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REVIEW

Novel Foam Adsorbents in Dyes and Heavy Metals Removal: A Review

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The present review comprises various novel foam adsorbents with unique adsorption performance in process of removal of dyes and heavy metals. Water pollution because of toxic dyes and heavy metals and its ill-effect on the ecosystem is of great concern to researchers, as it affects the living creatures on the planet. Novel foam adsorbents from carbon foam, chitosan foam, metal foam and polymer foam were developed as efficient materials with good chelating ability to adsorb dyes and heavy metal ions. Novel carbon foam adsorbents were reported to have superior adsorption capacity in removal of dyes and heavy metals. This review aims to look at various novel foam adsorbents used in adsorption studies and their potential in dyes and heavy metals removal. This work provides a worthy challenge and the future possibility for designing novel foam materials for various applications.

Keywords: Novel foam adsorbents, Dyes, Heavy metals, Adsorption, Adsorption capacity.

INTRODUCTION

Dyes and heavy metals contamination in water are associated with danger in human health due to their toxic, carcinogenic and mutagenic effects [1]. The accumulation of dyes and heavy metals in water leads to bioaccumulation in aquatic biota and pose serious health risks that significantly affect the biodiversity in the environment. Dyes and heavy metals used during the industrial processing find their way in mixing with surface water through effluents from textiles, metal plating, fertilizers, pharmaceutical, mineral processing industries [2]. Due to the toxic effects of industrial wastewater, there is a need to treat the dyes and heavy metals contaminated water to preserve the environment. A wide variety of treatment methodologies were in current use with different degree of success, such as chemical precipitations [3], photocatalysis [4], electrochemical method [5], reverse osmosis [6], adsorption [7,8], *etc*. Of all the treatment methods, adsorption has gained significant interest in testing novel materials by researchers due to its simplicity, the highest efficiency in the removal of pollutants. In literature, novel foam adsorbents were prepared and used as efficient adsorbents in adsorption studies. Moreover, some foam adsorbents proved to be promising materials in dyes and heavy metals removal and this have created interest to various researchers and scientists to develop novel foam adsorbents with superior adsorption capacity [9]. The development of novel foam adsorbents and their improved efficiency in removal of dyes and heavy metals in contaminated water and this has gained significant interest among researchers.

Toxic dyes and heavy metals: Dyes are needed for industrial process to colour variety of products. The dye contaminated water leads to various health issues that affect kidney, liver, brain, central nervous system and skin problems [10]. The existence of dyes in surface water imparts colour even at very low concentrations and resists the entry of light and harms the aquatic systems. The non-biodegradable dyes from textile, paper and pulp, paint and tannery industries if improperly managed significantly alters the quality of soil and water and slowly depletes the precious natural resources. Toxic metal ions that pollute water have also gained global attention due to its non-biodegradable nature. Toxic metals which are of primary concern in surface water include arsenic, mercury, lead, cadmium and chromium.

These heavy metals find their way into the streams through various industries like metal coating, batteries, metal moulding, *etc.* [11]. Accumulation of poisonous metal ions in water retards the health of aquatic species and passes through the food chain through bioaccumulation and biomagnification [12]. Hence, industrial effluent containing toxic dye and metal ions is gaining more priority and strict standards were imposed on the quality of effluent disposal. Various treatment methods were reported in literature for environmental remediation with varying success rate. Among those methods, adsorption technique is preferentially selected by researchers in testing the novel materials in industrial wastewater treatment process. Fig. 1 shows the general categories of novel foam adsorbents.

Types of novel foam adsorbents: Based on the foam matrix, it is clear that novel foam materials can be classified into carbon foam, chitosan foam, metal foam, polymer foam and other foam adsorbents and confer the adsorption performance in dyes and heavy metals removal.

Carbon foam adsorbents: Carbon foams also have distinctive features such as light weight, high porosity, adjustable electrical and thermal conductivity [13] and are commonly used in catalysis, energy, chemical and environmental protection. Carbon foams are ideal to be used in wastewater treatment as they are easy to recover. In literature, carbon foam materials have gained significant attention due to their higher adsorption performance. Hence, carbon foams were observed to be efficient materials in dyes and heavy metals removal. Also, recent research reports that some efficient carbon foam adsorbents with good chelating functionality helps to trap dyes and heavy metals for environmental remediation [9,14-18].

Chitosan foam adsorbents: Chitosan is commonly used polysaccharides obtained from chitin and possess greater affinity for dyes and heavy metals. Chitin is insoluble in lot of solvents due to its crystalline nature and hence this provides the hydrophobic stability to its composite foam in aqueous solution [19]. The presence of more active sites like hydroxyl (-OH) and amino ($-NH_2$) group in chitosan provides high adsorption performance in dye and heavy metal removal [20,21]. Chitosan was reported to have good adsorption in its modified form. Chitosan in its crystalline form as adsorbent affects the adsorption capacity [22]. The decrystallized form of chitosan has proved to have good dye adsorption performance because of the availability of amino groups [23]. Similarly, the incorporation of suitable materials with chitosan is also of significant interest to researchers due to their potential reactivity with dyes and metal ions.

Metal foam adsorbents: Silica foam adsorbents were developed as novel materials with binding sites located on the surface and provide easy access to the adsorbate for good adsorption performance [24]. The synthesis of Fe-Cu binary oxide and using it in the arsenic ion removal is a good option since Cu(II) and Fe(III) ions have a potential affinity to bind arsenic ions. Also, the binding of arsenic on CuO is not pH dependent, hence, $Cu_2Fe_2O_4$ foam was developed as an efficient adsorbent in arsenic adsorption [25]. These adsorbents were reported to have active surface functional groups that resulted in highly efficient materials in dyes and metal ions adsorption.

