kg}^{-1}~\mathrm{(ppm)}^a$	$mol L^{-1b}$	Element	$\mathrm{mg}~\mathrm{kg}^{-1}~\mathrm{(ppb)}^a$	${ m mol}\ { m L}^{-1b}$	
Na	10 800	0.468	Li	180	$25.9 imes10^{-6}$	
Mg	1290	$53 imes 10^{-3}$	Rb	120	$1.4 imes 10^{-6}$	
Ca	413	$10.3 imes10^{-3}$	Мо	10	$0.1 imes 10^{-6}$	
K	400	$10.2 \times 10^{-3}$	Ni	5	$85.2\times10^{-9}$	
Sr	8.1	$92.4\times10^{-6}$	Fe	3.4	$60.9 imes10^{-9}$	
Anions			U	3.3	$13.9 imes10^{-9}$	
Cl	19 400	0.547	V	1.83	$35.9 imes10^{-9}$	
$SO_4$	2701	$28.1  imes 10^{-3}$	Cu	0.9	$14.2 imes10^{-9}$	
HCO <sub>3</sub>	145	$2.38\times 10^{-3}$	Mn	0.2	$3.64 imes10^{-9}$	
Br	65	$0.814\times10^{-3}$	Pb	0.03	$0.145 imes 10^{-9}$	

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adsorbents have the advantages of fast kinetics and simple preparation but suffer from poor selectivity and low adsorption capacities. In contrast, organic adsorbents are more promising, especially for adsorbents based on high-affinity ligands such as oximes,68 amines/imines,67,69,70 phosphonates,71 phosphoramides,72 imidazoles,73 carboxyl or phenolic,74-76 and amidoxime groups.77 Among them, amidoxime has received the most attention. The oxime nitrogen, amino nitrogen and oxime oxygen in the amidoxime structure can all act as electron donors to coordinate with uranyl ions and the amphoteric nature allows amidoxime-based adsorbents to chelate uranium effectively under a wide pH range.78 In fact, screening studies with more than 200 organo-functionalized materials have identified that poly(acrylamidoxime) derived from polyacrylonitrile is the only adsorbent with the ability to selectively extract uranium at a pH value close to that of seawater.<sup>79</sup> Since the 1980s, amidoxime-based materials have been widely used to recover oceanic uranium.<sup>80</sup> After nearly 40 years of development, a variety of amidoxime-based materials have emerged one after another, and there are also many successful cases. For instance, researchers from Japan obtained more than 1 kg of uranium in yellow cake form using amidoxime-functionalized nonwoven cloth in a stack system after 240 days of submersion.<sup>81</sup> Thus, the feasibility of extracting uranium from seawater with amidoxime-group polymers has been demonstrated.82 In addition, motivated by the high affinity of amidoxime groups towards uranium, extensive attempts have been made to prepare amidoxime-bearing scavengers for removing Ucontaminants from wastewater.83,84

In the 21st century, research on amidoxime and uranium has witnessed growth as shown in Fig. 1. Although reviews on uranium extraction from seawater and uranium removal from aqueous solution have been published,<sup>8,85–87</sup> there are few reviews so far focusing on amidoxime-based materials for uranium recovery and removal. As the protagonist for capturing uranyl ions in seawater and contaminated water, all aspects of amidoxime-based adsorbents are in urgent need of a comprehensive review. In this paper, with amidoxime groups as a starting point, the synthesis, characterization and types of amidoxime-based materials (Chapters 2 and 3), the factors that

influence the extraction (Chapter 4), and the binding mechanisms between amidoxime ligands and uranyl ions (Chapter 5) as well as cost estimations (Chapter 6) are reviewed in detail. It was proposed for the first time that the development of the newgeneration of amidoxime-based adsorbents should be demandoriented, and means of enhancing the adsorbent performance were discussed with regards to four aspects, namely adsorption capacity, selectivity, kinetics and regenerability (Chapter 7). This article aims to provide guidance for the purposeful design of novel amidoxime-functionalized materials and to provide advice on solving the technical problems surrounding uranium enrichment from seawater and effluents.

# 2. Preparation of amidoxime-based materials

Amidoxime, as an effective functionality for uranium ion anchoring, possesses superb chemical activity and excellent



**Fig. 1** Growth in the number of publications regarding the keywords "amidoxime" and "uranium" in indexed journals between 2000 and 2018. The inset pie graph shows that amidoximes are mainly used for seawater uranium extraction. The data are sorted from the research on "Web of Science".

adsorption ability. This group can be structurally regarded as a product in which the oxygen atom on the amide moiety is replaced by an isonitroso group or the hydrogen atom of the imine on the amidine moiety is exchanged by a hydroxyl group.<sup>88</sup> Thereby, the preparation and physicochemical properties of amidoxime are closely related to its characteristic ligands, namely the oxime moiety and the amino moiety. In this section, the common routes for amidoxime synthesis and their characteristics are summarized in brief.

### 2.1 The preparation

As early as the nineteenth century, various amidoxime species were prepared, although they were not employed in the fields of energy and the environment. In an incipient review, Eloy and co-workers summarized ten different routes for synthesizing amidoxime, as shown in Fig. 2.<sup>ss</sup> However, Methods II to X (MII–X) are limited in operation or other ways, so can only be used in specific situations; thus, the mainstream strategy in later development is achieved *via* method I (MI), *i.e.* treating nitriles with hydroxylamine under basic conditions.

The nitrogen atom on hydroxylamine is expected to preferentially attack the carbon atom on the cyano group owing to the higher nucleophilicity. Imino hydroxylamine and amidoxime are thus formed, which are in dynamic equilibrium with each other (Fig. 3a, there are two different possible routes since the hydrogen atom and the hydroxyl moiety on the hydroxylamine molecule are not equivalent). In general, the products mainly exist in amidoxime form owing to its more stable structure. However, according to the results of quantum mechanical calculations (Fig. 3b),<sup>89</sup> the oxygen atom on the hydroxylamine may first attack the carbon atom on the nitrile group because the hydroxylamine oxygen atom is more strongly basic than the nitrogen atom ( $Q_{\rm O} = -0.563 \ vs. \ Q_{\rm N} = -0.331$ ). Thus,



Fig. 2 Ten synthesis pathways for amidoxime based on the work of Eloy and co-workers. Plotted according to ref. 88.

intermediate **3** is generated. Then, under the strong electrostatic attraction between the hydroxylamine nitrogen ( $Q_{\rm N} = -0.654$ ) and the imine carbon atom ( $Q_{\rm C} = 0.721$ ), a high-energy oxaziridine ring **4** is formed. Owing to the unstable threemembered ring of intermediate **4**, the C–O could cleave to provide intermediate **5**. After the tautomerization, acrylamidoxime **6** is obtained (Fig. 3c). Besides, the formation enthalpies of **5** and **6** provide a theoretical basis for the amidoxime structure to be more stable (Fig. 3d).

Since the carbon-nitrogen double bond in amidoxime structure is defective in rotation, two different configurations of Z and E forms may exist in the amidoxime structure, as seen in Fig. 4. Only a few studies have reported the formation of an E-type structure and all of them are N,N'-disubstituted amidoximes co-existing with the Z form.<sup>90</sup> There is a classic view that the resulting configuration depends on the steric and electronic effects of the R group.<sup>91</sup> Specifically, the substituted group, R, would result in steric hindrance preventing the formation of the Z form amidoxime owing to its relatively large size. However, when the hydrogen atoms on the amidoxime amino group are di-substituted by other functionalities, the resistance to forming the E form product also remarkably increases, and thus, both forms are generated.

There are two pathways that can be used to introduce cyano groups, i.e. in situ generation and functionality grafting/ modifying. The former is relatively rare and has only been reported by Yang et al.92 They pioneered a novel "one-pot" reaction, with  $K_4[Fe(CN)_6]$  as the starting substance and Pd compounds as catalysts, for synthesizing amidoxime compounds. By contrast, the latter is more widespread. Most of the amidoxime-based adsorbents deployed in the marine environment are various polymeric materials obtained from the polymerization of acrylonitrile followed by hydroxylamine treatment93 (this process cannot be reversed because the oxime moiety on the amidoxime groups is capable of quenching radicals, inhibiting the polymerization of olefins94). In addition, acrylonitrile can also be attached to various host materials by cyanoethylation or surface graft polymerization. The asfabricated adsorbents possess the exceptional physicochemical properties of the matrix materials, which can be employed in the adsorption of uranium or other metal ions from some specific situations, such as uranium removal or recovery from nuclear industrial effluents.95 For instance, acrylonitrile can be grafted onto a chitosan matrix by cyanoethylation reaction with the hydroxyl groups on the chitosan backbone.96 Other than chitosan, various materials, including silica gel,97 zeolite,95 multi-walled carbon nanotubes (MWCNTs),98 reduced graphene oxide (r-GO),99 potato starch,100 mesoporous silica,101 and metalorganic frameworks (MOFs),<sup>102</sup> have also been investigated as matrices for supporting amidoxime groups. Besides acrylonitrile, other cyano-bearing compounds have also been adopted for preparing/modifying adsorbing materials, including diaminomaleonitrile (DAMN),<sup>103,104</sup> 3,3-iminodipropionitrile,<sup>83,105</sup> malononitrile,<sup>106</sup> dicyandiamide,<sup>107</sup> 2-butenenitrile,<sup>108</sup> (3-cyanopropyl)triethoxysilane (CPTS)109 and 3-hexenedinitrile.110 The relevant content is reviewed in Chapter 3. It is reasonable to believe that more nitrile-containing small molecules will be



Fig. 3 Schematic illustration of (a) two possible routes for hydroxylamine to attack cyano compounds under alkaline conditions; (b) the optimized results of quantum mechanical calculations for reactants (1 and 2), intermediates (3 and 4) and products (5 and 6); (c) the mechanism of formation of the amidoximes based on the results of quantum mechanical calculations; (d) enthalpy of formation of compounds 3, 4, 5, and 6 generated by reagents 1 and 2. Reproduced with permission from ref. 89. Copyright 2009, Springer.



Fig. 4 E and Z forms of amidoximes. Reproduced with permission from ref. 90. Copyright 2016, Elsevier B.V.

explored and employed for optimizing and upgrading adsorbents, especially after amidoximation by hydroxylamine treatment.

Although the path to prepare the amidoxime-based material is simple (MI in Fig. 2), the synthesis details vary widely (Fig. 5). Approaches **3** and **4** are more popular and have been widely adopted. The alkaline reagents used in the processes consist of not only inorganic bases (*e.g.* sodium hydroxide,<sup>95,97</sup> sodium carbonate,<sup>111,112</sup> potassium hydroxide,<sup>9,28</sup> and potassium carbonate<sup>113,114</sup>). But also organic matter (*e.g.* triethylamine<sup>115</sup>),

and the polar organic solvents used include methanol,<sup>116</sup> tetrahydrofuran<sup>117</sup> and ethanol.<sup>118,119</sup> Kabay and colleagues compared the different conditions used for functionalization in detail and found that acidic conditions were not beneficial to the amidoximation process.<sup>120</sup> Zahri *et al.* carried out some trials to refine the operational details in terms of conservation of energy, resources and time.<sup>121</sup> However, they still did not break through the framework of these four approaches.

The syntheses of di-amidoximes and poly-amidoximes are similar to those of mono-amidoximes, and thus no detailed discussion is carried out in this paper. However, there are two structures worth mentioning: glutaroimide-dioxime and glutardiamidoxime. Rao and co-workers carried out a series of studies on these two amidoxime derivatives. According to their work, when hydroxylamine reacts with glutaronitrile in a 2 : 1 ratio, glutardiamidoxime is formed at room temperature, while at 80–90 °C, the resulting product is glutaroimide-dioxime.<sup>122</sup> Besides, the open-chain amidoxime can be converted into a cyclic imide dioxime structure *via* heat treatment in aprotic solvents.<sup>123</sup> It thus is reasonable to speculate that in the



Fig. 5 Four approaches for converting cyano groups to amidoxime groups by hydroxylamine treatment in the laboratory.

adsorbents containing the polyamidoxime moiety, two neighboring amidoxime units can strip off an ammonia molecule and form the cyclic imide dioxime structure. However, the actual situation and the conversion ratio are dependent on the specific reaction conditions, and in future research, it is expected that this will be studied in more detail.

### 2.2 The structure and characterization

In the classical amidoxime structure, a carbon atom is simultaneously bonded to an amine group and an oxime group connects with a substituent R, as exhibited in Fig. 2. The presence of both amino and oxime moieties in such a structure imparts amphoteric properties to amidoximes<sup>78</sup> There is some debate regarding the protonated structure displayed as structure I and I' in Fig. 6a. In general, at acidic pH, the conversion of the amino group in the amidoxime structure from  $-NH_2$  to  $-NH_3^+$  (as depicted as structure I in Fig. 6a) is widely recognized.<sup>124-126</sup> This result is supported by quantum mechanical calculations. In penylamidoxime, the amino nitrogen atom possesses a higher charge than that of the oxime nitrogen atom (-0.760 vs. -0.433),<sup>89</sup> which may imply that hydrogen ions tend to protonate the amino group in strongly acidic environments to form the structure I in Fig. 6a. However, another binding motif (structure I' in Fig. 6a) also has its followers.<sup>127</sup> Since this difference does not affect the external performance of amidoxime structures and their subsequent applications, few studies have focused on the correct protonation modes. More in-depth work is needed to explore the various situations and to propose a generally applicable mechanism. Inspired by atomic charges, the reason that *gem*-aminonitroso (Fig. 6b) has never been



Fig. 6 (a) Protonation and deprotonation of amidoximes, and (b) prototropic tautomeric forms of amidoximes. Reproduced with permission from ref. 90. Copyright 2016, Elsevier B.V.

identified anywhere and that amidoxime is more thermodynamically stable<sup>90</sup> can be easily explained. As the pH increases, the amidoxime groups are gradually deprotonated into the uncharged form and the negatively charged form (II and III in Fig. 6a). Therein, the point of zero charge (pHpzc) is pointed out because it plays a key role in explaining the adsorption performance of amidoxime-based adsorbents towards various adsorbates under different pH conditions. In general, at pH > pHpzc, owing to electrostatic forces, the negatively charged adsorbents can efficiently anchor cationic contaminants, but do not work for anionic ones, and *vice versa*. It is noteworthy that the pHpzc is generally an overall characteristic of strategic materials, which depends not only on the acid-base properties of the amidoxime groups but also on the nature of the matrices themselves and the other functional groups, if any. That is why the pHpzc values of various adsorbents differ. For example, the value is 4.3 for amidoximated polyacrylonitrile/exfoliated Na-me compose).129 More pHpzc values for various amidoxime-based materials are tabulated in Table 2. Most of these values fallissociation constant,  $pK_{a1}$ , (*i.e.*, 5.78 for acetamidoxime, an sp<sup>3</sup>hybridized form, and 4.85 for benzamidoxi between the firssite.125 for poly(acrylonitrile)/amidoxime/bentonite 6.3 composite128 and 10.5 for amidoximated MCM-41 silica decorated with polontmorillonity(acrylonitrilt-order dme, a sp<sup>2</sup>hybridized form, at 25 °C) and the second-order dissociation constant, pKa2, (i.e., 13.21 for acetamidoxime and 12.36 for benzamidoxime at 25 °C) of amidoxime compounds.127 As for the third-order dissociation of amidoxime (IV in Fig. 6a), there are no reports regarding the determination of  $pK_{a3}$  yet, and the value is thus unknown.90

Some basic physical structural features of amidoximes, including the average  $N^1$ -O,  $N^2$ -C and  $N^1$ -C bond lengths can be obtained from the Cambridge Crystallographic Data Center (CCDC). Functional group structures are mainly identified by infrared (IR) spectroscopy, X-ray photoelectron spectroscopy (XPS), and nuclear magnetic resonance (NMR) spectroscopy. As discussed above, reduction of cyano compounds by hydroxylamine is the main method used for the synthesis of amidoximes. The stretching vibration of the cyano group corresponds

Table 2         The pH <sub>pzc</sub> values of variation	ous amidoxime-based mat	erials
Adsorbent	$\mathrm{pH}_\mathrm{pzc}$ value	Ref
0.2AO-OMC <sup>a</sup>	2.80	108
AO-HTC <sup>a</sup>	4.69	195
P(AO)-g-CTS/BT <sup>b</sup>	6.7	110
AM-MG-CH <sup>b</sup>	8.13	106
Amidoxime-modified algal	10.0	211
cells <sup>b</sup>		
$ABS^{b}$	4	214
Ami-MSN <sup>c</sup>	2.5	138
AMD-MCM-41 <sup>c</sup>	10.5	129
PAO/organo-B composite <sup>d</sup>	6.3	128
Na-Mont-APAN <sup>d</sup>	4.3	125
FeOOH-APAN <sup>d</sup>	8.4	244

<sup>a</sup> Carbon-based materials.
 <sup>b</sup> Biosorbents.
 <sup>c</sup> Silica-based materials.
 <sup>d</sup> Others.

to a strong  $\nu$ (C=N) peak at *ca.* 2244 cm<sup>-1</sup> in the IR spectra. Therefore, the disappearance or weakening of this peak provides first-hand information on the conversion of the cyano moiety. More importantly, the appearance of some characteristic bands, such as the stretching vibration peaks of C=N (1500-1694 cm<sup>-1</sup>) and N-O (885-980 cm<sup>-1</sup>) bonds, provide decisive evidence for the formation of amidoximes.130 Similar to pHpzc, the exact position of these characteristic adsorption bands could be slightly affected by the matrix materials and/or the bulk circumstances (e.g. the presence of hydrogen bonds). The adsorption bands ascribed to O-H and N-H stretching vibrations often cannot be characteristic because they are usually affected by the solvent used and the water in the materials.90 Moreover, they are too common to be representative. More importantly, their bands are often overlapping (3000-3600 cm<sup>-1</sup> for  $\nu$ (O-H)<sup>27</sup> and 3000-3600 cm<sup>-1</sup> for  $\nu$ (N-H)<sup>20</sup>) and difficult to distinguish from each other.<sup>131</sup> The FT-IR spectral data for various amidoximes are tabulated in Table 3. The XPS results present the signals at 400.3 and 401.7 eV in the N 1s spectrum, corresponding to NH<sub>2</sub>-C=N-OH and NH<sub>2</sub>-C=N-OH, respectively,33 and the peaks at 286.18 eV in the C 1s spectrum and 531.08 eV in the O 1s spectrum are indicative of NH<sub>2</sub>-C=N-OH and NH<sub>2</sub>-C=N-OH, respectively.<sup>132</sup> In the <sup>1</sup>H NMR spectra, two strong characteristic peaks at 9.44 ppm and 5.81 ppm correspond to the OH and  $NH_2$  resonances, respectively.117 Similarly, two singlets in the ranges of -85.30 to -98.30 ppm and -317.40 to -319.40 ppm can be observed in the <sup>15</sup>N NMR spectra, which are attributed to NOH and NH<sub>2</sub> resonances, respectively.133,134 In the 13C NMR spectra, the signal at approximately 149 ppm is ascribed to the carbon in the cyclic imide dioxime, while the peak at around 157 ppm is indicative of the carbon in amidoximes.135,136 As a result, the low-field singlet of the  $C(NH_2)$ =NOH is found at 153.8 ppm.<sup>137</sup> The basic physical and chemical properties of the amidoxime structure are shown in Fig. 7.

Besides, thermogravimetric analysis (TGA) confirmed that amidoxime structures decompose in the temperature range of 400-500 °C (the peak is located at ~450 °C).<sup>109</sup> In the Raman spectrum, the characteristic peaks of C=N, C=N, and N–O were been found at 2254, 1662 and 943 cm<sup>-1</sup>, respectively.<sup>138</sup> Apart from these methods, some other techniques, such as Xray diffraction (XRD),<sup>106,139</sup> scanning electron microscopy (SEM),<sup>98</sup> <sup>29</sup>Si MAS NMR spectroscopy<sup>109</sup> and transmission electron microscopy (TEM),<sup>140</sup> have also been utilized to characterize the amidoxime-based materials. However, none of these technologies are directed towards amidoxime structures, and they tend to focus more on the matrix materials. Therefore, they are not discussed in detail in this paper.

# 3. Amidoxime-based materials and their uranium adsorption performance

The development of high-performance adsorbents for marine uranium extraction is an important response for dealing with the depletion of fossil fuel resources and serious environmental problems, to which great efforts have been devoted. Especially

### Table 3 The FT-IR data of various amidoxime-based materials

	Functional grou	p (cm <sup>-1</sup> )				
Adsorbent	0-Н	C–N	C=N	N-O	N-H	Ref.
Hydrogel containing PAO <sup>a</sup>	3000-3600	_	1650	920	3000-3600	20
AO-DETA <sup>a</sup>	_	_	1636	920	_	30
AI series adsorbents <sup>a</sup>	3230	_	1645	930	3390	9
AF series adsorbents <sup><i>a</i></sup>	_	1245	1670	950	3400, 3450	28
PE-GMA-AN-HEA <sup>a</sup>	_	1391	1642	931		44
MNPs@PAO <sup>a</sup>	3115		1659	916	3115	132
AO-IDAN <sup>a</sup>	_	_	1608	980	_	140
PP-g-PAO nonwoven fabric <sup>a</sup>	_	_	1656	938	_	156
PE-g-PAO nonwoven fabric <sup><math>a</math></sup>	3200-3500	_	1647	928	_	80
$PE-g-P(AO-co-AA)^a$	_	_	1643	928	_	157
UHMWPE-g-P(GMA-co-MA)-EDA-AO <sup>a</sup>	3000-3500	_	1655	923	3000-3500	161
UHMWPE- $g$ -(PAO- $co$ -PAA) <sup>a</sup>	3000-3600	_	1650	920	3000-3600	162
AF160-2 <sup><i>a</i></sup>	_	1277	1644	935	3391, 3267	179
H-ABP fiber <sup>a</sup>	3100-3500	1381	1642	916	3100-3500	166
$PAO/PVDA^{a}$	_		1647	945	_	84
AF1 <sup>a</sup>	_	1370	1670	950	1580 <sup>g</sup>	123
PIDO $NF^a$	_	1381	1638	933		191
PAAC <sup>a</sup>	_		1650	940	3390	341
$\Delta \Omega$ -mG $\Omega^b$	_		1651	923		104
AGH <sup>b</sup>	3440		1610	971	3440	140
AQ-MWCNTs <sup>b</sup>	-	_	-	926	1656 <sup>g</sup>	08
$p-4\Omega/CNF^b$	$\sim 3400$	1290	1500	935	~3400	289
AO-HTO <sup>b</sup>		1250	1631	927		105
C-Ami electrode <sup>c</sup>	3100-3300	1274	1635	927	1572 <sup>g</sup>	252
$MAO$ -chitosan- $II^c$	2442		1666	512	1574 <sup>g</sup>	06
$P(AO)_{-\alpha}$ -CTS/PT <sup>C</sup>	5445	1260	1604	020	2104	90 110
AM-MC-CH <sup>c</sup>		1209	1694	920	5194	110
AMAN <sup>C</sup>	2200 2500	_	1640	932		210
AMANI LI <sup>C</sup>	2200-2500	_	1649	902	—	210
$PAO P^{c}$	3300-3300	_	1629	025 4	—	210
S CD20* AOd	2400	_	1649.3	955.4	1 5 9 0 g	207
Ami MCN <sup>d</sup>	3400	_	1650	900	1360°	109
AIIII-IMON	3334	1245	1055	949	—	130
$SPA AO O A^d$		1345	1650	947		542
DDA - AO - 0.4	2200 2400	_	1051	944	1396	32
$\frac{PPN-0-PAO}{COE}$	3200-3400	—	1655	933	—	27
COF-1pDD-AO	—	—	1646	924	—	231
MIL-53(AI)-AO	_	_	1652	951	—	102
	_	_	1652	951	—	113
AO/MOF	_	_	1650	936	—	225
	_		1655	919	—	115
$RAF-1-CH_2AO^2$	_	1381	1638	933	_	137
Amidoxime-PIM-1			1656	915		11/
IMP-g-AU	3194	1269	1649	920	3194	239
TMP-g-AU-U	3194	1269	1649	913	3194	239
U8A-AU'	3376		1668	928	3481	240
SMON-PAO'	—	1386	1650	939	—	243
Na-Mont-APAN	_	1096	1652	924		125
Pal/PAO'	_	—	1653	910	3372	111

<sup>*a*</sup> Polymeric materials. <sup>*b*</sup> Carbon-based materials. <sup>*c*</sup> Biosorbents. <sup>*d*</sup> Silica-based materials. <sup>*e*</sup> New type of porous materials. <sup>*f*</sup> Others. <sup>*g*</sup> Peak corresponding to bending vibration of N–H. Those without special explanation are stretching vibrations. The upward and downward arrows respectively indicate that the adsorption peak is enhanced or weakened.

in recent years, the involvement of the U.S. Department of Energy (DOE) has greatly promoted the development of this field.<sup>141</sup> Although some other adsorbents with different groups, such as carboxyl groups, have also exhibited excellent performance for uranium recovery,<sup>142</sup> amidoxime-based materials are still the main force and are regarded as the most promising candidates for uranium enrichment owing to their high affinity

to uranyl ions and safety for the environment.<sup>143</sup> Since the 1980s, a large number of amidoxime-based materials have been designed and synthesized, as presented in Fig. 8, which can be roughly divided into polymeric materials, carbon-based materials, biosorbents, silica-based materials, new types of porous materials, and others. In this chapter, various types of



Fig. 7 The basic physical and chemical properties of the amidoxime structure. Red numbers and arrows correspond to the data from <sup>1</sup>H, <sup>13</sup>C, <sup>15</sup>N NMR spectra, ppm; dark blue numbers and arrows correspond to infrared data of various moieties, cm<sup>-1</sup>; brown numbers correspond to bond length, Å; and green numbers and arrows correspond to XPS data for some atoms, eV.

amidoxime-related adsorbents that have been developed are summarized.

### 3.1 Polymeric materials

Among a wide variety of amidoxime-based materials, polymeric adsorbents, as the most important ones for seawater uranium extraction, have been studied widely owing to their following merits: (i) capable of being deployed in seawater with high mechanical resistance against attrition; (ii) lightweight; and (iii) high plasticity in shapes and lengths.144 Common methods for obtaining them include treating commercial polyacrylonitrile with hydroxylamine<sup>130,145,146</sup> and amidoximating the grafting product of acrylonitrile and comonomers.38,147,148 Direct amidoximation of polyacrylonitrile was the simplest method for obtaining amidoxime-based materials in the early years. The degree of amidoximation profoundly affects the density of amidoxime groups and the mechanical properties of the resultant materials.149 Comparatively, the method of graft polymerization is more advantageous. Radiation-induced graft polymerization (RIGP)<sup>150-152</sup> and atom transfer radical polymerization (ATRP)93,153 are widely used to achieve the grafting reaction and their processes are illustrated in Fig. 9a and b. The advantages of RIGP are that the amounts of functional groups and the length of the graft chains can be controlled by the irradiation conditions (dose, dose ratio) and grafting conditions (reaction time, temperature).23 Since most of the ligands are on the polymeric backbone, the functional groups possess better accessibility for uranium.29 The common trunk materials includes fabric polymers,23,154,155 nonwoven fiber,80,156-159 highdensity polyethylene fibers (HDPE),13,160 ultrahigh molecular weight polyethylene (UHMWPE) fibers,161-164 polyethylenecoated polypropylene skin-core (PE/PP)<sup>165,166</sup> and some textiles like nylon-66 (ref. 167) and so on. In contrast, fewer host materials are selected for ATRP, and PE fibers dominate.

However, ATRP circumvents the drawbacks suffered by conventional radical polymerization, such as high-cost radiation-inducing devices, limited nitrile groups available for amidoximation caused by many undesirable reactions<sup>44</sup> and the inability to tune the polymer structure, including its composition, conformation, and morphology.168,169 ATRP-derived adsorbents generally have excellent adsorption properties because their various parameters can be tailored by controlling the synthesis conditions (feed ratio, catalyst, time, temperature, solvent, etc.). For instance, the adsorbent, p(2DVB-VBC)-2PAN, exhibited high capacity (1.99 mg-U per g-ads) and fast kinetics (0.33 mg-U per g d) after 27 d of contact with 5 gallons of seawater.21 Besides, the combination of RIGP and ATRP can further optimize the structure of the synthesized amidoximebased polymers. As reported, the as-prepared PE-g-PVBC-g-(PAO-co-PAA)s has the unique polymer architectures of brushes on a brush,<sup>144</sup> and the incorporation of glycidyl methacrylate (GMA) by RIGP has been proved to not only mitigate the hydrophobicity of the trunk material but also provide more reaction sites for ATRP, yielding a higher degree of grafting (d.g.).44 However, the hydrophilicity and grafting rate of adsorbents do not decide everything. Other factors, such as the conformational effect of the graft chain, could also affect the performance of the adsorbents. In practical applications, the accessibility and availability of the adsorption sites are more worthy of attention than the group density. In addition to GIRP and ATRP, other approaches, such as reversible additionfragmentation transfer (RAFT)<sup>132,170,171</sup> and surface-initiated single electron transfer living radical polymerization (SET-LRP),<sup>126</sup> have also been proven to be feasible and may find broader application prospects in the future.

Most of the monomers co-grafted with acrylonitrile are organic acids with vinyl moieties such as acrylic acid (AA),<sup>24</sup> methacrylic acid (MAA),154 2-hydroxyethyl methacrylate (HEMA),<sup>172</sup> acrylamide (AAm),<sup>157</sup> N,N-dimethylacrylamide (DMAAm),<sup>23</sup> vinyl sulfonic acid (VSA),<sup>155</sup> vinyl phosphonic acid (VPA),9 itaconic acid.28 The contribution of comonomers is mainly to improve the physicochemical properties of adsorbents and to provide additional adsorption sites.<sup>173,174</sup> On the one hand, their introduction can improve the hydrophilicity of the resultant adsorbents, promote the diffusion of uranyl ions inside the fabric adsorbents154,172 and help the ions approach the adsorption sites.<sup>124</sup> For this reason, the resins with amidoxime/carboxylic acid groups exhibited higher kinetics in artificial seawater than those with amidoxime groups alone.39 On the other hand, ionic groups can vary the local pH, affecting uranium species present in seawater and the types of complex that form between amidoxime and uranyl ions.<sup>24</sup> This may be why DAAm makes the adsorbent more hydrophilic but does not improve the performance as well as the carboxyl group.<sup>23</sup> In other words, although the synergistic effects of amidoxime and co-monomer groups together determine the final performance of the adsorbents,175 the effects of different monomers are varied. For example, amidoxime-functionalized polyethylene nonwoven fabric co-grafted with MAA displayed the best adsorption performance for uranium, followed by ITA and AA, with AAm being the worst.157 The co-grafting of various acidic



Fig. 8 Timeline for the development of various amidoxime-containing adsorbent materials for uranium recovery or removal from the 1980s to 2019.

monomers endows the PE fibers with the ability to adsorb uranium from simulated seawater in the following order: VPS > ITA > MAA > VSA > AA.<sup>155</sup> VPA performs best, which may be related to the lowest  $pK_a$  of 1.3 (ref. 155) and its ability to bind uranyl ions.<sup>176,177</sup> ITA with two carboxylic moieties per molecule can make PE fibers more hydrophilic and its co-grafting also affords a good result. AA is the worst co-monomer owing to homopolymerization, which can be suppressed by Mohr's salt.<sup>155</sup> In addition, a different order was observed in the uranium adsorption capacity in PE fibers and PE nonwoven fabric, which may imply that the trunk materials also affect the ultimate adsorption behavior. However, the impact of the interaction between comonomers and matrix materials on uranium adsorption remains unclear and needs further investigation in the future. Alkaline conditioning is an important process to carry out before the use of polyamidoxime-based materials. As reported, alkaline solutions can (i) deprotonate the acidic groups and amidoxime groups,<sup>178</sup> (ii) convert amidoxime groups into carboxylate anions (Fig. 10a),<sup>31,179,180</sup> (iii) convert unreacted cyano groups into carboxyl groups<sup>155,181</sup> to increase the hydrophilicity,<sup>182-184</sup> and (iv) convert two neighboring amidoximes into cyclic imide-dioxime<sup>150,185,186</sup> to improve the uranium binding ability.<sup>187</sup> The alkaline reagents that are widely used are KOH<sup>157,179</sup> and NaOH.<sup>124</sup> NaOH is considered to be better for AF1 adsorbents owing to the higher uranium adsorption capacity obtained and the lower cost.<sup>188</sup> Besides, increasing the alkaline concentration, temperature and time can lead to a higher uranium adsorption capacity in a simulated seawater solution.<sup>143</sup> However, in the natural seawater test, a long



Fig. 9 Schematic illustration of the entire process for preparing amidoxime-based polymeric adsorbents via (a) RIGP and (b) ATRP methods.

conditioning time is not conducive to uranium uptake, not only because of the conversion of amidoxime into less selective carboxylates, but also because of the degradation of adsorbents.<sup>178</sup> Therefore, it was critical to select the proper conditioning temperature and time to minimize the physical damage.

Fiber-based amidoxime-based materials have long played a pivotal role in recovering uranium from seawater.149,189,190 However, so far, they still suffer from some deficiencies, such as poor mechanical strength and corrosion resistance, undeveloped pore structure, and low site utilization, making their use very limited and costly. Moreover, the inevitable shrinkage of the polymeric structure caused by post-amidoximation treatment further deteriorates the mechanical nature and surface area of the grafted fibers,93,160 and melt-spinning fails to produce submicron or nanofibers.<sup>160</sup> In order to achieve further development, we must break out of the current inherent model and find a breakthrough. The work from Ning Wang's team seems to give us some inspiration.<sup>191</sup> They developed blow-spun PIDO NFs based on a pre-amidoximation treatment (Fig. 10b). The obtained adsorbent prevails over all commercially available or investigated fibers. More importantly, this method can achieve mass production and has extremely high practical application value, which has opened up the application field of amidoxime-based fibers to some extent and provides a new idea for overcoming the common defects of amidoximated polymeric materials.

### 3.2 Carbon-based materials

Carbon-based materials are characterized by a large specific surface area, high thermal/chemical stability, developed pore systems and a wide range of sources,<sup>192,193</sup> but their uranium adsorption capacities are generally low owing to their hydrophobicity and the lack of specific functional groups. As reported, the uranium uptake is only 27.6 mg  $g^{-1}$  for graphene oxide (GO),<sup>194</sup> 26.7 mg  $g^{-1}$  for soluble starch-derived hydrothermal carbon (HTCs)<sup>195</sup> and 24.9 to 39.1 mg  $g^{-1}$  for MWCNTs.<sup>196</sup> Even though the synthesis of the few-layer graphene oxide (FL-GO) weakened the self-aggregation problem to some extent and increased the uranium adsorption capacity to 97.5 mg  $g^{-1}$ ,<sup>30</sup> the increment was not encouraging. After being modified with amidoxime groups (Fig. 11a), the situation completely changed. Specifically, the incorporation of the amidoxime group increased the uranium adsorption amount to 398.41 mg g<sup>-1</sup> for the GO-based adsorbent,<sup>140</sup> 455.6 mg g<sup>-1</sup> for soluble starch-derived HTC<sup>195</sup> and 67.9 mg  $g^{-1}$  for AO-MWCNTs<sup>98</sup> at pH 5.0/6.0 and 298 K, respectively. Post-



**Fig. 10** (a) The proposed conversion of poly(acrylamidoximes) to poly(acrylimidedioximes) and eventually to carboxylates in 1 M NaOD at 80 °C. Reproduced with permission from ref. 31. Copyright 2015, Royal Society of Chemistry. The inset graph exhibits the proposed mechanism of conversion from amidoxime to carboxylate group in alkaline solution at 80 °C. Reproduced with permission from ref. 179. Copyright 2016, American Chemical Society. (b) The preamidoximation modification of PAN and the blow-spinning process for mass fabrication of PIDO nanofibers. Reproduced with permission from ref. 191. Copyright 2018, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.



**Fig. 11** (a) Modification of amidoxime groups on the surface of carbon-based materials by radiation polymerization or chemical grafting. (b) Two approaches for preparing amidoximated SBA-15.

modification with DM-AO doubled the uranium uptake compared to that of pristine GO and halved the equilibrium time.<sup>197</sup> In addition, GO can be converted into reduced GO (rGO) *via* hydroxylamine treatment. The generated PAO/rGO achieved

the maximum adsorption capacity of 872 mg  $g^{-1}$  at pH 4.0, much higher than that of rGO (29 mg  $g^{-1})$  and PAO (161 mg  $g^{-1}$ ).<sup>198</sup> Owing to the relatively low background sorption for U(vi), carbon-based materials can also be used as a platform to compare the affinity of various functional groups towards uranium.<sup>199</sup> Taking AO-g-MWCNTs as an example, its theoretical maximum adsorption amount for uranium reached 176 mg  $g^{-1}$ , which was 4.3 times higher than that on oxidized MWCNTs, providing strong evidence of the high affinity of the amidoxime group.146 It can also be seen from the above instances that, although various carbon-based materials are functionalized by amidoxime groups, the uranium uptake of the MWCNTs-derived ones is apparently inferior to those of others, perhaps implying that the matrix material largely determines the final adsorption properties of the adsorbents. A concrete example that can prove this point is that AOGONRs, obtained by amidoximating graphene oxide nanoribbons (GONRs) converted from MWCNTs based on longitudinal oxidation unzipping,<sup>200</sup> show a relatively high uranium adsorption capacity  $(560 \text{ mg g}^{-1})$  and a short equilibrium time (within 200 min).<sup>119</sup> In general, GOs are the best solid matrix for amidoxime groups, followed by HTCs, carbon nanofibers (CNFs), mesoporous carbon (MCs), activated carbon fibers (ACFs), and MWCNTs.

