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REVIEW ARTICLE

Advanced adsorbents for ibuprofen removal from aquatic environments: a review

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Abstract

The presence of pharmaceuticals in ecosystems is a major health issue, calling for advanced methods to clean wastewater before effluents reach rivers. Here, we review advanced adsorption methods to remove ibuprofen, with a focus on ibuprofen occurrence and toxicity, adsorbents, kinetics, and adsorption isotherms. Adsorbents include carbon- and silica-based materials, metal–organic frameworks, clays, polymers, and bioadsorbents. Carbon-based adsorbents allow the highest adsorption of ibuprofen, from 10.8 to 408 mg/g for activated carbon and 2.5–1033 mg/g for biochar. Metal–organic frameworks appear promising due to their high surface areas and tunable properties and morphology. 95% of published reports reveal that adsorption kinetics follow the pseudo-second-order model, indicating that the adsorption is predominantly governed by chemical adsorption. 70% of published reports disclose that the Langmuir model describes the adsorption isotherm, suggesting that adsorption involves monolayer adsorption.

Keywords Pharmaceutical · Antibiotic · Adsorption · Water treatment · Metal–organic framework · Polymer

Introduction

Over the past decade, the rapid growth of industrialization and human activities has led to pharmaceutical and personal care products emerging as significant pollutants in aquatic environments, posing a serious global concern. These compounds,

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along with their metabolites, enter water bodies through various sources such as households, hospitals, factories, and sewage treatment plants, resulting in detrimental effects on water quality and causing substantial harm to aquatic ecosystems (Davarnejad et al. 2018; Sophia and Lima 2018). Antibiotics and anti-inflammatory agents, among the various pharmaceutical contaminants, are particularly noteworthy due to their increasing global consumption (Akhil et al. 2021; Anand et al. 2022; Muñiz-González 2021; Nguyen et al. 2022b; Rameshwar et al. 2023).

Ibuprofen, scientifically known as 2-[4-(2-Methylpropyl) phenyl] propanoic acid, holds the distinction of being the third most commonly used drug worldwide, with an annual consumption of approximately 200 tons (Chopra and Kumar 2020). This non-steroidal anti-inflammatory drug is highly sought after in the market and is primarily produced by Shasun Chemicals and Drugs Ltd., with the lot number IBU0307598 (Mestre et al. 2007). It is commonly prescribed for rheumatoid arthritis, osteoarthritis, pain relief, inflammation, and fever management (Shaheen et al. 2022). Ibuprofen has been detected in wastewater and rivers across multiple countries (Brun. et al. 2006; Mestre et al. 2007; Nakada et al. 2006; Vieno et al. 2005), with increasing concentrations observed in wastewater treatment plants and water bodies. Given its bioactive nature, it poses a potential environmental hazard, as shown in Fig. 1.

Various methods have been explored for the removal of pharmaceutical compounds from different matrices (Caban