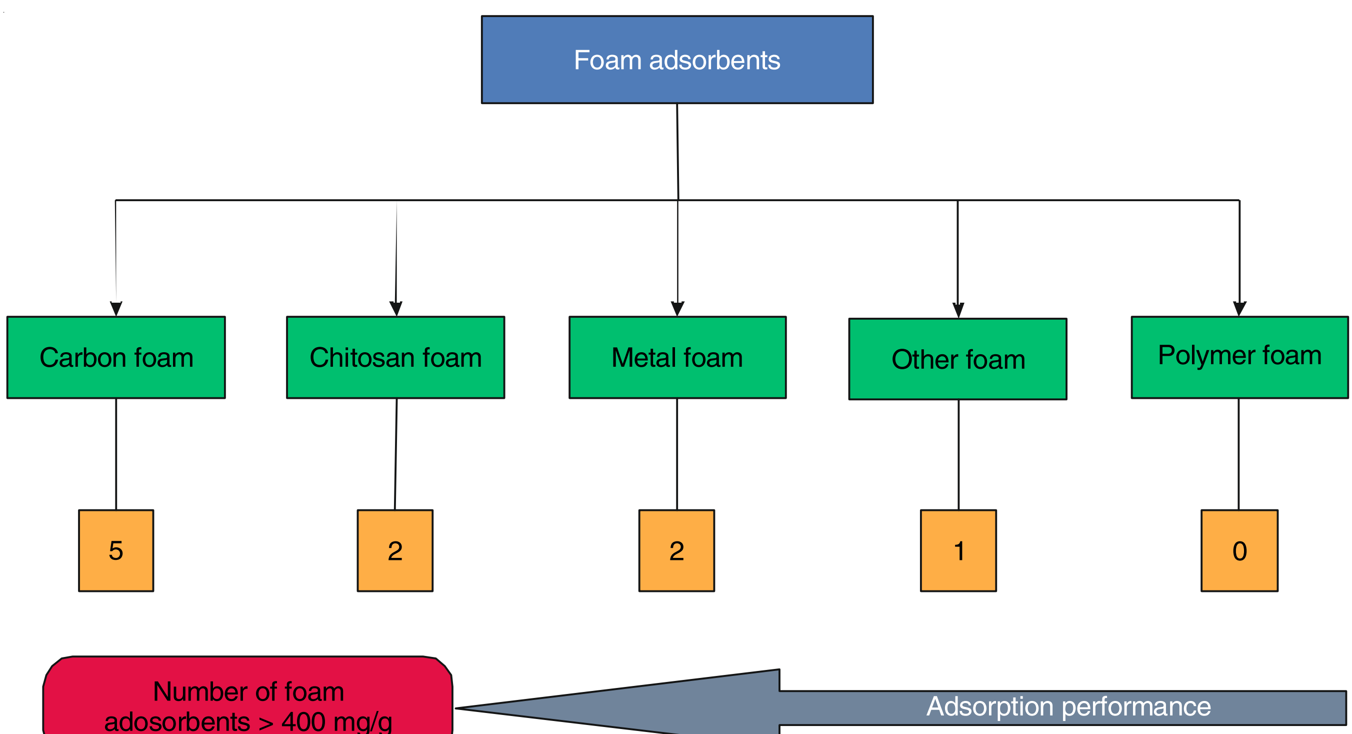

Fig. 1. Categories of novel foam adsorbents

Polymeric foam adsorbents: Polyurethane foams were reported to have light weight, porous structure and widely used in industrial effluent treatment applications. The addition of some reagents/materials into polyurethane foam was reported to increase the efficiency in adsorption of dye and heavy metals. In the synthesis of polyurethane foams (PUFs), recently, researchers used polysaccharides to get "biofoams" which are efficient materials with high surface area and increased porosity [26]. Polymeric foam having controllable pore space can protect certain functional groups and zero-valent metal particles in its matrix and hence possess strong selectivity for toxic metal ions removal.

Carbon foam adsorbents: Carbon foams were prepared from suitable mixed/modified carbon materials like graphene, carbon nanotubes, multi-walled carbon nanotubes (MWCNTs), *etc*. to prepare novel carbon foam adsorbents [9,14,15] and tested its adsorption performance in elimination of both dyes and/or heavy metals.

Carbon foam adsorbents for dyes removal: Priyanka & Saravanakumar [9] extracted the starch induced zinc oxide carbon foam (Zn-CFst) and examined the carbon foam's effectiveness towards adsorption of crystal violet, malachite green and Congo red dyes. The Zn-CFst was identified by an assessment of FTIR, XPS and BET. BET analysis has reported the extremely porous condition of $Zn\text{-}CF_{st}$ sample having an average pore diameter of 31 Å. The study concluded that the ultra-high adsorption capacity of carbon foam in dyes removal (crystal violet, malachite green and Congo red) was due to dipole-dipole H-bonding, Yoshida H-bonding, interaction of n-π and interaction of π-π. The Zn-CFst exhibited superior adsorption capacity for crystal violet (25000 mg/g), malachite green (1200 mg/g) and Congo red (1428 mg/g). Ong *et al.* [14] synthesized iron nanoflorets composite on macroporous grap-hene foam (INFGN) and investigated the usefulness of the adsorbent in removal of Congo red dye. The INFGNs inter-active behaviour with Congo red was analyzed using adsorption isotherms and the adsorption capacity was found to vary from 1191.47-1552.80 mg/g. The INFGN was easily recovered by direct lifting as it had sturdy foam like structure. The authors concluded that the material developed (INFGN) showed greater potential for water remediation. Zhang *et al.* [15] synthesized novel hierarchical stiff carbon foam (HSCF) and tested it as a bulk adsorbent towards removal of malachite green dye. The HSCF was described by SEM, XRD, FTIR and XPS. The adsorption of HSCF onto malachite green dye was examined in batch mode and the adsorption capacity was observed to be 425.2 mg/g.

Vijwani *et al.* [16] synthesized CNT-foam hybrid structure (RVC-CNT 40) and studied its adsorption onto methylene blue. The carbon foam hybrid structure was characterized by FE-SEM and the depth profile analysis of CNT carpet length was studied. The CNT foam adsorption onto methylene blue was analyzed using Langmuir isotherm and the adsorption capacity was observed to be 43.5 mg/g. Chen *et al.* [17] synthesized chitosan (CS)/rectorite (REC)/carbon nanotubes (CNTs) composite foam (CS/REC/CNTs) and studied its adsorption onto methyl orange. The FE-SEM image of CS/REC/CNTs foam showed porous structure of the material. The CS/REC/CNTs foam was investigated for the adsorption of methyl orange and the adsorption capacity was observed as 41.65 mg/g. Yu & Fugetsu [18] synthesized foam like CNT based adsorbent and tested its adsorption performance in the removal of dyes ethidium bromide, acridine orange, methylene blue, eosin B and eosin Y. The adsorption capacity was observed 625 µg/g for acridine orange, 476.19 µg/g for methylene blue, 384.62 µmol/g for ethidium bromide, 270.27 µmol/g for eosin B and 250 µmol/g for eosin Y, respectively.

Carbon foam adsorbents for heavy metals removal: Lei *et al.* [27] synthesized three dimensional graphene oxide foam (GOF) and explored its adsorption performance in the elimination of heavy metal ions. The synthesized GOF was reported to have abundant oxygen possessing functional groups on its surface and large surface area (578.4 m^2/g). The GOF has been analyzed for its adsorption onto metal ions such as Fe(III), Pb(II), Zn(II) and Cd(II) from aqueous solution. The adsorption capacity is reported to be 587, 381.3, 326.4 and 252.5 mg/g for Fe(III), Pb(II), Zn(II) and Cd(II), respectively. Lee *et al.* [28] synthesized phenolic resin based carbon foam with a well-developed open cell structure and reported high BET surface area (458.59 m^2/g). The carbon foam was investigated for the elimination of Pb(II) and Cu(II) using batch mode adsorption studies and the adsorption capacity was found to be 491 and 247 mg/g, respectively. Chen *et al.* [29] synthesized three dimensional graphene foam (GO) with higher electrical conductivity of 125 S/cm and larger surface area of 625.4 m^2/g. The GO foam adsorption was systematically studied by varying pH, adsorption time and solution temperature. The GO foam was observed to show excellent adsorption capability for As(V) (177.6 mg/g) and Pb(II) (399.3 mg/g) that validated its potential applications in environmental remediation.

Phytic acid induced graphene macrostructure was synthesized by Tan *et al.* [30] as a potential graphene foam to remove heavy metal ions. The PAGF was tested for Hg(II) adsorption and various experimental parameters were optimized. The isotherm data of PAGF suited well to Langmuir model and the adsorption capacity at pH-7.2 for Hg(II) removal was 361.01 mg/g. Li *et al.* [31] synthesized MgO hybrid sponge like carbonaceous composite (HSC) and studied its elimination of As(V) and Pb(II) from aqueous solution. The HSC foam adsorption onto As(V) and Pb(II) was observed as 157 and 103 mg/g, respectively. Zhang *et al.* [15] synthesized chitosan-cellulose magnetic carbon foam (CCMF) and investigated the removal of Cu(II) from industrial sewage. The CCMF adsorption onto Cu(II) was found to correlate well with Langmuir model and the adsorption capacity was observed as 115.65 mg/g at pH 6 and 30 ºC. Fe_2O_3-Carbon foam has been synthesized and the adsorption performance for Cr(VI), Cu(II) and Ni(II) ions has been studied. The carbon foam was found to have an adsorption capacity of 6.7, 3.8 and 6.4 mg/g for Cr(VI), Cu(II) and Ni(II), respectively. Graphite intercalation compound (GIC) functionalized phenolic resin based carbon foam (GICCF) was synthesized by Agrawal *et al.* [32] and they studied its adsorption capacity for As(V) ions from polluted water. The GICCF was characterized by XRD, FTIR and XPS to confirm the adsorption mechanism of As(V) onto the surface of GICCF. The adsorption capacity was observed as 62.5 µg/g. Wang *et al.* [33] synthesized β-cyclodextrin functionalized 3-D structured graphene foam (CDGF) and confirmed the successful grafting of β-CD onto GF by means of SEM, BET, XRD, FTIR and XPS analysis. The CDGF adsorption onto Cr(VI) was examined in batch mode and the adsorption capacity was observed as 107 mg/g. Khan *et al.* [34] synthesized multiwalled carbon nanotubes and diamond nanoparticles reinforced carbon foam (CF/MWCNT-DNPs) and investigated its adsorption onto Ni(II) and Cd(II) from aqueous solutions. The carbon foam was found to have maximum adsorption percentage of 84.6% and 86.9% for Ni(II) and Cd(II) ions.