Conventional surface functionalization processes generally result in pore blockage and may damage the surface and pore structure of carbonaceous materials. Some strategies, such as the one proposed by Choi and Ryoo,<sup>201</sup> have been adopted to solve this problem. The synthesized AO-OMC series materials increased the uranium adsorption capacity of pristine CMK-3 by nearly 7 times, while retaining the structural stability of the MC feedstock to the maximum extent.<sup>108</sup> HTC-AO prepared based on the chemical rationales of Morita-Baylis-Hillman and freeradical addition reactions is an almost perfect uranium adsorbent with the following features: (i) stable physicochemical properties with no significant change in its surface groups or the adsorption performance for uranium after y-irradiation treatment; (ii) fast kinetics owing to the absence of pores and voids; (iii) amazing saturation sorption capacity of 1021.6 mg g; and (iv) excellent selectivity towards uranium in simulated nuclear industry effluent under acidic conditions.<sup>202</sup> Besides, sonication was proved to induce the cavitation process, thereby circumventing potential pore blockage,33 and the assistance of ultrasound was reported to significantly increase the uranium adsorption speed of the material.<sup>203</sup> In a word, the excellent physicochemical properties of carbon-based materials provide a good loading platform for amidoxime groups, while the high affinity of amidoximes for uranium endows the specificity of carbon-based materials, and their synergistic effect gives amidoximated carbon-based materials unparalleled uranium adsorption properties.

### 3.3 Biosorbents

Compared with common polymer substrates, such as PP and PE fibers, natural biomass materials are more hydrophilic, biocompatible and non-toxic.<sup>204</sup> Not only is biosorption cheap, it also largely reuses waste materials.<sup>205</sup>

Taking chitosan as an example, it is an aminopolysaccharide with abundant hydroxyl and amino groups and it is widely regarded as an environmentally friendly adsorbent.<sup>100</sup> However, its porosity<sup>106</sup> and mechanical properties are poor.<sup>110</sup> Its solubility under acidic conditions is also a headache,110 making it difficult to separate and limiting its application. Therefore, it is usually imparted with magnetic properties96,106 or embedded in a clay mineral such as bentonite.<sup>110</sup> Cyano-containing reagents can be introduced into the chitosan backbone though substitution,106 cyanoethylation reaction,96 and free-radical polymerization.<sup>110</sup> The introduction of amidoxime groups significantly improves the uranium adsorption with the theoretic maximum adsorbed amount increasing from 117.65 mg  $g^{-1}$  to 372 mg  $g^{-1}$ . A previous review reported that chitin-/chitosan-bearing materials may be suitable for future uranium exploitation from seawater.206

In addition, the amidoximation of cell biomass, which is usually based on surface functional groups on the cell wall, such as  $-NH_3$ , -OH or -COOH,<sup>207</sup> has also achieved very efficient performance in uranium uptake (621 mg g<sup>-1</sup> for amidoximemodified *Aspergillus niger*),<sup>208</sup> kinetics (adsorption equilibrium can be established in only 45 min for amidoximated *Trametes trogii* pellets)<sup>209</sup> and selectivity.<sup>210</sup> Amidoxime-modified *Saccharomyces cerevisiae* achieved high adsorption efficiency (75– 100%) in salt lake samples with almost saturated metal ions (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, *etc.*) at pH 6.<sup>207</sup> Furthermore, the adsorption performance of amidoxime-modified algal biomass (366.8 mg g<sup>-1</sup>) was significantly better than that of PEI-modified (279.5 g) and native materials (194.6 mg g<sup>-1</sup>),<sup>211</sup> once again providing strong evidence for the important role played by amidoxime groups in uranium adsorption. Wool fiber-derived adsorbents overcome the drawbacks of most biomass adsorbents, which are easily degraded,<sup>212</sup> and the loading of nanosized ZnO endowed amidoximated wool fibers with good antibiofouling property.<sup>213</sup> In addition, cellulose and its derivatives also have important research value for developing novel amidoxime-based adsorbent materials,<sup>214,215</sup> which is worthy of further research.

### 3.4 Silica-based materials

Silica-based materials have been active in the field of organic and inorganic removal.<sup>216</sup> However, pure silica has poor selectivity toward specific target adsorbates. Silica-based organicinorganic hybrids have been considered as a breakthrough to overcome this dilemma since they not only retain the stable 3dimensional structure of inorganic silica but also possess the specific chemical properties belonging to organic functional groups.101,217,218 Most attention has been focused on mesoporous silica,<sup>129,176,219,220</sup> especially SBA-15. There are two approaches for fabricating amidoxime-functionalized SBA-15: co-condensation109 and post-grafting.221 The desired product can be obtained by converting the cyano groups on the precursor materials into amidoxime groups (Fig. 11b). From the perspective of green chemistry and waste utilization, the silica resource can also be obtained from several byproducts, such as coal fly ash.138 The key processes in determining the structural properties of mesoporous silica materials are template removal and pore formation, which are usually achieved by calcination or solvent extraction. The former is most commonly used and the latter may not remove the template completely.<sup>221</sup> However, calcination always suffers from the condensation of silanol groups, leading to fewer reactive sites for further grafting. Thus, some subsequent operations, such as treating with dilute  $H_2O_2$ or alkali solution, are necessary to recover the reduced silanol groups. In this period, the alkali concentration and operating temperature are particularly important.<sup>221</sup> Calcination does not apply to silica materials prepared by co-condensation method because they carry organic groups that cannot withstand high temperature. With regard to solvent extraction, research has proved that both the structural features and uranium extraction performance of the adsorbent treated by acidic ethanol are superior to those of the adsorbent treated by pure ethanol.<sup>109</sup> Despite the post-grafting process seeming to require more steps, its products exhibit a higher uranium adsorption capacity than the counterparts obtained by co-condensation. The reason could be that the organic groups are homogeneously distributed on the backbone of the co-condensation-derived mesoporous silica, while the amidoxime groups on the SBA-15 obtained by post-grafting method are concentrated on the outer surface and the pore entrance.222

During the preparation of SBA-15, morphology control is often achieved by using zirconium compounds (*e.g.*  $ZrOCl_{2}$ · $8H_2O$ ). The addition of zirconium compounds promotes the conversion of SBA-15 from long channels to short ones.<sup>223</sup> Since

the short axis of SBA-15 with short channels is parallel to its channels, which is beneficial for accelerating the diffusion of molecules and reducing the possibility of pore blockage, better adsorption performance and faster adsorption kinetics towards uranium ions are expected to be accomplished.<sup>221,224</sup> As reported, the addition of small amounts of Zr(IV) ions can generate platelet SBA-15.223 However, the lone pair electrons of the cyano groups in CTES can form dative bonds with Zr(IV) ions. Therefore, during co-condensation in the presence of zirconium compounds, as the ratio of CTES/TEOS increases, the morphology of the resulting products gradually changes from platelet to short rod shape and then to long shape. However, this is not true for the post-grafting process.<sup>222</sup> Even in the case without Zr(IV) ions, the ratio of CTES to TEOS can also have a profound effect on the morphology and uranium adsorption performance of the adsorbents.<sup>52</sup> The same is true for the case where the cvano-containing reagent is CPTS.<sup>109</sup> It is believed that the uranium adsorption behavior of silica-based materials depends on both the structural porosity and the density of amidoxime groups and that the best performance cannot be achieved unless they reach an ideal balance.52 Therefore, the application of zirconium ions can only play a role in controlling the morphology, which does not mean that adding zirconium ions will definitely lead to better adsorption.

### 3.5 New types of porous material

Porous materials have always played a pivotal role in adsorbents. Traditional ones such as carbon-based materials and porous silica have been mentioned already. Over the past several decades, as rising porous material stars, MOFs and covalent organic frameworks (COFs) have drawn wide attention. Among them, MOFs were developed earlier and received more research interest.

Similar to carbon-based materials, MOFs have outstanding physiochemical attributes but poor selectivity for target ions.<sup>102,115</sup> As expected, the synergistic effects of MOFs and amidoxime make the uranium adsorption applicable to a wider pH range, broadening the application fields of the resultant adsorbents, and significantly increasing the loading capacity and affinity of MOFs to uranium.<sup>113</sup> The methods for synthesizing amidoxime-functionalized MOFs involve chemical crosslinking cyano-bearing agents (such as DAMN) with a crosslinking agent (such as glutaraldehyde) prior to amidoximation.<sup>102</sup> Moreover, they can also be obtained with the assistance of microwave<sup>115</sup> or plasma technology.<sup>225</sup> Plasma-derived MOFs have more amidoxime groups than chemical-derived ones, but they exhibit similar uranium uptake in real seawater (2.74 mg g<sup>-1</sup> vs. 2.68 mg g<sup>-1</sup>).

COFs usually have highly ordered crystal and pore structures,<sup>226</sup> and various functional units can be specifically incorporated in a pre-designable porous framework through topological design.<sup>227</sup> In addition, the high thermal and chemical stability endow them with the ability to cope with the extreme environments<sup>228</sup> that MOFs cannot withstand.<sup>229</sup> The incorporation of amidoxime groups into a COF structure can be achieved through modifying diyne-based COFs, a versatile platform. The as-prepared TCD-AO presented the best selectivity for uranium as compared to hydroxyl- and cyanofunctionalized COFs.230 Moreover, amidoxime-functionalized COFs can be synthesized via two steps: solvothermal reaction and hydroxylamine treatment (Fig. 12). Owing to the exceptional accessibility of the chelating groups and the cooperation of adjacent groups in the specific channels, the resulting COFs exhibited much superior performance in adsorption capacity, kinetics and affinity toward uranium than the amorphous counterpart did. The produced COFs reduced the uranium concentration in various contaminated wastewater samples from 1 ppm to 0.01 ppb in just a few seconds.231 This shows the great potential of amidoxime-functionalized COFs in uranium extraction. So far, reports on amidoxime-functionalized COFs are strikingly absent from the literature and future research should focus on simpler preparation, more effective functional group exposure and lower prices for large-scale application.

Some other new types of porous organic polymers, such as porous aromatic frameworks (PAF) and polymers of intrinsic microporosity (PIM), also serve as modification platforms for the introduction of amidoxime groups. Under similar conditions, virgin PAF showed a negligible uranium adsorption capacity, while amidoxime-functionalized PAF presented high adsorption: 283 mg  $g^{-1}$  for PAF-1-CH<sub>2</sub>AO<sup>137</sup> and 385 mg  $g^{-1}$  for PAF-1-NH(CH<sub>2</sub>)<sub>2</sub>AO.<sup>232</sup> PIM is a porous organic polymer with inherent microporosity. Studies have shown that amidoximation does not destroy its inherent pores and that the resulting adsorbent can be easily fabricated into a film for actual field application.117,233 Considering the merits of porous organic polymers (POPs), including unique chemical stability, easy molecular design and controllable pore structure, 234,235 and inspired by the fact that second-sphere interaction in nature assists the chelation of proteins with well-folded scaffolds and metal ions,35,236 three amidoxime-containing POPs were designed to include uranyl binding for use as uranium nanotraps. The incorporated amino-ligand has been observed to enhance the overall uranophilicity of the adsorbents because it can serve as a hydrogen bond acceptor and reduce the electron density of uranium in the complex, and ortho-substitution works better than para-substitution.237 Moreover, simultaneous adsorption and detection of uranyl ions has been achieved using conjugated microporous polymers (CMPs) bearing amidoxime groups.<sup>238</sup> The development of these new materials offers potential possibilities for practical and efficient uranium recovery/removal, deserving further attention.

### 3.6 Others

Natural clays,<sup>139</sup> synthetic mineral salts,<sup>239</sup> cyclic compounds<sup>240,241</sup> and so on have also been tried as solid matrices for amidoxime groups out of consideration for economic effectiveness, ease of synthesis, biocompatibility or low toxicity. For example, amidoximated palygorskite shows several times higher uranium adsorption capacity than that of bare palygorskite (78.13 mg g<sup>-1</sup> *vs.* 37.90 mg g<sup>-1</sup>).<sup>111</sup> The surface modification of montmorillonite by polyamidoxime not only enhances the mechanical properties of the polymer, but also



**Fig. 12** Schematic description of (a) the synthesis of COF-TpDb through the condensation of Tp (black) and Db (blue) and corresponding chemical transformation from the cyano to amidoxime group, yielding COF-TpDb-AO and (b) the synthesis of COF-TpAab through the condensation of Tp (black) and Aab (green) and corresponding chemical transformation from the cyano to amidoxime group, yielding COF-TpAab and COF-TpAab-AO, respectively. Reproduced with permission from ref. 231. Copyright 2018, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

significantly improves the uranium adsorption efficiency of montmorillonite, which fully realizes the complementary advantages.<sup>242</sup> In particular, SMON-PAO fiber, a composite material of montmorillonite and polyacrylamidoxime prepared by blow-spinning method, is characterized by rich porosity, large surface area, high hydrophilicity and weak surface charge. Its adsorption capacity reached a surprising level of 9.59  $\pm$  0.64 mg g<sup>-1</sup> in filtered seawater at pH 8.0,<sup>243</sup> which is one of the highest values in closed-loop systems to date. In addition, iron oxide hydroxide (FeOOH) was used as a supporting material for amidoximes to extract theoretically 980.39 mg g<sup>-1</sup> of uranium

in 298 K, far higher than most of the reported uranium extractants.<sup>244</sup> As an iron compound,  $Fe_3O_4$  is often incorporated into various materials, owing to its magnetic properties, ease of preparation, and low toxicity, to enhance their separation performance. In addition to the aforementioned chitosan,<sup>96,106</sup> many materials, such as graphene oxide,<sup>104,203,245</sup> polymers,<sup>126,132,246</sup> and silicon,<sup>101</sup> have been made into amidoximated magnetic materials. These magnetic materials often have unique properties not found in other materials. For example, with the assistance of a magnetic field, MNPs@PAO can be separated from the bulk solution within 12 s.<sup>132</sup> The magnetic

nanoparticles in AO/mGO obtained by N2 plasma treatment have been proved to not only improve the separation efficiency but also promote the reduction of  $U(v_1)$  to  $U(v_2)$ , which could be beneficial for the deposition of uranium on the material surface and increase its uranium enrichment capacity.<sup>245</sup> However, this phenomenon is not limited to Fe<sub>3</sub>O<sub>4</sub>; ZVI/PAO adsorbent with zero-valent iron as the magnetic core shows similar separation and reduction performance.247 More recently, melamine sponge and halloysite nanotubes were shown to load amidoxime groups with high-efficiency for uranium extraction from seawater.<sup>248,249</sup> Black phosphorus nanosheets (BP), thanks to their photoinduced, photothermal, photoelectric and photocatalytic properties, endowed the amidoxime-based adsorbent with strong coordination interactions with uranyl ions, increased electrostatic attraction for uranyl carbonate ions, and high antifouling activity.<sup>250</sup> It is conceivable that in the future more matrix materials will appear for loading amidoxime, allowing us to obtain better uranium adsorption properties.

Maximizing the potential of the materials and the reachability of amidoxime will be the main research direction.

Recently, electrochemical methods have opened another door for ion extraction, which can overcome the drawbacks of the traditional approaches, such as low extraction capacity and slow adsorption kinetics.<sup>251</sup> Cui and co-workers used a half-wave rectified alternating current electrochemical (HW-ACE) method with an amidoximated electrode (C-Ami electrode), implementing nearly 9 times higher adsorption capacity (1932 mg  $g^{-1}$ vs. 200–220 mg g  $^{-1})$  and 4 times faster extraction kinetics (2.0  $\times$  $10^{-5} \text{ M}^{-1} \text{ s}^{-2} \nu s. 5.0 \times 10^{-6} \text{ M}^{-1} \text{ s}^{-2}$ ) than the physicochemical counterpart in uranium-spiked seawater. Moreover, in real seawater the extraction capacity of the HW-ACE method was found to be 3 times superior to that of the conventional method (1.62 µg vs. 0.56 µg) after a column-flow experiment with 4 L of seawater. The entire adsorption process consists of five steps and the absorbent can be efficiently regenerated by 0.1 M HCl with reverse bias (Fig. 13).252 Owing to the presence of amidoxime groups, this system also shows wonderful selectivity for



Fig. 13 Physical processes in HW-ACE extraction. Reproduced with permission from ref. 252. Copyright 2017, Springer Nature.

uranyl ions. The introduction of an external electric field may present some challenges and require additional investment for large-scale application. Nevertheless, the HW-ACE method is a promising alternative method for the extraction of uranium from seawater.

Tables 4 and 5 show the uranium adsorption amounts for various adsorbents in pure water, brine water (simulated wastewater), simulated seawater, U-spiked seawater and real seawater. It can be seen that the uranium adsorption capacities of the various adsorbents in pure water range from 6 to 1187.05 mg  $L^{-1}$ , which is significantly higher than those for other types of water. Because of the developed pores and excellent mechanical properties, carbon-based materials provide ideal loading platforms for amidoxime groups and generally exhibit superior uranium adsorption efficiency. In brine solutions, carbon-based materials still maintain excellent adsorption performance. 2.0 PAO/rGO afforded the highest uranium uptake of 872 mg g<sup>-1</sup>.<sup>198</sup> Therefore, amidoximated carbon-based materials have great potential in industrial wastewater treatment. Significantly lower extraction efficiencies and longer equilibrium times were observed in seawater and its simulants. Unlike pure water or brine water, polymer adsorbents are the most important materials used in real/simulated/spiked seawater. The uranyl uptakes of different amidoxime-based materials are in the range of 1.84-990.60 mg  $g^{-1}$  in simulated seawater and 0.10–1089.36 mg  $g^{-1}$  in U-spiked seawater, respectively. With the help of electrochemical adsorption, this value can reach an astonishing 1932 mg  $g^{-1}$ .<sup>252</sup> In real seawater, the extraction capacities of the adsorbents for uranium are 0.124–28.1 mg g<sup>-1</sup>. However, the result of 28.1 mg g<sup>-1</sup> reported by Kavakli and co-workers<sup>105</sup> was questioned by Abney et al.8 The values obtained from field experiments are obviously lower than those obtained from laboratory-scale tests, and the adsorption capacity is highly correlated with the adsorption time. The uranium adsorption performance of the materials used in field applications needs to be further strengthened for large-scale application. Unlike adsorption capacity, with its theoretical maximum value, the selectivity of various materials is hard to compare. Although the selectivity of materials towards uranium can be characterized by related parameters, such as the selectivity coefficient,132,202,220 it is greatly affected by experimental conditions and is usually only used to compare the selectivity of the materials for different ions in a fixed system, and the coefficients for various materials in different systems are not strictly comparable. Therefore, it is strongly recommended to establish a uniform standardized operating procedure or method to facilitate quantitative comparison of the uranium selectivity of various materials.

# 4. Factors influencing uranium extraction over amidoxime-based materials

The ultimate uranium adsorption performance of amidoximebased adsorbents is determined by the combined effects of many factors. In terms of the adsorbents themselves, their physiochemical properties, including surface area, pore size, grafting ratio, hydrophilicity, chain length, and conformation, may affect their uranium adsorption behavior.144,160,253-255 For example, an increased surface area can theoretically provide more grafting and more active sites,<sup>160</sup> but unless the active sites are available, uranium adsorption cannot be improved. Micropores are detrimental to adsorption, mesopores may affect the amount of adsorption by changing the surface area, while macropores are required for the active sites to contact the tricarbonatouranyl anion.<sup>253</sup> More importantly, uranium recovery by various adsorbents is seriously affected by water chemistry. Both natural seawater and contaminated effluent are complex systems that pose great challenges for the practical application of amidoxime-based adsorbents. In this chapter, four major influential factors, namely pH, temperature, co-existing ions and biofouling, are discussed with the aim of understanding the mechanisms of each influencing factor and providing guidance for the targeted design of the next generation of amidoxime adsorbents.

### 4.1 pH

The effect of pH is often multifaceted. In terms of the adsorbates, uranium speciation is complex as a function of the solution pH, irrespective of the kind of water body (Fig. 14a and b).102,256 This means that uranium ions exist in diverse forms under different pHs, which can alter the electrostatic interactions between uranium and amidoxime groups. In addition, the different uranium species have inconsistent hydration radii, and the accessibility of the functional ligands to uranium may change owing to steric hindrance. However, related research is relatively scarce. It is thus hard to determine the contribution of the radius to the adsorption behavior. In terms of the adsorbents, the H<sup>+</sup> concentration in the system plays a crucial role in the process of protonation/de-protonation of amidoxime groups, as discussed in Section 2.2. This phenomenon could further affect the binding of amidoximated materials to uranium species. As reported, the adsorbent hardly adsorbs uranyl ions when the pH is less than 1.0. However, as the pH was gradually increased and the amidoxime group was deprotonated, the adsorbent adsorption capacity correspondingly increased and reached the optimal value at pH 7.0 to 8.0.26 Besides, the swelling effect of polymeric adsorbents under different pH conditions may be another manifestation of the effect of solution acidity. The conformational change and other potential interactions caused by it could affect the availability of active sites on adsorbents and accelerate or decelerate the uptake kinetics (especially in the seawater system).144 However, few studies have taken this into account and more attention should be paid to it in future research.

In U-spiked systems and natural seawater, uranium species mainly exist in the form of coordinated anions (Fig. 14a). It is reported that  $H^+$  could convert the uranyl complex from tricarbonate-type to bicarbonate-type, which facilitates the exchange reaction between amidoxime groups and carbonate ligands and thus improves the adsorption efficiency.<sup>24</sup> In addition, it is believed that the de-complexation of  $[UO_2(CO_3)_3]^{4-}$  to  $UO_2^{2+}$  may be the rate-determining step for adsorption because

**Table 4** Adsorption performance of various amidoxime-based materials for uranium extraction from real seawater, U-spiked seawater and simulated seawater.<sup>4</sup> No biosorbent is reported to be used for seawater uranium extraction<sup>6</sup>

	Adsorption capacity		
Adsorbent	${ m mg~g^{-1}}$	Conditions	Ref.
Real seawater			
HDPE-g-PAA-co-PAO <sup>a</sup>	0.13	Seawater desalination plant; $m = 4$ g; FR = 80 cm s <sup>-1</sup> ; $T = 21 \pm 2^{\circ}$ C; $t = 15$ d; (SM)	13
AO-UHMWPE <sup>a</sup>	0.25	East China Sea of Xiamen Island; $\sim 3$ below the sea surface; $t = 60$ d; (BP)	164
UHMWPE-g-P $(AO-co-AA)^a$	0.77	Xiamen Island in the East China Sea; FR = 0.2–0.6 m s <sup>-1</sup> ; $t = 60$ d; (BP)	163
AO-phon-DETA-80 <sup>a</sup>	0.789	MSL of PNNL; $t = 20.8$ d; (BE)	30
MAA-co-grafted AO fiber <sup>a</sup>	0.90	15 m below the surface of the sea located about 6 km offshore at MutsuSekine-Hama in	172
		Aomori Prefecture in Japan; $m = 0.5$ g; $t = 20$ d; (SM)	
$PE-g-P(AO-co-MAA)^a$	1.05	MSL of PNNL; FR = 250–300 mL min <sup>-1</sup> ; $T = 20 \pm 2^{\circ}$ °C; $t = 56$ d; (FTCS)	157
AO-UHMWPE-7 <sup>a</sup>	1.41	East China Sea; pH 7.5-7.9; FR = 0.2-0.6 m s <sup>-1</sup> ; $S = 31$ psu; pH 7.5-7.9;	261
		$T = 21.4~^{\circ}\mathrm{C}; \ t = 15~\mathrm{d}; \ (\mathrm{BP})$	
$PE-g-PVBC-g-(PAO-co-PAA)-2^a$	1.56	MSL of PNNL; $m = 60 \text{ mg; FR} = 250-300 \text{ mL min}^{-1}$ ; $T = 20 \pm 2 \text{ °C}$ ; $t = 42 \text{ d; (FTCS)}$	144
P(2DVB-VBC)-2PAN <sup>a</sup>	1.99	ORNL; $m = 10 \pm 3$ mg; $V = 5$ gallons; $t = 27$ d; (BE)	21
$UHMWPE-g-(PAO-co-PAA)^a$	2.3	MSL of PNNL: $T = 20$ °C; $t = 42$ d; (FTCS)	162
PE-g-PVBC-g-(PAO-co-PAA)-	3.02	MSL of PNNL; $m = 60 \text{ mg; FR} = 250-300 \text{ mL min}^{-1}$ ; $T = 20 \pm 2 \text{ °C}$ ; $t = 56 \text{ d; (FTCS)}$	144
b-PAA-2.1 <sup>a</sup>			
AI 11(1 h conditioning) <sup><i>a</i></sup>	3.25	MSL of PNNL; $C_0 = 2.9$ ppb; $S = 30.8$ psu; FR = 250 mL min <sup>-1</sup> ; $T = 20 \pm 2$ °C; $t = 56$ d; (FTCS)	6
PAO-PE <sup>a</sup>	3.3	Sequim Bay; $G_{11} = 3.3$ ppb; $T = 20 \pm 2$ °C; $t = 56$ d; (FTCS)	82
AI 11 (3 h conditioning) <sup><math>a</math></sup>	3.35	MSL of PNNL; $C_{U} = 2.9$ ppb; $S = 30.8$ psu; FR = 250 mL min <sup>-1</sup> ; $T = 20 \pm 2^{\circ}C$ ; $t = 56$ d; (FTCS)	6
AF 1 (3 h conditioning) <sup><math>a</math></sup>	3.41	MSL of PNNL: $G_{11} = 2.9$ ppb; $S = 30.8$ psu; FR = 250 mL min <sup>-1</sup> : $T = 20 \pm 2^{\circ}$ C; $t = 56$ d; (FTCS)	28
AF 1 (1 h conditioning) <sup><i>a</i></sup>	3.83	MSL of PNNI: $C_{i1} = 2.9$ pbb; $S = 30.8$ psu; FR = 250 mL min <sup>-1</sup> ; $T = 20 \pm 2^{\circ}$ °C; $t = 56$ d; (FTCS)	28
DMSO-heat-treated $AF8^{a}$	4.48	MSL of PNNI; FR = 250 mL min <sup>-1</sup> ; $T = 20 \pm 0.2 \text{ °C}$ ; $t = 56 \text{ d}$ ; (FTCS)	123
LCW fiber <sup>a</sup>	6.02	Sequim Bay: $m = \sim 10$ e: FR = 250 mL min <sup>-1</sup> ; $T = 20 \pm 1^{\circ}$ C: $t = 56$ d; (FTCS)	189
PIDO NF <sup>a</sup>	8.7	South China Sea: $V = 5$ T: $r_{t}$ : $t = 56$ d: (FTCS)	191
H-ABP fiber <sup>a</sup>	11.50	Coastal marine areas of Guangdons. China: $G_{i} = 3.1$ mbb: $S = 29.6 \pm 0.4$ psu: pH $B.0 \pm 0.1$ :	166
		FR = 1.5 L min <sup>-1</sup> ; $T = 26.3 \pm 0.5$ °C; $t = 90$ d; (FTCS)	
Amidoximated poly(DPAAm) <sup>a</sup>	13.08	The seashore of MutsuSekine-Hama in Japan; $m = 0.05$ g; FR = 6 mL min <sup>-1</sup> at	105
		$T=25^\circ\mathrm{C};t=1\mathrm{h};\mathrm{(FTCS)}$	
Amidoximated $poly(DPAAm)^a$	27.13	The seashore of MutsuSekine-Hama in Japan; $m = 0.05$ g; FR = 6 mL min <sup>-1</sup> at	105
		T=25 °C; $t=7$ d; (FTCS)	
Amidoximated $poly(DPAAm)^a$	28.1	The seashore of MutsuSekine-Hama in Japan; $m = 0.05$ g; FR $= 6$ mL min <sup>-1</sup> at	105
		$T=25^\circ\mathrm{C};t=1\mathrm{d};\mathrm{(FTCS)}$	
UiO-66-AO <sup>e</sup>	2.68	Bohai in China; $m = 1 \text{ mg}$ ; $V = 1 \text{ L}$ ; $t.t$ ; $t = 3 \text{ d}$ ; (BE)	115
AO/MOF <sup>e</sup>	2.74	Huanghai in China; $m = 40 \text{ mg}$ ; $V = 40 \text{ mL}$ ; $t = 90 \text{ min}$ ; (BE)	225
$POP-oNH_2-AO^e$	4.36	m=5  mg;  V=5  gallons; 100 rpm; r.t.;  t=56  d; (BE)	237
MA@PIDO/Alg sponge <sup>f</sup>	1.87	South China Sea; $m \sim 60 \text{ mg; } V = 5000 \text{ L}$ ; pH 6.5; r.t. $t = 24 \text{ h}$ ; (FTCS)	249
AO-HNTs	5.70	South China Sea, near Haikou city; $m = 10$ mg; $V = 100$ L; pH 8.0; r.t.; $t = 5$ d; (FTCS)	248
AO-HNTs <sup>f</sup>	9.01	South China Sea, near Haikou city; $m = 10 \text{ mg}$ ; $V = 100 \text{ L}$ ; pH 8.0; r.t.; $t = 30 \text{ d}$ ; [FTCS]	248
SMON-PAO <sup>6</sup>	$9.59\pm0.64$	South China Sea, near the Boundary Island; FR = 1 L h <sup>-1</sup> ; pH 8.0; r.t.; $t = 56$ d. (FTCS)	243
$BP-PAO^{f}$	$9.27\pm0.43$	South China sea, near Wanning city, $m = 10$ mg; $V = 100$ L; pH 8.0; $T = 25$ °C.;	250
		t = 56 d; (BE, with natural light)	
BP-PAO <sup>6</sup>	$11.76\pm0.43$	South China Sea, near Wanning city; $m = 10 \text{ mg}$ ; $V = 100 \text{ L}$ ; pH 8.0;	250
		T = 25 °C; $t = 56$ d; (BE, with simulated light)	

Table 4 (Contd.)

	Adsorption capacity		
Adsorbent	${ m mg~g^{-1}}$	Conditions	Ref.
Spiked seawater PP-g-AO3 <sup>a</sup>	0.10	$\text{Bohai Sea; } m = 125 \text{ mg; } V = 500 \text{ mL; } C_{\mathrm{U}} = 1.26 \times 10^{-7} \text{ M; pH 8.0;}$	158
1		T = 298.15  K; t = 16  d; (BE)	
Polymer gel <sup>a</sup>	6.96	Andaman Ocean, Thailand; $C_{\rm U} = 300$ ppb; $T = 25$ °C; $t = 28$ d; (FTCS)	147
Polymer gel <sup>a</sup>	9.64	Andaman Ocean, Thailand; $C_{\mathrm{U}}=$ 840 ppb; $T=$ 25 $^\circ$ C; $t=$ 28 d; (FTCS)	147
Polymer gel <sup>a</sup>	334	Andaman Ocean, Thailand; $C_{\rm U} = 30$ ppm; $T = 25$ °C; $t = 7$ d; (FTCS)	147
Polymer gel <sup>a</sup>	409	Andaman Ocean, Thailand; $C_{\rm U}=2140$ ppm; $T=25$ °C; $t=7$ d; (FTCS)	147
AO/MAA hydrogel <sup>a</sup>	432.41	Andaman ocean, Thailand; $G_{11} = 2245$ ppm; $T = 25$ ° C; $t = 7$ d; (FTCS)	38
PIDO NF <sup>a</sup>	951	South China sea: $m = 15$ mo: $V = 5.1$ ; $nH = 0.6$ , $= 8$ nnm; $FR = 5.1$ ; $nm^{-1}$ ; $t = 24$ h; (FTCS)	191
	100 206	$m_{\rm M} = 0.6  m_{\rm C}^{-1}$ , $m_{\rm B} = 1.7 - 303  {\rm Ke} t - 9.4 h ({\rm Re})$	101
	177:20	$\lim_{m \to \infty} V = 0.05 \text{ m} \cdot 0.11 \text{ m} = 1.000 \text{ m} \cdot 0.11 \text{ m} = 1.010 \text{ m} \cdot 0.110 \text{ m} \cdot 0.110 \text{ m} = 0.010 \text{ m} \cdot 0.010 \text{ m} \cdot 0.010 \text{ m} = 0.010 \text{ m} \cdot 0.010 \text{ m} \cdot 0.010 \text{ m} = 0.010 \text{ m} \cdot 0.010 \text{ m} = 0.010 \text{ m} \cdot 0.010 \text{ m} \cdot 0.010 \text{ m} = 0.010 \text{ m} \cdot 0.010 \text{ m} \cdot 0.010 \text{ m} \cdot 0.010 \text{ m} = 0.010 \text{ m} \cdot 0.0$	000
P-AU/CINFS	246.14	IIIV = 0.0  g L  [P H 8.1] I = 293  K[I = 24  II, (DE)]	289
C-Ami electrode	200-220	Hair Moon Bay, USA; $C_{U} = 1000$ ppm; $t = 1$ d; by physiochemical adsorption (F1CS)	252
C-Ami electrode <sup>2</sup>	1932	Half Moon Bay, USA; $V = 15$ mL; $C_U = 1000$ ppm; $t = 1$ d; by HW-ACE (EA)	252
PPN-6-PAO (3% KOH 80 °C	4.81	Sequim Bay; $m = 10 \text{ mg; } V \sim 1 \text{ L}$ ; 100 rpm; $C_U \sim 80 \text{ ppb}$ ; $t = 42 \text{ d}$ ; (BE)	27
conditioning for $3 \text{ h})^e$			
COF-TpAab-AO <sup>e</sup>	127	$m = 5 \text{ mg; } V = 200 \text{ mL; } C_{\text{U}} = 20 \text{ ppm; } \text{r.t.; } t = 300 \text{ min; } (\text{BE})$	231
MA@PIDO/Alg sponge <sup>f</sup>	291.51	South China sea: $m \sim 60 \text{ me}$ : $V = 5000 \text{ L}$ : $G_{ii} = 5-150 \text{ mm}$ : pH 6.5: r.t. $t = 24 \text{ h}$ . (FTCS)	249
SMON-PAO	$1089.36 \pm 64.31$	South China Sea; $m = 10 \text{ mg}$ ; $V = 5 \text{ L}$ ; $C_U = 8 \text{ ppm}$ ; pH 8.0; r.t.; $t = 36 \text{ h}$ ; (FTCS)	243
Simulated seawater			
AAm/AO hydrogel <sup>a</sup>	$\sim 0.2$	$m \sim 1 \ { m ms}; V = 100 \ { m mL};$ various elements with a concentration 100 times higher than seawater;	38
		$C_{\rm U} = 4 \text{ ppb}; \text{ pH 8.3}; t = 3 \text{ d}; (BE)$	
$PP-g-AO3^{a}$	1.84	$m = 25 \text{ mg; } V = 100 \text{ mL; } C_{\text{U}} = 4.2 \times 10^{-6} \text{ M; } 0.438 \text{ M NaCl; } 2.297 \text{ mM NaHCO}_3; \text{ pH 8.0;}$	158
		T = 298.15  K; t = 4  cl; (BE)	
UHMWPE-g-P(GMA-co-MA)- EDA-AO <sup>a</sup>	1.97	$C_{ m U}=3.6~ m ppb;~S=35~ m psu;~ m FR=25\pm2~ m L~ m min^{-1};~ m pH~8.1\pm0.3,~T=25\pm1~^\circ C;~t=42~ m d;~ m (FTCS)$	161
$PE/PP-g-(PAAc-co-PAO)^{a}$	2.27	$100 \text{ mg; } V = 5 \text{ L; } C_{\rm U} = 330 \text{ µg } \text{L}^{-1}$ ; $100 \text{ rpm; various elements with a concentration 100 times}$	165
,		higher than seawater; pH 8.0; $T=25~^\circ{ m C};~t=1~{ m d};~({ m BE})$	
HDPE-g-PAA-co-PAO <sup>a</sup>	2.51	$m = 0.2 \text{ er} (U_1 = 3.6 \text{ pbb}; S = 35 \text{ psu; FR} = 35 \pm 2 \text{ mL min}^{-1}; T = 25 \pm 2 ^{\circ}C; t = 42 \text{ d; (FTCS)}$	13
AO-UHMWPE-1 <sup>a</sup>	2.93	$C_{11} = 331$ ppb: $S = 35$ psi; FR = $20 \pm 2$ mL min <sup>-1</sup> ; pH 8.1; $T = 25 \pm 2^{\circ}$ °C; $t = 42$ d; (FTCS)	261
	2.97	$m = 0.2 \text{ or } C_{12} = 3.6 \text{ mbr} \cdot S = 3.5 \text{ nsure FR} = 20 + 9 \text{ m} \cdot \text{min}^{-1}$ , $\text{nH} = 0.4 \text{ or } 2.7 + 2.5 + 2.0 \text{ (FTCS)}$	164
	4 54	$m = 0.2 \text{ geV} = 51 \text{ or } (r_1 = 330 \text{ mb}) \cdot S = 35 \text{ mer} \cdot 100 \text{ mm} \cdot M + B + 1 \cdot T = 25 \text{ or } (r_1 = -1) \cdot (r_2 = -2) \cdot (r_1 = -2) \cdot (r_1 = -2) \cdot (r_2 = -2) \cdot (r_1 = -2) \cdot $	164
	101	$m = 0.2 \text{ m/V} = 51.0 \text{ m} \cdot 0.231 \text{ m} \cdot 0.1 \text{ m} \cdot 0.251 \text{ m} \cdot 0.1 \text$	162
D(DDVR-VRC)-DDAN <sup>a</sup>	10.1	$m = 0.25$ , $r = 0.25$ , $Q = 0.21$ , $P(D, 0) = 0.2$ paul put 0.1, 100 tput, $t = 2.0$ , $Q_t = 2.1$ the put $C = 0.6$ for $m = 0.00$ for $r = 0.21$ h, $P(D)$	101
	00	$C_{\rm U} \sim 0$ ppini, proj. $(-24 \text{ II})$ (bc) $(-24 \text{ II})$ (bc) $(-24 \text{ II})$ (bc) $(-24 \text{ II})$ (c)	17
PE-g-PVBU-g-(PAU-c0-PAA)- h-DAA-2-1 <sup>a</sup>	/9.4	$m \sim 15$ mg; $V = 250$ mL; $C_{\rm U} = 6$ ppm; 10 123 ppm Na ; 15 529 ppm Cl ; 140 ppm HCO <sub>3</sub> ; pH 8; $T = 20-25$ °C· $t = 24$ h· (BF)	144
	0.00	$x_{1} = x_{2}$ or $y_{1} = x_{2}$ $x_{1}$ $x_{2}$ $x_{2}$ $x_{3}$ $x_{1}$ $x_{1}$ $x_{1} = x_{2}$ $x_{3}$ $x_{1}$ $x_{1} = x_{2}$ $x_{2}$ $x_{3}$ $x_{1}$ $x_{2}$ $x_{3}$ $x_{2}$ $x_{3}$ $x_{3}$ $x_{1}$ $x_{2}$ $x_{3}$ $x_{3}$ $x_{3}$ $x_{3}$ $x_{1}$ $x_{2}$ $x_{3}$ $x$	1 1 1
FE-g-FVBC-g-[FAO-c0-FAA]-2	80.0	$\Pi \sim 10 \text{ mg}$ , $v = 250 \text{ mg}$ ; $v_0 = 20 \text{ mg}$ ; $10 \text{ 125 ppm}$ are 1 to 329 ppm of 1 140 ppm from 3; pf 8; $T = 20-25 \circ \text{C}$ ; $t = 24 \text{ h}$ ; (BE)	144
$PE-g-PVBC-g-(PAO-co-PAA)-2^a$	174.1	$m \sim 15 \text{ mg; } V = 750 \text{ mL; } C_{\mathrm{U}} = 6 \text{ ppm; } 10\ 123 \text{ ppm Na}^+; 15\ 529 \text{ ppm Cl}^-; 140 \text{ ppm HCO}_3^-; \text{ pH 8};$	144
		$T=20{-}25$ °C; $t=24$ h; (BE)	
$PP-g-Vim^+Br^-AO^a$	$119.76^{h}$	m = 20.0  mg; V = 500  mL; 0.438  M NaCl; 2.297 mM NaHCO <sub>3</sub> ; pH 8.0; $T = 298.15  K; t = 50  h$ , (BE)	156
PE-GMA-AO-HEA $(400\% \text{ of d.g.})^a$	123	$m \sim 15 \text{ mg}; V = 750 \text{ mL}; C_U = 8 \text{ ppm}; 193 \text{ ppm NaHCO}_3; 25 600 \text{ ppm NaCl}; \text{pH} \sim 8; \text{r.t.}; t = 24 \text{ h}; (BE)$	44
PE-GMA-AO-HEA $(1900\% \text{ of } d.g.)^a$	165	$m \sim 15$ mg; $V = 750$ mL; $G_{\rm U} = 8$ ppm; 193 ppm NaHCO <sub>3</sub> ; 25 600 ppm NaCl; pH $\sim 8$ ; r.t.; $t = 24$ h, (BE)	44
AI series adsorbents <sup>a</sup>	171 - 187	$G_{11} = 8$ prom: 103 prom NaHCO <sub>3</sub> : 25 600 prom NGCI: pH $\sim 8$ : $V = 750$ mL: 400 prom: r.t.: $t = 24$ h: (BE)	6
		() (	1

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	Adsorption capacity		
Adsorbent	${ m mg~g^{-1}}$	Conditions	Ref.
AF series adsorhents <sup>a</sup>	170-200	$G_{\rm cr}=8$ nnm: 193 nnm NaHCO-: 25 600 nnm NaCl: nH $\sim 8$ : $V=750$ mL: 400 nnm: r+: $t=24$ h: (BF)	2.8
MC-Ph-AO <sup>b</sup>	$2.0 \pm 2.0$	$mN = 0.1 \text{ or } 1^{-1} C_1 = 5 \text{ transmission constraints}$ $refer = 1.1 \text{ (BE)}$	199
MC-CA <sup>b</sup>	$13.1\pm1.5$	$mN = 0.1 \text{ ev} \Gamma^{-1}$ : $\Gamma_1 = 5 \text{ ppm}$ : 300 rpm: pH 8.2; r.t.: $t = 1$ 1h (BE)	199
$ZS-CP40*-AO^d$	30.4	$m = 50 \text{ ms; } V = 50 \text{ mL; } G_{11} = 17 \text{ mg L}^{-1}; 25.6 \text{ g L}^{-1} \text{ of NaCl; } 193 \text{ mg L}^{-1} \text{ of NaHCO}_3; t = 24 \text{ h; (BE)}$	109
$S-CP40*-AO^d$	51.1	$m = 50 \text{ mg; } V = 50 \text{ mL; } C_{i1} = 17 \text{ mg L}^{-1}; 25.6 \text{ g L}^{-1} \text{ of NaCl; } 193 \text{ mg L}^{-1} \text{ of NaHCO}; t = 24 \text{ h; (BE)}$	109
$S-CP40 *^{E}-AO^{d}$	57.3	$m = 50 \text{ mg; } V = 50 \text{ mL; } C_0 = 17 \text{ mg L}^{-1}; 25.6 \text{ g L}^{-1} \text{ of NaCl; } 193 \text{ mg L}^{-1} \text{ of NaHCO}_3; t = 24 \text{ h; (BE)}$	109
MSA-III <sup>d</sup>	$31.1^g$	$m = 4 \text{ m}_{\mathrm{S}}$ , $V = 40 \text{ mL}$ , $C_{\mathrm{U}} = 5 \text{ ppm}$ ; 300 rpm; pH 8.3 $\pm$ 0.1; r.t.; $t = 1 \text{ h}$ ; (BE)	176
$MSCA-I^d$	$58.1^g$	$m=4\ { m ms}_{\rm S}\ V=40\ { m mL}_{\rm S}\ C_{\rm U}=5\ { m ppm}_{\rm S}\ { m 300\ rpm}_{\rm D}\ { m PH}\ { m 8.3}\pm0.1;\ { m r.t};\ t=1\ { m h}_{\rm S}\ ({ m BE})$	176
$\mathrm{RAF} ext{-}1 ext{-}\mathrm{CH}_2\mathrm{AO}^e$	40	$m = 5 \text{ mg; } V = 200 \text{ mL; } C_{\text{u}} = 7.05 \text{ ppm; } 438 \text{ mM Nacl; } 2.3 \text{ mM NaHCO}_{\text{s}} \text{ r.t.; } t = 25 \text{ h; (BE)}$	137
PPN-6-PAO (3% KOH r.t.	64.1	$m = 13.0 \pm 1.0 \text{ mg; } V = 250 \text{ mL;}$	27
conditioning for 3 h) $^{e}$		$C_{\rm U} = 0.034 \text{ mM}; 438.607 \text{ mM NaCl};$	
)		2.297 mM NaHCO3; DH 7.97; r.t.;	
		t = 24  h. (BE)	
PPN-6-PAO (3% KOH 80 $^\circ\mathrm{C}$	65.2	$m=13.0\pm1.0~{ m mg};$ $V=250~{ m mL};$ $C_{ m U}=0.034~{ m mM};$ $438.607~{ m mM}$ NaCl; 2.297 mM NaHCO3;	27
conditioning for $3 h)^e$		pH 7.97; r.t.; $t = 24 h$ ; (BE)	
POP-0NH2-AO <sup>e</sup>	290	$m = 3 \text{ mg; } V = 400 \text{ mL; } C_{\rm U} \sim 10.3 \text{ ppm; } 25.6 \text{ g } \text{L}^{-1} \text{ NaCl; } 0.198 \text{ g } \text{L}^{-1} \text{ NaClO}_{3} \text{ i.t.; } t = 300 \text{ min; } (\text{BE})$	237
AO-HNTs <sup>f</sup>	456.24	$m = 10 \text{ mg}; V = 1 \text{ L}; C_U = 32 \text{ ppm}; 438.607 \text{ mM NaCl}; 2.297 \text{ mM NaHCO}_3; \text{ pH } 8.0; T = 25 ^{\circ}\text{C};$	248
		$t = 13  ext{ d; (FTCS)}$	
BP-PAO <sup>f</sup>	$760.97\pm32.17$	$m = 10$ mg; $V = 5$ L; $C_0 = 8$ ppm; 438.607 mM NaCl; 2.297 mM NaHCO <sub>3</sub> ; pH 5.0; r.t.; $t = 40$ h; (BE, without simulated sunlight)	250
BP-PAO <sup>6</sup>	$990.60 \pm 37.39$	$m = 10 \text{ mg; } V = 5 \text{ L}; C_{\text{U}} = 8 \text{ ppm}; 438.607 \text{ mM NaCl}; 2.297 \text{ mM NaHCO}_3; \text{pH 5.0; r.t.; } t = 32 \text{ h}, (BE, with simulated sunlight)$	250
<sup>a</sup> Polymeric materials. <sup>b</sup> Carbon-ba <sup>h</sup> Theoretical value calculated by La flow rate; t is the time; $T$ is the tem	sed materials. <sup>c</sup> Biosorbents. <sup>d</sup> agmuir isotherm model. <sup><math>i</math></sup> <i>m</i> is berature; SM is submerged mo	Silica-based materials. <sup><math>e</math></sup> New type of porous materials. <sup><math>f</math></sup> Others. <sup><math>g</math></sup> The value converted from adsorption efficiency the mass of the adsorbents; $S$ is salinity; $V$ is the volume of the solution; $G_{\rm U}$ is the concentration of uranium species; I te; FTCS is flow-through column system; BE is batch experiments; BP is buoy platform; EA is electrochemical adsorption	ncy (%). es; FR is otion.

Table 5 Adsorption performance of various amidoxime-based materials for uranium extraction from pure water and brine solution<sup>*i*</sup>