Table-1 presents the adsorption capacity of some carbon foam adsorbents used in dyes and heavy metals removal. The adsorption capacity data (> 400 mg/g) of all carbon foam adsorbents used in dye removal, Zn-CF_{st} [9], INFGN [14] and HSCSF [13] foam adsorbents were found to possess high adsorption capacities. In heavy metals removal, GOF [27] and phenolic resin based carbon foam [28] was reported to have good adsorption performance. Accordingly, superior adsorption potential of novel carbon foam materials is clear in the removal of dyes and heavy metals.

Chitosan foam adsorbents for dyes and heavy metals removal: Chitosan foam adsorbents were prepared by various researchers [16,37,38] and its adsorption performance was tested towards the removal of dyes and heavy metals.

Chitosan foam adsorbents for dye removal: Kim *et al.* [37] synthesized DAC cross-linked cellulose chitosan foam (CCLBD) and studied its adsorption onto Congo red dye. The CCLBD foam was reported to have long nanofibrils interconnected with pores ranging from 40-200 nm wide and the specific surface area of the foam was observed to be 230 m^2/g. The CCLBD adsorption ability for Congo red dye was reported to be 1548.2 mg/g. Chitosan-cenospheres nanosyntactic foam (C_s-C_n foam) was synthesized by Markandeya *et al.* [38] and was applied its adsorption efficiency for disperse orange 25 and disperse blue dyes from the aqueous solution. The C_s-C_n nanosyntactic foam adsorption onto the dyes reached equilibrium within 120 min at optimized pH 6, 0.2 g/L adsorbent dose and 40 mg/L dye concentration with the shaking speed of 200 rpm. The C_s-C_n nanosynthactic foam was found to have high adsorption capacity of 500 and 500.4 mg/g for disperse orange 25 and disperse blue dyes, respectively.

Da Rosa Schio *et al.* [39] synthesized bio-based polyurethane/chitosan composite foam (PU/chitosan foam) and tested its adsorption onto food red 17(FR 17) dye from aqueous solution. The adsorption of FR 17 dye onto PU/chitosan foam was optimized (pH 2 using 1 g of adsorbent at 328 K). The

TABLE-1
CARBON FOAM ADSORBENTS IN DYE REMOVAL HEAVY METAL REMOVAL

S. No.	Carbon foam adsorbents	Dye	Adsorption capacity	Ref.
		Carbon foam adsorbents in dye removal		
1	Zn-CF_{st}	Crystal violet	25000 mg/g	[9]
		Malachite green	1200 mg/g	
		Congo red	1428.57 mg/g	
2	INFGN foam	Congo red	1191.47-1552.80 mg/g	[14]
3	HSCSF	Malachite green	425.2 mg/g	[15]
4	RVC-CNT 40	Methylene blue	43.5 mg/g	[16]
5	CS/REC/CNTs	Methyl orange	41.65 mg/g	[17]
6	CNT based foam	AO	625µmol/g	[35]
		Methylene blue	476.19 µmol/g	
		Ethidium bromide	384.62 µmol/g	
		Eosin Y	270.27 µmol/g	
		Eosin B	250 µmol/g	
		Carbon foam adsorbents in heavy metal removal		
7	GOF	Fe(III)	587 mg/g	[27]
		Pb(II)	381.3 mg/g	
		Zn(II)	326.4 mg/g	
		Cd(II)	252.5 mg/g	
8	PR Carbon foam	Pb(II)	491 mg/g	[28]
		Cu(II)	247 mg/g	
9	GO foam	Pb(II)	399.3 mg/g	[29]
		As(V)	177.6 mg/g	
10	PAGF	Hg(II)	361.01 mg/g	[30]
11	HSC	As(V)	157 mg/g	[31]
		Pb(II)	103 mg/g	
12	CDGF	Cr(VI)	107 mg/g	[33]
13	CCMF	Cu(II)	115.65 mg/g	[13]
14	Fe_2O_3-Carbon foam	Cr(VI)	6.7 mg/g	[36]
		Cu(II)	3.8 mg/g	
		Ni(II)	6.4 mg/g	
15	GICCF	As(V)	62.5 µg/g	[32]
16	CF/MWCNT-DNPs	Ni(II)	–	[34]
		Cd(II)	–	

authors demonstrated that PU/chitosan foam was a potential adsorbent with an adsorption capacity of 267.24 mg/g. Graphene oxide/chitin nanofibrils (GO-CNF) composite foam was studied by Ma *et al.* [40] for removal of methylene blue. The GO-CNF foam was reported to have higher crystalinity, porous network structure and interfacial adhesion that arises from electrostatic interaction and hydrogen bond amid GO and CNF.

The adsorption of GO-CNF foam was well suited to the Langmuir model and adsorption capacity has been found to be 173.3 mg/g. Hydrophobically modified chitosan (HMCS) foam was prepared by Vo & Lee [22] and studied its adsorption onto methyl orange. The HMCS foam adsorption capacity was improved because of both electrostatic attractions and hydrophobic interactions. The adsorption of HMCS foam followed Langmuir isotherm and the adsorption capacity was observed to be 168 mg/g. Wang *et al.* [41] synthesized biporous bioinspired chitosan foams (CS-EA) by a unidirectional freeze drying method (UFDM) thereby studied its adsorption onto xylenol orange dye. The adsorption capacity of CS-EA foam was found to be 122 mg/g.

Chitosan foam adsorbents for heavy metals removal: Novel chitosan foam was prepared by Allouche *et al.* [21] and successfully applied its adsorption onto Hg(II) ions. The sorption capacity of chitosan foam onto Hg(II) was found to be 350 mg/g. Chitosan-vermiculite bionanocomposite foams was synthesized by Padilla-Ortega *et al.* [42] and used as the adsorbent for Cd(II) removal in aqueous media, where its capacity was found to be 125 mg/g.

Su *et al.* [43] synthesized zero-valent iron/chitosan composite foam (ICCFs) as adsorbent to eliminate As(III) and As(V) ions from aqueous solution. The ICCFs honey comb like porous material showed a good adsorption performance in As(III) and As(V) ions with 114.9 and 86.87 mg/g, respectively. Similarly, Chitosan foam was prepared by Kaminski *et al.* [44] and its adsorption onto Cu(II), Zn(II) and Cr(VI) ions were well characterized by the isotherm models. The authors also observed the good mechanical properties and high porosity which enhanced the sorption process.

The adsorption performance based on chitosan foam adsorbents in dyes and heavy metals removal are shown in Table-2. It is observed that CCLBD foam [37] and Cs-Cn foam [38] were reported to have an adsorption capacity > 400 mg/g and chitosan foam adsorbent prepared by Allouche *et al.* [21] reported to have an adsorption capacity of 350 mg/g, significantly greater than other adsorbents in heavy metals removal. Thus, adsorption of dyes and metal ions by chitosan foam adsorbents prove the efficiency of these novel foam adsorbents in water treatment.