Adsorbent         mg g <sup>-1</sup> Conditions         ted           Pure swar         Pure swar         Pure swar         Pure swar         Pure swar           Pace spectromAtDPAO <sup>2</sup> 11.09 $m = 15 mg$ , V = 50 mL; $C_0 = 1-25 mg$ L <sup>-1</sup> , pH 5.0; T = 25 °C; t = 36 h, [BE)         167           Pace SpectromAtDPAO <sup>2</sup> 11.09 $m = 15 mg$ ; V = 50 mL; $C_0 = 10^{-1.55} mg$ L <sup>-1</sup> , pH 5.0; T = 298.15 K; t = 10 h, [BE)         158           PACHAL         Pure SpectromAtDPAO <sup>2</sup> 116.94         T = 298.15 K; t = 10 h, [BE)         133           MNN-RQPAO <sup>2</sup> 216.45         m = 10 mg; V = 20 mL; $C_0 = 10.97 m$ ; K = 5 Lm in <sup>1</sup> ; t = 24 h, [PCS)         191           PIDO NP <sup>4</sup> 1167.05 ± 28.45         m = 10 mg; V = 5 mL; $C_0 = 200 pm$ ; t, t = 1 h, [BE)         191           PIDO NP <sup>4</sup> 1167.05 ± 28.45         m = 10 mg; V = 0 mL; $C_0 = 100 pm$ ; L = 1 h, [BE)         191           PIDO NP <sup>4</sup> 1167.05 ± 28.45         m = 10 mg; V = 0 mL; $C_0 = 10.10 mg$ ; L = 1 h, [BE)         191           AD WCNTN <sup>5</sup> G = 2.60         m = 10 mg; V = 0 mL; $C_0 = 10.10 mg$ ; L = 1 h, [BE)         191           AD WCNTN <sup>5</sup> G = 2.60         m = 10 mg; V = 0 mL; $C_0 = 10.10 mg$ ; L = 10 h, [BE]         198           AD WCNTN <sup>5</sup> G = 2.00         m = 10 mg; V = 0 mL; $C_0 = 10.10 mg$ ; L = 10 h, [BE]         10		Adsorption capaci	ty	
Pure saw: <b>Parce saw:</b> <b>Parce saw:</b> <b>Par</b>	Adsorbent	${ m mg~g^{-1}}$	Conditions	Ref.
$\begin{aligned} \begin{array}{ll} \begin{array}{ll} 2166 \\ $	Pure water			
$\begin{aligned} \begin{array}{lll} p_{46} \oplus p_{10}^{10} \operatorname{GGAA}, DDAO^{1} & 11.03 & m - 15 mg V - 30 mL C_{0} - 12^{-1} \oplus p_{11}^{-1} D_{11}^{-1} D_{12}^{-1} \oplus D_{12}^{-1} D_{11}^{-1} D_{12}^{-1} D_$	$P_{A66-q}$ - $P_{GMA}$ - $IDP_{AO}^{a}$	21.09	$m = 15 \text{ mg} \cdot V = 50 \text{ mL} \cdot C_{11} = 1-25 \text{ mg} \text{ L}^{-1} \cdot \text{nH} = 5 \text{ 0} \cdot T = 25 ^{\circ}\text{C} \cdot t = 36 \text{ h} \cdot (\text{RF})$	167
$\begin{aligned} & \text{prog-solution} \\ & \text{prog-solution} \\ & \text{product} \\ & p$	$P_{A66-q}$ - $P_{GMA}$ - $IDP_{AO}^{a}$	41.98	$m = 15 \text{ mg}, V = 50 \text{ mL}; C_{12} = 1.25 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 25^{\circ}\text{ C}; t = 36 \text{ h}; (\text{BE})$	167
$ \begin{aligned} p_{A}, 0 = 1, 0 = 0, 0 = 1, 0 = 0, 0 = $	$PP-\sigma-\Delta\Omega^a$	112 0 <sup>g</sup>	$m = 15 \text{ mg}, v = 30 \text{ mL}, 00 = 1.25 \text{ mg} \text{ L}^2$ , pri 3.0, $T = 35 \text{ C}, t = 30 \text{ m}, (\text{BE})$ $m = 25 \text{ mg} \cdot V = 100 \text{ mL} \cdot C_m = 10-100 \text{ nnm} \cdot \text{ nH} + 8.0 \cdot T = 298.15 \text{ K} \cdot t = 15 \text{ h} \cdot (\text{BE})$	158
UIMMPREPAO" 176.99 <sup>4</sup> m = 0 mg V = 5 ml; $C_0 = 30 - 35$ mg L <sup>-1</sup> pH 4, $b_1 = 208$ K; $t = 24$ h (gB) 33 MNRS8PAO" 216.45 m = 10 mg V = 20 ml, pH 6, $b_1 = 284$ is $K_1 = 20$ k (gF) 113 PIDO NI <sup>4</sup> 860.58 + 1.3.56 m = 15 mg V = 5 i; pH 6, $C_0 = 8$ ppm; R = 5 l min <sup>1</sup> $t = 24$ h (gTCS) 191 MCPh, AO <sup>4</sup> 6.0 $\pm 3.0$ mV = 1 g L <sup>-1</sup> pH 4, $b_1 C_0 = 100$ ppm; R = 5 l min <sup>1</sup> $t = 24$ h (gTCS) 191 MCPh, AO <sup>4</sup> 6.0 $\pm 3.0$ mV = 1 g L <sup>-1</sup> pH 4, $b_1 C_0 = 100$ ppm; R = 6 l min <sup>1</sup> $t = 24$ h (gTCS) 191 MCPh, AO <sup>4</sup> 6.0 $\pm 3.0$ mV = 1 g L <sup>-1</sup> pH 4, $b_1 C_0 = 100$ ppm; R = 6 l min <sup>1</sup> $t = 24$ h (iFCS) 191 AD-MUCNT8 <sup>4</sup> 7.9.8 m = 10 mg V = 10 ml; $C_0 = 10 - 100$ mg L <sup>-1</sup> pH 5, $b_1 T = 298$ K $t = 240$ min; (RE) 98 AD-MUCNT8 <sup>4</sup> 7.9.8 m = 10 mg V = 10 ml; $C_0 = 10 - 100$ mg L <sup>-1</sup> pH 5, $b_1 T = 298$ K $t = 240$ min; (RE) 98 AD-MUCNT8 <sup>4</sup> 9.3.3 m = 10 mg V = 20 ml; pH 4, 5, $T = 298$ K $t = 240$ min; (RE) 203 AD <sub>2</sub> -MUCNT8 <sup>5</sup> 193.6 m = 20 mg V = 20 ml; pH 4, 5, $T = 298$ K is $t = 440$ min; (RE) 198 AD-MUCNT8 <sup>6</sup> 191.6 <sup>6</sup> m = 10 mg V = 20 ml; pH 5, $b_1 T = 298$ K is $t = 440$ min; (RE) 208 AD-MUCNT8 <sup>6</sup> 191.6 <sup>6</sup> m = 10 mg V = 20 ml; pH 5, $b_1 T = 298$ K is $t = 100$ min; (RE) 108 C.2AO-OMC <sup>6</sup> 242.6 <sup>6</sup> m = 10 mg V = 20 ml; pH 5, $b_1 T = 298$ L 5 K is $t = 400$ min; (RE) 108 C.2AO-OMC <sup>6</sup> 242.6 <sup>7</sup> m = 10 mg V = 20 ml; pH 5, $b_1 T = 298$ L 5 K is $t = 200$ min; (RE) 108 C.2AO-OMC <sup>6</sup> 322.6 <sup>7</sup> m = 10 mg V = 20 ml; pH 5, $b_1 T = 298$ L 5 K is $t = 100$ min; (RE) 118 AD+HTC <sup>1</sup> ADM <sup>4</sup> 398.4 <sup>12</sup> m = 10 mg V = 20 ml; pH 5, $b_1 T = 298$ L 5 K is $t = 100$ min; (RE) 108 C.2AO-OMC <sup>6</sup> 242.6 <sup>7</sup> m = 00 mg V = 20 ml; pH 5, $b_1 T = 298$ K is $t = 120$ min; (RE) 107 HTC-AO <sup>4</sup> 10.1 m = 10 mg V = 10 mis; C = 20.0 mg L <sup>-1</sup> ; pH 4, h T = 200 C; t = 6 h (RE) 197 HTC-AO <sup>4</sup> 10.1 m = 10 mg V = 10 mis; C = 20.0 mg L <sup>-1</sup> ; pH 4, h T = 200 C; t = 6 h (RE) 197 HTC-AO <sup>4</sup> 10.1 L 5 m = 00 mg V = 10 mis; C = 15.200 mg L <sup>-1</sup> ; pH 4, h T = 200 min; (RE) 102 HTC-AO <sup>4</sup> 10.1 L 5 m = 00 mg V = 10 mis; C = 15.200 mg L <sup>-1</sup> ; pH 4, h T = 200	PAOBL- <sup>a</sup>	169 49 <sup>g</sup>	$m = 25$ mg, $v = 100$ mL, $C_{\rm H} = 10^{-100}$ ppm, pri 8.0, $T = 250.15$ K, $t = 15$ H, (BE) $m = 17.6$ mg, $V = 200$ mL, $C_{\rm H} = 10^{-3}$ -5 × 10 <sup>-5</sup> M, pH 7, $T = 298.15$ K, $t = 12$ h, (BE)	171
$\begin{aligned} \begin{split} & \text{NNPs} Shot^{O} & 216.45 & \text{m} = 10 \ \text{m}; y = 20 \ \text{m}; y = 16 \ \text{m}; y = 20 \ \text{m}; y = 50 \ \text{m}; y = 50 \ \text{m}; y = 20 \ \text{m}; y = 50 \ \text{m}; y = 20 \ m$	$1 H M W D F F_{A} O^{a}$	176 99 <sup>g</sup>	$m = 5 \text{ mg}; V = 5 \text{ mL}; C_1 = 50-350 \text{ mg} \text{ L}^{-1}; \text{ nH } 4.0; T = 200 \text{ K}; t = 24 \text{ h}; (\text{BE})$	53
$ \begin{array}{c} \mbox{mod} \\ \mbox{mod} \mbox{mod} \\ \mbox{mod} \\ \mbox{mod} \\ \mbox{mod} \\ \mbox{mod} \$	$MND_{C} \oplus DAO^{a}$	216.45	$m = 10 \text{ mg}, V = 20 \text{ mL}, \text{ CU} = 50,550 \text{ mg} \text{ L}^{-1}, \text{ pri 4.0, 1} = 250 \text{ K}, t = 24 \text{ m}, (\text{BE})$ m = 10  mg, V = 20  mL,  nH = 6.0, T = 200, 15  K, t = 20  h, (PE)	122
$ \begin{aligned} & \text{Linco} Nt^{\mu} & \text{Linco} Nt^{\mu} & \text{Linco} State 2 + 1, \text{pl} 1 > 0, \text{c} = 1, \text{pl} 1 > 0, \text{c} = 0 & \text{pprin}; \text{IR} = 1, \text{min}^{-1}; \text{i} = 24 \text{ h}; (\text{ICO}) & \text{Linco} Nt^{-1} \\ & \text{MCC} A^{h} & \text{Linco} A^{h} & $	$PIDO NF^{a}$	210.43 860 58 $\pm$ 13 56	m = 15  mg, V = 20  mL,  pr 0.0, T = 258.13  K, t = 20  n, (BE) $m = 15 \text{ mg}, V = 5 \text{ L}, \text{ nH 8 0; } C = 8 \text{ nnm; FR} = 5 \text{ L} \text{ min}^{-1}; t = 24 \text{ h; (FTCS)}$	101
$ \begin{array}{c} 100 - 0.6 \ dots \\ 100 -$	PIDO NE <sup>a</sup>	$1197.05 \pm 29.45$	$m = 15 \text{ mg}, V = 5 \text{ L}, \text{ pH } 5.0, \text{ C}_{\text{U}} = 0 \text{ ppm}, \text{ FR} = 5 \text{ L} \text{ min}^{-1}, t = 24 \text{ h}, (\text{FICS})$	101
$ \begin{aligned} & \text{metric} &$	$MC-Pb-AO^{b}$	$1187.03 \pm 28.43$	m = 15  mg, v = 5  L,  pr 7.0,  CU = 6  ppm,  rK = 5  L  mm - 1, t = 24  m, (F1C5) $m/V = 1 \text{ g L}^{-1}, \text{ pH} 4.0; C = 100 \text{ ppm}; \text{ rt}; t = 1 \text{ h}; (\text{PE})$	191
$ \begin{aligned} & Access & Acces$	MC-FIFAO	$0.0 \pm 3.0$	$m/V = 1 \text{ g L}^{-1}$ , pH 4.0, $C_U = 100 \text{ ppm}$ , r.t., $t = 1 \text{ h}$ , (BE)	199
$ \begin{aligned} & \text{ACMAYCATS}^{4} & \text{O}, \text{S}^{-1} & \text{ID}, \text{ID}, \text{ID}^{-1} & \text{ID}, \text{ID}^{-1} & \text{ID}$	$AO MWCNITa^b$	$13.0 \pm 0.0$	$m_i V = 1 \text{ g L}^2$ , pri 4.0, CU = 100 ppin, 1.1., $t = 1 \text{ in}$ , (BE) $m = 10 \text{ mm} V = 10 \text{ ml} \cdot C_2 = 10 100 \text{ mm} \text{ J}^{-1}$ , pH 5 0, $T = 200 \text{ V}$ , $t = 240 \text{ min}$ (BE)	199
$\begin{aligned} & \text{ACMAYCATS}^{13} & \text{72.5} & \text{fm} = 10 \ \text{mg}, t = 10 \ \text{mi}, t = 10 \ \text{mo}, t = 30 \ \text{mo}, t = 20 \ \text{mo}, t = 10 \ \text{mo}, t = 50 \ \text{mo}, t = 20 \ \text{mo}, t = 10 \ \text{mo}, t = 50 \ \text{mo}, t = 40 \ \text{mo}, t = 10 \ \text{mo}, t = 50 \ \text{mo}, t = 40 \ \text{mo}, t = 10 \ \text{mo}, t = 50 \ \text{mo}, t = 40 \ \text{mo}, t = 10 \ \text{mo}, t = 50 \ \text{mo}, t = 10 \ \text{mo}, t = 50 \ \text{mo}, t = 10 \ \text{mo}, t = 30 \ \text{mo}, t = 10 \ \text{mo}, t = 30 \ \text{mo}, t = 10 \ \text{mo}, t = 30 \ \text{mo}, t = 10 \ \text{mo}, t = 10$	AO-WWCNTs $AO$ MWCNTs <sup>b</sup>	70.9	$m = 10 \text{ mg}; V = 10 \text{ mL}; C_{\rm U} = 10-100 \text{ mg L}^{-1}; \text{ pH 5.0}; T = 298 \text{ K}; t = 240 \text{ mm}; (\text{BE})$ $m = 10 \text{ mg}; V = 10 \text{ mL}; C_{\rm U} = 10, 100 \text{ mg L}^{-1}; \text{ pH 5.0}; T = 208 \text{ K}; t = 240 \text{ mm}; (\text{BE})$	90
$ \begin{aligned} & \text{ACMWARIS} & \text{So.5.} & \text{m} = 0 \ \text{mg} \ Y = 50 \ \text{mL}; \ \text{C} = 10 - 100 \ \text{m} \ U_1 + 101 - 301 \ \text{K}; \ t = 240 \ \text{mm} \ (\text{De}) & \text{303} \\ & \text{AOg}_{2}\text{MWCNTs}^{4} & \text{10} \ \text{mg} \ Y = 30 \ \text{mL}; \ \text{pH} \ \text{Ao}; \ T = 298 \ \text{K}; \ t = 240 \ \text{mm} \ (\text{De}) & \text{303} \\ & \text{AOg}_{2}\text{MWCNTs}^{4} & \text{110} \ \text{mg} \ Y = 30 \ \text{mL}; \ \text{pH} \ \text{Ao}; \ T = 298 \ \text{K}; \ t = 240 \ \text{mm} \ (\text{BE}) & \text{110} \\ & \text{AOg}_{2}\text{MWCNTs}^{4} & \text{110} \ \text{GeV} & \text{30} \ \text{mL}; \ \text{pH} \ \text{Aot}; \ T = 298 \ \text{K}; \ t = 340 \ \text{m} \ (\text{BE}) & \text{110} \\ & \text{303} \ \text{AOg}_{2}\text{MWCNTs}^{4} & \text{110} \ \text{GeV} & \text{30} \ \text{mL}; \ \text{pH} \ \text{Aot}; \ T = 298 \ \text{K}; \ t = 30 \ \text{m} \ \text{m}; \ \text{BE}) & \text{110} \\ & \text{AOH}^{4} & \text{308} \ \text{A1}^{4} & \text{m} = 10 \ \text{mg}; \ V = 50 \ \text{mL}; \ \text{GeV} \ \text{AO} \ \text{mm}; \ \text{BE}) & \text{110} \\ & \text{AOH}^{4} & \text{398} \ \text{A1}^{4} & \text{m} = 10 \ \text{mg}; \ V = 20 \ \text{mL}; \ \text{pH} \ \text{Ao}; \ T = 298 \ \text{K}; \ t = 90 \ \text{min}; \ (\text{BE}) & \text{110} \\ & \text{AOH}^{4} & \text{398} \ \text{A1}^{4} & \text{m} = 10 \ \text{mg}; \ V = 20 \ \text{mL}; \ \text{pH} \ \text{Ao}; \ T = 290 \ \text{mL}; \ \text{T} \ \text{H} \ \text{AoH} \ \text{AO}; \ T = 298 \ \text{K}; \ t = 120 \ \text{min}; \ (\text{BE}) & \text{110} \\ & \text{AOH}^{4} & \text{AOH}^{2} & \text{20} \ \text{mL}; \ \text{pH} \ \text{Ao}; \ T = 298 \ \text{K}; \ t = 120 \ \text{min}; \ (\text{BE}) & \text{110} \\ & \text{P(AO)}_{2} \ \text{CTSMT}^{4} & \text{40} \ \text{AO}^{2} & \text{m} = 0.023 \ \text{gV} \ \ 125 \ \text{mL}; \ \text{GO} \ \text{AO} \ \text{AO} \ \ \text{m} \ 1100 \ \text{mg}; \ V = 125 \ \text{mL}; \ \text{AO} \ \text{AO} \ \text{m} \ \text{m} \ 110 \ \text{m}; \ \text{AO} \ \text{AO} \ \text{m} \ \text{AO} \ \text{AO} \ \text{m} \ \text{m} \ \text{AO} \ \text{AO} \ \text{m} \ \text{AO} \ \text{AO} \ \text{m} \ \text{m} \ \text{AO} \ \text{AO} \ \text{AO} \ \text{m} \ \text{m} \ \text{AO} \ \text{AO} \ \text{m} \ \text{m} \ \text{AO} \ \text{AO} \ \text{m} \ \text{AO} \ \text{AO} \ \text{AO} \ \text{AO} \ \text{m} \ \text{AO} \ \text{AO}$	AO-MWCNTs $AO$ MWCNTs $b$	/9.8	$m = 10 \text{ mg; } V = 10 \text{ mL; } C_{\text{U}} = 10{-}100 \text{ mg L}^{-1}; \text{ pH 5.0; } T = 308 \text{ K; } t = 240 \text{ mm; (BE)}$	98
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$mCO BAO^b$	93.3	$m = 10 \text{ mg}; v = 10 \text{ mL}; C_U = 10-100 \text{ mg L}$ ; pH 5.0; $I = 518 \text{ K}; t = 240 \text{ mm}; (BE)$	98
$ \begin{array}{cccc} AC S^{AC} & AC \\ AC \\ AC & AC \\ AC \\ AC \\ AC \\ AC$	$\frac{1}{100} - \frac{1}{100} = \frac{1}$	89.9°	m = 20  mg; v = 50  mL; pH 6.0; T = 298  K; t = 24  n; (BE)	203
ALEYAD         101,0° $m = 10 \text{ mg}; V = 30 \text{ m1}; \text{ pri} 30; T = 293 = 0.5, V_1 = 498 \text{ m1}; \text{ (pr)}$ 288           0.2AO-OMC <sup>6</sup> 322,4 <sup>6</sup> $m = 10 \text{ mg}; V = 50 \text{ m1}; C_0 = 50 \text{ mg}; PI = 30; T = 293.55 K; t = 90 \text{ min}; (BE)         100           0.ACH6         322,46         m = 10 \text{ mg}; V = 20 \text{ m1}; PI = 60; C_1 = 293.55 K; t = 90 \text{ min}; (BE)         140           AOHTC6         724.6         m = 10 \text{ mg}; V = 20 \text{ m1}; PI = 60; C_1 = 293.55 K; t = 20 \text{ min}; (BE)         195           GO-DMAO6         935         m = 10 \text{ mg}; V = 20 \text{ m1}; PI = 60, T = 500 \text{ mg}; T = 50; T = 298.15 K; t = 120 \text{ min}; (BE)         195           GO-DMAO6         935         m = 10 \text{ mg}; V = 20 \text{ m1}; PI = 60, T = 300 \text{ mg}; T^{-1}; PI 4.5, T = 298.15 K; t = 120 \text{ min}; (BE)         100           P(AO)2CTSIBT4         49.096         m = 0.025 \text{ g}; V = 125 \text{ m1}; C_0 = 25-300 \text{ mg}; L^{-1}; PI 4.5, T = 30 °C; t = 60 \text{ min}; (BE)         110           P(AO)2CTSIBT4         165.096         m = 0.025 \text{ g}; V = 125 \text{ m1}; C_0 = 15-200 \text{ mg}; L^{-1}; PI 4.5, T = 30 °C; t = 60 \text{ min}; (BE)         110           P(AO)2CTSIBT4         165.096         m = 0.025 \text{ g}; V = 125 \text{ m1}; C_0 = 15-200 \text{ mg}; L^{-1}; PI 4.5, T = 20 °C; t = 60 \text{ min}; (BE)         110           P(AO)2CTSIBT4         175.56         m = 20 \text{ mg}; V = 100 \text{ m1}; C_0 = 15-200 \text{ mg}; L^{-1}; PI 4.5, 0; T = 24 °C; t = 15, (BE)         $	AO-g-MWCN1S	$1/6^{\circ}$	m = 20  mg; v = 20  mL; pH  4.5; T = 298.15  K; t = 240  min; (BE)	146
$ \begin{array}{ccc} 0.2AO-OMC & 245 & m = 10 \ mg; \ V = 50 \ mL; \ C_{1} = 50 \ mg; \ P1 = 50, \ 1 = 296 \ 1 S, \ t = 90 \ mn; \ (EE) & 106 \ AGH^{\circ} & 398.41^{\circ} & m = 10 \ mg; \ V = 50 \ mL; \ D_{1} = 50, \ 1 S, \ t = 90 \ mn; \ (EE) & 106 \ AGH^{\circ} & 398.41^{\circ} & m = 10 \ mg; \ V = 50 \ mL; \ D_{1} = 20, \ 1 S, \ SL = 120 \ mn; \ (EE) & 108 \ AGH^{\circ} & 398.41^{\circ} & m = 10 \ mg; \ V = 20 \ mL; \ C_{1} = 20 \ mL; \ D_{1} \ H = 0.5 \ SL = 120 \ mn; \ (EE) & 118 \ AO+HTC-DANN^{\circ} & 93^{\circ} & m = 10 \ mg; \ V = 20 \ mL; \ C_{1} = 300 \ mg; \ L^{-1}, \ p14 \ 4.51, \ T = 235, \ SL = 6 \ h; \ (EE) & 197 \ HTC-AO^{\circ} & 935 & m = 10 \ mg; \ V = 100 \ mg; \ V = 100 \ mg; \ L^{-1}, \ p14 \ 4.51, \ T = 235, \ SL = 6 \ h; \ (EE) & 120 \ P(AO)g \ CTS/BT^{\circ} & 190.09^{\circ} & m = 0.025 \ gV = 12.5 \ mL; \ C_{0} = 305 \ mg; \ L^{-1}, \ p14 \ 8.0, \ T = 30, \ C_{1} \ t = 60 \ mn; \ (EE) & 110 \ P(AO)g \ CTS/BT^{\circ} & 163.09^{\circ} & m = 0.025 \ gV = 12.5 \ mL; \ C_{0} = 25-300 \ mg; \ L^{-1}, \ p14 \ 8.0, \ T = 30, \ C_{1} \ t = 60 \ mn; \ (EE) & 110 \ P(AO)g \ CTS/BT^{\circ} & 105.09^{\circ} & m = 0.025 \ gV = 12.5 \ mL; \ C_{0} = 35-300 \ mg; \ L^{-1}, \ p14 \ 8.0, \ T = 30, \ C_{1} \ t = 60 \ mn; \ (EE) & 110 \ P(AO)g \ CTS/BT^{\circ} & 105.05^{\circ} & m = 0.025 \ gV = 12.5 \ mL; \ C_{0} = 25-300 \ mg; \ L^{-1}, \ p14 \ 8.0, \ T = 30, \ C_{1} \ t = 60 \ mn; \ (EE) & 110 \ P(AO)g \ CTS/BT^{\circ} & 105.05^{\circ} & m = 0.025 \ gV = 12.5 \ mL; \ C_{0} = 15-300 \ mg; \ L^{-1}, \ p14 \ 8.0, \ T = 30, \ C_{1} \ t = 60 \ mn; \ (EE) & 110 \ P(AO)g \ CTS/BT^{\circ} & 105.05^{\circ} & m = 0.00 \ mg; \ V = 100 \ mL; \ C_{0} = 15-300 \ mg; \ L^{-1}, \ p15 \ 8.0 \ T = 208 \ S^{\circ} \ L^{\circ} \$	ACFS-AU	191.6	$m = 10 \text{ mg}; v = 30 \text{ mL}; \text{ pH } 5.0; T = 298 \pm 0.5 \text{ K}; t = 48 \text{ n}; (\text{BE})$	288
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	0.2AO-OMC	245	$m = 10 \text{ mg}; v = 50 \text{ mL}; C_U = 50 \text{ mg}; \text{pH} 5.0; T = 298.15 \text{ K}; t = 90 \text{ min}; (BE)$	108
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	0.2AO-OMC	322.6	m = 10  mg; V = 50  mL;  pH  5.0; T = 298.15  K; t = 90  min; (BE)	108
$ \begin{array}{cccc} AdvAHCC 14AAN' & 49.5^{*} & m = 10 mg V = 25 mL; C_{U} = 20-300 mg L ^{-1} gH 4.3; T = 29 a k; T = 120 mL; (BE) & 118 GV = 10 ML; (BE) & m = 10 mg V = 10 mL; C_{U} = 500 mg L ^{-1} gH 4.3; T = 29 a k; T = 120 mL; (BE) & 195 GO - MAAO^{0} & 935 & m = 10 mg V = 10 mL; C_{U} = 500 mg L ^{-1} gH 4.3; T = 298 k; T = 120 mL; (BE) & 197 MCAO^{0} & 1021.6 & m = 10 mg V = 150 mL; C_{U} = 300 mg L ^{-1} gH 4.3; T = 298 k; T = 100 mL; (BE) & 100 P(AO)_{5}CCTS/BT' & 49.09^{5} & m = 0.025 g; V = 12.5 mL; GH 8.0; C_{U} = 100 mg L ^{-1} ; T = 298 k; T = 60 mL; (BE) & 110 P(AO)_{5}CCTS/BT' & 165.09' & m = 0.025 g; V = 12.5 mL; GU = 25-300 mg L ^{-1}; PH 8.0; T = 30 °C; t = 60 mL; (BE) & 110 P(AO)_{5}CCTS/BT' & 208.96' & m = 0.025 g; V = 12.5 mL; GU = 25-300 mg L ^{-1}; PH 8.0; T = 30 °C; t = 60 mL; (BE) & 110 P(AO)_{5}CCTS/BT' & 208.96' & m = 0.025 g; V = 12.5 mL; GU = 25-300 mg L ^{-1}; PH 5.0; T = 20 s L ^{+1}; C = 12 h; (BE) & 110 P(AO)_{5}CCTS/BT' & 208.96' & m = 0.025 g; V = 12.5 mL; GU = 25-300 mg L ^{-1}; PH 5.0; T = 20 s L ^{+1}; C = 12 h; (BE) & 100 P(AO)_{5}CCTS/BT' & 208.96' & m = 0.025 g; V = 12.5 mL; GU = 25-300 mg L ^{-1}; PH 5.0; 150 rm; T = 20 s L ^{+1}; C = 12 h; (BE) & 100 P(AO)_{5}CCTS/BT' & 120 P(AO)_{5}CTS/BT' & m = 20 mg V = 20 mL; C_{0} = 15-300 mg L ^{-1}; PH 5.0; 150 rm; T = 20 s L ^{+1}; C = 12 h; (BE) & 207 P(AO)_{5}CCTS/BT' & 100 P(A)_{5}CTS/BT' & m > 0.02 g L ^{-1}; C = 15-300 mg L ^{-1}; PH 4.0; 150 rm; T = 20 s L ^{+1}; C = 12 h; (BE) & 100 P(C)_{5} P(A)_{5}P($	AGH <sup>2</sup>	398.41 <sup>s</sup>	m = 10  mg; V = 20  mL;  pH 6.0;  r.t.; t = 6  h; (BE)	140
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	AO-HTC-DAMN <sup>o</sup>	4938	$m = 10 \text{ mg}; V = 25 \text{ mL}; C_U = 20-300 \text{ mg L}^{-1}; \text{ pH } 4.3; T = 293 \text{ K}; t = 120 \text{ min}; (BE)$	118
	AO-HTC	/24.6	m = 10  mg; V = 10  mL;  pH  5.0; T = 308.15  K; t = 240  min; (BE)	195
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	GO-DM-AO <sup>o</sup>	935	$m = 10 \text{ mg}; V = 20 \text{ mL}; C_{\rm U} = 500 \text{ mg L}^{-1}; \text{ pH } 8.04 \pm 0.01; T = 25 \text{ °C}; t = 6 \text{ h}; (BE)$	197
$\begin{split} & \text{PAO}_{2}\text{CTS/BT}^{-} & 49.09^{\circ} & m = 0.025 \text{ g}; V = 12.5 \text{ mL}; D = 8.0; C_{u} = 100 \text{ mL}^{-1}; P1 = 308 \text{ k}; t = 60 \text{ min}; (BE) & 110 \\ & \text{PAO}_{2}\text{CTS/BT}^{-} & 165.09^{i} & m = 0.025 \text{ g}; V = 12.5 \text{ mL}; C_{u} = 25-300 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 8.0}; T = 40^{\circ}; C; t = 60 \text{ min}; (BE) & 110 \\ & \text{PAO}_{2}\text{CTS/BT}^{-} & 208.96^{i} & m = 0.025 \text{ g}; V = 12.5 \text{ mL}; C_{u} = 25-300 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 8.0}; T = 30^{\circ}; C; t = 60 \text{ min}; (BE) & 110 \\ & \text{PAO}_{2}\text{CTS/BT}^{-} & 208.96^{i} & m = 0.025 \text{ g}; V = 12.5 \text{ mL}; C_{u} = 25-300 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 8.0}; T = 30^{\circ}; C; t = 60 \text{ min}; (BE) & 211 \\ & \text{MOO}_{2}\text{ACO}^{-} & 53.35^{\circ} & m = 100 \text{ mg}; V = 100 \text{ mL}; C_{u} = 15-220 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 8.0}; T = 30^{\circ}; C; t = 5 \text{ h}; (BE) & 207 \\ & \text{AM-GC-H}^{i} & 357^{h} & \text{m} > 0.2 \text{ g} \text{ L}^{-1}; C_{u} = 15-300 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 4.0}; 150 \text{ rpm}; \text{ p1} \text{ 6.7}; t = 2 \text{ h}; (BE) & 207 \\ & \text{AM-MG-CH}^{i} & 372.95^{6h} & m/V = 0.2 \text{ g} \text{ L}^{-1}; C_{u} = 15-300 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 4.0}; 150 \text{ rpm}; T = 20 \pm 1^{\circ}; C; t = 40 \text{ h}; (BE) & 106 \\ & \text{Am-Mor-CH}^{i} & 36.8 & m = 50 \text{ mg}; V = 5 \text{ mL}; C_{u} = 6.2 \text{ ond mg} \text{ L}^{-1}; \text{ p14} \text{ 5.0}; T = 25 \text{ m}; C; t = 2.0 \text{ h}; (BE) & 211 \\ & \text{agal cells}^{i} & \text{call}^{i} & \text{m} = 0 \text{ mg}; V = 100 \text{ mL}; C_{u} = 0.2 \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 5.0}; \text{ 70} = 25^{\circ}; t = 2.0 \text{ h}; (BE) & 129 \\ & \text{AOO-SBA-15}^{d} & \text{call}^{i} & \text{m} = 5 \text{ mg}; V = 5 \text{ mL}; C_{u} = 50 \text{ cond} \text{ mg} \text{ L}^{-1}; \text{ p14} \text{ 5.0}; T = 25^{\circ}; C; t = 2.0 \text{ m}; (BE) & 220 \\ & \text{AMD-MCM-4}^{i} & 493.6 & m = 10 \text{ mg}; V = 50 \text{ m1}; 150 \text{ rm}; P = 50; \text{ m}; 25^{\circ}; C; t = 2.0 \text{ m}; (BE) & 221 \\ & \text{AOO-SBA-15}^{d} & \text{call}^{i} & \text{m}; 19 \text{ H}; 0, 0; T = 25^{\circ}; C; t = 2.0 \text{ m}; (BE) & 222 \\ & \text{AOO-SBA-15}^{d} & \text{call}^{i} & \text{m}; 0 \text{ m}; 1; \text{ p14} \text{ 5.0}; T = 25^{\circ}; C; t = 2.0 \text{ m}; (BE) & 222 \\ & AO$	HTC-AO <sup>2</sup>	1021.6	$m = 10 \text{ mg}; V = 150 \text{ mL}; C_{\rm U} = 300 \text{ mg L}^{-1}; \text{ pH } 4.5; T = 298.15 \text{ K}; t = 120 \text{ min}; (BE)$	202
$\begin{aligned} & P(AO)_{2}cCTS/BT^{*} & 143.59^{*} & m = 0.025 \text{ gf} V = 12.5 \text{ mL}; C_{2} = 25-300 \text{ mg} L^{-1}; \text{pH} 8.0; T = 40^{-1}C; t = 60 \text{ min}; (BE) & 110 \\ & P(AO)_{2}cCTS/BT^{*} & 208.96^{t} & m = 0.025 \text{ gf} V = 12.5 \text{ mL}; C_{2} = 25-300 \text{ mg} L^{-1}; \text{pH} 8.0; T = 40^{-1}C; t = 60 \text{ min}; (BE) & 110 \\ & Wool-gcAO^{*} & 59.35 & m = 20 \text{ mg}; V = 12.5 \text{ mL}; C_{2} = 25-300 \text{ mg} L^{-1}; \text{pH} 8.0; T = 40^{-1}C; t = 60 \text{ min}; (BE) & 110 \\ & Wool-gcAO^{*} & 59.35 & m = 20 \text{ mg}; V = 12.5 \text{ mL}; C_{0} = 15-220 \text{ mg} L^{-1}; \text{pH} 5.0; T = 30^{-1}C; t = 60 \text{ min}; (BE) & 212 \\ & MAOc-hitosan^{c} & 117.65^{d} & m = 20 \text{ mg}; V = 20 \text{ mL}; C_{0} = 10-600 \text{ mg} L^{-1}; \text{ pH} 5.0; T = 20^{-1}L^{-1}C; t = 21^{+1}C; t = $	P(AO)-g-CTS/BT	49.09 <sup>5</sup>	$m = 0.025 \text{ g}; V = 12.5 \text{ mL}; \text{ pH } 8.0; C_{\text{U}} = 100 \text{ mg L}^{-1}; T = 298 \text{ K}; t = 60 \text{ min}; (\text{BE})$	110
$\begin{split} &  AO _{2}cCTS/BT^{-} & 165.09^{\circ} & m = 0.025 \text{ g} V = 12.5 \text{ m1}; (C_{0} = 25-300 \text{ mg } L^{-}; \text{pH } 8.0; T = 50^{\circ} \text{C}; t = 60 \text{ min}; (BE) & 110 \\ & \text{Wool-g-AO}^{\circ} & 59.35^{\circ} & m = 0.025 \text{ g}; V = 12.5 \text{ m1}; (C_{0} = 25-300 \text{ mg } L^{-}; \text{pH } 8.0; T = 50^{\circ} \text{C}; t = 60 \text{ min}; (BE) & 212 \\ & \text{MAO-chitosan}^{\circ} & 117.65^{\circ} & m = 20 \text{ mg}; V = 20 \text{ m1}; C_{0} = 10-600 \text{ mg } L^{-}; \text{ pH } 5.0; T = 30^{\circ} \text{C}; t = 60 \text{ min}; (BE) & 212 \\ & \text{MAO-CH}^{\circ} & 126.9^{\circ} & m = 5 \text{ mg}; V = 5 \text{ m1}; C_{0} = 51-300 \text{ mg } L^{-}; \text{ pH } 4.0; 150 \text{ rpm}; T = 20 \pm 1^{\circ} \text{C}; t = 48 \text{ h}; (BE) & 106 \\ & \text{AM-MG-CH}^{\circ} & 372.95^{\circ}h & m/V = 0.2 \text{ g} L^{-1}; C_{0} = 15-300 \text{ mg } L^{-1}; \text{ pH } 4.0; 150 \text{ rpm}; T = 20 \pm 1^{\circ} \text{C}; t = 48 \text{ h}; (BE) & 106 \\ & \text{Am-MG-CH}^{\circ} & 372.95^{\circ}h & m/V = 0.2 \text{ g} L^{-1}; C_{0} = 40 \text{ mg } L^{-1}; \text{ pH } 4.0; 150 \text{ rpm}; T = 20 \pm 1^{\circ} \text{C}; t = 48 \text{ h}; (BE) & 106 \\ & \text{Am-MG-CH}^{\circ} & 372.95^{\circ}h & m/V = 0.2 \text{ g} L^{-1}; C_{0} = 40 \text{ mg } L^{-1}; \text{ pH } 5.0; 300 \text{ rpm}; T = 20 \pm 1^{\circ} \text{ C}; t = 48 \text{ h}; (BE) & 106 \\ & \text{Am-Mo-CH}^{\circ} & 584.60 & m/V = 0.05 \text{ g} L^{-1}; C_{0} = 40 \text{ mg } L^{-1}; \text{ pH } 5.0; 300 \text{ rpm}; T = 20 \pm 1^{\circ} \text{ C}; t = 20 \text{ h}; (BE) & 211 \\ & \text{algal cells}^{\circ} & m = 5 \text{ mg}; V = 5 \text{ mL}; C_{0} = 50-200 \text{ mg } L^{-1}; \text{ pH } 5.0; 300 \text{ rpm}; \\ & T = 298 \text{ K}; t = 3 \text{ h}; (BE) & 220 \\ & \text{AMD-MCM-41}^{\circ} & 105 \pm 3^{\circ} \text{ m} = 10 \text{ mg}; V = 5 \text{ m}; L^{\circ} \text{ m} = 0 \text{ mg}; V = 5 \text{ m}; C_{0} = 100 \text{ mg } L^{-1}; \text{ pH } 6.0; T = 25^{\circ} \text{ C}; t = 24 \text{ m}; (BE) & 222 \\ & \text{AAG} \otimes BA.15^{\circ} & \text{fm} = 10 \text{ mg}; V = 0.1 \text{ g}; L^{-1}; \text{ pH } 6.0; T = 25^{\circ} \text{ C}; t = 240 \text{ min}; (BE) & 222 \\ & \text{AO-HSBA.15^{\circ}} & \text{fm} = 0 \text{ mg}; V = 20 \text{ mL}; C_{0} = 500 \text{ mg } L^{-1}; \text{ pH } 8.00; T = 25^{\circ} \text{ C}; t = 24 \text{ h}; (BE) & 222 \\ & \text{AO-BSBA.15^{\circ}} & \text{fm} 10 \text{ mg}; V = 20 \text{ mL}; C_{0} = 500 \text{ mg } L^{-1}; \text{ pH } 8.00; T = 25^{\circ} \text{ C}; t = 24 \text{ h}; (BE) & 221 \\ & \text{AMD-MCM-41}^{\circ} $	P(AO)-g-CTS/BT <sup>c</sup>	$143.59^{i}$	$m = 0.025 \text{ g}; V = 12.5 \text{ mL}; C_{\rm U} = 25-300 \text{ mg L}^{-1}; \text{ pH 8.0}; T = 30 \text{ °C}; t = 60 \text{ min}; (BE)$	110
$\begin{split} P(AO)_{\mathcal{Z}} CTS/BT^* & 208.96^{\circ} & m = 0.025 \text{ g}; V = 12.5 \text{ m1}; C_{U} = 25-300 \text{ mg} \text{ L}; p \text{H } 8.0; T = 50  ^\circ\text{C}; t = 60 \text{ min}; (\text{BE}) & 110 \text{ mol}; C_{U} = (100 \text{ mg}; C_{U} = 15-220 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 30  ^\circ\text{C}; t = 60 \text{ min}; (\text{BE}) & 212 \text{ MAO-chitosan}^{\circ} & 117.63^{\beta'} & m = 20 \text{ mg}; V = 20 \text{ mL}; C_{U} = 15-220 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 25 \text{ m}^{\circ}; t = 61 \text{ min}; (\text{BE}) & 212 \text{ MAO-chitosan}^{\circ} & 126.9^{\beta'} & m = 20 \text{ mg}; V = 20 \text{ mL}; C_{U} = 15-300 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 25 \pm 1  ^\circ\text{C}; t = 24 \text{ h}; (\text{BE}) & 207 \text{ M}-MG-CH^{\circ} & 357^{h} & m/V = 0.2 \text{ g} \text{ L}^{-1}; C_{U} = 15-300 \text{ mg} \text{ L}^{-1}; \text{ pH } 4.0; 150 \text{ rpm}; T = 20 \pm 1  ^\circ\text{C}; t = 48 \text{ h}; (\text{BE}) & 106 \text{ Am-MG-CH}^{\circ} & 372.95^{\beta h} & m/V = 0.2 \text{ g} \text{ L}^{-1}; C_{U} = 15-300 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 25 \pm 1  ^\circ\text{C}; t = 2.0 \text{ h}; (\text{BE}) & 211 \text{ algal cells}^{\circ} & m = 50 \text{ mg}; V = 20 \text{ mL}; C_{U} = 6.2 \text{ no mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 25 \pm 1  ^\circ\text{C}; t = 2.0 \text{ h}; (\text{BE}) & 344 \text{ AmAA}^{\circ} & 54.60 & m/V = 0.05 \text{ g} \text{ L}^{-1}; C_{U} = 100 \text{ mL}; C_{U} = 0.2 \text{ -0.8 mg} \text{ L}^{-1}; \text{ pH } 5.0; 300 \text{ rpm}; & 208 \text{ MS}^{-15} & m = 5 \text{ mg}; V = 5 \text{ mL}; C_{U} = 50.00 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; 300 \text{ rpm}; & 208 \text{ MS}^{-15} & \text{m}; (\text{BE}) & 220 \text{ MMD-MCM-41}^{4} & 493.6 & m = 10 \text{ mg}; V = 5.0 \text{ mL}; 150 \text{ rpm}; \text{ pH } 5.0; T = 23  ^\circ\text{C}; t = 24 \text{ min}; (\text{BE}) & 222 \text{ MO-SBA-15}^{4} & 601 & m/V = 0.1 \text{ g} \text{ L}^{-1}; \text{ C}^{-1} = 100 \text{ mg} \text{ L}^{-1}; \text{ pH } 5.0; T = 32  ^\circ\text{S}; t = 24 \text{ min}; (\text{BE}) & 222 \text{ MO-SBA-15}^{4} & 601 & m/V = 0.1 \text{ g} \text{ L}^{-1}; \text{ pH } 6.0; T = 25  ^\circ\text{ C}; t = 24 \text{ min}; (\text{BE}) & 222 \text{ MO-SBA-15}^{4} & 601 & m/V = 0.1 \text{ g} \text{ L}^{-1}; \text{ pH } 6.0; C_U = 100 \text{ mg} \text{ L}^{-1}; \text{ pH } 6.0; T = 25  ^\circ\text{C}; t = 24 \text{ min}; (\text{BE}) & 221 \text{ MNS/pDA/AOPNI}^{4} & 625 & m = 10 \text{ mg}; V = 20 \text{ mL}; C_U = 500 \text{ mg} \text{ L}^{-1}; \text{ pH } 8.0; T = 25  ^\circ\text{C}; t = 2$	P(AO)-g-CTS/BT	$165.09^{i}_{j}$	$m = 0.025 \text{ g}; V = 12.5 \text{ mL}; C_{\text{U}} = 25-300 \text{ mg L}^{-1}; \text{ pH 8.0}; T = 40 \text{ °C}; t = 60 \text{ min}; (BE)$	110
$\begin{split} & \text{Wool}_{\mathcal{F}} AO & \text{59.35} & m = 100 \text{ mg}, V = 100 \text{ mL}, C_{U} = 15-20 \text{ mg}, L^{-1}; \text{ pH} 5.0; T = 30 ~\text{°C}; t = 60 \text{ min}; \text{ (BE)} & 212 \text{ MAC-chitosan}^{\circ} & 117.65^{\circ} & m = 20 \text{ mg}; V = 5 \text{ mL}; C_{U} = 15-300 \text{ mg}, L^{-1}; \text{ pH} 5 \pm 0.3; T = 25 \pm 1 ~\text{°C}; t = 2 \text{ h}; \text{ (BE)} & 96 \text{ MAM-G-CH}^{\circ} & 377^{\circ} & \text{m}/V = 0.2 \text{ g} L^{-1}; C_{U} = 15-300 \text{ mg} L^{-1}; \text{ pH} 4.0; 150 \text{ rpm}; T = 20 \pm 1 ~\text{°C}; t = 48 \text{ h}; \text{ (BE)} & 106 \text{ Amidoxime-modified} & 366.8 & m = 50 \text{ mg}; V = 25 \text{ mL}; C_{U} = 15-300 \text{ mg} L^{-1}; \text{ pH} 4.0; 150 \text{ rpm}; T = 20 \pm 1 ~\text{°C}; t = 48 \text{ h}; \text{ (BE)} & 106 \text{ Amidoxime-modified} & 366.8 & m = 50 \text{ mg}; V = 25 \text{ mL}; C_{U} = 40 \text{ mg} L^{-1}; \text{ pH} 5.5; t = 120 \text{ min}; \text{ (BE)} & 344 \text{ AMAN}^{\circ} & 621 & m = 20 \text{ mg}; V = 100 \text{ mL}; C_{U} = 0.2-0.8 \text{ mg} L^{-1}; \text{ pH} 5.5; t = 120 \text{ min}; \text{ (BE)} & 344 \text{ AMAN}^{\circ} & 621 & m = 20 \text{ mg}; V = 50 \text{ mL}; 150 \text{ rpm}; \text{ pH} 5.0; 300 \text{ rpm}; & 208 \text{ MCM-0.4}^{d} & 105 \pm 3^{d} & m = 5 \text{ mg}; V = 5 \text{ mL}; C_{U} = 50-200 \text{ mg} L^{-1}; \text{ pH} 4.5; T = 25 ~\text{°C}; t = 2 \text{ h}; \text{ (BE)} & 220 \text{ AMD-MCM-41}^{d} & 493.6 & m = 10 \text{ mg}; V = 50 \text{ mL}; 150 \text{ rpm}; \text{ pH} 5.0; T = 323 \text{ K}; t = 2.0 \text{ h}; \text{ (BE)} & 222 \text{ gAO} \text{ gaSBA-15}^{d} & 611 & m/V = 0.1 \text{ g} L^{-1}; \text{ pH} 6.0; T = 25 ~\text{°C}; t = 24 \text{ min}; \text{ (BE)} & 222 \text{ gAO} \text{ gaSBA-15}^{d} & 611 & m/V = 0.1 \text{ g} L^{-1}; \text{ pH} 6.0; C_{U} = 25 ~\text{°C}; t = 240 \text{ min}; \text{ (BE)} & 222 \text{ gAO} \text{ gaSBA-15}^{d} & 611 & m/V = 0.1 \text{ g} L^{-1}; \text{ pH} 6.0; C_{U} = 25 ~\text{°C}; t = 240 \text{ min}; \text{ (BE)} & 221 \text{ gAO} \text{ gaSA-15}^{d} & 611 & m/V = 0.1 \text{ g} L^{-1}; \text{ pH} 6.0; T = 25 ~\text{°C}; t = 240 \text{ min}; \text{ (BE)} & 221 \text{ grAO} \text{ gaSA-15}^{d} & 611 & m/V = 0.1 \text{ g} L^{-1}; \text{ pH} 6.0; T = 25 ~\text{°C}; t = 12 \text{ h}; \text{ (BE)} & 221 \text{ grAO} \text{ gaSA-15}^{d} & 611 & m/V = 0.1 \text{ g} L^{-1}; \text{ pH} 6.0; T = 25 ~\text{°C}; t = 12 \text{ h}; \text{ (BE)} & 221 \text{ DFNS} \text{ pDA/AOPNI}^{d} & 626 & m = 10 \text{ mg}; V = 20 \text{ mL}; C_{U} = 100  m$	P(AO)-g-CTS/BT	208.96 <sup>°</sup>	$m = 0.025$ g; $V = 12.5$ mL; $C_{\rm U} = 25-300$ mg L; pH 8.0; $T = 50$ °C; $t = 60$ min; (BE)	110
$\begin{split} & \text{MAO-chitosan'} & 117.65^{\circ} & m = 20 \ \text{mg; } V = 20 \ \text{mL; } C_0 = 10-600 \ \text{mg L}^{-1}; 150 \ \text{rpm; pH} 6; T = 298 \ \text{K; } t = 5 \ \text{h; } (\text{BE}) & 96 \ \text{PAO-B'} & 357^{h} & \text{m/V} = 0.2 \ \text{g L}^{-1}; C_0 = 15-300 \ \text{mg L}^{-1}; \text{pH} 4.0; 150 \ \text{rpm; } T = 20 \pm 1 \ ^\circ\text{C}; t = 48 \ \text{h; } (\text{BE}) & 106 \ \text{Am-MG-CH'} & 372.95^{eh} & m/V = 0.2 \ \text{g L}^{-1}; C_0 = 15-300 \ \text{mg L}^{-1}; \text{pH} 4.0; 150 \ \text{rpm; } T = 20 \pm 1 \ ^\circ\text{C}; t = 48 \ \text{h; } (\text{BE}) & 106 \ \text{Am-MG-CH'} & 32.95^{eh} & m/V = 0.2 \ \text{g L}^{-1}; C_0 = 15-300 \ \text{mg L}^{-1}; \text{pH} 5.0; T = 25 \pm 1 \ ^\circ\text{C}; t = 48 \ \text{h; } (\text{BE}) & 211 \ \text{algal cells'} & m = 50 \ \text{mg; } V = 25 \ \text{mL; } (C_0 = ea.1000 \ \text{mg L}^{-1}; \text{pH} 5.0; T = 25 \pm 1 \ ^\circ\text{C}; t = 2.0 \ \text{h; } (\text{BE}) & 211 \ \text{algal cells'} & m = 20 \ \text{mg; } V = 100 \ \text{mL; } C_0 = 0.2-0.8 \ \text{mg L}^{-1}; \text{pH} 5.0; 31 = 20 \ \text{h; } (\text{BE}) & 244 \ \text{AMAN'} & 105 \pm 3^{g} & m = 5 \ \text{mg; } V = 5 \ \text{mL; } C_0 = 50-200 \ \text{mg L}^{-1}; \text{pH} 5.0; 31 = 2.0 \ \text{h; } (\text{BE}) & 220 \ \text{AMD-MCM-41}^d & 105 \pm 3^{g} & m = 5 \ \text{mg; } V = 5 \ \text{mL; } C_0 = 50-200 \ \text{mg L}^{-1}; \text{pH} 4.5; T = 25 \ ^\circ\text{C}; t = 24 \ \text{min; } (\text{BE}) & 220 \ \text{AMD-MCM-41}^d & 493.6 & m = 10 \ \text{mg; } V = 50 \ \text{mL; 150 \ \text{rpm; pH} 5.0; T = 233 \ \text{K}; t = 2.0 \ \text{h; } (\text{BE}) & 222 \ \text{AO-BSBA-15}^d & 516 & m/V = 0.1 \ \text{g L}^{-1}; \text{PL} 6.0; \ \text{T} = 25 \ ^\circ\text{C}; t = 240 \ \text{min; } (\text{BE}) & 222 \ \text{AO-BSBA-15}^d & 625 & m/V = 0.1 \ \text{g L}^{-1}; \text{pH} 6.0; T = 25 \ ^\circ\text{C}; t = 240 \ \text{min; } (\text{BE}) & 221 \ \text{AO-HSBA-15}^d & 709 & m/V = 0.1 \ \text{g L}^{-1}; \text{pH} 6.0; \ \text{C} = 100 \ \text{mg L}^{-1}; \text{pH} 8.00; T = 25 \ ^\circ\text{C}; t = 12 \ \text{h; } (\text{BE}) & 342 \ \text{DFNS/pDA/AOPNI}^d & 626 & m = 10 \ \text{mg; } V = 20 \ \text{mL; } C_0 = 500 \ \text{mg L}^{-1}; \text{pH} 8.00; T = 25 \ ^\circ\text{C}; t = 12 \ \text{h; } (\text{BE}) & 342 \ \text{DFNS/pDA/AOPNI}^d & 678 & m = 50 \ \text{mg; } V = 20 \ \text{mL; } C_0 = 500 \ \text{mg L}^{-1}; \text{pH} 8.00; T = 25 \ ^\circ\text{C}; t = 12 \ \text{h; } (\text{BE}) & 342 \ \text{DFNS/pDA/AOPNI}^d & 102^{g} & m = 5 \ mg;$	Wool-g-AO	59.35 ″	$m = 100 \text{ mg}; V = 100 \text{ mL}; C_{\text{U}} = 15-220 \text{ mg } \text{L}^{-1}; \text{ pH 5.0}; T = 30 ^{\circ}\text{C}; t = 60 \text{ min}; (BE)$	212
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	MAO-chitosan	117.65 <sup>g</sup>	$m = 20 \text{ mg}; V = 20 \text{ mL}; C_{\rm U} = 10-600 \text{ mg L}^{-1}; 150 \text{ rpm}; \text{pH 6}; T = 298 \text{ K}; t = 5 \text{ h}; (BE)$	96
$\begin{array}{llllllllllllllllllllllllllllllllllll$	PAO-B <sup>c</sup>	$126.9^{g}$	$m = 5 \text{ mg}; V = 5 \text{ mL}; C_{\text{U}} = 5120 \text{ mg L}^{-1}; \text{ pH } 5 \pm 0.3; T = 25 \pm 1 \text{ °C}; t = 2 \text{ h}; (\text{BE})$	207