Metal foam adsorbents: Metal foam adsorbents were observed to be highly effective in the removal of dyes and metal ions [35,45]. A new porous copper-nickel foam electrode attuned with graphene oxide/polypyrrole (GO-ppy@CNF) was synthesized by Yu *et al.* [35] and they studied its electrosorption of rhodamine B dye. The GO-ppy@CNF was reported to have porous interconnected nanodendritic structure with greater functional groups of GO-ppy which significantly increased the sorption performance. The results of GO-ppy@CNF electrosorption onto rhodamine B was found to fit well with Langmuir isotherm (Q_m = 416.7 mg/g) and adapted pseudo-second order kinetics. Snoussi *et al.* [45] synthesized polyethylenimine functionalized mesocellular silica foam (pPEI-MCF) and they studied its adsorption of Cd(II) ions from the aqueous solution. The hybrid foam material showed high affinity to the Cd(II) uptake reaching 625 mg/g and thus proves favourable adsorption at the lower concentration.

Graphene oxide/copper ferrite foam (CCFF) was synthesized by Wu *et al.* [46] and its adsorption behaviour towards As(III) and As(V) ions were optimized. The authors concluded that GCFF is an efficient adsorbent in arsenic removal with the adsorption capacity of As(III) and As(V) of 51.64 and 124.69 mg/g, respectively. Sharifpour *et al.* [19] synthesized mesocellular silica foam functionalized by polymixin B and the monolayer adsorption capacity has been reported as 48.31 and 36.50 mg/g for Cu(II) and Zn(II) ions, respectively. Wu *et al.* [46] synthesized highly porous copper ferrite foam (CFF) and analyzed its efficiency to remove arsenic from aqueous

TABLE-2
CHITOSAN FOAM ADSORBENTS IN DYE AND HEAVY METAL REMOVAL

S. No.	Carbon foam adsorbents	Dye/ Heavy metal	Adsorption capacity	Ref.
		Chitosan foam material adsorbents in dye removal		
1	CCLBD	Congo red	1548.2 mg/g	[37]
2	Cs-Cn foam	Disperse orange 25	500 mg/g	[38]
		Disperse blue	500.4 mg/g	
3	PU/Chitosan foam	Food red 17	267.24 mg/g	[20]
4	GO-CNF 40	Methylene blue	173.3 mg/g	[19]
5	HMCS foam	Methyl orange	168 mg/g	[22]
6	CS-EA	Xylenol orange	122 mg/g	[41]
		Chitosan foam material adsorbents in heavy metal removal		
7	Chitosan foam	Hg(II)	350 mg/g	[21]
8	VU/CHT	Cd(II)	125 mg/g	[42]
9	ICCFs	As(III)	114.9 mg/g	[43]
		As(V)	86.87 mg/g	
10	Chitosan foam	Cu(II)	–	[44]
		Zn(II)	–	
		Cr(VI)	–	

solution. The adsorption capacity of CFF in As(III) and As(V) ions removal was observed as 44 and 85.4 mg/g, respectively. Nano mesocellular foam silica (MCFs) was synthesized by Li & Zhai [47] and studied its adsorption of Ni(II) from aqueous solution. The optimum adsorption conditions on the adsorption of Ni(II) by MCFs were examined and the adsorption capacity was observed as 7.69 mg/g.

Table-3 presents some of the metal foam adsorbents that were reported in the removal of dyes and heavy metals with its adsorption capacity. Among all the metal foam adsorbents, the adsorption performance of pPEI-MCF [45] is comparatively better in Cd(II) with the adsorption capacity of 625 mg/g. This is followed by GO-ppy@CNF [35] in rhodamine B dye removal with an adsorption capacity of 416.7 mg/g. Hence, it is clear that metal foam adsorbents are efficient in the removal of dyes and heavy metals ions.

Other foam adsorbents: In search of novel adsorbents, researchers synthesized alginic acid foam [48] tannin foam [49], geopolymeric foam [50] and analyzed their adsorption performance in heavy metals ions removal.

Sodium alginate foam (H-F) was prepared by Pettignano *et al.* [48] for the adsorption of a basic dye (methylene blue) from aqueous solution. The adsorption properties of H-F were evaluated by selecting a basic dye (methylene blue) as the carboxylic functional group available in H-F, which might permit the development of acid-base interaction. The Q_m value obtained from Langmuir model for the adsorption of methylene blue on the H-F foam was found to be 1201 mg/g. Tannin rigid foams (TRF) were synthesized by Sanchez-Martin *et al.* [49] and used for the removal of methylene blue dye. The adsorption capacity of TRF has been observed as 215.8 mg/g. Biobased epoxy thermosetting foam (ETA foam) was synthesized by Esmaeili *et al.* [51] and this foam showed favourable adsorption performance for methylene blue dye and the higher adsorption capacity from Langmuir isotherm was reported as 36.25 mg/g.

Ma *et al.* [40] synthesized porous cellulose based foams with best loading of zeolitic imidzolate framework-8 (ZIF-8 @CNF@cellulose foam) and reported the adsorption capacity of methylene blue dye and chromium(VI) as 24.6 and 35.6 mg/g, respectively. Khatib *et al.* [50] synthesized geopolymeric foam (60-malachite green foam) which possessed a high adsorption capacity of Cd(II), making it a promising material in the environmental remediation.

An efficient and recyclable floatable alginate based attapulgite foam (SA/ATP) adsorbent was synthesized by Wang *et al.* [52] and examined for the removal of heavy metals ions. The adsorption capacity of SA/ATP foam for Cu(II) is 119.0 mg/g and 160.0 mg/g for Cd(II), respectively. The lower density of SA/ATP foam makes them float and easier to recycle. Therefore, this porous foam was reported to be environmental friendly and low-cost adsorbent for the removal of heavy metal in large-scale applications. Zeolite foam geopolymer (ZFG) was synthesized by Han *et al.* [53] and analyzed the possibility of this innovative material in Pb(II) adsorption. The ZFG was reported to have lower apparent density (approximately 355 kg/m^2) and higher compressive strength (1.03 MPa to 2.96 MPa). The adsorption equilibrium time was as fast as 60 min in Pb(II) removal from aqueous solution. The adsorption capacity in Pb(II) removal was reported to be 123.2 mg/g.

Cashin *et al.* [54] synthesized sinapinaldehyde functionalized mesocellular foam (SA-MCF) and studied its adsorption efficiency in Pb(II) removal. The novel SA-MCF possessed the adsorption capacity of 48.3 mg/g. Pan *et al.* [55] synthesized Hierarchical porous foams (HPFs) and tested its adsorption for Cu(II) removal. The HPFs were reported to have active binding sites that can beneficially capture Cu(II) ions. The adsorption capacity of HPFs for Cu(II) removal was observed as 21.79 mg/g at 288 K.

Foamed urea-formaldehyde microspheres (UF) were synthesized by Qu *et al.* [56] and studied its removal of Pb(II) from aqueous solution. The UF foam was found to be effective in Pb(II) adsorption and its adsorption capacity was 21.5 mg/g. Turco *et al.* [57] synthesized environmental friendly polydimethylsiloxane (PDMS) foam with a mussel inspired polydopamine (PDA) (PDMS/PDA) and studied its adsorption for the removal of Cu(II) ions. The adsorption capacity was found to be 16.47 mg/g. Tannin based rigid foam (TBRF) was synthesized by Tondi *et al.* [58] for the adsorption of Cu(II) and Pb(II) ions. The TBRF was reported to adsorb up to 12% of Cu(II) and 20.1% of Pb(II) ions. Natural rubber composite foam was synthesized by Prapruddivongs & Thomyasirigul [59] and tested its adsorption of Pb(II) from aqueous solution. The inclusion of SiO_2 into the rubber foam improved the blowing efficiency and hence favoured Pb(II) ion diffusion in to the rubber matrix.