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	AM-MG-CH <sup>c</sup>	357 <sup>n</sup>	$m/V = 0.2 \text{ g L}^{-1}$ ; $C_U = 15-300 \text{ mg L}^{-1}$ ; pH 4.0; 150 rpm; $T = 20 \pm 1$ °C; $t = 48 \text{ h}$ ; (BE)	106
Amidoxime-modified366.8 $m = 50 \text{ mg; } V = 25 \text{ mL; } C_{\rm U} = ca. 1000 \text{ mg L}^{-1}; \text{ pH 5.0; } T = 25 \pm 1 °\text{C}; t = 2.0 \text{ h; (BE)}$ 211algal cells <sup>6</sup> ZCEA <sup>c</sup> 584.60 $m/V = 0.05 \text{ g L}^{-1}; C_{\rm U} = 40 \text{ mg L}^{-1}; \text{ pH 5.5}; t = 120 \text{ min; (BE)}$ 344AMAN <sup>c</sup> 621 $m = 20 \text{ mg; } V = 100 \text{ mL; } C_{\rm U} = 0.2 - 0.8 \text{ mg L}^{-1}; \text{ pH 5.0}; 300 \text{ rpm;}$ 208AMCM-0.4 <sup>d</sup> 105 ± 3 <sup>g</sup> $m = 5 \text{ mg; } V = 5 \text{ mL; } C_{\rm U} = 50 - 200 \text{ mg L}^{-1}; \text{ pH 5.0}; T = 25 °C; t = 2 \text{ h; (BE)}$ 220AMD-MCM-41 <sup>d</sup> 493.6 $m = 10 \text{ mg; } V = 5.0 \text{ mL; 150 rpm; pH 5.0; } T = 323 \text{ K; } t = 2.0 \text{ h; (BE)}$ 222QAO@SBA-15 <sup>d</sup> 516 $m/V = 0.1 \text{ g L}^{-1}; C_{\rm U} = 100 \text{ mg L}^{-1}; \text{ pH 6.0; } T = 25 °C; t = 240 \text{ min; (BE)}$ 222QAOBSBA-15 <sup>d</sup> 601 $m/V = 0.1 \text{ g L}^{-1}; C_{\rm U} = 100 \text{ mg L}^{-1}; \text{ pH 6.0; } T = 25 °C; t = 240 \text{ min; (BE)}$ 221AO-HSBA-15 <sup>d</sup> 709 $m/V = 0.1 \text{ g L}^{-1}; \text{ CU} = 100 \text{ mg L}^{-1}; \text{ pH 6.0; } T = 25 °C; t = 240 \text{ min; (BE)}$ 221DFNS/pDA/AOPNI <sup>d</sup> 626 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_{\rm U} = 500 \text{ mg L}^{-1}; \text{ pH 8.00; } T = 25 °C; t = 12 \text{ h; (BE)}$ 342DFNS/pDA/AOPNI-NH <sub>2</sub> <sup>d</sup> 678 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_{\rm U} = 100 \text{ mg L}^{-1}; \text{ pH 8.00; } T = 25 °C; t = 24 \text{ h; (BE)}$ 232RAF-1-NH(CH <sub>2</sub> ) <sub>2</sub> /AO <sup>c</sup> 385 <sup>g</sup> $m = 5 \text{ mg; } V = 10 \text{ mL; } C_{\rm U} = 1400 \text{ ppm; pH ~ 6; r.t; t = 24 \text{ h; (BE)}$ 232UIO-66-AO <sup>c</sup> 194.1. <sup>d</sup> $m = 20 \text{ mg; } V = 50 \text{ mL; } C_{\rm U} = 1400 \text{ ppm; pH ~ 6; r.t; t = 24 \text{ h; (BE)}$ 133CMPAO-4 <sup>e</sup> <td< td=""><td>AM-MG-CH<sup>c</sup></td><td><math>372.95^{gn}</math></td><td><math>m/V = 0.2 \text{ g L}^{-1}</math>; <math>C_{\rm U} = 15-300 \text{ mg L}^{-1}</math>; pH 4.0; 150 rpm; <math>T = 20 \pm 1</math> °C; <math>t = 48 \text{ h}</math>; (BE)</td><td>106</td></td<>	AM-MG-CH <sup>c</sup>	$372.95^{gn}$	$m/V = 0.2 \text{ g L}^{-1}$ ; $C_{\rm U} = 15-300 \text{ mg L}^{-1}$ ; pH 4.0; 150 rpm; $T = 20 \pm 1$ °C; $t = 48 \text{ h}$ ; (BE)	106
algal cells <sup>6</sup> ZGEA <sup>c</sup> 584.60 $m/V = 0.05$ g L <sup>-1</sup> ; $C_U = 40$ mg L <sup>-1</sup> ; pH 5.5; $t = 120$ min; (BE) 344 AMAN <sup>c</sup> 621 $m = 20$ mg; $V = 100$ mL; $C_U = 0.2$ -0.8 mg L <sup>-1</sup> ; pH 5.0; 300 pm; T = 298 K; $t = 3$ h; (BE) AMCM-0.4 <sup>d</sup> 105 ± 3 <sup>g</sup> $m = 5$ mg; $V = 5$ mL; $C_U = 50$ -200 mg L <sup>-1</sup> ; pH 4.5; $T = 25$ °C; $t = 2$ h; (BE) 220 AMD-MCM-41 <sup>d</sup> 433.6 $m = 10$ mg; $V = 5.0$ mL; 150 rpm; pH 5.0; $T = 323$ K; $t = 2.0$ h; (BE) 129 c-AO@SBA-15 <sup>d</sup> 516 $m/V = 0.1$ g L <sup>-1</sup> ; $C_U = 100$ mg L <sup>-1</sup> ; pH 6.0; $T = 25$ °C; $t = 240$ min; (BE) 222 g-AO@SBA-15 <sup>d</sup> 601 $m/V = 0.1$ g L <sup>-1</sup> ; $C_U = 100$ mg L <sup>-1</sup> ; pH 6.0; $T = 25$ °C; $t = 240$ min; (BE) 221 AO-SBA-15 <sup>d</sup> 601 $m/V = 0.1$ g L <sup>-1</sup> ; $C_U = 100$ mg L <sup>-1</sup> ; T = 25 °C; $t = 3$ h; (BE) 221 DFNS/pDA/AOPNI-ML <sup>d</sup> 626 $m = 10$ mg; $V = 20$ mL; $C_U = 500$ mg L <sup>-1</sup> ; pH 8.00; $T = 25$ °C; $t = 12$ h; (BE) 342 DFNS/pDA/AOPNI-ML <sup>d</sup> 626 $m = 10$ mg; $V = 20$ mL; $C_U = 500$ mg L <sup>-1</sup> ; pH 8.00; $T = 25$ °C; $t = 12$ h; (BE) 342 DFNS/pDA/AOPNI-ML <sup>d</sup> 626 $m = 10$ mg; $V = 20$ mL; $C_U = 500$ mg L <sup>-1</sup> ; pH 8.00; $T = 25$ °C; $t = 12$ h; (BE) 342 DFNS/pDA/AOPNI-ML <sup>d</sup> 626 $m = 5$ mg; $V = 10$ mL; $C_U = 1-400$ ppm; pH ~ 6; r.t.; $t = 24$ h; (BE) 239 PAF-1-CH <sub>2</sub> NHAO <sup>c</sup> 102 <sup>g</sup> $m = 5$ mg; $V = 10$ mL; $C_U = 1-400$ ppm; pH ~ 6; r.t.; $t = 24$ h; (BE) 232 CMO-64 <sup>c</sup> 184.1 <sup>g</sup> $m = 20$ mg; $V = 50$ mL; $C_U = 160$ mg L <sup>-1</sup> pH 5.5 ± 0.1; $T = 25$ °C; $t = 24$ h; (BE) 113 UiO-66-AO <sup>c</sup> 194.8 $m = 20$ mg; $V = 50$ mL; $C_U = 9.25$ ppm; pH ~ 6; r.t.; $t = 24$ h; (BE) 113 CMPAO-4 <sup>c</sup> 251.9 <sup>g</sup> $m/V = 0.25$ g L <sup>-1</sup> ; $C_U = 5 \times 10^{-5}$ mol L <sup>-1</sup> ; $T = 298.15$ K; (BE) 231 POP-TpDb-AO <sup>c</sup> 322 $m = 4.5$ mg; $V = 400$ mL; $C_U = 9.25$ ppm; pH ~ 6; (BE) 231 POP-TpDb-AO <sup>c</sup> 322 $m = 4.5$ mg; $V = 400$ mL; $C_U = 9.25$ ppm; pH ~ 6; (BE) 231 POP-TpDb-AO <sup>c</sup> 364 $m = 4.5$ mg; $V = 400$ mL; $C_U = 9.25$ ppm; pH ~ 6; (BE) 231 COF-TpDb-AO <sup>c</sup> 304 $m = 4.5$ mg; $V = 400$ mL; $C_U = 9.25$ ppm; pH ~ 6; (BE) 231 COF-TpDb-AO <sup>c</sup> 408 <sup>g</sup> $m/V = 0.45$ mg mL <sup>-1</sup> ; $C_U = 23.1-265.2$ ppm; pH ~ 6; orenright; (BE) 331	Amidoxime-modified	366.8	$m = 50 \text{ mg}; V = 25 \text{ mL}; C_{\text{U}} = ca. 1000 \text{ mg L}^{-1}; \text{ pH 5.0}; T = 25 \pm 1 \text{ °C}; t = 2.0 \text{ h}; (\text{BE})$	211
$ \begin{array}{ccccc} ZGEA^c & 584.60 & m/V = 0.05 \ {\rm g} \ {\rm L}^{-1}; \ {\rm G}_U = 40 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm pH} \ 5.5; \ t = 120 \ {\rm min}; \ ({\rm BE}) & 344 \\ {\rm AMAN}^c & 621 & m = 20 \ {\rm mg}; \ V = 100 \ {\rm ml}; \ {\rm G}_U = 0.2-0.8 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm pH} \ 5.0; \ 300 \ {\rm rpm}; \\ T = 298 \ {\rm K}; \ t = 3 \ {\rm h}; \ ({\rm BE}) & 220 \\ {\rm AMD-MCM-41}^d & 493.6 & m = 10 \ {\rm mg}; \ V = 5.0 \ {\rm mL}; \ {\rm G}_U = 50-20.0 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm pH} \ 4.5; \ T = 25 \ {}^\circ{\rm C}; \ t = 2 \ {\rm h}; \ ({\rm BE}) & 220 \\ {\rm AMD-MCM-41}^d & 493.6 & m = 10 \ {\rm mg}; \ V = 5.0 \ {\rm mL}; \ {\rm G}_U = 100 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm pH} \ 6.0; \ T = 25 \ {}^\circ{\rm C}; \ t = 2.0 \ {\rm min}; \ ({\rm BE}) & 222 \\ {\rm g} \ {\rm AOQ} \ {\rm SBA-15}^d & 625 & m/V = 0.1 \ {\rm g} \ {\rm L}^{-1}; \ {\rm Cu} = 100 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm pH} \ 6.0; \ T = 25 \ {}^\circ{\rm C}; \ t = 240 \ {\rm min}; \ ({\rm BE}) & 221 \\ {\rm AO-HSBA-15}^d & 601 & m/V = 0.1 \ {\rm g} \ {\rm L}^{-1}; \ {\rm Cu} = 100 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm T} = 25 \ {}^\circ{\rm C}; \ t = 3 \ {\rm h}; \ ({\rm BE}) & 221 \\ {\rm AO-HSBA-15}^d & 709 & m/V = 0.1 \ {\rm g} \ {\rm L}^{-1}; \ {\rm pH} \ 6.0; \ {\rm Cu} = 100 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm T} = 0.0; \ {\rm T} = 25 \ {}^\circ{\rm C}; \ t = 3 \ {\rm h}; \ ({\rm BE}) & 342 \\ {\rm DFNS/pDA/AOPNI^d} & 626 & m = 10 \ {\rm mg}; \ V = 20 \ {\rm ml}; \ {\rm Cu} = 500 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm pH} \ 8.00; \ T = 25 \ {}^\circ{\rm C}; \ t = 12 \ {\rm h}; \ ({\rm BE}) & 342 \\ {\rm DFNS/pDA/AOPNI^d} & 102^{E} & m = 50 \ {\rm mg}; \ V = 50 \ {\rm mL}; \ {\rm Cu} = 1400 \ {\rm pm}; \ {\rm pH} \ {\rm -6}; \ {\rm cl}; \ t = 3 \ {\rm d}; \ ({\rm BE}) & 342 \\ {\rm DFNS/pDA/AOPNI^d} & 102^{E} & m = 50 \ {\rm mg}; \ V = 50 \ {\rm mL}; \ {\rm Cu} = 1400 \ {\rm pm}; \ {\rm PH} \ {\rm -6}; \ {\rm cl}; \ t = 24 \ {\rm h}; \ ({\rm BE}) & 342 \\ {\rm DFNS/pDA/AOPNI^d} & 102^{E} & m = 50 \ {\rm mg}; \ V = 50 \ {\rm mL}; \ {\rm Cu} = 1400 \ {\rm pm}; \ {\rm PH} \ {\rm -6}; \ {\rm cl}; \ t = 24 \ {\rm h}; \ ({\rm BE}) & 342 \\ {\rm DIO-66-AO^c} & 184.1^{E} & m = 20 \ {\rm mg}; \ V = 50 \ {\rm mL}; \ {\rm Cu} = 160 \ {\rm mg} \ {\rm L}^{-1}; \ {\rm PH} \ 5.5 \ {\rm cl}; \ {\rm t} = 24 \ {\rm $	algal cells			
$\begin{array}{llllllllllllllllllllllllllllllllllll$	ZGEA	584.60	$m/V = 0.05 \text{ g L}^{-1}$ ; $C_{\rm U} = 40 \text{ mg L}^{-1}$ ; pH 5.5; $t = 120 \text{ min}$ ; (BE)	344
$\begin{array}{llllllllllllllllllllllllllllllllllll$	AMAN	621	$m = 20 \text{ mg}; V = 100 \text{ mL}; C_{\text{U}} = 0.2-0.8 \text{ mg L}^{-1}; \text{ pH 5.0; 300 rpm};$ T = 298  K; t = 3  h; (BE)	208
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	AMCM- $0.4^d$	$105\pm3^g$	$m = 5 \text{ mg}; V = 5 \text{ mL}; C_{\text{U}} = 50200 \text{ mg L}^{-1}; \text{ pH 4.5}; T = 25 \text{ °C}; t = 2 \text{ h}; (\text{BE})$	220
c-AO@SBA-15 <sup>d</sup> 516 $m/V = 0.1 \text{ g } \text{L}^{-1}; C_{\text{U}} = 100 \text{ mg } \text{L}^{-1}; \text{ pH } 6.0; T = 25 °C; t = 240 \text{ min; (BE)}$ 222g-AO@SBA-15 <sup>d</sup> 625 $m/V = 0.1 \text{ g } \text{L}^{-1}; C_{\text{U}} = 100 \text{ mg } \text{L}^{-1}; \text{ pH } 6.0; T = 25 °C; t = 240 \text{ min; (BE)}$ 221AO-SBA-15 <sup>d</sup> 601 $m/V = 0.1 \text{ g } \text{L}^{-1}; \text{ pH } 6.0; C_{\text{U}} = 100 \text{ mg } \text{L}^{-1}; \text{ T } = 25 °C; t = 3 \text{ h; (BE)}$ 221AO-H-SBA-15 <sup>d</sup> 709 $m/V = 0.1 \text{ g } \text{L}^{-1}; \text{ pH } 6.0; C_{\text{U}} = 100 \text{ mg } \text{L}^{-1}; \text{ T } = 25 °C; t = 3 \text{ h; (BE)}$ 221DFNS/pDA/AOPNI <sup>d</sup> 626 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_{\text{U}} = 500 \text{ mg } \text{L}^{-1}; \text{ pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}$ 342DFNS/pDA/AOPNI-NH2 <sup>d</sup> 678 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_{\text{U}} = 500 \text{ mg } \text{L}^{-1}; \text{ pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}$ 342DFNS/pDA/AOPNI-NH2 <sup>d</sup> 102 <sup>g</sup> $m = 50 \text{ mg; } V = 50 \text{ mL; pH } 8.2 \pm 0.1; T = 298.15 \text{ K; t = 3 d; (BE)}$ 232DAF-1CH2NHAO <sup>c</sup> 102 <sup>g</sup> $m = 5 \text{ mg; } V = 10 \text{ mL; } C_{\text{U}} = 1-400 \text{ ppm; pH ~ 6; r.t.; t = 24 \text{ h; (BE)}$ 232UiO-66-AO <sup>c</sup> 184.1 <sup>g</sup> $m = 20 \text{ mg; } V = 50 \text{ mL; } C_{\text{U}} = 160 \text{ mg } \text{L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; (BE)}$ 113UiO-66-AO <sup>c</sup> 194.8 $m = 20 \text{ mg; } V = 50 \text{ mL; } C_{\text{U}} = 5 \times 10^{-5} \text{ mol } 1^{-1}; \text{ pH } 6.0 \pm 0.1; T = 298.15 \text{ K; (BE)}$ 238COF-TpAab-AO <sup>c</sup> 256 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{\text{U}} = 9.25 \text{ pm; } \text{ PH ~ 6; (BE)}$ 231COF-TpAab-AO <sup>c</sup> 305 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{\text{U}} = 9.25 \text{ pm; } \text{ PH ~ 6; (BE)}$ 231COF-TpDb-	AMD-MCM-41 <sup>d</sup>	493.6	m = 10  mg; V = 5.0  mL; 150  rpm;  pH  5.0; T = 323  K; t = 2.0  h; (BE)	129
g-AQ@SBA-15 <sup>d</sup> 625 $m/V = 0.1 \text{ g } \text{L}^{-1}; C_U = 100 \text{ mg } \text{L}^{-1}; \text{pH } 6.0; T = 25 °C; t = 240 \text{ min; (BE)}222AO-SBA-15d601m/V = 0.1 \text{ g } \text{L}^{-1}; \text{pH } 6.0; C_U = 100 \text{ mg } \text{L}^{-1}; T = 25 °C; t = 3 \text{ h; (BE)}221AO-H-SBA-15d709m/V = 0.1 \text{ g } \text{L}^{-1}; \text{pH } 6.0; C_U = 100 \text{ mg } \text{L}^{-1}; T = 25 °C; t = 3 \text{ h; (BE)}221DFNS/pDA/AOPNId626m = 10 \text{ mg; } V = 20 \text{ mL; } C_U = 500 \text{ mg } \text{L}^{-1}; \text{pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}342DFNS/pDA/AOPNI-NH2d678m = 10 \text{ mg; } V = 20 \text{ mL; } C_U = 500 \text{ mg } \text{L}^{-1}; \text{pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}342DFNS/pDA/AOPNI-NH2d678m = 50 \text{ mg; } V = 20 \text{ mL; } C_U = 500 \text{ mg } \text{L}^{-1}; \text{pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}342DFNS/pDA/AOPNI-NH2d678m = 50 \text{ mg; } V = 50 \text{ mL; } C_U = 500 \text{ mg } \text{L}^{-1}; \text{pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}239PAF-1-CH2NHAOe102gm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 1-400 \text{ ppm; pH ~ 6; r.t.; t = 24 \text{ h; (BE)}232UiO-66-AOe184.1gfm = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 160 \text{ mg } \text{L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; (BE)}113UiO-66-AOe184.1gfm = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 160 \text{ mg } \text{L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; (BE)}113UiO-66-AOe194.8m = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 9.25 \text{ pm; pH ~ 6; (BE)}231CMPAO-4e251.9gfm/V = 0.25 \text{ g } \text{ g } V = 400 \text{ mL; } C_U = 9.25 \text{ pm; pH ~ 6; (BE)}231COF-TpAab-AOe305m = 4.5 \text{ mg; } V = $	c-AO@SBA-15 <sup>d</sup>	516	$m/V = 0.1 \text{ g L}^{-1}$ ; $C_{\rm U} = 100 \text{ mg L}^{-1}$ ; pH 6.0; $T = 25 \text{ °C}$ ; $t = 240 \text{ min}$ ; (BE)	222
AO-SBA-15 <sup>d</sup> 601 $m/V = 0.1 \text{ g } \text{L}^{-1}; \text{ pH } 6.0; C_{\text{U}} = 100 \text{ mg } \text{L}^{-1}; T = 25 ^{\circ}\text{C}; t = 3 \text{ h; (BE)}$ 221AO-H-SBA-15 <sup>d</sup> 709 $m/V = 0.1 \text{ g } \text{L}^{-1}; \text{ pH } 6.0; C_{\text{U}} = 100 \text{ mg } \text{L}^{-1}; T = 25 ^{\circ}\text{C}; t = 3 \text{ h; (BE)}$ 221DFNS/pDA/AOPNI <sup>d</sup> 626 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_{\text{U}} = 500 \text{ mg } \text{L}^{-1}; \text{ pH } 8.00; T = 25 ^{\circ}\text{C}; t = 12 \text{ h; (BE)}$ 342DFNS/pDA/AOPNI-NH2 <sup>d</sup> 678 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_{\text{U}} = 500 \text{ mg } \text{L}^{-1}; \text{ pH } 8.00; T = 25 ^{\circ}\text{C}; t = 12 \text{ h; (BE)}$ 342DFNS/pDA/AOPNI-NH2 <sup>d</sup> 102 <sup>g</sup> $m = 50 \text{ mg; } V = 50 \text{ mL; } \text{C}_{\text{U}} = 1-400 \text{ ppm; pH } \sim 6; \text{r.t; } t = 24 \text{ h; (BE)}$ 239PAF-1-CH_NHAO <sup>e</sup> 102 <sup>g</sup> $m = 5 \text{ mg; } V = 10 \text{ mL; } C_{\text{U}} = 1-400 \text{ ppm; pH } \sim 6; \text{r.t; } t = 24 \text{ h; (BE)}$ 232UiO-66-AO <sup>e</sup> 184.1 <sup>g</sup> $m = 20 \text{ mg; } V = 50 \text{ mL; } C_{\text{U}} = 160 \text{ mg } \text{L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 ^{\circ}\text{C}; t = 24 \text{ h; (BE)}$ 113UiO-66-AO <sup>e</sup> 194.8 $m = 20 \text{ mg; } V = 50 \text{ mL; } C_{\text{U}} = 160 \text{ mg } \text{L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 ^{\circ}\text{C}; t = 24 \text{ h; (BE)}$ 113CMPAO-4 <sup>e</sup> 251.9 <sup>g'</sup> $m/V = 0.25 \text{ g } \text{L}^{-1}; C_{\text{U}} = 5 \times 10^{-5} \text{ mol } \text{L}^{-1}; \text{ pH } 6.0 \pm 0.1; T = 25 ^{\circ}\text{C}; t = 24 \text{ h; (BE)}$ 113COF-TpAab-AO <sup>e</sup> 256 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{\text{U}} = 9.25 \text{ ppm; pH } - 6; (BE)$ 231COF-TpAab-AO <sup>e</sup> 305 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{\text{U}} = 9.25 \text{ ppm; pH } ~ 6; (BE)$ 231COF-TpDb-AO <sup>e</sup> 322 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{\text{U}} = 9.25 \text{ ppm; pH } ~ 6; (BE)$	g-AO@SBA-15 <sup>d</sup>	625	$m/V = 0.1 \text{ g L}^{-1}$ ; $C_{\rm U} = 100 \text{ mg L}^{-1}$ ; pH 6.0; $T = 25 \text{ °C}$ ; $t = 240 \text{ min}$ ; (BE)	222
AO-H-SBA-15 <sup>d</sup> 709 $m/V = 0.1 \text{ g L}^{-1}; \text{ pH } 6.0; C_U = 100 \text{ mg L}^{-1}; T = 25 °C; t = 3 \text{ h; (BE)}$ 221DFNS/pDA/AOPNI <sup>d</sup> 626 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_U = 500 \text{ mg L}^{-1}; \text{ pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}$ 342DFNS/pDA/AOPNI-M12 <sup>d</sup> 678 $m = 10 \text{ mg; } V = 20 \text{ mL; } C_U = 500 \text{ mg L}^{-1}; \text{ pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}$ 342TMP-grA0 <sup>e</sup> 35.37 <sup>g</sup> $m = 50 \text{ mg; } V = 20 \text{ mL; } C_U = 500 \text{ mg L}^{-1}; \text{ pH } 8.00; T = 25 °C; t = 12 \text{ h; (BE)}$ 342PAF-1-CH_2NHA0 <sup>e</sup> 102 <sup>g</sup> $m = 50 \text{ mg; } V = 50 \text{ mL; pH } 8.2 \pm 0.1; T = 298.15 \text{ K; } t = 3 \text{ d; (BE)}$ 232RAF-1-NH(CH_2)_2A0 <sup>e</sup> 385 <sup>g</sup> $m = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 1-400 \text{ ppm; pH ~ 6; r.t; t = 24 \text{ h; (BE)}$ 232UiO-66-A0 <sup>e</sup> 184.1 <sup>g</sup> $m = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 1-400 \text{ ppm; pH ~ 6; r.t; t = 24 \text{ h; (BE)}$ 113CMPAO-4 <sup>e</sup> 251.9 <sup>g</sup> $m = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 1-60 \text{ mg L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; (BE)}$ 113CMPAO-4 <sup>e</sup> 251.9 <sup>g</sup> $m/V = 0.25 \text{ g L}^{-1}; C_U = 5 \times 10^{-5} \text{ mol L}^{-1}; \text{ pH } 6.0 \pm 0.1; T = 298.15 \text{ K; (BE)}$ 231POP-TpAab-A0 <sup>e</sup> 305 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH ~ 6; (BE)}$ 231COF-TpDb-A0 <sup>e</sup> 322 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH ~ 6; (BE)}$ 231COF-TpDb-A0 <sup>e</sup> 394 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH ~ 6; (BE)}$ 231COF-TpDb-A0 <sup>e</sup> 304 <sup>g</sup> $m = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 23.1-265.2 \text{ ppm; pH ~ 6; overnight; (BE)}$ 231	AO-SBA-15 <sup>d</sup>	601	$m/V = 0.1 \text{ g L}^{-1}$ ; pH 6.0; $C_{\rm U} = 100 \text{ mg L}^{-1}$ ; $T = 25 \text{ °C}$ ; $t = 3 \text{ h}$ ; (BE)	221
$\begin{array}{llllllllllllllllllllllllllllllllllll$	AO-H-SBA-15 <sup>d</sup>	709	$m/V = 0.1 \text{ g L}^{-1}$ ; pH 6.0; $C_{\rm U} = 100 \text{ mg L}^{-1}$ ; $T = 25 \text{ °C}$ ; $t = 3 \text{ h}$ ; (BE)	221
$\begin{array}{llllllllllllllllllllllllllllllllllll$	DFNS/pDA/AOPNI <sup>d</sup>	626	$m = 10 \text{ mg}; V = 20 \text{ mL}; C_{\text{U}} = 500 \text{ mg L}^{-1}; \text{ pH 8.00}; T = 25 \text{ °C}; t = 12 \text{ h}; (\text{BE})$	342
TMP-g-AOe $35.37^g$ $m = 50 \text{ mg}; V = 50 \text{ mL}; \text{ pH } 8.2 \pm 0.1; T = 298.15 \text{ K}; t = 3 \text{ d}; (BE)$ 239PAF-1-CH_2NHAOe $102^g$ $m = 5 \text{ mg}; V = 10 \text{ mL}; C_U = 1-400 \text{ ppm}; \text{ pH } \sim 6; \text{ r.t.}; t = 24 \text{ h}; (BE)$ 232RAF-1-NH(CH_2)_2AOe $385^g$ $m = 5 \text{ mg}; V = 10 \text{ mL}; C_U = 1-400 \text{ ppm}; \text{ pH } \sim 6; \text{ r.t.}; t = 24 \text{ h}; (BE)$ 232UiO-66-AOe $184.1^g$ $m = 20 \text{ mg}; V = 50 \text{ mL}; C_U = 160 \text{ mg } L^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 ^{\circ}\text{ C}; t = 24 \text{ h}; (BE)$ 113UiO-66-AOe $194.8$ $m = 20 \text{ mg}; V = 50 \text{ mL}; C_U = 160 \text{ mg } L^{-1} \text{ pH } 5.5 \pm 0.1; T = 258 ^{\circ}\text{ C}; t = 24 \text{ h}; (BE)$ 113CMPAO-4e $251.9^g$ $m/V = 0.25 \text{ g } L^{-1}; C_U = 5 \times 10^{-5} \text{ mol } L^{-1}; \text{ pH } 6.0 \pm 0.1; T = 298.15 \text{ K}; (BE)$ 231COF-TpAab-AOe $305$ $m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{ pH } \sim 6; (BE)$ 231COF-TpAb-AOe $305$ $m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{ pH } \sim 6; (BE)$ 231COF-TpDb-AOe $394$ $m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{ pH } \sim 6; (BE)$ 231COF-TpDb-AOe $355^g$ $m/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm}; \text{ pH } \sim 6; (BE)$ 231COF-TpDb-AOe $304^g$ $m = 5 \text{ mg}; V = 20 \text{ mL}; C_U = 8.6-165.7 \text{ ppm}; \text{ pH } \sim 6; \text{ r.t.}; overnight; (BE)$ 231RAF-1-CH_2AOe $304^g$ $m = 5 \text{ mg}; V = 20 \text{ mL}; C_U = 36-356 \text{ ppm}; \text{ pH } 6; \text{ r.t.}; t = 12 \text{ h}; (BE)$ 345POP-AOe $440^g$ $m = 5 \text{ mg}; V = 10 \text{ mL}; C_U = 36-356 \text{ ppm}; \text{ pH } 6; \text{ r.t.}; t = 12 \text{ h}; (BE)$ 237<	DFNS/pDA/AOPNI-NH2 <sup>d</sup>	678	$m = 10 \text{ mg}; V = 20 \text{ mL}; C_{\text{U}} = 500 \text{ mg L}^{-1}; \text{ pH 8.00}; T = 25 \text{ °C}; t = 12 \text{ h}; (\text{BE})$	342
PAF-1-CH2NHAO $102^g$ $m = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 1-400 \text{ ppm; pH} ~ 6; r.t.; t = 24 \text{ h; } (BE)232RAF-1-NH(CH2)2AO385^gm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 1-400 \text{ ppm; pH} ~ 6; r.t.; t = 24 \text{ h; } (BE)232UiO-66-AO184.1^gm = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 1-400 \text{ ppm; pH} ~ 6; r.t.; t = 24 \text{ h; } (BE)113UiO-66-AO194.8m = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 160 \text{ mg L}^{-1} \text{ pH} 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; } (BE)113CMPAO-4251.9^gm/V = 0.25 \text{ g L}^{-1}; C_U = 5 \times 10^{-5} \text{ mol L}^{-1} \text{ pH} 6.0 \pm 0.1; T = 298.15 \text{ K; } (BE)231COF-TpAab-AO256m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH} ~ 6; (BE)231COF-TpAb-AO305m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH} ~ 6; (BE)231COF-TpDb-AO322m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH} ~ 6; (BE)231COF-TpDb-AO394m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH} ~ 6; (BE)231COF-TpDb-AO355^gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; pH} ~ 6; (BE)231COF-TpDb-AO304^gm = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; pH} ~ 6; \text{ overnight; } (BE)231RAF-1-CH2AO304^gm = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 36-356 \text{ ppm; pH} ~ 6; r.t.; t = 12 \text{ h; } (BE)345POP-AO440^gm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; pH} ~ 6; r.t.; t = 12 \text{ h; } (BE)237$	TMP-g-AO <sup>e</sup>	35.37 <sup>g</sup>	$m = 50$ mg; $V = 50$ mL; pH 8.2 $\pm$ 0.1; $T = 298.15$ K; $t = 3$ d; (BE)	239
RAF-1-NH(CH2)2AO $385^g$ $m = 5 mg; V = 10 mL; C_U = 1-400 ppm; pH ~6; r.t.; t = 24 h; (BE)$ 232UiO-66-AO $184.1^g$ $m = 20 mg; V = 50 mL; C_U = 160 mg L^{-1} pH 5.5 \pm 0.1; T = 25 °C; t = 24 h; (BE)113UiO-66-AO194.8m = 20 mg; V = 50 mL; C_U = 160 mg L^{-1} pH 5.5 \pm 0.1; T = 25 °C; t = 24 h; (BE)113CMPAO-4251.9^gm/V = 0.25 g L^{-1}; C_U = 5 \times 10^{-5} mol L^{-1}; pH 6.0 \pm 0.1; T = 298.15 K; (BE)238POP-TpAab-AO256m = 4.5 mg; V = 400 mL; C_U = 9.25 ppm; pH ~ 6; (BE)231COF-TpAab-AO305m = 4.5 mg; V = 400 mL; C_U = 9.25 ppm; pH ~ 6; (BE)231POP-TpDb-AO322m = 4.5 mg; V = 400 mL; C_U = 9.25 ppm; pH ~ 6; (BE)231COF-TpDb-AO355^gm/V = 0.45 mg mL^{-1}; C_U = 23.1-265.2 ppm; pH ~ 6; (BE)231COF-TpDb-AO304^gm = 4.5 mg; V = 20 mL; C_U = 36.165.7 ppm; pH ~ 6; overnight; (BE)231RAF-1-CH2AO304^gm = 5 mg; V = 20 mL; C_U = 36-356 ppm; pH ~ 6; r.t.; vernight; (BE)345POP-AO440^gm = 5 mg; V = 10 mL; C_U = 36-356 ppm; pH ~ 6; r.t.; vernight; (BE)237$	PAF-1-CH <sub>2</sub> NHAO <sup>e</sup>	$102^g$	$m = 5 \text{ mg}; V = 10 \text{ mL}; C_{\text{U}} = 1400 \text{ ppm}; \text{pH} \sim 6; \text{r.t.}; t = 24 \text{ h}; (\text{BE})$	232
UiO-66-AOe $184.1^g$ $m = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 160 \text{ mg } L^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; } (BE)113UiO-66-AOe194.8m = 20 \text{ mg; } V = 50 \text{ mL; } C_U = 160 \text{ mg } L^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 °C; t = 24 \text{ h; } (BE)113CMPAO-4e251.9gm/V = 0.25 \text{ g } L^{-1}; C_U = 5 \times 10^{-5} \text{ mol } L^{-1}; \text{ pH } 6.0 \pm 0.1; T = 298.15 \text{ K; } (BE)238POP-TpAab-AOe256m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH } \sim 6; (BE)231COF-TpAab-AOe305m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH } \sim 6; (BE)231POP-TpDb-AOe322m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH } \sim 6; (BE)231COF-TpDb-AOe355gm = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; pH } \sim 6; (BE)231COF-TpDb-AOe355gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; pH } \sim 6; (BE)231COF-TpDb-AOe304ggm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; pH } \sim 6; overnight; (BE)231RAF-1-CH2AOe304ggm = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; pH } \sim 6; overnight; (BE)231TFPT-BTAN-AOe427ggm = 5 \text{ mg; } V = 25 \text{ mL; pH 4.0; r.t.; overnight; (BE)345POP-AOe440ggm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356  ppm; pH 6; r.t.; t = 12 \text{ h; (BE)237$	$RAF-1-NH(CH_2)_2AO^e$	385 <sup>g</sup>	$m = 5 \text{ mg}; V = 10 \text{ mL}; C_{\text{U}} = 1-400 \text{ ppm}; \text{ pH } \sim 6; \text{ r.t.}; t = 24 \text{ h}; (\text{BE})$	232
UiO-66-AOe194.8 $m = 20 \text{ mg; } V = 50 \text{ mL; } C_{U} = 160 \text{ mg L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 ^{\circ}\text{C}; t = 24 \text{ h; (BE)}$ 113CMPAO-4e251.9g $m/V = 0.25 \text{ g L}^{-1}; C_{U} = 5 \times 10^{-5} \text{ mol L}^{-1}; \text{ pH } 6.0 \pm 0.1; T = 298.15 \text{ K; (BE)}$ 238POP-TpAab-AOe256 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{U} = 9.25 \text{ ppm; pH} \sim 6; (BE)$ 231COF-TpAab-AOe305 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{U} = 9.25 \text{ ppm; pH} \sim 6; (BE)$ 231POP-TpDb-AOe322 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{U} = 9.25 \text{ ppm; pH} \sim 6; (BE)$ 231COF-TpDb-AOe394 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_{U} = 9.25 \text{ ppm; pH} \sim 6; (BE)$ 231POP-TpDb-AOe355g $m/V = 0.45 \text{ mg mL}^{-1}; C_{U} = 9.25 \text{ ppm; pH} \sim 6; (BE)$ 231COF-TpDb-AOe355g $m/V = 0.45 \text{ mg mL}^{-1}; C_{U} = 23.1-265.2 \text{ ppm; pH} \sim 6; (Overnight; (BE))$ 231COF-TpDb-AOe304gg $m/V = 0.45 \text{ mg mL}^{-1}; C_{U} = 23.1-265.2 \text{ ppm; pH} \sim 6; overnight; (BE)$ 231RAF-1-CH <sub>2</sub> AOe304gg $m = 5 \text{ mg; } V = 20 \text{ mL; } C_{U} = 8.6-165.7 \text{ ppm; pH} \sim 6; \text{ r.t.; overnight; (BE)}$ 137TFPT-BTAN-AOe427gg $m = 5 \text{ mg; } V = 25 \text{ mL; pH 4.0; r.t.; overnight; (BE)}$ 345POP-AOe440gg $m = 5 \text{ mg; } V = 10 \text{ mL; } C_{U} = 36-356 \text{ ppm; pH 6; r.t.; t = 12 h; (BE)}$ 237	UiO-66-AO <sup>e</sup>	$184.1^{g}$	$m = 20 \text{ mg}; V = 50 \text{ mL}; C_{\text{U}} = 160 \text{ mg L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 \text{ °C}; t = 24 \text{ h}; (BE)$	113
CMPAO-4e $251.9^g$ $m/V = 0.25 \text{ g L}^{-1}; C_U = 5 \times 10^{-5} \text{ mol L}^{-1}; \text{ pH } 6.0 \pm 0.1; T = 298.15 \text{ K}; (BE)238POP-TpAab-AOe256m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)231COF-TpAab-AOe305m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)231POP-TpDb-AOe322m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)231COF-TpDb-AOe322m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_U = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)231POP-TpDb-AOe355^gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm}; \text{pH} \sim 6; (BE)231COF-TpDb-AOe304^gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm}; \text{pH} \sim 6; overnight; (BE)231RAF-1-CH2AOe304^gm = 5 \text{ mg}; V = 20 \text{ mL}; C_U = 8.6-165.7 \text{ ppm}; \text{pH} \sim 6; \text{ r.t.}; overnight; (BE)137TFPT-BTAN-AOe427^gm = 5 \text{ mg}; V = 25 \text{ mL}; \text{pH } 4.0; \text{ r.t.}; overnight; (BE)345POP-AOe440^gm = 5 \text{ mg}; V = 10 \text{ mL}; C_U = 36-356 \text{ ppm}; \text{pH } 6; \text{ r.t.}; t = 12 \text{ h}; (BE)237$	UiO-66-AO <sup>e</sup>	194.8	$m = 20 \text{ mg}; V = 50 \text{ mL}; C_{\text{U}} = 160 \text{ mg L}^{-1} \text{ pH } 5.5 \pm 0.1; T = 25 \text{ °C}; t = 24 \text{ h}; (BE)$	113
POP-TpAab-AOe256 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } pH ~ 6; (BE)231COF-TpAab-AOe305m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } pH ~ 6; (BE)231POP-TpDb-AOe322m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } pH ~ 6; (BE)231COF-TpDb-AOe322m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } pH ~ 6; (BE)231COF-TpDb-AOe394m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } pH ~ 6; (BE)231POP-TpDb-AOe355gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } pH ~ 6; overnight; (BE)231COF-TpDb-AOe408gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } pH ~ 6; overnight; (BE)231RAF-1-CH2AOe304gm = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; } pH ~ 6; r.t.; overnight; (BE)137TFPT-BTAN-AOe427gm = 5 \text{ mg; } V = 25 \text{ mL; } pH 4.0; r.t.; overnight; (BE)345POP-AOe440gm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; } pH 6; r.t.; t = 12 \text{ h; } (BE)237$	CMPAO-4 <sup>e</sup>	$251.9^{g}$	$m/V = 0.25$ g L <sup>-1</sup> ; $C_{\rm U} = 5 \times 10^{-5}$ mol L <sup>-1</sup> ; pH 6.0 $\pm$ 0.1; $T = 298.15$ K; (BE)	238
COF-TpAab-AOe305 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } \text{pH} \sim 6; (BE)231POP-TpDb-AOe322m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } \text{pH} \sim 6; (BE)231COF-TpDb-AOe394m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } \text{pH} \sim 6; (BE)231POP-TpDb-AOe355gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 9.25 \text{ ppm; } \text{pH} \sim 6; (BE)231COF-TpDb-AOe355gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } \text{pH} \sim 6; \text{ overnight; } (BE)231COF-TpDb-AOe408gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } \text{pH} \sim 6; \text{ overnight; } (BE)231RAF-1-CH_2AOe304gm = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; } \text{pH} \sim 6; \text{ r.t.; overnight; } (BE)137TFPT-BTAN-AOe427gm = 5 \text{ mg; } V = 25 \text{ mL; } \text{pH} 4.0; \text{ r.t.; overnight; } (BE)345POP-AOe440gm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; } \text{pH} 6; \text{ r.t.; } t = 12 \text{ h; } (BE)237$	POP-TpAab-AO <sup>e</sup>	256	$m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_{\text{U}} = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)$	231
POP-TpDb-A0e322 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } \text{pH} \sim 6; (BE)$ 231COF-TpDb-A0e394 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } \text{pH} \sim 6; (BE)$ 231POP-TpDb-A0e355g $m/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } \text{pH} \sim 6; \text{ overnight; } (BE)$ 231COF-TpDb-A0e408g $m/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } \text{pH} \sim 6; \text{ overnight; } (BE)$ 231RAF-1-CH <sub>2</sub> AOe304g $m = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; } \text{pH} \sim 6; \text{ r.t.; overnight; } (BE)$ 137TFPT-BTAN-AOe427g $m = 5 \text{ mg; } V = 25 \text{ mL; } \text{pH } 4.0; \text{ r.t.; overnight; } (BE)$ 345POP-AOe440g $m = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; } \text{pH } 6; \text{ r.t.; } t = 12 \text{ h; } (BE)$ 237	COF-TpAab-AO <sup>e</sup>	305	$m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_{\rm U} = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)$	231
COF-TpDb-A0e394 $m = 4.5 \text{ mg; } V = 400 \text{ mL; } C_U = 9.25 \text{ ppm; } \text{pH} ~ 6; (BE)$ 231POP-TpDb-A0e $355^g$ $m/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } \text{pH} ~ 6; overnight; (BE)$ 231COF-TpDb-A0e $408^g$ $m/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; } \text{pH} ~ 6; overnight; (BE)$ 231RAF-1-CH_2A0e $304^g$ $m = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; } \text{pH} ~ 6; r.t.; overnight; (BE)$ 137TFPT-BTAN-A0e $427^g$ $m = 5 \text{ mg; } V = 25 \text{ mL; } \text{pH } 4.0; r.t.; overnight; (BE)$ 345POP-A0e $440^g$ $m = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; } \text{pH } 6; r.t.; t = 12 \text{ h; } (BE)$ 237	POP-TpDb-AO <sup>e</sup>	322	$m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_{\rm U} = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)$	231
POP-TpDb-A0e $355^g$ $m/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; pH} ~ 6; overnight; (BE)231COF-TpDb-A0e408^gm/V = 0.45 \text{ mg mL}^{-1}; C_U = 23.1-265.2 \text{ ppm; pH} ~ 6; overnight; (BE)231RAF-1-CH_2A0e304^gm = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; pH} ~ 6; r.t.; overnight; (BE)137TFPT-BTAN-A0e427^gm = 5 \text{ mg; } V = 25 \text{ mL; pH 4.0; r.t.; overnight; (BE)345POP-A0e440^gm = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; pH 6; r.t.; } t = 12  h; (BE)237$	COF-TpDb-AO <sup>e</sup>	394	$m = 4.5 \text{ mg}; V = 400 \text{ mL}; C_{\rm U} = 9.25 \text{ ppm}; \text{pH} \sim 6; (BE)$	231
COF-TpDb-A0e $408^g$ $m/V = 0.45 \text{ mg mL}^{-1}$ ; $C_U = 23.1-265.2 \text{ ppm; pH} \sim 6$ ; overnight; (BE)231RAF-1-CH2AOe $304^g$ $m = 5 \text{ mg; } V = 20 \text{ mL; } C_U = 8.6-165.7 \text{ ppm; pH} \sim 6$ ; r.t.; overnight; (BE)137TFPT-BTAN-AOe $427^g$ $m = 5 \text{ mg; } V = 25 \text{ mL; pH } 4.0$ ; r.t.; overnight; (BE)345POP-AOe $440^g$ $m = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; pH } 6$ ; r.t.; $t = 12 \text{ h; (BE)}$ 237	POP-TpDb-AO <sup>e</sup>	$355^{g}$	$m/V = 0.45 \text{ mg mL}^{-1}$ ; $C_{\rm U} = 23.1 - 265.2 \text{ ppm}$ ; pH ~ 6; overnight; (BE)	231
RAF-1-CH <sub>2</sub> AO <sup>e</sup> $304^g$ $m = 5 \text{ mg}; V = 20 \text{ mL}; C_U = 8.6-165.7 \text{ ppm}; \text{pH} ~ 6; \text{r.t.}; \text{ overnight; (BE)}$ 137         TFPT-BTAN-AO <sup>e</sup> $427^g$ $m = 5 \text{ mg}; V = 25 \text{ mL}; \text{ pH } 4.0; \text{ r.t.}; \text{ overnight; (BE)}$ 345         POP-AO <sup>e</sup> $440^g$ $m = 5 \text{ mg}; V = 10 \text{ mL}; C_U = 36-356 \text{ ppm}; \text{pH } 6; \text{ r.t.}; t = 12 \text{ h; (BE)}$ 237	COF-TpDb-AO <sup>e</sup>	$408^g$	$m/V = 0.45 \text{ mg mL}^{-1}$ ; $C_{\rm U} = 23.1 - 265.2 \text{ ppm}$ ; pH ~ 6; overnight; (BE)	231
TFPT-BTAN-AO <sup>e</sup> 427 <sup>g</sup> $m = 5 \text{ mg}; V = 25 \text{ mL}; \text{ pH 4.0; r.t.; overnight; (BE)}$ 345         POP-AO <sup>e</sup> 440 <sup>g</sup> $m = 5 \text{ mg}; V = 10 \text{ mL}; C_U = 36-356 \text{ ppm; pH 6; r.t.; } t = 12 \text{ h; (BE)}$ 237	RAF-1-CH <sub>2</sub> AO <sup>e</sup>	$304^g$	$m = 5 \text{ mg}; V = 20 \text{ mL}; C_{II} = 8.6-165.7 \text{ ppm}; \text{pH} \sim 6; \text{r.t.; overnight; (BE)}$	137
POP-AO <sup>e</sup> $440^g$ $m = 5 \text{ mg; } V = 10 \text{ mL; } C_U = 36-356 \text{ ppm; pH 6; r.t.; } t = 12 \text{ h; (BE)}$ 237	TFPT-BTAN-AO <sup>e</sup>	$427^g$	m = 5 mg; $V = 25$ mL; pH 4.0; r.t.; overnight; (BE)	345
	POP-AO <sup>e</sup>	$440^g$	$m = 5$ mg; $V = 10$ mL; $C_{\rm U} = 36-356$ ppm; pH 6; r.t.; $t = 12$ h; (BE)	237

### Table 5 (Contd.)

	Adsorption cap	pacity	
Adsorbent	${ m mg~g^{-1}}$	Conditions	Ref.
MIL-53(Al)-AO <sup>e</sup>	$454.54^{g}$	$m = 20 \text{ mg}; V = 50 \text{ mL}; C_{\text{U}} = 50-225 \text{ mg L}^{-1}; \text{ pH 5.5}; T = 15 \text{ °C}; t = 500 \text{ min}; (BE)$	102
POP-oNH2-AOe	$530^g$	$m = 5 \text{ mg}; V = 10 \text{ mL}; C_{\text{U}} = 36-356 \text{ ppm}; \text{ pH } 6; \text{ r.t.}; t = 12 \text{ h}; (\text{BE})$	237
POP-pNH <sub>2</sub> -AO <sup>e</sup>	$580^{g}$	$m = 5 \text{ mg}; V = 10 \text{ mL}; C_{\text{U}} = 36-356 \text{ ppm}; \text{ pH } 6; \text{ r.t.}; t = 12 \text{ h}; (\text{BE})$	237
MIL-101-AO <sup>e</sup>	586	$m = 5 \text{ mg}; V = 50 \text{ mL}; C_{\text{U}} = 1\text{-}300 \text{ mg L}^{-1}; \text{ pH 7}; T = 298 \text{ K}; t = 6 \text{ h}; (\text{BE})$	346
Pal/PAO <sup>f</sup>	78.13 <sup>g</sup>	m = 50 mg; $V = 100$ mL; 100 rpm; pH 5.0; $T = 30$ °C; $t = 24$ h; (BE)	111
ND-AO <sup>f</sup>	$285.8^{g}$	m = 10 mg; $V = 25$ mL; pH 4.5; $T = 25$ °C; $t = 2$ h; (BE)	78
FeOOH-APAN <sup>f</sup>	980.39 <sup>g</sup>	$m = 20$ mg; $V = 50$ mL; $C_{\rm U} = 25.98$ –654.1 ppm; 160 rpm; pH 8; $T = 298$ K; $t = 4$ h; (BE)	244
Brine solution			
PAO <sup>a</sup>	161	$m/V = 0.05 \text{ g L}^{-1}$ ; pH 4.0 $\pm$ 0.1; IS = 0.1 M NaCl; $T = 20 \pm 1$ °C; $t = 48 \text{ h}$ ; (BE)	198
0.25 PAO/rGO <sup>b</sup>	206	$m/V = 0.05 \text{ g L}^{-1}$ ; pH 4.0 $\pm$ 0.1; IS = 0.1 M NaCl; $T = 20 \pm 1$ °C; $t = 48 \text{ h}$ ; (BE)	198
0.5 PAO/rGO <sup>b</sup>	227	$m/V = 0.05 \text{ g L}^{-1}$ ; pH 4.0 $\pm$ 0.1; IS = 0.1 M NaCl; $T = 20 \pm 1$ °C; $t = 48 \text{ h}$ ; (BE)	198
1.0 $PAO/rGO^b$	253	$m/V = 0.05~{ m g~L}^{-1};~{ m pH}~4.0 \pm 0.1;~{ m IS} = 0.1~{ m M}$ NaCl; $T = 20 \pm 1$ °C; $t = 48~{ m h};~{ m (BE)}$	198
4.0 PAO/rGO <sup><math>b</math></sup>	439	$m/V = 0.05~{ m g~L^{-1}};~{ m IS} = 0.1~{ m M}$ NaCl; pH 4.0 $\pm$ 0.1; $T = 20 \pm 1$ °C; $t = 48~{ m h};~({ m BE})$	198
$2.0 \text{ PAO/rGO}^{b}$	872	$m/V = 0.05~{ m g~L}^{-1};~{ m IS} = 0.1~{ m M}$ NaCl; pH 4.0 $\pm$ 0.1; $T = 20~{\pm}~{ m 1}~{ m °C};~t = 48~{ m h};~({ m BE})$	198
c-AO/CNFs <sup>b</sup>	$263.18^{g}$	$m/V = 0.6 \text{ g L}^{-1}$ ; IS = 0.01 M NaCl; pH 3.5; $T = 293$ K; $t = 24$ h; (BE)	289
p-AO/CNFs <sup>b</sup>	$588.24^{g}$	$m/V = 0.6 \text{ g L}^{-1}$ ; IS = 0.01 M NaCl; pH 3.5; $T = 293$ K; $t = 24$ h; (BE)	289
AOMGO <sup>b</sup>	$284.89^{g,h}$	$m/V = 0.2~{ m g~L}^{-1}; { m I} = 0.01~{ m M}~{ m NaClO}_4; { m pH}~5.0 \pm 0.01; T = 298~{ m K}; t = 24~{ m h}; { m (BE)}$	104
AOGONRs <sup>b</sup>	502.6	$m = 10 \text{ mg}; V = 50 \text{ mL}; \text{ IS} = 0.01 \text{ M NaClO}_4; \text{ pH 4.5}; T = 298 \text{ K}; t = 240 \text{ min}; (BE)$	119
KIT-6-AO-20% <sup>d</sup>	323.94 <sup>g</sup>	$m/V = 0.1 \text{ g L}^{-1}$ ; IS = 0.01 M NaNO <sub>3</sub> ; $C_{\rm U} = 10$ -80 mg L <sup>-1</sup> ; pH 5.0; T = 298 K; t = 24 h; (BE)	219
SBA-AO-0.4 <sup>d</sup>	$386.75^{g,h}$	$m/V = 0.2 \text{ g L}^{-1}$ ; IS = 0.01 M NaClO <sub>4</sub> ; pH 5.0 $\pm$ 0.1; $T = 298$ K; $t = 24$ h; (BE)	52
SBA-AO-0.4 <sup>d</sup>	$414.36^{g,h}$	$m/V = 0.2$ g L <sup>-1</sup> ; IS = 0.01 M NaClO <sub>4</sub> ; pH 5.0 $\pm$ 0.1; $T = 318$ K; $t = 24$ h; (BE)	52
SBA-AO-0.4 <sup>d</sup>	$465.05^{g,h}$	$m/V = 0.2 \text{ g L}^{-1}$ ; IS = 0.01 M NaClO <sub>4</sub> ; pH 5.0 $\pm$ 0.1; $T = 338$ K; $t = 24$ h; (BE)	52
HCMP-AO <sup>e</sup>	450	$m = 4 \text{ mg}$ ; $V = 20 \text{ mL}$ ; IS = 0.01 M NaClO <sub>4</sub> ; $C_{\text{U}} = 10-200 \text{ ppm}$ ; pH 6; r.t.; overnight; (BE)	336
AO/MOF <sup>e</sup>	454.55 <sup>g</sup>	$m/V = 0.5 \text{ g L}^{-1}$ ; $C_{\text{U}} = 10-50 \text{ mg L}^{-1}$ ; IS = 0.01 M NaClO <sub>4</sub> ; pH 5.0; T = 293 K; t = 24 h; (BE)	225
$PAO/MoS_2^{f}$	$47.4^{g}$	$m/V = 0.20 \text{ g L}^{-1}$ ; IS = 0.1 M NaCl; pH 5.0 ± 0.1; T = 298 ± 1 K; t = 24 h; (BE)	139
Fe <sub>3</sub> O <sub>4</sub> @PDA@PAO <sup>f</sup>	162.5	$C_{\rm U} = 100 \text{ mg L}^{-1}$ ; IS = 0.01 M NaClO <sub>4</sub> ; T = 298 K; t = 26 h; (BE)	126
ZVI/PAO <sup>f</sup>	$206^g$	$m/V = 0.20~{ m g~L}^{-1}$ ; IS = 0.1 M NaCl; pH 5.0 $\pm$ 0.1; $T = 298 \pm$ 1 K; $t = 24$ h; (BE)	247

<sup>*a*</sup> Polymeric materials. <sup>*b*</sup> Carbon-based materials. <sup>*c*</sup> Biosorbents. <sup>*d*</sup> Silica-based materials. <sup>*e*</sup> New type of porous materials. <sup>*f*</sup> Others. <sup>*g*</sup> The theoretical value calculated by the Langmuir isotherm model. <sup>*h*</sup> The value converted from the molar mass of uranium of 238 g mol<sup>-1</sup>. <sup>*i*</sup> The value converted from adsorption efficiency (%). <sup>*j*</sup> *m* is the mass of the adsorbents, *V* is the volume of the solution; FR is the flow rate;  $C_U$  is the initial concentration of uranium species; *t* is the time; *T* is the temperature; IS represents ionic strength; FTCS is flow-through column system; BE is batch experiments.

the tricarbonate-type anion is highly stable and hard to directly complex under seawater conditions.<sup>175</sup> The process could be catalyzed by protons in the bulk solution and the decreased pH

would accelerate the overall adsorption process,<sup>20</sup> which could be why acidic monomers such as AA and MAA often play an important role in polymeric materials. In batch experiments,



Fig. 14 (a) The relative proportion of U(v) species,  $P_{CO_2} = 3.8 \times 10^{-4}$  atm,  $C_{[U(VI)]initial} = 40.0 \text{ mg L}^{-1}$ ;  $T = 298 \pm 2 \text{ K}$ , m V<sup>-1</sup> = 0.10 g L<sup>-1</sup>,  $I = 0.01 \text{ mol } L^{-1}$  NaNO<sub>3</sub>. Reproduced with permission from ref. 256. Copyright 2018, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) Distribution of uranium(vI) species in aqueous solution with a total concentration of 100 mg L<sup>-1</sup> and pH values ranging from 1 to 10. Calculated using a Medusa program. Reproduced with permission from ref. 83. Copyright 2016, Elsevier B.V.

the pH varies over a wide range and the uranyl species may vary dramatically with the change in pH (Fig. 14b), as does the surface charge on the materials. As the pH gradually increases, the surface charge of the material changes from positive to negative. This has a profound effect on the entire adsorption process. Under the combined effect of various factors, many studies have found that the adsorption efficiency first increases and then decreases with increasing pH, and the optimal adsorption pH is usually 4–6 (Table 5).

Given all that, changing the uranyl species and the surface properties of the materials are the main mechanisms through which the solution pH influences the adsorption. Therefore, in the case of effluent, some pretreatments such as pH conditioning are beneficial in improving the performance of amidoxime-based adsorbents. In the case of seawater, although the pH value is almost constant in the marine environment, the adsorption capacity of deployed adsorbents can be maximized by the introduction of appropriate functional groups (*e.g.* carboxyl group) into the matrix materials, which can change the local pH conditions and enhance the uranium uptake.

### 4.2 Temperature

Temperature is one of the factors that must be considered when selecting the location of uranium recovery plants in the ocean and for the optimization of wastewater treatment conditions. Thermodynamic studies usually show that the adsorption of uranium by amidoxime-based adsorbents is a spontaneous and endothermic process with increased randomness at high temperature and that high temperature effectively promotes the adsorption.198,240 Both the diffusion of uranyl ions from the bulk solution to the active sites and ligand exchange reactions between uranium and amidoxime groups will be accelerated at elevated temperature.186 The macroscopic reflection is that a 10 K increase in the seawater temperature (293-303 K) increased the uranium adsorption kinetics of AO hollow fibers by a factor of 3.36 More recently, Kuo et al. found that increasing the temperature from 8 °C to 31 °C not only increased the uranium adsorption rate of AF1 and AI8 from seawater by near 7-fold, but also promoted vanadium adsorption. Nevertheless, the mass ratio of vanadium to uranium adsorbed on the adsorbents (V/U, w/w) diminished remarkably with increased temperature.<sup>257</sup> That is to say, the amidoxime-containing adsorbents exhibited higher selectivity for uranium over vanadium at elevated temperature. This may provide a strategy to moderate the vanadium inhibition of uranium recovery by amidoxime-based adsorbents from seawater, which is described in Section 4.3. From that perspective, seawater recovery plants should be built in warmer ocean currents, which are conducive to improved uranium capture performance. However, some important aspects, such as the temperature sensitivity of the adsorption process of competitive ions other than vanadium and the effect of high temperature on the longevity of the adsorbent materials, have not received sufficient attention and research.

### 4.3 Co-existing ions

Seawater is an extremely complex system that contains almost all the naturally occurring elements. The average salt content in seawater is about 3.5%, which is  $10^6-10^7$  times higher than the uranium content,<sup>109</sup> posing a major challenge for extracting uranium from seawater. Among these co-existing ions, the Na content is the highest, followed by Mg, Ca and K (Table 1). The influence of alkali metals (Na and K) is generally neglected since the extraction of uranium by amidoxime-group adsorbents is usually inner-sphere adsorption that is not affected by the ionic strength.104,111 However, owing to their overwhelmingly high concentrations, their influence on other ions (such as vanadium) may indirectly affect the adsorption of uranium by amidoxime-based materials.<sup>258</sup> In contrast, Ca and Mg cause much greater interference because they can form Ca/Mg-UO<sub>2</sub>-CO3 complexes with uranyl carbonate anions in seawater. Their formation not only has an impact on the affinity between uranium and amidoxime, but also reduces the favorable adsorption based on electrostatic attraction or even changes the adsorption mechanism since they are charge neutral.17 Although the complexing ability of  $Ca(\pi)/Mg(\pi)$  ions with amidoxime groups is much smaller than that of U(vI),10 they can still occupy some important sites on adsorbents owing to their high concentrations. Fe is considered to be one of the main competing species. Compared with uranium, it has a 3-fold higher molar concentration in seawater (Table 1) and stronger complexation stability with amidoxime groups because it has a greater charge density and its d orbital electrons have greater overlap with the donor atoms (such as N and O) on amidoxime groups.<sup>259</sup> Consequently, the amounts of iron adsorbed by amidoxime-based materials are often 4 times or even higher than the amounts of uranium adsorbed.13,259 Amidoxime groups also have moderately strong complexation with other transition metals, such as  $Pb(\pi)$ ,  $Cu(\pi)$ ,  $Ni(\pi)$  and  $Mn(\pi)$ , but none of these can significantly affect the uranium adsorption.<sup>259,260</sup>

Vanadium(v) is considered to be the biggest challenge.242,261 Although its mass fraction is smaller than that of uranium, it has a higher molar content and affinity for amidoxime.<sup>262</sup> The complexes formed by amidoxime and vanadium, whether V(IV) or V(v), are documented to be more stable than their uranium counterparts.263 As reported, the vanadium adsorption capacity of AF1 is about five times higher than that for uranium,9 and vanadium accounts for almost 20 times the adsorption sites of uranium.<sup>264</sup> The presence of vanadyl ions also brings trouble to material elution.<sup>265</sup> Owing to the strong interaction between amidoxime groups and vanadium, the elution process requires harsh conditions, such as strong acid and high temperature, which could result in irreversible damage to the adsorbents.37,266 Regarding the high affinity of amidoxime for vanadium, a series of experimental and theoretical studies have been carried out.<sup>37,159,264,266-270</sup> Vanadium mainly exists as V(rv) and V(v) in seawater, of which the former accounts for only 10% to 15%.271 Not withstanding, the interaction between V(IV) and amidoxime groups cannot be ignored because of the irreversible damage to the adsorbents resulting from the oxidation of V(v) to V(v) by amidoxime groups during extraction<sup>267</sup> and the much faster chelation kinetics of V(IV).268 When vanadium is bonded to the cyclic imide dioxime, the organic group can even replace the oxygen in vanadyl ions.<sup>264</sup> The stability of the generated nonoxido V(v) complex is higher than that of the uranium

counterparts, resulting in the active sites occupied by vanadium no longer being accessible to uranyl ions. Moreover, the complex remains stable over a wide pH range, which also rationalizes the fact that it is difficult to elute vanadium from the adsorbents even under acidic conditions.<sup>262</sup>

For anions, the main influence comes from carbonate and bicarbonate ions. Carbonate ions can form stable uranyl tricarbonate anions with uranyl cations, and the replacement of carbonate in uranyl tricarbonate is considered as the ratedetermining step for uranium extraction.<sup>20,175</sup> The influence of bicarbonate ion on uranium adsorption is similar to carbonate ion,24 and it even can strongly compete with the amidoxime to bond uranium, thus decelerating the uranium adsorption kinetics.<sup>258</sup> The influence of other anions, such as sulfate, nitrate, chloride and perchlorate, on uranium extraction is rarely mentioned, but they need to be taken into account when studying the strength of background ions, among which chloride ions and perchlorate are often used in the preparation of simulated seawater (Table 4). Inspired by the high affinity of phosphoryl groups for uranyl,199 it is speculated that phosphate ions, related to eutrophication,272 also exhibit strong binding with uranyl ions, thus affecting the uranium extraction behavior of amidoxime-based adsorbents from natural water to some extent, which should also be noted.

Whether the adsorbents are employed into real seawater or industrial wastewater, a large amount of cations and anions inevitably co-exist. Compared with the influence of cations, the role of anions is often neglected and studies are very scarce. Therefore, systematic observation and exploration should be carried out in future studies.

### 4.4 Biofouling

Biofouling is one of the most fundamental reasons for the discrepancies in adsorbent performance between laboratory tests and field experiments.273 Biofouling is the accumulation of microorganisms, algae, plants or animals on the madid materials surfaces, which may even lead to the failure of uranium extraction from seawater.261,274 In general, biofouling involves four stages: (i) marine microorganisms rapidly cover the surface once the adsorbent is deployed in seawater; (ii) the individual bacterial cells and diatoms start to adhere, settle and colonize; (iii) a microbial membrane gradually forms and the resulting rough surfaces can further capture more particles and organisms; and (iv) organisms overgrow and form complex community structures on the surface of the materials.158 The adverse impact of biofouling on uranium extraction is mainly reflected in: (i) prohibiting the contact between the ligands and seawater, making the reactive sites on adsorbents inaccessible; (ii) interfering with the uranium extraction owing to microbial activity; and (iii) restricting the reusability of the adsorbing materials.<sup>167</sup> Light is an important factor influencing the degree of biofouling275 and deployment of the adsorbents below the photic zone can diminish the impact of biological contamination.276 Within a certain range, the biological activity will increase with increasing temperature,190,277 which exacerbates the biofouling, thereby reducing the uranium uptake by the adsorbents.<sup>278</sup>

However, this does not mean that implementing the uranium recovery at a deeper position is a perfect solution for this issue. Regardless of the cost, both the low temperature and the high pressure in deep sea may have negative effects on the adsorption behavior of uranium over amidoxime-based materials. The development of antifouling adsorbents is an important strategy to deal with this dilemma. The antibacterial moieties used in these materials can be divided into two categories: inorganic nanoparticles (e.g., nano-TiO<sub>2</sub>,<sup>279</sup> AgNPs,<sup>280,281</sup> and nano-ZnO<sup>213</sup>) and organic components (e.g., guanidine group,<sup>158</sup> quaternary ammonium salts,<sup>282</sup> chitosan,<sup>273</sup> and antibiotics<sup>274</sup>). The mechanism of nanoparticle sterilization is mainly due to its cytotoxicity. Organic compounds are more likely to adsorb bacteria, change the permeability of their cell membranes, and affect their physiological functions, thereby inhibiting their growth, eventually leading to their death.<sup>273</sup> In addition, the mechanism of generating active oxygen radicals by photocatalytic properties to achieve sterilization effects may provide new ideas for designing materials with high resistance to biofouling.250,283 Research on these anti-biofouling adsorbents has afforded encouraging results in the laboratory.284 However, the composition of microorganisms that cause biofouling in the ocean is complex, including anaerobic bacteria, aerobic bacteria, fungi and algae.<sup>213</sup> At present, only a single target species is typically selected for laboratory-scale antibacterial tests and research on amidoximated antifouling materials is insufficient. Challenges remain in on-site uranium extraction from the ocean. How to effectively shield adsorbents from biofouling or minimize the impact of biofouling on uranium recovery from seawater while ensuring adsorption performance is still a hot topic of future research. In addition, biofouling in industrial wastewater has not received enough attention. Inspired by the research on biofouling in seawater, the negative effects of biological contamination in the process of removing uranium from polluted water by amidoxime adsorbents must be taken seriously.

In addition, the impacts of dissolved organic matter (DOM) and current velocity on the uranium uptake behavior of amidoxime-based adsorbents have attracted attention. It is recommended that adsorbents be deployed in areas of sea with a local oceanic current velocity of greater than 8 cm s<sup>-1</sup> to minimize mass transfer resistance and maximize adsorption efficiency,285 while sea areas with abundant DOM and dissolved iron should be avoided.286 The research on the interactions and cross-effects of various influencing factors needs further improvement. Therefore, for specific seawater and wastewater conditions, amidoxime-based adsorbents should be purposefully synthesized according to the characteristics of different types of materials, such as pH-sensitive, temperature-sensitive, antibacterial and corrosion-resistant adsorbents. That is to say, demandoriented new-generation adsorbents should provide targeted uranium adsorption with improved selectivity and the ability to adapt to different environments due to stronger durability.

## 5. Binding mechanisms

Although amidoxime-based sorbents have been used to capture uranium from seawater for decades, the underlying mechanism

Table 6	The XPS data	of various	amidoxime-	based i	materials
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	Binding energy (eV	/)					
	C1s	N1s		O1s	U4f <sub>7/2</sub>	U4f <sub>5/2</sub>	
Adsorbent	NH <sub>2</sub> - <u>C</u> =N-OH	$\underline{N}H_2$ -C=N-OH	NH <sub>2</sub> −C= <u>N</u> −OH	NH <sub>2</sub> -C=N- <u>O</u> H	<u>U</u> -AO	U– <u>U</u>	Ref.
PIDO NFs <sup>a</sup>	286.4	400.90	399.05	532.50	_	_	191
PIDO-U <sup>a</sup>	_	_	_	531.44	381.60	392.65	191
PAO/rGO <sup>b</sup>	_	$400.2\pm0.2$	$399.4\pm0.2$	_			140
AO-MWCNTs <sup>b</sup>	_	399.5	400.2	532.2	_	_	98
AO-g-MWCNTs <sup>b</sup>		399.7	400.4	533.3			146
$0.2 \text{AO-OMC}^{b}$		399.35	399.75	532.2	_	_	108
0.2AO-OMC-U <sup>b</sup>		399.35	401.1	533.1	381.48	392.39	108
<i>p</i> -AO/CNFs <sup><i>b</i></sup>		402.9	401.3				289
AO-HTC <sup>b</sup>	286.8	399.19	400.21	_	_	_	195
AO-HTC-U <sup>b</sup>	_	399.19	400.21	531.5	381.48	392.39	195
AOGONRs <sup>b</sup>	_	39	9.6	531.5	382.3	393.0	119
HTC-AO <sup>b</sup>	286.4	39	9.7	530.8	_	_	202
$ACFs-AO^b$		399.2	400.0	533.1	_	_	288
mGO-PAO <sup>b</sup>	_	399.72	400.18	531.62	_	_	203
mGO-PAO-U <sup>b</sup>	_	399.72	400.54	531.78	_	_	203
P(AO)-g-CTS/BT <sup>c</sup>	285.89	399.7	400.5	532.1			288
U-P(AO)-g-CTS/BT <sup>c</sup>	286.08	399.41	401.29	533.1	381.39	392.24	110
Ami-MSN <sup>d</sup>		399.27	399.89	531.07	_	_	138
Ami-MSN <sup>d</sup>		399.40	400.29	532.45	_	_	146
SBA-AO- $0.4^d$	287.1	399.3	400.8	530.9	_	_	52
$SBA-AO-U^d$	_	399.7	401.0	531.1	381.7	391.8	52
TMP-h-AO-U <sup>e</sup>	285.89	401.29	399.41	_	_	_	239
Na-Mont-APAN <sup>f</sup>	_	399.7	400.5	_	_	_	125
FeOOH-APAN <sup>f</sup>	_	399.4	400.3	532.3	_	_	244
FeOOH-APAN-Uf	_	399.4	401.8	533.2	_	_	244
Pal/PAO <sup>f</sup>	286.37	399.72	400.58	_	_	_	111
$PAO/MoS_2^{f}$	287.62	400.40	399.20	531.08	—	—	139

<sup>a</sup> Polymeric materials. <sup>b</sup> Carbon-based materials. <sup>c</sup> Biosorbents. <sup>d</sup> Silica-based materials. <sup>e</sup> New type of porous materials. <sup>f</sup> Others.

is still not completely clear. Understanding the binding mechanism between amidoxime groups and uranyl ions can guide the rational design and field operation of adsorbents.<sup>287</sup> Therefore, it is extremely important for the development of new amidoxime-based adsorbents with higher adsorption capacity and better selectivity.

The investigations on the mechanism for the adsorption of uranyl ions by amidoxime-based materials are mainly accomplished through model fitting, technical characterizations and theoretic calculations. It is assumed that the overall adsorption process contains four steps: (1) interparticle diffusion; (2) liquid film mass transfer; (3) intraparticle diffusion; and (4) binding reaction.<sup>29</sup> Interparticle diffusion is often negligible for fluidized adsorbents but this may not be the case for fixed ones deployed in seawater. Nevertheless, research at this stage rarely takes it into account. Liquid film diffusion is often very rapid owing to the hydrophilic surface that amidoxime-based materials generally have. Intraparticle diffusion directly determines the kinetic properties of the adsorbents, which is related to the matrix materials. The adsorption of uranium by non-porous substrates like nano-diamond does not undergo intraparticle diffusion, affording ultrafast kinetics.78 However, for porous substrates, such as carbon-based materials, the complex pore structure can significantly limit the diffusion of the target adsorbates and prolong the equilibration time.<sup>288</sup> Owing to the high uranium affinity of amidoxime groups, binding reactions are often favorable. Many isotherm, kinetic and thermodynamic models have been widely used to describe the adsorption processes. The fitting results indicate that the adsorption of uranyl ions by most of the amidoxime-based adsorbents is a monolayer, spontaneous, endothermic and entropyincreasing processes, with obvious characteristics of chemisorption.<sup>212,289</sup>

The specific chemical interactions between amidoxime and uranium are mainly studied by means of adsorbent characterization before and after adsorption, in which FT-IR spectroscopy and XPS are the most widely used techniques. The type and contribution of the active groups can be determined based on the appearance/disappearance, enhancement/attenuation and red/blue shift of the characteristic peaks in the FT-IR spectra. For example, the peak at 830–920 cm<sup>-1</sup> is usually used to identify uranyl ions on the loaded materials.<sup>53,138</sup> Some spectral results provide strong evidence that the N–O moiety could be the main active site,<sup>125,239</sup> while others suggest that the amino group may also play a role in anchoring uranium,<sup>138</sup> perhaps implying that no single group determines uranium adsorption by amidoxime-based materials. XPS provides detailed information on the binding reaction based on the peak position of



**Fig. 15** (a) The proposed coordination motifs for how amidoxime binds uranyl with corresponding crystal structures and CCDC identifiers when available. Reproduced with permission from ref. 290. Copyright 2016, Royal Society of Chemistry. (b) Structure models of oxygens used to fit the EXAFS data for uranyl-contacted polymer samples. Reproduced with permission from ref. 254. Copyright 2019, Royal Society of Chemistry.

the elemental bonding energy. The N 1s spectrum of AO-*g*-MWCNTs composites demonstrates that both amino nitrogen and oxime nitrogen could participate in binding uranium,<sup>146</sup> but that of 0.2AO-OMC shows that uranium is anchored by oxime groups rather than amino ones.<sup>108</sup> The O 1s spectrum for AO-*g*-MWCNTs-U confirms the importance of the oxygen-containing groups hanging on the composite surface, particularly the oxime moiety.<sup>157</sup> XPS analysis of AO-HTC provides evidence that the uranium adsorption on the functionalized

HTC is relevant to both amino nitrogen and oxime oxygen.<sup>195</sup> The FTIR and XPS information on the adsorbents are summarized in Tables 3 and 6, respectively.

By comparison, X-ray absorption fine structure (XAFS) spectra provide more detailed information involving the binding motif. The fits of extended XAFS (EXAFS) on small molecules like benzamidoxime, acetamidoxime, and gluta-rimidedioxime proved that (i) the U=O bond remains after coordination; (ii) the two oxygen atoms are located in the axial



Fig. 16 (a) Schematic diagram of the gradual replacement of coordination water in hydrated uranyl ions by amidoxime through  $\eta^2$  motif based on the results of ref. 296. (b) Proposed structural models of the  $[UO_2(CO_3)_{3-x}(AO)_x]^{(4-x)-}$  complexes when AO ligands gradually substitute carbonate ligands that bind to uranyl ions. Reproduced with permission from ref. 300. Copyright 2016, American Chemical Society. (c) Structures of uranyl complexes with formamidoxime obtained after geometry optimization at the B3LYP/SSC/6-311++G(d,p) level of theory. Reproduced with permission from ref. 290. Copyright 2016, Royal Society of Chemistry.

direction of the complex; (iii) the coordination atoms (N or/and O) coordinate with the uranyl ion in the equatorial plane; and (iv) the coordination number (CN) is mostly 5 to 6.225,290 Currently, the reported binding motifs mainly include (Fig. 15a): (I) monodentate coordination,<sup>291</sup> (II) bidentate chelation,  $^{292,293}$  (III)  $\eta^2$  motif,  $^{203,294}$  and (IV) tridentate fashion.  $^{187}$ The formation of motif I is usually accompanied by tautomerization from amidoxime to aminoitrone (Fig. 6b). Then the generated anionic oxygen can form 1:4 coordination with a uranyl center.<sup>291</sup> Motif II is widely accepted as its theoretically stable five-membered ring configuration and is supported by the FT-IR spectrum and XPS data.288,295 Generally, in this motif, two to three ligands bind to one uranyl center.22,292 After investigating the binding motif in a series of  $[UO_2(AO)_x(OH_2)_y]^{2-x}$  (x = 1–3) complexes using DFT calculation, it was found that the  $\eta^2$  motif was the most thermodynamically stable form regardless of the CN, which was confirmed by single-crystal X-ray diffraction (S-XRD) analysis of UO<sub>2</sub><sup>2+</sup> complexing with a small amidoxime molecule.<sup>294</sup> In addition, it has been suggested that motif **III** remains the most stable form, no matter what the pH level or the ratio of uranyl/amidoxime in the complexes,296 even in an ionic liquid.<sup>297</sup> As reported, the bond lengths of U-O (2.34 Å) and U–N (2.44 Å) in acetamidoxime bonded via the  $\eta^2$  motif (Fig. 15b)<sup>254</sup> are shorter than that of U–O (2.46  $\pm$  0.02 Å) in coordinated water or methanol molecules, confirming the high thermodynamic stability of  $\eta^2$ -type complexes.<sup>298</sup> The excellent binding behavior results from the fact that (N, O) 2p on the oxime moiety has a strong covalent interaction and orbital hybridization with U 5f/6d,<sup>299</sup> and their interaction is more remarkable than that between U 5f/6d and the  $CO_3^{2-}/carboxyl$ group,300,301 which theoretically explains the mechanism through which amidoxime-based materials extract uranium from seawater. Furthermore, it has been discovered that amidoxime groups are progressively bonded to the uranyl equatorial plane of  $UO_2(OH)_2(H_2O)_2$  and  $[UO_2(CO_3)_3]^{4-}$  in the  $\eta^2$  motif as shown in Fig. 16a and b, respectively.<sup>296,300</sup> However, some different results show that the UO<sub>2</sub>(AO)<sub>2</sub>(H<sub>2</sub>O) complex with mixed motifs for the two amidoximes is a little more stable than that with only  $\eta^2$  motif at the CCSD(T) level (Fig. 16c).<sup>290</sup> It is believed that the cyclic imide dioxime produced by the two adjacent amidoxime groups in polymeric adsorbents is primarily responsible for the high uranyl affinity and is responsible for uranium anchoring (motif IV),<sup>178</sup> which is supported by crystallographic,187 thermodynamic302 and computational<sup>303</sup> studies. It has been claimed that the cyclic imide dioxime has the ability to coordinate with uranyl in tridentate form with a higher binding constant<sup>304</sup> and that it can serve as a better electron donor thanks to its conjugated system, which endows the adsorbent with enhanced uranium uptake from seawater.123

Other than the four aforementioned binding motifs, the  $\mu_2$ oxo-bridged transition metal was found though the EXAFS fitting of the fiber in contact with seawater, perhaps implying that the uranium extraction from the ocean occurs only after forming an advantageous binding pocket *in situ* by chelation of Ni<sup>290</sup> or Fe.<sup>305</sup> Recently, a novel bridging ( $\mu_2$ ) zwitterionic amidoxime binding mode was put forward.<sup>306</sup> These seem to imply that the enigmatic binding mechanism between uranium species and amidoxime ligands is more complex than we have imagined, and the relentless pursuit of it will remain one of the main research priorities. Besides, the environment in which the adsorbents are deployed, the nature of the materials, the types of adsorbates, and other factors all cause a difference in the binding motif between amidoxime and uranyl ion. However, most of the current research remains at the small molecule level, and the contributions of various factors and the synergy between the factors still lack relevant publications.

# 6. Cost estimation

It is plausible to evaluate the quality and practicability of an adsorbent based on the adsorption performance involving adsorption capacity and kinetics, but in actual large-scale applications, the cost factor is an inescapable topic. Up to now, few publications have accurately calculated the cost of uranium extraction from seawater as it is a nontrivial task. The difficulty lies in the existence of too many uncertainties in this process, of which reduction will be one of the main directions for future research.82 With the continuous development of technology, the number of cost-driven design parameters will gradually increase. It is increasingly impractical to manually optimize system parameters to achieve the cost estimation of uranium production, so various cost budget models have thus been developed.278 The cost of seawater uranium extraction is driven by three major components: (i) adsorbent preparation; (ii) deployment and mooring; and (iii) elution and purification (Fig. 17).<sup>307</sup> The former involves the expenses of matrix materials, the operations, amidoximation and possible base conditioning, of which the price of matrix materials often dominates. For emerging materials, such as MOFs and COFs, although they



Fig. 17 Cost drivers for seawater uranium extraction.

have excellent adsorption properties, their high production costs are often the chief restriction to their practical application, while the cost of polymeric adsorbents depends mainly on the monomers. Synthesis methods and conditioning conditions determine the expense of the operations and base conditioning. It has been reported that using NaOH in place of KOH can reduce the cost of recovering uranium by 21-30%.<sup>188</sup> The capital consumption of the amidoximation process is relatively fixed because of the similar hydroxylamine treatments (Fig. 5). In contrast, the field operation costs (including mooring and deployment) are more variable, which relates to factors such as the deployment mode (the amount of adsorbent use, etc.) and the ambient environment (temperature, pH, NOM, etc.). The proper amount of adsorbents used and the selection of pH and temperature are critical to maximizing the adsorbent performance. Furthermore, the impact of NOM needs to be considered in economic assessment since it is ubiquitous.<sup>286</sup> The period of uranium extraction from seawater is very long (usually several months), and the length of a campaign is directly related to the efficiency of uranium extraction from seawater. A study has shown that the overall costs associated with adsorbent preparation account for approximately 48% of the total uranium production cost.<sup>308</sup> However, this is not always the case; when the adsorbent is stable enough to be reused many times, the mooring and recovery costs will dominate.85

In addition, the cost derived from biofouling should be taken into consideration. On the one hand, the two factors associated with biologic accumulation: length of campaign<sup>309</sup> and seawater temperature,<sup>310</sup> have an impact on the cost analysis. As mentioned above, biofouling is capable of restricting the reusability of adsorbents. Severe biofouling thus leads to a significant increase in the uranium extraction cost.278 Regenerability and reusability are very important for assessing the use value and economic performance of adsorbents.<sup>116,311</sup> Meanwhile, the separation of the desired fuel elements from the loaded adsorbents is the ultimate goal and a key step in uranium extraction from seawater. The eluting agents commonly used involve inorganic acids (HCl and HNO<sub>3</sub>, etc.),<sup>147</sup> organic acids (tartaric acid, malic acid and oxalic acid, etc.)<sup>150</sup> and Na<sub>2</sub>CO<sub>3</sub> solution.<sup>117,233</sup> Acid solutions can achieve relatively thorough elution, but they may hydrolyze the amidoxime group, thereby deteriorating the reusability of the amidoxime-based materials and ultimately resulting in increased costs.<sup>125</sup> After their elution, the eluent usually needs to be further separated owing to the lack of selectivity for the eluting elements, and the eluted material must undergo alkaline conditioning before each reuse. The situation with organic acids is similar to that of inorganic acids. As protic acids, they also have the potential to degrade the active ligands, such as glutardiamidoxime.<sup>178</sup> The elution of the adsorbed material by the Na<sub>2</sub>CO<sub>3</sub> solution is more targeted and the eluted material can be reused directly without the need for alkaline conditioning again.<sup>182</sup> On the basis of Na<sub>2</sub>CO<sub>3</sub> solution, the Na<sub>2</sub>CO<sub>3</sub>-H<sub>2</sub>O<sub>2</sub> system has been further developed in recent years<sup>180,311</sup> This system allows for selectivity based on Le Chatelier's principle and can even quantitatively elute uranium at room temperature during a certain period of time.<sup>311,312</sup> In addition, the rate of elution of uranium can be

accelerated by increasing the  $H_2O_2$  concentration.<sup>180</sup> However, higher concentration means higher costs. At the same time, as an oxidant, the damage of the adsorbent materials by highconcentration  $H_2O_2$  cannot be ignored.<sup>311</sup> Its concentration, thus, must be rationally controlled. In general, most adsorbents maintain good adsorption performance after desorption, with only a 3% to 5% decrease, but the difference may also result in significant changes to the final cost.<sup>82</sup>

Taking all these factors into account, Japanese researchers estimated the cost of uranium production from seawater using a polymeric adsorbent from JAEA to be about 90 000 yen per kg-U under the assumption of uranium uptake of 2 mg-U per kgads after 60 days of exposure.<sup>313</sup> An independent cost analysis in the U.S. estimates that the cost is S a 95% confidence interval from \$1030 per kg-U to \$1430 per kg-U.<sup>314</sup> In the total cost of \$1230 per kg-U, adsorbent preparation and mooring each accounted for approximately 45% of the quota.85 The ORNL adsorbent achieved nearly half of the cost reduction to \$610 per kg-U due to the updated material.<sup>160</sup> Optimization of operating parameters including the length of the campaign, amount of use and seawater temperature can reduce the cost by 20%.278 However, this is still much higher than the cost of land uranium mining of \$60–260 per kg-U.<sup>315,316</sup> Therefore, improving the cost of seawater uranium is a major issue that needs to be addressed

There are two main ways to reduce the uranium production cost: (i) developing high loading adsorbents and (ii) preparing high-tolerance adsorbents that can be reused multiple times efficiently.<sup>85</sup> It is estimated that a uranium uptake of 30 mg g<sup>-1</sup> or a uranium uptake of 6 mg  $g^{-1}$  and the ability to be reused 10 times with an adsorption capacity loss of no more than 3% per cycle (*i.e.*, total adsorption capacity of 51.9 mg  $g^{-1}$ ), is needed for the cost of adsorbents (\$290 per kg-U) be comparable to the price of traditional terrestrial uranium supply and meet the economic requirements of seawater uranium extraction.<sup>166</sup> Therefore, the new generation of amidoxime-based adsorbents with high loading capacity, superior selectivity, fast adsorption rate, as well as excellent antibacterial ability and environmental tolerance may attain this end, providing the possibility of the genuine realization of uranium extraction from seawater instead of land.<sup>317</sup> Recently, a dual-surface amidoximated halloysite nanotube, AO-HNTs, exhibited an acceptable cost of \$154 per kg-U benefiting from low-cost raw materials and a long service life.248 In addition, a symbiotic system that combines an adsorbent with existing facilities, such as offshore wind turbines, has been suggested to reduce the mooring costs of uranium extraction from seawater.277,318-321 This strategy, with high operability and practical feasibility, is likely to have great potential in future marine uranium mining activities.