Table-4 listed some adsorbents with varying foam matrix (other foam adsorbents) which are unique in dyes and heavy metals adsorption performance. Among all other foam used adsorbents in the removal of dyes and heavy metals, it is observed that alginic acid foam (H-F) [48] had superior adsorption

TABLE-3
METAL FOAM ADSORBENTS IN DYE REMOVAL HEAVY METAL REMOVAL

S. No.	Metal foam adsorbents	Dye/heavy metal	Adsorption capacity	Ref.
1	$_P$PEI-MCF	Cd(II)	625 mg/g	[45]
2	GO-ppy@CNF	Rhodamine B	416.7 mg/g	[35]
3	GCFF	As(V)	124.69 mg/g	[46]
		As(III)	51.64 mg/g	
4	MCSiF-PM-B	Cu(II)	48.31 mg/g	[24]
		Zn(II)	36.50 mg/g	
5	CFF	As(III)	44 mg/g	[25]
		As(V)	85.4 mg/g	
6	MCFs	Ni(II)	7.69 mg/g	[47]

TABLE-4
OTHER FOAM ADSORBENTS IN DYE AND HEAVY METAL REMOVAL

S. No.	Other foam adsorbents	Dye/heavy metal	Adsorption capacity	Ref.
1	H-F	Methylene blue	1201 mg/g	[48]
2	Geopolymeric foam	Cd(II)	280 mg/g	[50]
3	TRF	Methylene blue	215.8 mg/g	[49]
4	SA/ATP foam	Cu(II)	119 mg/g	[52]
		Cd(II)	160 mg/g	
5	ZFG	Pb(II)	123.2 mg/g	[53]
6	ETA foam	Methylene blue	36.25 mg/g	[51]
7	ZIF-8@CNF@Cellulose foam	Rhodamine B	24.6 mg/g	[40]
		Cr(VI)	35.6 mg/g	
8	SA-MCF	Pb(II)	48.3 mg/g	[54]
9	HPFs	Cu(II)	21.79 mg/g	[55]
10	Foamed UF	Pb(II)	21.5 mg/g	[56]
11	PDMS/PDA foams	Cu(II)	16.47 mg/g	[57]
12	TBRF	Cu(II)	–	[58]
		Pb(II)	–	
13	NR foam	Pb(II)	–	[59]

performance (1201 mg/g) in dyes removal. This is followed by geopolymeric foam [50] in Cd(II) for metal ions removal. Accordingly, adsorption capacity of some novel foam adsorbents proved efficient in environmental remediation of dyes and heavy metals.

Polymer foam adsorbents: Most of the studies in polymer foam adsorbents used polyurethane foam [60] in preparing the polymer and testing its adsorption. Lefebvre *et al.* [61] synthesized combined polydopamine polyurethane open cell foam (OCPUF@PDA@AC) with carbon media and studied its adsorption of methylene blue from aqueous solution. The adsorption capacity of methylene blue by OCPUF@PDA@AC was observed to be 245 mg/g at 298 K. Novel polyurethane foam material adjusted with coal (C/PUF) was evaluated by Kong *et al.* [62] and analyzed its adsorption in the removal of brilliant green dye from aqueous solution. The brilliant green adsorption by C/PUF was optimized and the highest adsorption efficiency was reported to be 99.40%. The isotherm studies indicate monolayer adsorption onto C/PUF and the adsorption capacity was observed as 134.95 mg/g. *Moringa oleifera* gum based bifunctional polyurethane foam (MOG-PUF) was synthesized by Ranote *et al.* [26] studied its adsorption for malachite green dye from aqueous solution. Batch mode adsorption studies over the removal of malachite green using MOG-PUF revealed that almost 100% of malachite green was removed within 30 min. The adsorption method followed Langmuir isotherm with highest adsorption capacity of 125.945 mg/g.

Novel cellulose nanowhiskers based polyurethane foam (CNW-PUF) was synthesized by Kumari *et al.* [63] and studied its removal of methylene blue dye as a model pollutant from aqueous solution. The effect of contact time on methylene blue by CNW-PUF was studied and the adsorption equilibrium was reported as 20 min. The isotherm study shows that the adsorption of methylene blue on CNW-PUF followed monolayer adsorption process with higher adsorption capacity of 110.5 mg/g. Centenaro *et al.* [64] synthesized polyurethane foam chitosan coated (PU chitosan coated) and studied its adsorption of reactive blue dye (RB 198). The adsorption capacity was observed as 86.43 mg/g. Mohammadi *et al.* [65] synthesized *p-tert*-butyl thiacalix[4]arene (TC4A) based polyurethane foam (TC-PUF) and tested it adsorption performance in malachite green dye removal. The TC-PUF was reported to have an adsorption capacity of 58.82 mg/g. Lefebvre *et al.* [66] synthesized polydopamine coated open cell polyurethane foam (OCPUF@PDA) and tested its adsorption of methylene blue from aqueous solution. The adsorption capacity was observed as 30.2 mg/g. Polyether type polyurethane foam (PUF) was prepared by Baldez *et al.* [67] and studied its adsorption of methylene blue. The adsorption capacity was reported as 20.4 mg/g. Porous multifunctional fluoropolymer composite foams were also prepared and its adsorption of methylene blue from aqueous solution was studied. The adsorption capacity of this fluoropolymer to adsorb methylene blue was observed as 10.25 mg/g of foam.

Yang *et al.* [68] synthesized polyurethane foam filled with humic acid chitosan cross-linked gel (HA-CS-PUF) and studied its adsorption in methylene blue, rhodamine B and methyl orange. The HA-CS-PUF was found to have an adsorption capacity of 10.31, 8.26 and 5.29 mg/g for methylene blue, rhodamine B and methyl orange, respectively. Polyurethane foam (PUF) was prepared by Neta *et al.* [39] and investigated its adsorption in removal of direct red 81 and reactive blue 21 from aqueous solution. The adsorption capacity of PUF for direct red 80 and reactive blue 21 was observed as 4.50 and 8.31 mg/g, respectively. Polyurethane foam comprising of cellulose from wood furniture industry waste (PU/CEL) was characterized by Góes *et al.* [69] and tested its adsorption performance in methylene blue, procion yellow HE-4R and procion red HE-7B dye. The adsorption capacity was observed as 1.83, 1.63 and 2.19 mg/g for methylene blue, HE-4R and HE-7R, respectively. Robaina *et al.* [70] synthesized polyurethane foam loaded with SDS(PUF/SDS) and examined the adsorption of four cationic dyes. The PUF/SDS was tested for the removal of methylene blue, rhodamine B, crystal violet and malachite green dye. The adsorption efficiency was reported to be good (> 90%) for the dye solution containing 2×10^{-5} and 1.0×10^{-4} mol/L of each dye.

Polymer foam adsorbents in heavy metal removal: Carboxymethylated cellulose nanofibrils (CMCNFs) embedded in polyurethane foam (PU/CMCNFs) was synthesized by Hong *et al.* [60] studied the adsorption efficiency of three divalent metal ions Cu(II), Cd(II) and Pb(II). The pH of the solution was maintained at 5 in the adsorption of metal ions onto PU/CMCNFs for avoiding the precipitation of metal hydroxides. The adsorption capacity of PU/CMCNF was observed as 216.1 mg/g for Pb(II), 78.7 mg/g for Cu(II) and 98 mg/g for Cd(II).

Vali *et al.* [71] prepared hydroxyapatite/polyurethane (Hap/PU) composite foam and studied its adsorption of Pb(II) from aqueous solution. This composite foam was reported to exhibit well developed open pore structure that favours the adsorption of Pb(II) ions. The highest adsorption capacity of Hap/PU composite was observed as 150 mg/g. Jang *et al.* [72] synthesized polyaniline nanoparticles coated polyurethane foam (PUF@PANI) and studied its adsorption in the removal of Hg(II) ions. The adsorption of PUF@PANI in Hg(II) removal reached a full removal efficiency of 97.4% under the experimental conditions (pH 7; 5 mg/L Hg(II) and adsorption time of 60 min). The adsorption capacity was observed as 103.2 mg/g.

Wang & Min [77] synthesized hydroxyapatite/poly(vinyl alcohol HAp/PVA cryogel immobilized on PVA (PVA foam) and Hap/PVA cryogel immobilized on polyurethane (PU foam) and studied the removal of Cd(II) from aqueous solution. The adsorption capacity of the adsorbent was observed as 53.1 mg/g for PVA foam and 47.7 mg/g for PU foam. Alginate/polyurethane composite (ALG/PUCF) was synthesized by Sone *et al.* [78] and tested its adsorption against Pb(II) ions. The adsorption capacity of ALG/PUCF was observed as 16 ± 2.1 μmol. Polymer foam coated with zerovalent copper (Cu^0) (Cu^0-PEI(1800)PAA) was prepared by Li *et al.* [73] and studied its adsorption in Cr(VI) removal. The adsorption capacity of Cu^0-PEI(1800)PAA was reported as 9.16 mg/g. Alhakawati & Banks [74] prepared biomass immobilized in hydrophilic polyurethane foam (biomass/PU foam) and studied its adsorption onto Cu(II) ions. The adsorption capacity was observed as 0.416-0.613 mmol/g. Hussein & Abu Zahra [75] prepared iron oxide nanoparticles (IONPs) incorporated inside porous polyurethane foam (PU-IONPs foam) and studied its removal capacity of arsenic species. The adsorption capacity for arsenic sorption on the PU-IONPs foam was found to be 0.0209 mg/g. The adsorption performance of polymer foam adsorbents are listed in Table-5. Some polymeric foams [60-62,72] are reported to be good adsorbents with good adsorption in dye and heavy metal removal.

An elaborative literature review described various types of novel foam adsorbents and its adsorption in dyes and heavy

TABLE-5
POLYMER FOAM ADSORBENTS IN DYE AND HEAVY METAL REMOVAL

S. No.	Polymer foam adsorbents	Dye	Adsorption capacity	Ref.
		Polymer foam material adsorbents in dye removal		
1	OCPUF@PDA@AC	Methylene blue	245 mg/g	[61]
2	C/PUF	Brilliant green	134.95 mg/g	[62]
3	MOG-PUF	Malachite green	125.945 mg/g	[21]
4	CNW-PUF	Methylene blue	110.5 mg/g	[63]
5	PU foam	Reactive blue 198	86.43 mg/g	[64]
6	TC-PUF	Malachite green	58.82 mg/g	[65]
7	OCPUF@PDA	Methylene blue	30.2 mg/g	[66]
8	PUF	Methylene blue	20.4 mg/g	[67]
9	FLUOROPOLYMER FOAM	Methylene blue	10.25 mg/g	[76]
10	HA-CS-PUF	Methylene blue	10.31 mg/g	[68]
		Rhodamine B	8.26 mg/g	
		Methyl orange	5.29 mg/g	
11	PUF	Direct red 80	4.50 mg/g	[39]
		Reactive blue 21	8.31 mg/g	
12	PU/CEL 1:1	Methylene blue	1.83 mg/g	[69]
		HE-4R	1.63 mg/g	
		HE-7B	2.19 mg/g	
13	PUF/SDS	Rhodamine B	–	[70]
		Methylene blue	–	
		Crystal violet	–	
		Malachite green	–	
		Polymer foam material adsorbents in heavy metal removal		
14	PU/CMCNFs	Pb(II)	216.1 mg/g	[60]
		Cu(II)	78.7 mg/g	
		Cd(II)	98 mg/g	
15	HA_p/PU	Pb(II)	150 mg/g	[72]
16	PUF@PANI	Hg(II)	103.2 mg/g	[71]
17	PVA foam	Cd(II)	53.1 mg/g	[77]
	PU foam	Cd(II)	47.7 mg/g	
18	ALG/PUCF	Pb(II)	16.0±2.1 μmol	[78]
19	Cu^0-PEI(1800)-PAA	Cr(VI)	9.16 mg/g	[73]
20	Biomass/PU foam	Cu(II)	0.416 – 0.613 mmol/g	[74]
21	PU-IONPs foam	As	0.0209 mg/g	[75]

metals removal. On comparing various foam adsorbents, it is observed that carbon foam adsorbents are reported to have superior adsorption capacity. This is followed by chitosan foam and metal foam adsorbents with good adsorption performance. Some other foam adsorbent like alginic acid foam adsorbent (1201 mg/g) was also reported to have higher adsorption performance. Thus, it is clear that novel foam adsorbents were effective materials in the removal of dyes and heavy metals.