# 7. Outlook and prospects

Adsorption of uranium from seawater and wastewater is an important issue in the fields of energy and the environment. Polymeric fibers are the most mature materials in seawater uranium extraction.<sup>322</sup> There are significant differences between field experiments and laboratory tests in terms of the

compositions of the water samples and the operating environments, and these differences can even affect the chelating mechanism.<sup>305</sup> Therefore, field experiments with non-polymer adsorbents are urgently required. In wastewater, polymeric adsorbents may be degraded under extreme conditions (like strong acid and radiation, high temperature, *etc.*) and experience swelling, shrinkage and/or cracking, resulting in reduced uranium extraction efficiency and even secondary pollution.<sup>323</sup> In contrast, non-polymeric adsorbents, such as carbon-based materials, appear to be more advantageous. Nevertheless, research on their removal behaviors in real industrial wastewater is still rare and should receive more attention.

The high affinity of amidoxime for uranium is the basis for the wide application of amidoxime-based adsorbents as uranium extractants. Owing to the abundant amidoxime groups, polymeric adsorbents will continue to be the backbone for seawater uranium recovery in the future. However, the current polymeric materials still cannot meet the requirements of industrial applications in terms of economic benefits and performance. In order to obtain further upgrades in polymer properties, we must face up to their shortcomings and make more attempts at the material and technical levels to seek breakthroughs. A series of groundbreaking work has set an example for us.<sup>166,191,243,324</sup> Relative to the amount, the accessibility and availability of active groups are factors that should be paid more attention to.<sup>166</sup> How to expose as many active groups as possible and make them effectively contact with uranyl ions is a problem that needs to be focused on in future research. For polymer adsorbents, it should be emphasized to increase the effective area during uranium adsorption as much as possible. Although designing microporous structures<sup>155</sup> and ultra-thin nanofibers191,243 are effective strategies, they may not meet the cost requirements of large-scale applications. Cationic crosslinking may be a means to break the bottleneck, which is worthy of further research.<sup>325</sup> For non-polymer adsorbents, the characteristics of the matrix material and the amidoxime group should be fully combined to achieve complementary advantages. In addition, it will be a major concern in the future to consciously design the chemical structure of materials to enhance their performance to capture uranyl ions. As reported, some microenvironments including hydrogen bonding, conjugate effect, and hydrophobic interaction may affect the stability of uranium complexes. Specifically, hydrogen bonding can lengthen the U-O bond length on the corresponding uranyl ion, while shortening the bond length between the coordination atom on the near equatorial plane and the central uranium ion.326 Therefore, the incorporation of functional groups that are capable of forming hydrogen bonds, such as amino groups, can improve the stability of the uranyl complexes obtained by interacting with the amidoxime group, thereby facilitating adsorption.237 Conjugated systems, on the one hand, as electron donors can bond well with uranium, an electron acceptor.<sup>327</sup> On the other hand, their existence can make the coordination plane perpendicular to the uranyl ion, thereby reducing the steric hindrance during the complexation process.328,329 The hydrophobic interaction can separate the coordinated uranyl ion from the water system and make it stable.<sup>330</sup> As a result, the



**Fig. 18** Ligand selectivity for  $UO_2^{2^+}$  over (a)  $VO_2^{+}$  and (b)  $VO_2^+$  ions. Ligands: acetamidoximate (Acetam); *N*,*N*-dimethylacetamidoximate (Dimeacetam); benzamidoximate (Bzam); and *N*,*N*-dimethylbenzamidoximate (Dimebzam). Reproduced with permission from ref. 270. Copyright 2016, Royal Society of Chemistry.

cyclic imide dioxime with the conjugated structure has higher reactivity towards uranium than amidoxime,123 and the amidoxime group connected with the aromatic moiety is expected to exert excellent uranium coordination ability.331,332 Besides, the spatial distance between amidoxime groups and their amount in each unit also have an impact on uranium adsorption.<sup>301</sup> Amidoxime with an additional di-ethylene spacer unit is reported to more easily anchor uranium than those without the units.333 The adsorbents with bis-amidoximes were found to be more capable of trapping uranyl ions selectively<sup>334</sup> and efficiently335 than those with mono-amidoximes. The relationship between the chemical structure and the adsorption performance needs to be further explored in future research. Based on this further research and combined with arbitrarily designed substrate platforms, such as COFs and POPs, we can design and synthesize adsorption materials with higher uranium affinity.336

The selectivity of amidoxime-based materials for uranium can also be regulated by modifying their chemical structure. As mentioned in Section 4.3, the presence of vanadium in seawater is the biggest obstacle to uranium uptake over amidoximebased adsorbents.<sup>242</sup> Two structures, namely the cyclic imide dioxime<sup>262</sup> and the imino hydroxylamine,<sup>269</sup> may be responsible for the high affinity for vanadyl species. Cyclic imide dioxime can be formed during the synthesis and alkaline conditioning of the polymeric materials.123 As a strong electron donor, it plays an even more important role in the uranium adsorption process than the amidoxime group,<sup>191</sup> and a method of maximizing the cyclic form was thus proposed to enhance the uranium adsorption efficiency.<sup>19,185,337</sup> Obviously, it may be feasible in systems without vanadium, but not for seawater. Recently, the concept of random rotation of functional groups, which offers equal opportunities for active sites and various competing ions to contact,338 has provided new insights into the poor selectivity of materials. Since the complexation of glutaroimide-dioxime with uranium has faster kinetics than that with vanadium,

even if its binding strength is weaker than that of the latter, uranium will preferentially occupy the adsorption sites.<sup>339</sup> Once bonded, the ligand in the 3D hierarchical porous amidoxime fiber can no longer rotate freely owing to the pore confinement effect, thereby avoiding the easy replacement of anchored uranium by vanadium or other ions as the traditional adsorbents do.166 This exhibits the great potential of 3D hierarchical porous structures for improving uranium selectivity. Imino hydroxylamine is formed by tautomeric rearrangement of the amidoxime moiety.<sup>269</sup> Accordingly, the use of structural interventions to prevent the rearrangement can theoretically reduce the affinity of the material for vanadium and thereby increase its selectivity for uranium. One strategy is to remove the amino group from amidoxime.265 This may be beneficial for the uranium selectivity of the material, but not for uranium affinity. Another way is to substitute the amino hydrogen atoms in the amidoxime structure with an alkyl group. This strategy indeed makes the adsorbents much more selective to uranium versus vanadium and ensures the non-compromised affinity of amidoxime for uranium (Fig. 18),<sup>270</sup> which appears to be worthy of widespread promotion. In addition to regulation at the structural level, methods such as ion imprinting340 and bionic technology237 can also be applied to improve the selectivity of materials. Selectivity studies on uranium versus other competitors with adsorbents under different conditions (such as temperature<sup>257</sup> or pH<sup>341</sup>) can guide us to conduct appropriate pretreatments before adsorption and help us to circumvent undesirable reactions. At present, parameters that can be used for the comparison of selectivity between various adsorbents are lacking. It is recommended to establish a standardized operating system or method as soon as possible to quantitatively characterize the selectivity of different materials.

Slow kinetics greatly hamper the practical use of the adsorbents.342 There are many aspects that need to be considered for the improvement of the kinetics. For polymeric adsorbents, the hydrophilic groups on the bifunctional adsorbents can promote the formation of a hydrogel layer on the surface of the material, which contributes to the diffusion of the target ions.<sup>342</sup> For nonpolymer adsorbents, non-porous matrix materials (such as nanodiamonds<sup>78</sup>) and materials with ordered pores structure (such as mesoporous silica<sup>221,224</sup> or COFs<sup>230</sup>) can effectively avoid or accelerate the diffusion of ions in the pores, thereby reducing the equilibrium time. Considering that microorganisms can hinder the contact between uranium and reactive groups and affect the kinetic properties of materials, the development of adsorbents with biological resistance is encouraged. In addition, the combination of the high affinity of the amidoxime group with electrochemical adsorption can provide rapid and massive uranyl uptake,252 which opens up a new idea for simultaneously improving the uptake and kinetics. In the future, further similar work needs to be carried out and more attempts are needed to determine various parameters so as to realize their industrial application as soon as possible.

The regeneration of adsorbents puts forward new requirements for the stability of adsorption materials and the selection of desorption reagents. On the one hand, the adsorbents are supposed to exhibit good mechanical strength, and it would be

better to have separation properties like magnetism. Even if the application of magnetic materials in the field of uranium extraction from seawater is not promising,8 they still have potential in the field of uranium removal from contaminated water on the premise of ensuring magnetic nuclear stability and material properties. In general, more robust matrix materials and stronger functional group bonding have positive significance for improving the reusability of adsorbent materials. The selection of eluting agents, on the other hand, is also crucial. As mentioned in Chapter 6, Na<sub>2</sub>CO<sub>3</sub> solution is better as an eluent than acid solution in terms of selectivity and material protection. The Na<sub>2</sub>CO<sub>3</sub>-H<sub>2</sub>O<sub>2</sub> system is regarded as a promising eluent for regenerating amidoxime-based materials on the premise of controlling the H2O2 content. Moreover, considering that the solution pH is closer to the 8.0-8.3 of seawater, bicarbonate solution is recommended as a better alternative for eluting seawater uranium.14,116 The development of emerging eluents and elution systems has profound practical significance for uranium extraction from seawater. More potential reagents need to be investigated and developed, and the material regeneration tests also need to be refined and systematic.

Uranium extraction from seawater has developed rapidly in recent years. As the most important adsorbent, amidoximebased materials have also made great progress in various aspects. However, there is still a certain distance to realize industrial application. Cost is the most fundamental cause of this situation. Therefore, the development of more advanced materials to cut down the cost of uranium extraction from seawater is a top priority for future research. To achieve this, the following four issues must be addressed: (i) further improving the adsorption performance of the materials, including adsorption capacity, selectivity and kinetics; (ii) further improving the regenerability of the materials and extending their longevity; (iii) further strengthening the study of the binding mechanism and revealing the structure-properties relationship of amidoxime-based materials; and (iv) further improving the environmental adaptability of the materials, such as antifouling property. In these processes, more experiments should be performed in situ rather than in the laboratory and more advanced characterization techniques and theories, such as EXAFS,<sup>245</sup> DFT,<sup>287</sup> de novo design,<sup>304</sup> and first-principles integrated modeling approach,343 are should be used. For materials used for uranium removal from contaminated water, the above ideas still hold true. However, the environment in which materials are exposed may be more variable, which imposes additional requirements on the acid resistance and the optimal adsorption conditions of the adsorbents used. The design, synthesis and application of adsorbents based on the physicochemical properties of the water body to be treated (i.e. "demand-oriented") may lead to more targeted uranium enrichment and separation.

# 8. Conclusion

The fossil energy crisis and radionuclide pollution have attracted increasing attention to the utilization and management of uranium. The exploitation of uranyl resources from seawater is of strategic importance for the energy crisis that mankind is about to face or is facing. Meanwhile, the damage of the ecological environment by uranium pollution also needs to be solved urgently. Amidoxime-based adsorbents as the uranium extractors and scavengers with most potential have been studied over the past four decades. Researchers from Japan, the U.S. and other countries have taken great efforts and made major breakthroughs in this field. In this paper, many aspects of amidoxime-based materials, including synthesis, characterization, types (polymers, carbon-based materials, silica-based materials, biosorbents, new types of porous materials, and others), and influencing factors (pH, temperature, co-existing ions, and biofouling), binding mechanism as well as cost evaluation, were reviewed in detail. From the perspectives of adsorption capacity, selectivity, kinetics and regenerability, different strategies for improving the performance of adsorbents were comprehensively analyzed. In short, the essence of cost reduction lies in the improvement of material performance, and the key to the improvement of material performance lies in the realization of high dispersion and exposure of active sites (herein, amidoxime groups) as much as possible. Moreover, the development of new-generation adsorbents needs to be demand-oriented to meet different needs. It is essential to use more advanced characterization methods and theories to thoroughly explore the binding mechanism between uranium and amidoxime groups and the relationship between the chemical structure and material properties to guide the design and synthesis of next-generation materials. Amidoxime groups should be introduced into more new materials, such as COFs. Perfectly integrating the merits of ligands and matrices enables excellent synergistic effects. Future amidoxime-based materials must have high capacity and selectivity, fast kinetics, good reusability as well as strong antibacterial and acid resistance, which can cope with the complex marine environment and extreme wastewater conditions.

Based on the strong affinity and high selectivity of amidoxime groups towards uranyl ions, the development of newgeneration adsorbents with amidoxime will continue as before. This paper is expected to provide guidance for rationally designing and synthesizing new-generation adsorbents with amidoxime groups and to provide suggestions for solving the technical problems surrounding uranium extraction from seawater and uranium removal from effluents as soon as possible.

# Conflicts of interest

There are no conflicts to declare.

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## References

- J. Milano, H. C. Ong, H. H. Masjuki, W. T. Chong, M. K. Lam, P. K. Loh and V. Vellayan, *Renewable Sustainable Energy Rev.*, 2016, 58, 180–197.
- 2 W. Xing, J. Liang, W. Tang, D. He, M. Yan, X. Wang, Y. Luo, N. Tang and M. Huang, *Desalination*, 2020, **482**, 114390.
- 3 S. Shafiee and E. Topal, Energy Policy, 2009, 37, 181-189.
- 4 N. Abas, A. Kalair and N. Khan, Futures, 2015, 69, 31-49.
- 5 M. Asif and T. Muneer, *Renewable Sustainable Energy Rev.*, 2007, **11**, 1388–1413.
- 6 S. Chu and A. Majumdar, Nature, 2012, 488, 294-303.
- 7 S. Kahouli, Energy Policy, 2011, 39, 358-376.
- 8 C. W. Abney, R. T. Mayes, T. Saito and S. Dai, *Chem. Rev.*, 2017, **117**, 13935–14013.
- 9 S. Das, Y. Oyola, R. T. Mayes, C. J. Janke, L. J. Kuo, G. Gill, J. R. Wood and S. Dai, *Ind. Eng. Chem. Res.*, 2015, 55, 4103–4109.
- 10 C. J. Leggett and L. Rao, Polyhedron, 2015, 95, 54-59.
- 11 R. V. Davies, J. kennedy, R. W. Mcllroy, R. Spence and K. M. Hill, *Nature*, 1964, **203**, 1110–1115.
- 12 B. F. Parker, Z. Zhang, L. Rao and J. Arnold, *Dalton Trans.*, 2018, 47, 639–644.
- 13 L. Xu, J. Hu, H. Ma, C. Ling, M. Wang, R. Shen, X. Guo, Y. Wang, J. Li and G. Wu, *Nucl. Sci. Technol.*, 2017, 28, 45.
- 14 H. Pan, C. M. Wai, L. Kuo, G. Gill, G. Tian, L. Rao, S. Das, R. T. Mayes and C. J. Janke, *ChemistrySelect*, 2017, 2, 3769–3774.
- 15 W. Chouyyok, J. W. Pittman, M. G. Warner, K. M. Nell, D. C. Clubb, G. A. Gill and R. S. Addleman, *Dalton Trans.*, 2016, 45, 11312–11325.
- 16 D. S. Sholl and R. P. Lively, Nature, 2016, 532, 435-437.
- 17 F. Endrizzi and L. Rao, *Chem. Eur. J.*, 2014, **20**, 14499–14506.
- 18 F. Endrizzi, C. J. Leggett and L. Rao, Ind. Eng. Chem. Res., 2016, 55, 4249–4256.
- 19 F. Endrizzi, A. Melchior, M. Tolazzi and L. Rao, *Dalton Trans.*, 2015, 44, 13835–13844.
- 20 S. Das, A. K. Pandey, T. Vasudevan, A. A. Athawale and V. K. Manchanda, *Ind. Eng. Chem. Res.*, 2009, **48**, 6789–6796.
- 21 Y. Yue, R. T. Mayes, J. Kim, P. F. Fulvio, X.-G. Sun, C. Tsouris, J. Chen, S. Brown and S. Dai, *Angew. Chem.*, *Int. Ed.*, 2013, **52**, 13458–13462.
- 22 A. Zhang, T. Asakura and G. Uchiyama, *React. Funct. Polym.*, 2003, 57, 67–76.
- 23 H. Omichi, A. Katakai, T. Sugo and J. Okamoto, Sep. Sci. Technol., 2006, 20, 163–178.
- 24 H. Omichi, A. Katakai, T. Sugo and J. Okamoto, *Sep. Sci. Technol.*, 1986, **21**, 299–313.
- 25 J. Okamoto, T. Sugo, A. Katakai and H. Omichi, *J. Appl. Polym. Sci.*, 1985, **30**, 2967–2977.
- 26 A. Zhang, G. Uchiyama and T. Asakura, *React. Funct. Polym.*, 2005, **63**, 143–153.
- 27 Y. Yue, C. Zhang, Q. Tang, R. T. Mayes, W.-P. Liao, C. Liao, C. Tsouris, J. J. Stankovich, J. Chen, D. K. Hensley,

Published on 20 March 2020. Downloaded on 4/29/2020 2:34:08 AM.

C. W. Abney, D.-e. Jiang, S. Brown and S. Dai, *Ind. Eng. Chem. Res.*, 2015, 55, 4125-4129.

- 28 S. Das, Y. Oyola, R. T. Mayes, C. J. Janke, L. J. Kuo, G. Gill, J. R. Wood and S. Dai, *Ind. Eng. Chem. Res.*, 2015, 55, 4110–4117.
- 29 J. Kim, Y. Oyola, C. Tsouris, C. R. Hexel, R. T. Mayes,
  C. J. Janke and S. Dai, *Ind. Eng. Chem. Res.*, 2013, 52, 9433–9440.
- 30 S. D. Alexandratos, X. Zhu, M. Florent and R. Sellin, Ind. Eng. Chem. Res., 2016, 55, 4208-4216.
- 31 H. Pan, L. Kuo, J. Wood, J. Strivens, G. A. Gill, C. J. Janke and C. M. Wai, *RSC Adv.*, 2015, 5, 100715–100721.
- 32 T. Wang, T. Khangaonkar, W. Long and G. Gill, *J. Mari. Sci. Eng.*, 2014, 2, 81–92.
- 33 J. Górka, R. T. Mayes, L. Baggetto, G. M. Veith and S. Dai, J. Mater. Chem. A, 2013, 1, 3016–3026.
- 34 M. J. Manos and M. G. Kanatzidis, J. Am. Chem. Soc., 2012, 134, 16441–16446.
- 35 L. Zhou, M. Bosscher, C. Zhang, S. Ozcubukcu, L. Zhang, W. Zhang, C. J. Li, J. Liu, M. P. Jensen, L. Lai and C. He, *Nat. Chem.*, 2014, 6, 236–241.
- 36 K. Sekiguchi, K. Saito, S. Konishi and S. Furusaki, *Ind. Eng. Chem. Res.*, 1994, **33**, 662–666.
- 37 T. Suzuki, K. Saito, T. Sugo, H. Ogura and K. Oguma, *Anal. Sci.*, 2000, 16, 429–432.
- 38 K. Hara, S. Fujiwara, T. Fujii, S. Yoshioka, Y. Hidaka and H. Okabe, *Prog. Nucl. Energy*, 2016, 92, 228–233.
- 39 S. H. Choi, M. S. Choi, Y. T. Park, K. P. Lee and H. D. Kang, *Radiat. Phys. Chem.*, 2003, 67, 387–390.
- 40 W. Wongjaikham, D. Wongsawaeng and P. Hosemann, J. Nucl. Sci. Technol., 2019, 56, 541–552.
- 41 S. Su, R. Chen, Q. Liu, J. Liu, H. Zhang, R. Li, M. Zhang, P. Liu and J. Wang, *Chem. Eng. J.*, 2018, 345, 526–535.
- 42 J. Zhang, H. Zhang, Q. Liu, D. Song, R. Li, P. Liu and J. Wang, *Chem. Eng. J.*, 2019, **368**, 951–958.
- 43 F. Wu, N. Pu, G. Ye, T. Sun, Z. Wang, Y. Song, W. Wang,
   X. Huo, Y. Lu and J. Chen, *Environ. Sci. Technol.*, 2017, 51, 4606–4614.
- 44 V. S. Neti, S. Das, S. Brown, C. J. Janke, L.-J. Kuo, G. A. Gill, S. Dai and R. T. Mayes, *Ind. Eng. Chem. Res.*, 2017, 56, 10826–10832.
- 45 P. C. Burns, R. C. Ewing and A. Navrotsky, *Science*, 2012, 335, 1184–1188.
- 46 P. Metilda, K. Prasad, R. Kala, J. M. Gladis, T. P. Rao and G. R. K. Naidu, *Anal. Chim. Acta*, 2007, **582**, 147–153.
- 47 T. P. Rao, P. Metilda and J. M. Gladis, *Talanta*, 2006, 68, 1047–1064.
- 48 P. Kurttio, A. Harmoinen, H. Saha, L. Salonen, Z. Karpas,
  H. Komulainen and A. Auvinen, *Am. J. Kidney Dis.*, 2006,
  47, 972–982.
- 49 F. Fan, Z. Qin, J. Bai, W. Rong, F. Fan, W. Tian, X. Wu, Y. Wang and L. Zhao, *J. Environ. Radioact.*, 2012, **106**, 40–46.
- 50 Y. He, S. Li, X. Li, Y. Yang, A. Tang, L. Du, Z. Tan, D. Zhang and H. Chen, *Chem. Eng. J.*, 2018, **338**, 333–340.
- 51 Y. Xie, C. Chen, X. Ren, X. Wang, H. Wang and X. Wang, *Prog. Mater. Sci.*, 2019, **103**, 180–234.

- 52 Y. Zhao, X. Wang, J. Li and X. Wang, *Polym. Chem.*, 2015, 6, 5376–5384.
- 53 C. Xie, S. Jing, Y. Wang, X. Lin, H. Bao, C. Guan, C. Jin and J. Wang, *Nucl. Sci. Technol.*, 2017, 28, 94.
- 54 O. Hazer and S. Kartal, Talanta, 2010, 82, 1974–1979.
- 55 A. P. Gilman, D. C. Villeneuve, V. E. Secours, A. P. Yagminas, B. L. Tracy, J. M. Quinn, V. E. Valli, R. J. Willes and M. A. Moss, *Toxicol. Sci.*, 1998, **41**, 117–128.
- 56 H. H. El-Maghrabi, S. M. Abdelmaged, A. A. Nada, F. Zahran, S. A. El-Wahab, D. Yahea, G. M. Hussein and M. S. Atrees, *J. Hazard. Mater.*, 2017, **322**, 370–379.
- 57 M. S. Diallo, M. R. Kotte and M. Cho, *Environ. Sci. Technol.*, 2015, **49**, 9390–9399.
- 58 A. Mellah, S. Chegrouche and M. Barkat, J. Colloid Interface Sci., 2006, 296, 434–441.
- 59 Y. Dong, Z. Dong, Z. Zhang, Y. Liu, W. Cheng, H. Miao, X. He and Y. Xu, ACS Appl. Mater. Interfaces, 2017, 9, 22088–22092.
- 60 M. J. Comarmond, T. E. Payne, J. J. Harrison, S. Thiruvoth, H. K. Wong, R. D. Aughterson, G. R. Lumpkin, K. Muller and H. Foerstendorf, *Environ. Sci. Technol.*, 2011, 45, 5536–5542.
- 61 R. Donat, J. Chem. Thermodyn., 2009, 41, 829-835.
- W. Linghu, Y. Sun, H. Yang, K. Chang, J. Ma, Y. Huang, W. Dong, A. Alsaedi and T. Hayat, *J. Radioanal. Nucl. Chem.*, 2017, **314**, 1825–1832.
- 63 S. Ma, L. Huang, L. Ma, Y. Shim, S. M. Islam, P. Wang,
  L. D. Zhao, S. Wang, G. Sun, X. Yang and
  M. G. Kanatzidis, *J. Am. Chem. Soc.*, 2015, 137, 3670–3677.
- 64 K. Oshita, A. Sabarudin, T. Takayanagi, M. Oshima and S. Motomizu, *Talanta*, 2009, **79**, 1031–1035.
- 65 T. S. Anirudhan, L. Divya and P. S. Suchithra, *J. Environ. Manage.*, 2009, **90**, 549–560.
- 66 L. Dong, J. Yang, Y. Mou, G. Sheng, L. Wang, W. Linghu, A. M. Asiri and K. A. Alamry, J. Radioanal. Nucl. Chem., 2017, 314, 377–386.
- 67 G. Huang, W. Li, Q. Liu, J. Liu, H. Zhang, R. Li, Z. Li, X. Jing and J. Wang, *New J. Chem.*, 2018, **42**, 168–176.
- 68 G. Tian, J. Geng, Y. Jin, C. Wang, S. Li, Z. Chen, H. Wang,
  Y. Zhao and S. Li, *J. Hazard. Mater.*, 2011, **190**, 442–450.
- 69 J. Zhu, Q. Liu, Z. Li, J. Liu, H. Zhang, R. Li and J. Wang, J. Hazard. Mater., 2018, 353, 9–17.
- 70 R. Sellin and S. D. Alexandratos, *Ind. Eng. Chem. Res.*, 2013, 52, 11792–11797.
- 71 P. Yang, Q. Liu, J. Liu, R. Chen, R. Li, X. Bai and J. Wang, *J. Hazard. Mater.*, 2019, **363**, 248–257.
- 72 P. Singhal, B. G. Vats, A. Yadav and V. Pulhani, J. Hazard. Mater., 2020, 384, 121353.
- 73 J. Li, X. Yang, C. Bai, Y. Tian, B. Li, S. Zhang, X. Yang, S. Ding, C. Xia, X. Tan, L. Ma and S. Li, *J. Colloid Interface Sci.*, 2015, 437, 211–218.
- 74 S. Zhang, X. Shu, Y. Zhou, L. Huang and D. Hua, *Chem. Eng. J.*, 2014, 253, 55–62.
- 75 L. L. Wang, F. Luo, L. L. Dang, J. Q. Li, X. L. Wu, S. J. Liu and M. B. Luo, *J. Mater. Chem. A*, 2015, 3, 13724–13730.
- 76 P. Metilda, K. Sanghamitra, J. Mary Gladis, G. R. Naidu and T. Prasada Rao, *Talanta*, 2005, 65, 192–200.

- 77 J. Wang and S. Zhuang, *Rev. Environ. Sci. Biotechnol.*, 2019, 18, 437–452.
- 78 Y. Li, L. Wang, B. Li, M. Zhang, R. Wen, X. Guo, X. Li, J. Zhang, S. Li and L. Ma, ACS Appl. Mater. Interfaces, 2016, 8, 28853–28861.
- 79 H. J. Schenk, L. Astheimer, E. G. Witte and K. Schwochau, *Sep. Sci. Technol.*, 1982, **17**, 1293–1308.
- 80 X. Liu, H. Liu, H. Ma, C. Cao, M. Yu, Z. Wang, B. Deng, M. Wang and J. Li, *Ind. Eng. Chem. Res.*, 2012, **51**, 15089– 15095.
- 81 N. Seko, A. Katakai, S. Hasegawa, M. Tamada, N. Kasai, H. Takeda, T. Sugo and K. Saito, *Nucl. Technol.*, 2017, 144, 274–278.
- 82 J. Kim, C. Tsouris, Y. Oyola, C. J. Janke, R. T. Mayes, S. Dai, G. Gill, L. J. Kuo, J. Wood, K. Y. Choe, E. Schneider and H. Lindner, *Ind. Eng. Chem. Res.*, 2014, **53**, 6076–6083.
- 83 D. Yuan, L. Chen, X. Xiong, L. Yuan, S. Liao and Y. Wang, *Chem. Eng. J.*, 2016, 285, 358–367.
- 84 S. Xie, X. Liu, B. Zhang, H. Ma, C. Ling, M. Yu, L. Li and J. Li, J. Mater. Chem. A, 2015, 3, 2552–2558.
- 85 J. Kim, C. Tsouris, R. T. Mayes, Y. Oyola, T. Saito, C. J. Janke,
  S. Dai, E. Schneider and D. Sachde, *Sep. Sci. Technol.*, 2013,
  48, 367–387.
- 86 M. Gao, G. Zhu and C. Gao, *Energy Environ. Focus*, 2014, 3, 219–226.
- 87 M. M. Aly and M. F. Hamza, J. Dispersion Sci. Technol., 2013, 34, 182–213.
- 88 F. Eloy and R. Lenaers, Chem. Rev., 1962, 62, 155-183.
- 89 R. M. Srivastava, M. C. Pereira, W. W. M. Faustino, K. Coutinho, J. V. dos Anjos and S. J. de Melo, *Monatsh. Chem.*, 2009, **140**, 1319–1324.
- 90 D. S. Bolotin, N. A. Bokach and V. Y. Kukushkin, *Coord. Chem. Rev.*, 2016, 313, 62–93.
- 91 H. Egawa and H. Harada, *Nippon Kagaku Kaishi*, 1979, **1979**, 958–959.
- 92 C. Yang, J. Han, J. Liu, M. Gu, Y. Li, J. Wen, H. Yu, S. Hu and X. Wang, Org. Biomol. Chem., 2015, 13, 2541–2545.
- 93 S. Brown, S. Chatterjee, M. Li, Y. Yue, C. Tsouris, C. J. Janke,
   T. Saito and S. Dai, *Ind. Eng. Chem. Res.*, 2015, 55, 4130–4138.
- 94 F. G. Bordwell and G. Ji, J. Org. Chem., 1992, 57, 3019-3025.
- 95 K. Z. Elwakeel, A. A. El-Bindary, E. Y. Kouta and E. Guibal, *Chem. Eng. J.*, 2018, **332**, 727–736.
- 96 S. Zhuang, R. Cheng, M. Kang and J. Wang, J. Cleaner Prod., 2018, 188, 655–661.
- 97 J. Chen, R. Qu, Y. Zhang, C. Sun, C. Wang, C. Ji, P. Yin, H. Chen and Y. Niu, *Chem. Eng. J.*, 2012, **209**, 235–244.
- 98 J. Wu, K. Tian and J. Wang, *Prog. Nucl. Energy*, 2018, **106**, 79–86.
- 99 H. Chen, D. Shao, J. Li and X. Wang, *Chem. Eng. J.*, 2014, 254, 623–634.
- 100 E. S. Dragan, D. F. Apopei Loghin and A. I. Cocarta, ACS Appl. Mater. Interfaces, 2014, 6, 16577-16592.
- 101 Y. Zhao, J. Li, S. Zhang and X. Wang, *RSC Adv.*, 2014, 4, 32710–32717.
- 102 J. Liu, T. Liu, C. Wang, X. Yin and Z. Xiong, *J. Mol. Liq.*, 2017, **242**, 531–536.

- 103 Y. Zhao, J. Li, L. Zhao, S. Zhang, Y. Huang, X. Wu and X. Wang, *Chem. Eng. J.*, 2014, **235**, 275–283.
- 104 Y. Zhao, J. Li, S. Zhang, H. Chen and D. Shao, *RSC Adv.*, 2013, 3, 18952–18959.
- 105 P. A. Kavakli, N. Seko, M. Tamada and O. Güven, *Adsorption*, 2005, **10**, 309–315.
- 106 M. F. Hamza, J. C. Roux and E. Guibal, *Chem. Eng. J.*, 2018, 344, 124–137.
- 107 Y. Wang, X. Ma, Y. Li, X. Li, L. Yang, L. Ji and Y. He, *Chem. Eng. J.*, 2012, **209**, 394–400.
- 108 Z. Zhang, Z. Dong, X. Wang, D. Ying, F. Niu, X. Cao, Y. Wang, R. Hua, Y. Liu and X. Wang, *Chem. Eng. J.*, 2018, 341, 208–217.
- 109 C. Gunathilake, J. Górka, S. Dai and M. Jaroniec, *J. Mater. Chem. A*, 2015, **3**, 11650–11659.
- 110 T. S. Anirudhan, G. S. Lekshmi and F. Shainy, J. Colloid Interface Sci., 2019, 534, 248–261.
- 111 H. Yu, S. Yang, H. Ruan, J. Shen, C. Gao and B. Van der Bruggen, *Appl. Clay Sci.*, 2015, **111**, 67–75.
- 112 N. Seko, M. Tamada and F. Yoshii, *Nucl. Instrum. Methods Phys. Res., Sect. B*, 2005, **236**, 21–29.
- 113 J. Liu, X. Yin and T. Liu, *J. Taiwan Inst. Chem. Eng.*, 2019, **95**, 416–423.
- 114 H. Egawa, T. Nonaka and M. Nakayama, *J. Macromol. Sci., Chem.*, 1988, **25**, 1407–1425.
- 115 L. Chen, Z. Bai, L. Zhu, L. Zhang, Y. Cai, Y. Li, W. Liu, Y. Wang, L. Chen, J. Diwu, J. Wang, Z. Chai and S. Wang, ACS Appl. Mater. Interfaces, 2017, 9, 32446–32451.
- 116 L. J. Kuo, H. B. Pan, C. M. Wai, M. F. Byers, E. Schneider, J. E. Strivens, C. J. Janke, S. Das, R. T. Mayes, J. R. Wood, N. Schlafer and G. A. Gill, *Ind. Eng. Chem. Res.*, 2017, 56, 11603–11611.
- 117 Y. H. Sihn, J. Byun, H. A. Patel, W. Lee and C. T. Yavuz, *RSC Adv.*, 2016, 6, 45968–45976.
- 118 J. Geng, L. Ma, H. Wang, J. Liu, C. Bai, Q. Song, J. Li, M. Hou and S. Li, *J. Nanosci. Nanotechnol.*, 2012, **12**, 7354–7363.
- 119 Y. Wang, Z. Wang, R. Ang, J. Yang, N. Liu, J. Liao, Y. Yang and J. Tang, *RSC Adv.*, 2015, **5**, 89309–89318.
- 120 N. Kabay, A. Katakai, T. Sugo and H. Egawa, *J. Appl. Polym. Sci.*, 1993, **49**, 599–607.
- 121 N. A. M. Zahri, S. N. A. M. Jamil, L. C. Abdullah, T. c. S. Y. Yaw, M. N. Mobarekeh, S. J. Huey and N. S. M. Rapeia, *Polymers*, 2015, 7, 1205–1220.
- 122 C. J. Leggett, F. Endrizzi and L. Rao, *Ind. Eng. Chem. Res.*, 2015, **55**, 4257–4263.
- 123 S. Das, S. Brown, R. T. Mayes, C. J. Janke, C. Tsouris, L. J. Kuo, G. Gill and S. Dai, *Chem. Eng. J.*, 2016, **298**, 125– 135.
- 124 S. Das, A. K. Pandey, A. A. Athawale and V. K. Manchanda, *J. Phys. Chem. B*, 2009, **113**, 6328–6335.
- 125 W. P. Li, X. Y. Han, X. Y. Wang, Y. Q. Wang, W. X. Wang, H. Xu, T. S. Tan, W. S. Wu and H. X. Zhang, *Chem. Eng. J.*, 2015, **279**, 735–746.
- 126 Y. Yang, J. Wang, F. Wu, G. Ye, R. Yi, Y. Lu and J. Chen, *Polym. Chem.*, 2016, 7, 2427–2435.

- 127 N. Mehio, M. A. Lashely, J. W. Nugent, L. Tucker, B. Correia, C. L. Do-Thanh, S. Dai, R. D. Hancock and V. S. Bryantsev, J. Phys. Chem. B, 2015, 119, 3567–3576.
- 128 T. S. Anirudhan and M. Ramachandran, *Ind. Eng. Chem. Res.*, 2008, 47, 6175-6184.
- 129 G. Bayramoglu and M. Y. Arica, *Microporous Mesoporous Mater.*, 2016, **226**, 117–124.
- 130 F. Ma, B. Dong, Y. Gui, M. Cao, L. Han, C. Jiao, H. Lv, J. Hou and Y. Xue, *Ind. Eng. Chem. Res.*, 2018, **57**, 17384–17393.
- 131 N. Tang, C. G. Niu, X. T. Li, C. Liang, H. Guo, L. S. Lin,
  C. W. Zheng and G. M. Zeng, *Sci. Total Environ.*, 2018,
  635, 1331–1344.
- 132 Z. Dai, H. Zhang, Y. Sui, D. Ding, N. Hu, L. Li and Y. Wang, J. Radioanal. Nucl. Chem., 2018, 316, 369–382.
- 133 L. P. F. de Morais, F. Hallwass, I. Malvestiti and R. M. Srivastava, *J. Mol. Struct.*, 2006, **782**, 200–203.
- 134 U. Girreser, M. König and B. Clement, *Magn. Reson. Chem.*, 2002, **40**, 202–206.
- 135 C. Gunathilake and M. Jaroniec, *ACS Appl. Mater. Interfaces*, 2014, **6**, 13069–13078.
- 136 H. Egawa, N. Kabay, T. Shuto and A. Jyo, *J. Appl. Polym. Sci.*, 1992, 46, 129–142.
- 137 B. Li, Q. Sun, Y. Zhang, C. W. Abney, B. Aguila, W. Lin and S. Ma, ACS Appl. Mater. Interfaces, 2017, 9, 12511–12517.
- 138 B. Wang, Y. Zhou, L. Li and Y. Wang, *Sci. Total Environ.*, 2018, **626**, 219–227.
- 139 D. Shao, X. Liu, T. Hayat, J. Li and X. Ren, *J. Radioanal. Nucl. Chem.*, 2019, **319**, 379–386.
- 140 F. Wang, H. Li, Q. Liu, Z. Li, R. Li, H. Zhang, L. Liu, G. A. Emelchenko and J. Wang, *Sci. Rep.*, 2016, **6**, 19367.
- 141 A. P. Ladshaw, A. I. Wiechert, S. Das, S. Yiacoumi and C. Tsouris, *Materials*, 2017, **10**, 1268.
- 142 G. S. Chauhan and A. Kumar, *J. Appl. Polym. Sci.*, 2008, **110**, 3795–3803.
- 143 L. Xie, Y. Wang, Y. Wang, X. Li, Q. Tian, D. Liu, G. Sun and X. Wang, *Mater. Lett.*, 2018, **220**, 47–49.
- 144 T. Saito, S. Brown, S. Chatterjee, J. Kim, C. Tsouris, R. T. Mayes, L. J. Kuo, G. Gill, Y. Oyola, C. J. Janke and S. Dai, *J. Mater. Chem. A*, 2014, 2, 14674–14681.
- 145 H. Malik, U. A. Qureshi, M. Muqeet, R. B. Mahar, F. Ahmed and Z. Khatri, *Environ. Sci. Pollut. Res.*, 2018, **25**, 3557–3564.
- 146 Y. Wang, Z. Gu, J. Yang, J. Liao, Y. Yang, N. Liu and J. Tang, *Appl. Surf. Sci.*, 2014, **320**, 10–20.
- 147 W. Wongjaikham, D. Wongsawaeng, P. Hosemann, C. Kanokworakan and V. Ratnitsai, *J. Environ. Chem. Eng.*, 2018, 6, 2768–2777.
- 148 A. Kanjilal, K. K. Singh, K. K. Bairwa and M. Kumar, *Polym. Eng. Sci.*, 2019, **59**, 863–872.
- 149 H. Zhao, X. Liu, M. Yu, Z. Wang, B. Zhang, H. Ma, M. Wang and J. Li, *Ind. Eng. Chem. Res.*, 2015, **54**, 3101–3106.
- 150 N. Seko, A. Katakai, M. Tamada, T. Sugo and F. Yoshii, *Sep. Sci. Technol.*, 2005, **39**, 3753–3767.
- 151 S. H. Choi and Y. C. Nho, *Radiat. Phys. Chem.*, 2000, 58, 157–168.
- 152 M. M. Nasef and O. Güven, *Prog. Polym. Sci.*, 2012, **37**, 1597–1656.