Conclusion

This review revealed that the foam adsorbents are one of the the potential materials in adsorption technique. Toxicity due to dyes and heavy metals and its adverse effect is of serious concern to preserve the environment. Hence, efficient adsorbents with more promising adsorption performance, *i.e.* carbon foam, chitosan foam and metal foam adsorbents are synthesized and tested for the removal of dyes and heavy metals. Out of the adsorption capacity of all the novel foam adsorbents described in the literature, carbon foam adsorbents, chitosan foam adsorbents and metal foam adsorbents are superior with higher adsorption capacity (> 400 mg/g). A positive effort in synthesizing the novel foam adsorbents may prove effective and give fruitful results in future. Furthermore, novel foam adsorbents which are already reported may suitably be modified or developed in further researches to get unique materials for various other applications.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. Z.N. Garba, I. Lawan, W. Zhou, M. Zhang, L. Wang and Z. Yuan, *Sci. Total Environ.*, **717**, 135070 (2020); https://doi.org/10.1016/j.scitotenv.2019.135070
2. M. Manyangadze, N.H.M. Chikuruwo, T.B. Narsaiah, C.S. Chakra, M. Radhakumari and G. Danha, *S. Afr. J. Chem. Eng.*, **31**, 25 (2020); https://doi.org/10.1016/j.sajce.2019.11.003
3. L.K. Wang, D.A. Vaccari, Y. Li and N.K. Shammas, *Physicochem. Treat. Process.*, **3**, 141 (2005); https://doi.org/10.1385/1-59259-820-x:141
4. A. Fatehizadeh, S. Rahimi, M. Ahmadian, R. Barati, N. Yousefi, S.P. Moussavi, K. Rahimi, S. Reshadat, S.R. Ghasemi and N.R. Gilan, *Int. J. Environ. Health Eng.*, **3**, 31 (2014); https://doi.org/10.4103/2277-9183.139756
5. H. Huang, P. Zhang, Z. Zhang, J. Liu, J. Xiao and F. Gao, *J. Clean. Prod.*, **127**, 302 (2016); https://doi.org/10.1016/j.jclepro.2016.04.002
6. Z. Yang, Y. Zhou, Z. Feng, X. Rui, T. Zhang and Z. Zhang, *Polymer*, **11**, 1252 (2019); https://doi.org/10.3390/polym11081252
7. S. Suresh and S. Ravichandran, *J. Xidian Univ.*, **14**, 1257 (2020); https://doi.org/10.37896/jxu14.4/148
8. S. Suresh, S. Shanmugan and S. Ravichandran, *J. Xidian Univ.*, **14**, 2602 (2020); https://doi.org/10.37896/jxu14.4/288
9. M. Priyanka and M.P. Saravanakumar, *J. Clean. Prod.*, **197**, 511 (2018); https://doi.org/10.1016/j.jclepro.2018.06.197
10. R. Gusain, K. Gupta, P. Joshi and O.P. Khatri, *Adv. Colloid Interface Sci.*, **272**, 102009 (2019); https://doi.org/10.1016/j.cis.2019.102009
11. A.N. Kamarudzaman, T.C. Chay, A. Amir and S.A. Talib, *Procedia Soc. Behav. Sci.*, **195**, 2709 (2015); https://doi.org/10.1016/j.sbspro.2015.06.379
12. T.M. Marella, A. Saxena and A. Tiwari, *Bioresour. Technol.*, **305**, 123068 (2020); https://doi.org/10.1016/j.biortech.2020.123068
13. Z. Zhang, H. Li, J. Li, X. Li, Z. Wang, X. Liu and L. Zhang, *Chem. Phys. Lett.*, **731**, 136573 (2019); https://doi.org/10.1016/j.cplett.2019.07.001
14. C.C. Ong, R. Jose and M.S.M. Saheed, *Chem. Eng. J.*, **388**, 124306 (2020); https://doi.org/10.1016/j.cej.2020.124306
15. Q. Zhang, Q. Lin, X. Zhang and Y. Chen, *Environ. Res.*, **179**, 108746 (2019); https://doi.org/10.1016/j.envres.2019.108746
16. H. Vijwani, M.N. Nadagouda, V. Namboodiri and S.M. Mukhopadhyay, *Chem. Eng. J.*, **268**, 197 (2015); https://doi.org/10.1016/j.cej.2015.01.027
17. J. Chen, X. Shi, Y. Zhan, X. Qiu, Y. Du and H. Deng, *Appl. Surf. Sci.*, **397**, 133 (2017); https://doi.org/10.1016/j.apsusc.2016.10.211
18. H. Yu and B. Fugetsu, *J. Hazard. Mater.*, **177**, 138 (2010); https://doi.org/10.1016/j.jhazmat.2009.12.007
19. Z. Ma, D. Liu, Y. Zhu, Z. Li, Z. Li, H. Tian and H. Liu, *Carbohydr. Polym.*, **144**, 230 (2016); https://doi.org/10.1016/j.carbpol.2016.02.057
20. R. Da Rosa Schio, B.C. Da Rosa, J.O. Gonçalves, L.A.A. Pinto, E.S. Mallmann and G.L. Dotto, *Int. J. Biol. Macromol.*, **121**, 373 (2019); https://doi.org/10.1016/j.ijbiomac.2018.09.186
21. F.N. Allouche, E. Guibal and N. Mameri, *Colloids Surf. A Physicochem. Eng. Asp.*, **446**, 224 (2014); https://doi.org/10.1016/j.colsurfa.2014.01.025
22. D.T. Vo and C.K. Lee, *J. Environ. Chem. Eng.*, **5**, 5688 (2017); https://doi.org/10.1016/j.jece.2017.10.042
23. T.S. Trung, C.H. Ng and W.F. Stevens, *Biotechnol. Lett.*, **25**, 1185 (2003); https://doi.org/10.1023/A:1024562900548
24. E. Sharifpour, H. Haddadi, M. Ghaedi, K. Dashtian and A. Asfaram, *J. Environ. Chem. Eng.*, **6**, 4864 (2018); https://doi.org/10.1016/j.jece.2018.07.029
25. L.K. Wu, H. Wu, H.B. Zhang, H.Z. Cao, G.Y. Hou, Y.P. Tang and G.Q. Zheng, *Chem. Eng. J.*, **334**, 1808 (2018); https://doi.org/10.1016/j.cej.2017.11.096
26. S. Ranote, D. Kumar, S. Kumari, R. Kumar, G.S. Chauhan and V. Joshi, *Chem. Eng. J.*, **361**, 1586 (2019); https://doi.org/10.1016/j.cej.2018.10.194
27. Y. Lei, F. Chen, Y. Luo and L. Zhang, *Chem. Phys. Lett.*, **593**, 122 (2014); https://doi.org/10.1016/j.cplett.2013.12.066
28. C.G. Lee, J.W. Jeon, M.J. Hwang, K.H. Ahn, C. Park, J.W. Choi and S.H. Lee, *Chemosphere*, **130**, 59 (2015); https://doi.org/10.1016/j.chemosphere.2015.02.055
29. G. Chen, Y. Liu, F. Liu and X. Zhang, *Appl. Surf. Sci.*, **311**, 808 (2014); https://doi.org/10.1016/j.apsusc.2014.05.171
30. B. Tan, H. Zhao, Y. Zhang, X. Quan, Z. He, W. Zheng and B. Shi, *J. Colloid Interface Sci.*, **512**, 853 (2018); https://doi.org/10.1016/j.jcis.2017.10.092
31. R. Li, W. Liang, J.J. Wang, L.A. Gaston, D. Huang, H. Huang, S. Lei, M.K. Awasthi, B. Zhou, R. Xiao and Z. Zhang, *J. Environ. Manage.*, **212**, 77 (2018); https://doi.org/10.1016/j.jenvman.2017.12.034
32. P.R. Agrawal, N. Singh, S. Kumari and S.R. Dhakate Sr., *J. Hazard. Mater.*, **377**, 274 (2019); https://doi.org/10.1016/j.jhazmat.2019.05.097
33. Z. Wang, F. Lin, L. Huang, Z. Chang, B. Yang, S. Liu, M. Zheng, Y. Lu and J. Chen, *Environ. Pollut.*, **254**, 112854 (2019); https://doi.org/10.1016/j.envpol.2019.07.022
34. M. Khan, L. Tiehu, T.K. Zhao, Z. Ali, A. Malik, A. Khan, I. Khan, A. Ullah, S. Jiao, M. Idrees and C. Xiong, *Diamond Rel. Mater.*, **79**, 119 (2017); https://doi.org/10.1016/j.diamond.2017.09.008

35. H. Yu, M. Che, B. Zhao, Y. Lu, S. Zhu, X. Wang, W. Qin and M. Huo, *Synth. Met.*, **262**, 116332 (2020); https://doi.org/10.1016/j.synthmet.2020.116332
36. C.G. Lee, S. Lee, J.A. Park, C. Park, S.J. Lee, S.B. Kim, B. An, S.T. Yun, S.H. Lee and J.W. Choi, *Chemosphere*, **166**, 203 (2017); https://doi.org/10.1016/j.chemosphere.2016.09.093
37. U.J. Kim, S. Kimura and M. Wada, *Carbohydr. Polym.*, **214**, 294 (2019); https://doi.org/10.1016/j.carbpol.2019.03.058
38. N. Markandeya, N. Dhiman, S.P. Shukla, D. Mohan, G.C. Kisku and S. Patnaik, *J. Clean. Prod.*, **182**, 206 (2018); https://doi.org/10.1016/j.jclepro.2018.01.244
39. J. de Jesus da Silveira Neta, G. Costa Moreira, C.J. da Silva, C. Reis and E.L. Reis, *Desalination*, **281**, 55 (2011); https://doi.org/10.1016/j.desal.2011.07.041
40. S. Ma, M. Zhang, J. Nie, J. Tan, S. Song and Y. Luo, *Carbohydr. Polym.*, **208**, 328 (2019); https://doi.org/10.1016/j.carbpol.2018.12.081
41. X. Wang, W. Kong, W. Xie, L. Li, Y. Liu, X. Wu and J. Gao, *Chem. Eng. J.*, **197**, 509 (2012); https://doi.org/10.1016/j.cej.2012.03.059
42. E. Padilla-Ortega, M. Darder, P. Aranda, R. Figueredo Gouveia, R. Leyva-Ramos and E. Ruiz-Hitzky, *Appl. Clay Sci.*, **130**, 40 (2016); https://doi.org/10.1016/j.clay.2015.11.024
43. F. Su, H. Zhou, Y. Zhang and G. Wang, *J. Colloid Interface Sci.*, **478**, 421 (2016); https://doi.org/10.1016/j.jcis.2016.06.035
44. W. Kaminski, E. Tomczak and U. Wilicka, *Computer-Aided Chem. Eng.*, **26**, 1203 (2009); https://doi.org/10.1016/S1570-7946(09)70200-7
45. Y. Snoussi, M. Abderrabba and A. Sayari, *J. Taiwan Inst. Chem. Eng.*, **66**, 372 (2016); https://doi.org/10.1016/j.jtice.2016.06.015
46. L.-K. Wu, H. Wu, Z.-Z. Liu, H.-Z. Cao, G.-Y. Hou, Y.-P. Tang and G.-Q. Zheng, *J. Hazard. Mater.*, **347**, 15 (2018); https://doi.org/10.1016/j.jhazmat.2017.12.048
47. X. Li and Q. Zhai, *Water Sci. Eng.*, **12**, 298 (2019); https://doi.org/10.1016/j.wse.2019.12.006
48. A. Pettignano, N. Tanchoux, T. Cacciaguerra, T. Vincent, L. Bernardi, E. Guibal and F. Quignard, *Carbohydr. Polym.*, **178**, 78 (2017); https://doi.org/10.1016/j.carbpol.2017.09.022
49. J. Sanchez-Martin, J. Beltran-Heredia, A. Delgado-Regana, M.A. Rodriguez-Gonzalez and F. Rubio-Alonso, *Chem. Eng. J.*, **228**, 575 (2013); https://doi.org/10.1016/j.cej.2013.05.009
50. K. Khatib, H. Kerroumi and M. El Azhar, *Mater. Today Proced.*, **22**, 120 (2020); https://doi.org/10.1016/j.matpr.2019.08.120
51. N. Esmaeili, A. Salimi, M.J. Zohuriaan-Mehr, M. Vafayan and W. Meyer, *J. Hazard. Mater.*, **357**, 30 (2018); https://doi.org/10.1016/j.jhazmat.2018.05.045
52. Y. Wang, Y. Feng, X.F. Zhang, X. Zhang, J. Jiang and J. Yao, *J. Colloid Interface Sci.*, **514**, 190 (2018); https://doi.org/10.1016/j.jcis.2017.12.035
53. L. Han, J. Wang, Z. Liu, Y. Zhang, Y. Jin, J. Li and D. Wang, *J. Hazard. Mater.*, **393**, 122468 (2020); https://doi.org/10.1016/j.jhazmat.2020.122468
54. V.B. Cashin, D.S. Eldridge, P. Kingshott and A. Yu, *Colloids Surf. A Physicochem. Eng. Asp.*, **552**, 153 (2018); https://doi.org/10.1016/j.colsurfa.2018.05.021
55. J. Pan, J. Zeng, Q. Cao, H. Gao, Y. Gen, Y. Peng, X. Dai and Y. Yan, *Chem. Eng. J.*, **284**, 1361 (2016); https://doi.org/10.1016/j.cej.2015.09.023
56. P. Qu, Y. Li, H. Huang, G. Wu, J. Chen, F. He, H. Wang and B. Gao, *Chemosphere*, **241**, 125004 (2020); https://doi.org/10.1016/j.chemosphere.2019.125004
57. A. Turco, A. Pennetta, A. Caroli, E. Mazzotta, A.G. Monteduro, E. Primiceri, G. De Benedetto and C. Malitesta, *J. Colloid Interface Sci.*, **552**, 401 (2019); https://doi.org/10.1016/j.jcis.2019.05.059
58. G. Tondi, C.W. Oo, A. Pizzi, A. Trosa and M.F. Thevenon, *Ind. Crops Prod.*, **29**, 336 (2009); https://doi.org/10.1016/j.indcrop.2008.06.006
59. C. Prapruddivongs and S. Thomyasirigul, *Polym. Test.*, **77**, 105891 (2019); https://doi.org/10.1016/j.polymertesting.2019.05.007
60. H.J. Hong, J.S. Lim, J.Y. Hwang, M. Kim, H.S. Jeong and M.S. Park, *Carbohydr. Polym.*, **195**, 136 (2018); https://doi.org/10.1016/j.carbpol.2018.04.081
61. L. Lefebvre, G. Agusti, A. Bouzeggane and D. Edouard, *Catal. Today*, **301**, 98 (2018); https://doi.org/10.1016/j.cattod.2017.05.025
62. L. Kong, F. Qiu, Z. Zhao, X. Zhang, T. Zhang, J. Pan and D. Yang, *J. Clean. Prod.*, **137**, 51 (2016); https://doi.org/10.1016/j.jclepro.2016.07.067
63. S. Kumari, G.S. Chauhan and J. Ahn, *Chem. Eng. J.*, **304**, 728 (2016); https://doi.org/10.1016/j.cej.2016.07.008
64. G.S.N. Machado Centenaro, B.R. Facin, A. Valério, A.A.U. de Souza, A. da Silva, J.V. de Oliveira and D. de Oliveira, *J. Water Process Eng.*, **20**, 201 (2017); https://doi.org/10.1016/j.jwpe.2017.11.008
65. A. Mohammadi, M.M. Lakouraj and M. Barikani, *React. Funct. Polym.*, **83**, 14 (2014); https://doi.org/10.1016/j.reactfunctpolym.2014.07.003
66. L. Lefebvre, J. Kelber, L. Jierry, V. Ritleng and D. Edouard, *J. Environ. Chem. Eng.*, **5**, 79 (2017); https://doi.org/10.1016/j.jece.2016.11.025
67. E.E. Baldez, N.F. Robaina and R.J. Cassella, *J. Hazard. Mater.*, **159**, 580 (2008); https://doi.org/10.1016/j.jhazmat.2008.02.055
68. H.C. Yang, J.L. Gong, G.M. Zeng, P. Zhang, J. Zhang, H.Y. Liu and S.Y. Huan, *J. Colloid Interface Sci.*, **505**, 67 (2017); https://doi.org/10.1016/j.jcis.2017.05.075
69. M.M. Góes, M. Keller, V. Masiero Oliveira, L.D.G. Villalobos, J.C.G. Moraes and G.M. Carvalho, *Ind. Crops Prod.*, **85**, 149 (2016); https://doi.org/10.1016/j.indcrop.2016.02.051
70. N.F. Robaina, S. Soriano and R.J. Cassella, *J. Hazard. Mater.*, **167**, 653 (2009); https://doi.org/10.1016/j.jhazmat.2009.01.033
71. S.A. Vali, M. Baghdadi and M.A. Abdoli, *J. Environ. Chem. Eng.*, **6**, 6612 (2018); https://doi.org/10.1016/j.jece.2018.09.042
72. S.H. Jang, B.G. Min, Y.G. Jeong, W.S. Lyoo and S.C. Lee, *J. Hazard. Mater.*, **152**, 1285 (2008); https://doi.org/10.1016/j.jhazmat.2007.08.003
73. C. Li, Z. Du, W. Zou, H. Li and C. Zhang, *React. Funct. Polym.*, **88**, 24 (2015); https://doi.org/10.1016/j.reactfunctpolym.2015.02.001
74. M.S. Alhakawati and C.J. Banks, *J. Environ. Manage.*, **72**, 195 (2004); https://doi.org/10.1016/j.jenvman.2004.04.010
75. F.B. Hussein and N.H. Abu-Zahra, *J. Water Process Eng.*, **13**, 1 (2016); https://doi.org/10.1016/j.jwpe.2016.07.005
76. U. Azhar, C. Huyan, X. Wan, C. Zong, A. Xu, J. Liu, J. Ma, S. Zhang and B. Geng, *Arab. J. Chem.*, **12**, 559 (2019); https://doi.org/10.1016/j.arabjc.2018.04.003
77. X. Wang and B.G. Min, *J. Hazard. Mater.*, **156**, 381 (2008); https://doi.org/10.1016/j.jhazmat.2007.12.027
78. H. Sone, B. Fugetsu and S. Tanaka, *J. Hazard. Mater.*, **162**, 423 (2009); https://doi.org/10.1016/j.jhazmat.2008.05.093