- 153 F. Chi, J. Wen, J. Xiong, H. Sheng, Z. Gong, T. Qiu, G. Wei, F. Yi and X. Wang, *J. Radioanal. Nucl. Chem.*, 2015, **309**, 787–796.
- 154 T. Kawai, K. Saito, K. Sugita, T. Kawakami, J.-i. Kanno, A. Katakai, N. Seko and T. Sugo, *Radiat. Phys. Chem.*, 2000, **59**, 405–411.
- 155 Y. Oyola and S. Dai, Dalton Trans., 2016, 45, 8824-8834.
- 156 Z. Zeng, Y. Wei, L. Shen and D. Hua, *Ind. Eng. Chem. Res.*, 2015, **54**, 8699–8705.
- 157 R. Li, H. Ma, Z. Xing and G. Wu, *J. Radioanal. Nucl. Chem.*, 2017, **315**, 111–117.
- 158 H. Zhang, L. Zhang, X. Han, L. Kuang and D. Hua, *Ind. Eng. Chem. Res.*, 2018, **57**, 1662–1670.
- 159 P. A. Kavaklı, N. Seko, M. Tamada and O. Güven, *Sep. Sci. Technol.*, 2005, **39**, 1631–1643.
- 160 Y. Oyola, C. J. Janke and S. Dai, *Ind. Eng. Chem. Res.*, 2016, 55, 4149–4160.
- 161 Q. Gao, J. Hu, R. Li, Z. Xing, L. Xu, M. Wang, X. Guo and G. Wu, *Radiat. Phys. Chem.*, 2016, 122, 1–8.
- 162 Z. Xing, J. Hu, M. Wang, W. Zhang, S. Li, Q. Gao and G. Wu, *Sci. China: Chem.*, 2013, **56**, 1504–1509.
- 163 R. Li, L. Pang, H. Ma, X. Liu, M. Zhang, Q. Gao, H. Wang, Z. Xing, M. Wang and G. Wu, *J. Radioanal. Nucl. Chem.*, 2017, **311**, 1771–1779.
- 164 J. Hu, H. Ma, Z. Xing, X. Liu, L. Xu, R. Li, C. Lin, M. Wang, J. Li and G. Wu, *Ind. Eng. Chem. Res.*, 2015, 55, 4118–4124.
- 165 X. Xu, X. Ding, J. Ao, R. Li, Z. Xing, X. Liu, X. Guo, G. Wu,
  H. Ma and X. Zhao, *Nucl. Sci. Technol.*, 2019, **30**, 20.
- 166 X. Xu, H. Zhang, J. Ao, L. Xu, X. Liu, X. Guo, J. Li, L. Zhang, Q. Li, X. Zhao, B. Ye, D. Wang, F. Shen and H. Ma, *Energy Environ. Sci.*, 2019, **12**, 1979–1988.
- 167 M. Zhang, Q. Gao, C. Yang, L. Pang, H. Wang, H. Li, R. Li, L. Xu, Z. Xing, J. Hu and G. Wu, *Ind. Eng. Chem. Res.*, 2016, 55, 10523–10532.
- 168 V. Coessens, T. Pintauer and K. Matyjaszewski, *Prog. Polym. Sci.*, 2001, 26, 337–377.
- 169 S. Chatterjee, V. S. Bryantsev, S. Brown, J. C. Johnson, C. D. Grant, R. T. Mayes, B. P. Hay, S. Dai and T. Saito, *Ind. Eng. Chem. Res.*, 2016, 55, 4161–4169.
- 170 L. Huang, L. Zhang and D. Hua, J. Radioanal. Nucl. Chem., 2015, **305**, 445–453.
- 171 Y. Wei, J. Qian, L. Huang and D. Hua, *RSC Adv.*, 2015, 5, 64286–64292.
- 172 T. Kawai, K. Saito, K. Sugita, A. Katakai, N. Seko, T. Sugo, J.-i. Kanno and T. Kawakami, *Ind. Eng. Chem. Res.*, 2000, 39, 2910–2915.
- 173 M. Piechowicz, C. W. Abney, X. Zhou, N. C. Thacker, Z. Li and W. Lin, *Ind. Eng. Chem. Res.*, 2016, 55, 4170–4178.
- 174 Y. Cheng, P. He, F. Dong, X. Nie, C. Ding, S. Wang,Y. Zhang, H. Liu and S. Zhou, *Chem. Eng. J.*, 2019, 367, 198–207.
- 175 C. Wang, J. Lan, Q. Wu, Q. Luo, Y. Zhao, X. Wang, Z. Chai and W. Shi, *Inorg. Chem.*, 2014, **53**, 9466–9476.
- 176 J. L. Vivero-Escoto, M. Carboni, C. W. Abney, K. E. deKrafft and W. Lin, *Microporous Mesoporous Mater.*, 2013, **180**, 22– 31.

- 177 S. Katragadda, H. D. Gesser and A. Chow, *Talanta*, 1997, **44**, 1865–1871.
- 178 S. O. Kang, S. Vukovic, R. Custelcean and B. P. Hay, *Ind. Eng. Chem. Res.*, 2012, **51**, 6619–6624.
- 179 S. Das, C. Tsouris, C. Zhang, J. Kim, S. Brown, Y. Oyola,
  C. J. Janke, R. T. Mayes, L. J. Kuo, J. R. Wood, G. A. Gill and S. Dai, *Ind. Eng. Chem. Res.*, 2015, 55, 4294–4302.
- 180 H. B. Pan, L. J. Kuo, C. M. Wai, N. Miyamoto, R. Joshi, J. R. Wood, J. E. Strivens, C. J. Janke, Y. Oyola, S. Das, R. T. Mayes and G. A. Gill, *Ind. Eng. Chem. Res.*, 2016, 55, 4313–4320.
- 181 T. Kago, A. Goto, K. Kusakabe and S. Morooka, *Ind. Eng. Chem. Res.*, 1992, **31**, 204–209.
- 182 S. Das, A. K. Pandey, A. Athawale, V. Kumar, Y. K. Bhardwaj, S. Sabharwal and V. K. Manchanda, *Desalination*, 2008, 232, 243–253.
- 183 A. Zhang, G. Uchiyama and T. Asakura, Sep. Sci. Technol., 2003, 38, 1829–1849.
- 184 H. Omichi, A. Katakai, T. Sugo and J. Okamoto, Sep. Sci. Technol., 2006, 21, 563–574.
- 185 Y. Kobuke, H. Tanaka and H. Ogoshi, *Polym. J.*, 1990, **22**, 179–182.
- 186 L. Astheimer, H. J. Schenk, E. G. Witte and K. Schwochau, *Sep. Sci. Technol.*, 1983, **18**, 307–339.
- 187 G. Tian, S. J. Teat, Z. Zhang and L. Rao, *Dalton Trans.*, 2012, 41, 11579–11586.
- 188 S. Das, W. P. Liao, M. Flicker Byers, C. Tsouris, C. J. Janke, R. T. Mayes, E. Schneider, L. J. Kuo, J. R. Wood, G. A. Gill and S. Dai, *Ind. Eng. Chem. Res.*, 2015, 55, 4303–4312.
- 189 H. B. Pan, C. M. Wai, L. J. Kuo, G. A. Gill, J. S. Wang, R. Joshi and C. J. Janke, *Dalton Trans.*, 2020, 49, 2803–2810.
- 190 J. A. Drysdale and K. O. Buesseler, *Prog. Nucl. Energy*, 2020, 119, 103170.
- 191 D. Wang, J. Song, J. Wen, Y. Yuan, Z. Liu, S. Lin, H. Wang, H. Wang, S. Zhao, X. Zhao, M. Fang, M. Lei, B. Li, N. Wang, X. Wang and H. Wu, *Adv. Energy Mater.*, 2018, 8, 1802607.
- 192 R. Demir-Cakan, N. Baccile, M. Antonietti and M. M. Titirici, *Chem. Mater.*, 2009, **21**, 484–490.
- 193 R. Ryoo, S. H. Joo, M. Kruk and M. Jaroniec, *Adv. Mater.*, 2001, **13**, 677–681.
- 194 A. Y. Romanchuk, A. S. Slesarev, S. N. Kalmykov, D. V. Kosynkin and J. M. Tour, *Phys. Chem. Chem. Phys.*, 2013, **15**, 2321–2327.
- 195 Z. Zhang, Z. Dong, Y. Dai, S. Xiao, X. Cao, Y. Liu, W. Guo,
   M. Luo and Z. Le, *RSC Adv.*, 2016, 6, 102462–102471.
- 196 I. I. Fasfous and J. N. Dawoud, *Appl. Surf. Sci.*, 2012, 259, 433–440.
- 197 P. Yang, H. Zhang, Q. Liu, J. Liu, R. Chen, J. Yu, J. Hou, X. Bai and J. Wang, *J. Hazard. Mater.*, 2019, 375, 320–329.
- 198 D. Shao, J. Li and X. Wang, *Sci. China: Chem.*, 2014, 57, 1449–1458.
- 199 M. Carboni, C. W. Abney, K. M. L. Taylor-Pashow, J. L. Vivero-Escoto and W. Lin, *Ind. Eng. Chem. Res.*, 2013, 52, 15187–15197.
- 200 D. V. Kosynkin, A. L. Higginbotham, A. Sinitskii, J. R. Lomeda, A. Dimiev, B. K. Price and J. M. Tour, *Nature*, 2009, **458**, 872–876.

- 201 M. Choi and R. Ryoo, Nat. Mater., 2003, 2, 473-476.
- 202 X. Yang, J. Li, J. Liu, Y. Tian, B. Li, K. Cao, S. Liu, M. Hou, S. Li and L. Ma, *J. Mater. Chem. A*, 2014, 2, 1550–1559.
- 203 Z. Dai, H. Zhang, Y. Sui, D. Ding and L. Li, J. Chem. Eng. Data, 2018, 63, 4215–4225.
- 204 N. K. Gupta, A. Sengupta, A. Gupta, J. R. Sonawane and H. Sahoo, *J. Environ. Chem. Eng.*, 2018, **6**, 2159–2175.
- 205 S. V. Bhat, J. S. Melo, B. B. Chaugule and S. F. D'Souza, J. Hazard. Mater., 2008, 158, 628–635.
- 206 R. A. A. Muzzarelli, Carbohydr. Polym., 2011, 84, 54-63.
- 207 J. Bai, X. Yin, Y. Zhu, F. Fan, X. Wu, W. Tian, C. Tan, X. Zhang, Y. Wang, S. Cao, F. Fan, Z. Qin and J. Guo, *Chem. Eng. J.*, 2016, **283**, 889–895.
- 208 L. Li, N. Hu, D. Ding, X. Xin, Y. Wang, J. Xue, H. Zhang and Y. Tan, *RSC Adv.*, 2015, **5**, 65827–65839.
- 209 G. Bayramoglu and M. Y. Arica, J. Radioanal. Nucl. Chem., 2015, **307**, 373–384.
- 210 S. Lu, L. Chen, M. F. Hamza, C. He, X. Wang, Y. Wei and E. Guibal, *Chem. Eng. J.*, 2019, **368**, 459–473.
- 211 G. Bayramoglu, A. Akbulut and M. Y. Arica, *Environ. Sci. Pollut. Res.*, 2015, **22**, 17998–18010.
- 212 Z. Yin, J. Xiong, M. Chen, S. Hu and H. Cheng, *J. Radioanal. Nucl. Chem.*, 2016, **307**, 1471–1479.
- 213 H. Ma, F. Zhang, Q. Li, G. Chen, S. Hu and H. Cheng, *RSC Adv.*, 2019, **9**, 18406–18414.
- 214 T. S. Anirudhan, L. Divya and P. S. Suchithra, *Toxicol. Environ. Chem.*, 2009, **91**, 1237–1252.
- 215 S. Ş. Başarır and N. P. Bayramgil, *Cellulose*, 2013, **20**, 827–839.
- 216 A. Walcarius and L. Mercier, *J. Mater. Chem.*, 2010, **20**, 4478–4511.
- 217 A. Mehdi, C. Reye and R. Corriu, *Chem. Soc. Rev.*, 2011, **40**, 563–574.
- 218 P. Van der Voort, D. Esquivel, E. De Canck, F. Goethals,
  I. Van Driessche and F. J. Romero-Salguero, *Chem. Soc. Rev.*, 2013, 42, 3913–3955.
- 219 J. Xiao, Y. Jing, Y. Yao, X. Wang and Y. Jia, *J. Mol. Liq.*, 2019, 277, 843–855.
- 220 X. Yin, J. Bai, W. Tian, S. Li, J. Wang, X. Wu, Y. Wang,
  F. Fan, Q. Huang and Z. Qin, *J. Radioanal. Nucl. Chem.*,
  2017, 313, 113-121.
- 221 X. Wang, G. Ji, G. Zhu, C. Song, H. Zhang and C. Gao, *Sep. Purif. Technol.*, 2019, **209**, 623–635.
- 222 G. Ji, G. Zhu, X. Wang, Y. Wei, J. Yuan and C. Gao, *Sep. Purif. Technol.*, 2017, **174**, 455–465.
- 223 S. Y. Chen, C. Y. Tang, W. T. Chuang, J. J. Lee, Y. L. Tsai, J. C. C. Chan, C. Y. Lin, Y. C. Liu and S. Cheng, *Chem. Mater.*, 2008, **20**, 3906–3916.
- 224 M. Gao, G. Zhu, X. Wang, P. Wang and C. Gao, *J. Radioanal. Nucl. Chem.*, 2015, **304**, 675–682.
- 225 F. Li, X. Li, P. Cui and Y. Sun, *Environ. Sci.: Nano*, 2018, 5, 2000–2008.
- 226 C. S. Diercks and O. M. Yaghi, Science, 2017, 355, eaal1585.
- 227 N. Huang, L. Zhai, H. Xu and D. Jiang, J. Am. Chem. Soc., 2017, **139**, 2428–2434.
- 228 X. Feng, X. Ding and D. Jiang, Chem. Soc. Rev., 2012, 41, 6010-6022.

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- 229 Q. Sun, B. Aguila and S. Ma, Trends Chem., 2019, 1, 292–303.
- 230 C. Bai, M. Zhang, B. Li, X. Zhao, S. Zhang, L. Wang, Y. Li, J. Zhang, L. Ma and S. Li, *RSC Adv.*, 2016, **6**, 39150–39158.
- 231 Q. Sun, B. Aguila, L. D. Earl, C. W. Abney, L. Wojtas, P. K. Thallapally and S. Ma, *Adv. Mater.*, 2018, **30**, 1705479.
- 232 B. Aguila, Q. Sun, H. Cassady, C. W. Abney, B. Li and S. Ma, *ACS Appl. Mater. Interfaces*, 2019, **11**, 30919–30926.
- 233 B. Satilmis, T. Isık, M. M. Demir and T. Uyar, *Appl. Surf. Sci.*, 2019, **467–468**, 648–657.
- 234 A. G. Slater and A. I. Cooper, Science, 2015, 348, 8075.
- 235 S. Das, P. Heasman, T. Ben and S. Qiu, *Chem. Rev.*, 2017, 117, 1515–1563.
- 236 S. O. Odoh, G. D. Bondarevsky, J. Karpus, Q. Cui, C. He, R. Spezia and L. Gagliardi, *J. Am. Chem. Soc.*, 2014, **136**, 17484–17494.
- 237 Q. Sun, B. Aguila, J. Perman, A. S. Ivanov, V. S. Bryantsev,L. D. Earl, C. W. Abney, L. Wojtas and S. Ma, *Nat. Commun.*, 2018, 9, 1644.
- 238 M. Xu, T. Wang, P. Gao, L. Zhao, L. Zhou and D. Hua, J. Mater. Chem. A, 2019, 7, 11214–11222.
- 239 J. Zeng, H. Zhang, Y. Sui, N. Hu, D. Ding, F. Wang, J. Xue and Y. Wang, *Ind. Eng. Chem. Res.*, 2017, **56**, 5021–5032.
- 240 X. Lu, S. He, D. Zhang, A. T. Reda, C. Liu, J. Feng and Z. Yang, *RSC Adv.*, 2016, **6**, 101087–101097.
- 241 L. Yang, L. Bi, Z. Lei, Y. Miao, B. Li, T. Liu and W. Wu, *Polymers*, 2018, **10**, 236.
- 242 J. Shen, J. Yu, Y. Chu, Y. Zhou and W. Chen, *Adv. Mater. Res.*, 2012, **476-478**, 2317-2322.
- 243 Y. Yuan, S. Zhao, J. Wen, D. Wang, X. Guo, L. Xu, X. Wang and N. Wang, *Adv. Funct. Mater.*, 2019, **29**, 1805380.
- 244 X. Wei, Q. Liu, H. Zhang, Z. Lu, J. Liu, R. Chen, R. Li, Z. Li, P. Liu and J. Wang, *Dalton Trans.*, 2017, 46, 15746–15756.
- 245 B. Hu, X. Guo, C. Zheng, G. Song, D. Chen, Y. Zhu, X. Song and Y. Sun, *Chem. Eng. J.*, 2019, **357**, 66–74.
- 246 G. Bayramoglu and M. Y. Arica, *Chem. Eng. Res. Des.*, 2019, 147, 146–159.
- 247 D. Shao, X. Wang, X. Wang, S. Hu, T. Hayat, A. Alsaedi, J. Li,
  S. Wang, J. Hu and X. Wang, *RSC Adv.*, 2016, 6, 52076–52081.
- 248 S. Zhao, Y. Yuan, Q. Yu, B. Niu, J. Liao, Z. Guo and N. Wang, Angew. Chem., Int. Ed., 2019, 58, 14979–14985.
- 249 D. Wang, J. Song, S. Lin, J. Wen, C. Ma, Y. Yuan, M. Lei,
  X. Wang, N. Wang and H. Wu, *Adv. Funct. Mater.*, 2019,
  29, 1901009.
- 250 Y. Yuan, B. Niu, Q. Yu, X. Guo, Z. Guo, J. Wen, T. Liu,
  H. Zhang and N. Wang, *Angew. Chem., Int. Ed.*, 2019, 59(3), 1220–1227.
- 251 F. Chi, S. Zhang, J. Wen, J. Xiong and S. Hu, *Ind. Eng. Chem. Res.*, 2018, **57**, 8078–8084.
- 252 C. Liu, P. C. Hsu, J. Xie, J. Zhao, T. Wu, H. Wang, W. Liu, J. Zhang, S. Chu and Y. Cui, *Nat. Energy*, 2017, **2**, 17007.
- 253 R. T. Mayes, J. Górka and S. Dai, *Ind. Eng. Chem. Res.*, 2016, 55, 4339–4343.
- 254 L. D. Earl, C. Do, Y. Wang and C. W. Abney, *Phys. Chem. Chem. Phys.*, 2019, 21, 554–560.

- 255 A. I. Wiechert, W.-P. Liao, E. Hong, C. E. Halbert,
  S. Yiacoumi, T. Saito and C. Tsouris, *J. Colloid Interface Sci.*, 2018, 524, 399–408.
- 256 J. Xiao, Y. Jing, X. Wang, Y. Yao and Y. Jia, *ChemistrySelect*, 2018, 3, 12346–12356.
- 257 L. J. Kuo, G. A. Gill, C. Tsouris, L. Rao, H. B. Pan, C. M. Wai,
  C. J. Janke, J. E. Strivens, J. R. Wood, N. Schlafer and
  E. K. D'Alessandro, *ChemistrySelect*, 2018, 3, 843–848.
- 258 A. P. Ladshaw, S. Das, W. P. Liao, S. Yiacoumi, C. J. Janke, R. T. Mayes, S. Dai and C. Tsouris, *Ind. Eng. Chem. Res.*, 2015, 55, 4241–4248.
- 259 X. Sun, C. Xu, G. Tian and L. Rao, *Dalton Trans.*, 2013, 42, 14621–14627.
- 260 X. Xie, Y. Tian, Z. Qin, Q. Yu, H. Wei, D. Wang, X. Li and X. Wang, *Sci. Rep.*, 2017, 7, 43503.
- 261 C. Ling, X. Liu, X. Yang, J. Hu, R. Li, L. Pang, H. Ma, J. Li,
  G. Wu, S. Lu and D. Wang, *Ind. Eng. Chem. Res.*, 2017, 56, 1103–1111.
- 262 A. S. Ivanov, C. J. Leggett, B. F. Parker, Z. Zhang, J. Arnold, S. Dai, C. W. Abney, V. S. Bryantsev and L. Rao, *Nat. Commun.*, 2017, 8, 1560.
- 263 C. Wang, Q. Wu, J. Lan, Z. Chai, G. Wu and W. Shi, *Radiochim. Acta*, 2017, **105**, 541–553.
- 264 C. J. Leggett, B. F. Parker, S. J. Teat, Z. Zhang, P. D. Dau,
  W. W. Lukens, S. M. Peterson, A. J. P. Cardenas,
  M. G. Warner, J. K. Gibson, J. Arnold and L. Rao, *Chem. Sci.*, 2016, 7, 2775–2786.
- 265 M. Xu, X. Han and D. Hua, J. Mater. Chem. A, 2017, 5, 12278–12284.
- 266 S. P. Kelley, P. S. Barber, P. H. K. Mullins and R. D. Rogers, *Chem. Commun.*, 2014, **50**, 12504–12507.
- 267 B. F. Parker, S. Hohloch, J. R. Pankhurst, Z. Zhang, J. B. Love, J. Arnold and L. Rao, *Dalton Trans.*, 2018, 47, 5695–5702.
- 268 N. Mehio, A. S. Ivanov, A. P. Ladshaw, S. Dai and V. S. Bryantsev, *Ind. Eng. Chem. Res.*, 2015, 55, 4231-4240.
- 269 N. Mehio, J. C. Johnson, S. Dai and V. S. Bryantsev, *Phys. Chem. Chem. Phys.*, 2015, **17**, 31715–31726.
- 270 A. S. Ivanov and V. S. Bryantsev, *Dalton Trans.*, 2016, 45, 10744–10751.
- 271 D. Wang and S. A. Sañudo Wilhelmy, *Mar. Chem.*, 2009, **11**7, 52–58.
- 272 Y. Zhang, J. Liang, G. Zeng, W. Tang, Y. Lu, Y. Luo, W. Xing, N. Tang, S. Ye, X. Li and W. Huang, *Sci. Total Environ.*, 2020, 705, 135979.
- 273 X. Guo, R. Chen, Q. Liu, J. Liu, H. Zhang, J. Yu, R. Li, M. Zhang and J. Wang, *Polym. J.*, 2018, 5, 2346–2356.
- 274 Q. Yu, Y. Yuan, J. Wen, X. Zhao, S. Zhao, D. Wang, C. Li, X. Wang and N. Wang, *Adv. Sci.*, 2019, 6, 1900002.
- 275 G. A. Gill, L. J. Kuo, C. J. Janke, J. Park, R. T. Jeters, G. T. Bonheyo, H. B. Pan, C. Wai, T. Khangaonkar, L. Bianucci, J. R. Wood, M. G. Warner, S. Peterson, D. G. Abrecht, R. T. Mayes, C. Tsouris, Y. Oyola, J. E. Strivens, N. J. Schlafer, R. S. Addleman, W. Chouyyok, S. Das, J. Kim, K. Buesseler, C. Breier and E. D'Alessandro, *Ind. Eng. Chem. Res.*, 2016, 55, 4264–4277.

- 276 J. Park, G. A. Gill, J. E. Strivens, L. J. Kuo, R. T. Jeters,
  A. Avila, J. R. Wood, N. J. Schlafer, C. J. Janke,
  E. A. Miller, M. Thomas, R. S. Addleman and
  G. T. Bonheyo, *Ind. Eng. Chem. Res.*, 2016, 55, 4328–4338.
- 277 M. N. Haji, J. A. Drysdale, K. O. Buesseler and A. H. Slocum, *Environ. Sci. Technol.*, 2019, **53**, 2229–2237.
- 278 M. Flicker Byers and E. Schneider, *Ind. Eng. Chem. Res.*, 2016, 55, 4351–4361.
- 279 J. Wen, Q. Li, H. Li, M. Chen, S. Hu and H. Cheng, *Ind. Eng. Chem. Res.*, 2018, 57, 1826–1833.
- 280 F. Zhang, H. Zhang, R. Chen, Q. Liu, J. Liu, C. Wang, Z. Sun and J. Wang, J. Colloid Interface Sci., 2019, 534, 172–182.
- 281 J. Zhu, H. Zhang, R. Chen, Q. Liu, J. Liu, J. Yu, R. Li, M. Zhang and J. Wang, *J. Colloid Interface Sci.*, 2019, 543, 192–200.
- 282 P. Zhu and G. Sun, J. Appl. Polym. Sci., 2004, 93, 1037–1041.
- 283 J. Guo, J. Liang, X. Yuan, L. Jiang, G. Zeng, H. Yu and J. Zhang, *Chem. Eng. J.*, 2018, **352**, 782–802.
- 284 J. Ao, Y. Yuan, X. Xu, L. Xu, Z. Xing, R. Li, G. Wu, X. Guo, H. Ma and Q. Li, *Ind. Eng. Chem. Res.*, 2019, 58, 8026–8034.
- 285 A. Ladshaw, L. J. Kuo, J. Strivens, J. Wood, N. Schlafer, S. Yiacoumi, C. Tsouris and G. Gill, *Ind. Eng. Chem. Res.*, 2017, 56, 2205–2211.
- 286 L. J. Kuo, H. B. Pan, J. E. Strivens, N. Schlafer, C. J. Janke, J. R. Wood, C. M. Wai and G. A. Gill, *Ind. Eng. Chem. Res.*, 2019, **58**, 8536–8543.
- 287 C. W. Abney, S. Liu and W. Lin, *J. Phys. Chem. A*, 2013, **11**7, 11558–11565.
- 288 X. Lu, D. Zhang, A. Tesfay Reda, C. Liu, Z. Yang, S. Guo, S. Xiao and Y. Ouyang, *Ind. Eng. Chem. Res.*, 2017, 56, 11936–11947.
- 289 Y. Sun, S. Lu, X. Wang, C. Xu, J. Li, C. Chen, J. Chen, T. Hayat, A. Alsaedi, N. S. Alharbi and X. Wang, *Environ. Sci. Technol.*, 2017, **51**, 12274–12282.
- 290 C. W. Abney, R. T. Mayes, M. Piechowicz, Z. Lin, V. S. Bryantsev, G. M. Veith, S. Daib and W. Lin, *Energy Environ. Sci.*, 2016, 9, 448–453.
- 291 E. G. Witte and K. S. Schwochau, *Inorg. Chim. Acta*, 1984, **94**, 323–331.
- 292 S. Katragadda, H. D. Gesser and A. Chow, *Talanta*, 1997, 45, 257–263.
- 293 K. Singh, C. Shah, C. Dwivedi, M. Kumar and P. N. Bajaj, J. Appl. Polym. Sci., 2013, **127**, 410–419.
- 294 S. Vukovic, L. A. Watson, S. O. Kang, R. Custelcean and B. P. Hay, *Inorg. Chem.*, 2012, **51**, 3855–3859.
- 295 N. Horzum, T. Shahwan, O. Parlak and M. M. Demir, *Chem. Eng. J.*, 2012, **213**, 41–49.
- 296 X. Guo, Y. Wang, C. Li, P. Huai and G. Wu, *Mol. Phys.*, 2015, **113**, 1327–1336.
- 297 P. S. Barber, S. P. Kelley and R. D. Rogers, *RSC Adv.*, 2012, 2, 8526–8530.
- 298 M. A. Lashley, N. Mehio, J. W. Nugent, E. Holguin, C.-L. Do-Thanh, V. S. Bryantsev, S. Dai and R. D. Hancock, *Polyhedron*, 2016, **109**, 81–91.
- 299 L. Zhang, M. Qie, J. Su, S. Zhang, J. Zhou, J. Li, Y. Wang, S. Yang, S. Wang, J. Li, G. Wu and J.-Q. Wang, *J. Synchrotron Radiat.*, 2018, 25, 514–522.

- 300 L. Zhang, J. Su, S. Yang, X. Guo, Y. Jia, N. Chen, J. Zhou, S. Zhang, S. Wang, J. Li, J. Li, G. Wu and J.-Q. Wang, *Ind. Eng. Chem. Res.*, 2015, 55, 4224–4230.
- 301 X. Guo, X. Xiong, C. Li, H. Gong, P. Huai, J. Hu, C. Jin, L. Huang and G. Wu, *Inorg. Chim. Acta*, 2016, **441**, 117–125.
- 302 X. Sun, G. Tian, C. Xu, L. Rao, S. Vukovic, S. O. Kang and B. P. Hay, *Dalton Trans.*, 2014, 43, 551–557.
- 303 S. Vukovic, B. P. Hay and V. S. Bryantsev, *Inorg. Chem.*, 2015, 54, 3995–4001.
- 304 S. Vukovic and B. P. Hay, Inorg. Chem., 2013, 52, 7805-7810.
- 305 C. W. Abney, S. Das, R. T. Mayes, L. J. Kuo, J. Wood, G. Gill, M. Piechowicz, Z. Lin, W. Lin and S. Dai, *Phys. Chem. Chem. Phys.*, 2016, **18**, 23462–23468.
- 306 D. A. Decato and O. B. Berryman, *Org. Chem. Front.*, 2019, 6, 1038–1043.
- 307 H. Lindner and E. Schneider, Energy Econ., 2015, 49, 9–22.
- 308 E. Schneider and G. Gill, *Characterization and Deployment* Studies and Cost Analysis of Seawater Uranium Recovered by a Polymeric Adsorbent System, IAEA, Vienna, Austria, 2014.
- 309 H. Fleeming, P. Sriyutha Murthy and R. Venkatesan, Marine and Industrial Biofouling, Springer-Verlag, Berlin Heidelberg, Germany, 2009.
- 310 P. A. White, J. Kalff, J. B. Rasmussen and J. M. Gasol, *Microb. Ecol.*, 1991, 21, 99–118.
- 311 Y. Oyola, S. Vukovic and S. Dai, *Dalton Trans.*, 2016, 45, 8532–8540.
- 312 H. B. Pan, W. Liao, C. M. Wai, Y. Oyola, C. J. Janke, G. Tian and L. Rao, *Dalton Trans.*, 2014, **43**, 10713–10718.
- 313 M. Tamada, N. Seko, N. Kasai and T. Shimizu, *Nippon Kikai Gakkai Ronbunshu*, 2006, **5**, 358–363.
- 314 E. Schneider and D. Sachde, *Sci. Global Secur.*, 2013, **21**, 134–163.
- 315 U. EIA, 2016 Uranium Marketing Annual Report, June 2017, https://www.eia.gov/uranium/marketing/pdf/ 2016umar.pdf, accessed on 26 October, 2017.
- 316 OECD/NEA, Uranium 2011: Resources, Production, and Demand, OECD Publishing, 2012.
- 317 K. Dungan, G. Butler, F. R. Livens and L. M. Warren, *Prog. Nucl. Energy*, 2017, 99, 81–85.
- 318 M. N. Haji, J. Gonzalez, J. A. Drysdale, K. O. Buesseler and A. H. Slocum, *Ind. Eng. Chem. Res.*, 2018, 57, 15534–15541.
- 319 M. Picard, C. Baelden, Y. Wu, L. Chang and A. H. Slocum, *Nucl. Technol.*, 2017, **188**, 200–217.
- 320 M. F. Byers, M. N. Haji, A. H. Slocum and E. Schneider, *Ocean. Eng.*, 2018, **169**, 227–241.
- 321 M. N. Haji and A. H. Slocum, *Trans. Am. Nucl. Soc.*, 2016, 115, 4264–4267.
- 322 H. Sodaye, S. Nisan, C. Poletiko, S. Prabhakar and P. K. Tewari, *Desalination*, 2009, **235**, 9–32.
- 323 K. S. Bae and J. O. Lee, Resour. Environ. Eng., 1997, 2, 61–72.
- 324 C. Ma, J. Gao, D. Wang, Y. Yuan, J. Wen, B. Yan, S. Zhao,
  X. Zhao, Y. Sun, X. Wang and N. Wang, *Adv. Sci.*, 2019, 6, 1900085.
- 325 B. Yan, C. Ma, J. Gao, Y. Yuan and N. Wang, *Adv. Mater.*, 2020, 1906615.
- 326 T. S. Franczyk, K. R. Czerwinski and K. N. Raymon, J. Am. Chem. Soc., 1992, **114**, 8138–8146.

- 327 J. P. Dognon, Coord. Chem. Rev., 2014, 266-267, 110-122.
- 328 P. L. Arnold, D. Patel, A. J. Blake, C. Wilson and J. B. Love, *J. Am. Chem. Soc.*, 2006, **128**, 9610–9611.
- 329 P. L. Arnold, G. M. Jones, Q. J. Pan, G. Schreckenbach and J. B. Love, *Dalton Trans.*, 2012, **41**, 6595–6597.
- 330 S. Beer, O. B. Berryman, D. Ajami and J. Rebek Jr, *Chem. Sci.*, 2010, **1**, 43–47.
- 331 D. A. Penchoff, C. C. Peterson, J. P. Camden, J. A. Bradshaw, J. D. Auxier, G. K. Schweitzer, D. M. Jenkins, R. J. Harrison and H. L. Hall, ACS Omega, 2018, 3, 13984–13993.
- 332 Z. Qin, Y. Ren, S. Shi, C. Yang, J. Yu, S. Wang, J. Jia, H. Yu and X. Wang, *RSC Adv.*, 2017, 7, 18639–18642.
- 333 I. H. Park and J. M. Suh, Angew. Makromol. Chem., 1996, 239, 121–132.
- 334 M. Piechowicz, R. Chiarizia and L. Soderholm, *Dalton Trans.*, 2018, 47, 5348–5358.
- 335 J. Stemper, W. Tuo, E. Mazarío, A. S. Helal, A. Djurovic, C. Lion, J. M. El Hage Chahine, F. Maurel, M. Hémadi and T. Le Gall, *Tetrahedron*, 2018, 74, 2641–2649.
- 336 L. Zhang, N. Pu, B. Yu, G. Ye, J. Chen, S. Xu and S. Ma, *ACS Appl. Mater. Interfaces*, 2020, **12**, 3688–3696.
- 337 G. Tian, S. J. Teat and L. Rao, *Dalton Trans.*, 2013, 42, 5690– 5696.

- 338 W. Zhang, B. Zheng, W. Shi, X. Chen, Z. Xu, S. Li, Y. R. Chi, Y. Yang, J. Lu, W. Huang and F. Huo, *Adv. Mater.*, 2018, 30, 1800643.
- 339 B. F. Parker, Z. Zhang, C. J. Leggett, J. Arnold and L. Rao, *Dalton Trans.*, 2017, **46**, 11084–11096.
- 340 D. James, G. Venkateswaran and T. Prasada Rao, *Microporous Mesoporous Mater.*, 2009, **119**, 165–170.
- 341 J. Xiong, S. Hu, Y. Liu, J. Yu, H. Yu, L. Xie, J. Wen and X. Wang, *ACS Sustainable Chem. Eng.*, 2017, **5**, 1924–1930.
- 342 P. Yang, R. Chen, Q. Liu, H. Zhang, J. Liu, J. Yu, P. Liu, X. Bai and J. Wang, *Inorg. Chem. Front.*, 2019, 6, 746–755.
- 343 A. P. Ladshaw, A. S. Ivanov, S. Das, V. S. Bryantsev, C. Tsouris and S. Yiacoumi, ACS Appl. Mater. Interfaces, 2018, 10, 12580–12593.
- 344 J. Han, L. Hu, L. He, K. Ji, Y. Liu, C. Chen, X. Luo and N. Tan, *Environ. Sci. Pollut. Res.*, 2020, DOI: 10.1007/ s11356-020-07746-z.
- 345 W. R. Cui, C. R. Zhang, W. Jiang, F. F. Li, R. P. Liang, J. Liu and J. D. Qiu, *Nat. Commun.*, 2020, **11**, 436.
- 346 L. Liu, Y. Fang, Y. Meng, X. Wang, F. Ma, C. Zhang and H. Dong, *Desalination*, 2020, **478**, 114300.