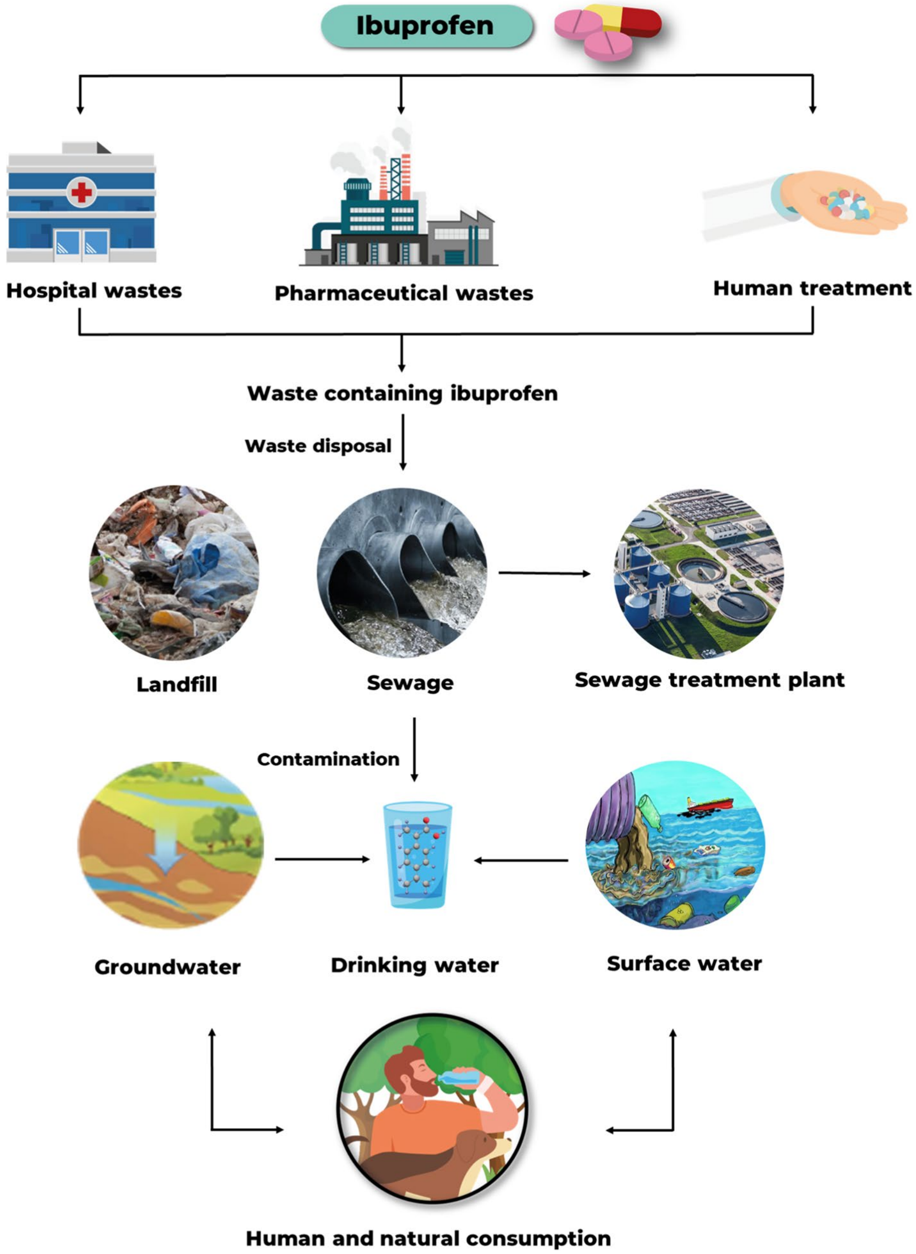

Fig. 1 Fate of ibuprofen in the environment. The daily usage of ibuprofen is steadily rising, leading to a corresponding increase in waste containing ibuprofen. This waste is generated by pharmaceutical industries, hospitals, and households and is often disposed of in sewage systems, landfills, or municipal treatment plants. Unfortunately, this disposal method allows ibuprofen to enter water bodies, where living organisms can absorb it and subsequently enter the food chain. Improper disposal of ibuprofen poses a significant risk of bioaccumulation and ecological harm

and Stepnowski 2021; Taoufik et al. 2020), including filtration (Femina Carolin et al. 2021; Gu et al. 2018; Taheran et al. 2016), advanced oxidation processes (Akbari Beni et al. 2020; Bastami et al. 2017; Brillas 2022; Kanakaraju et al. 2014; Sruthi et al. 2021), ion exchange (Jiang et al. 2015), biological treatment (Tiwari et al. 2017), and adsorption (Bello and Raman 2019; Duarte et al. 2022; Osman et al. 2023a; Ranjbari et al. 2020). However, among these methods, adsorption has gained significant attention due to its cost-effectiveness, simplicity, high efficiency, regenerability, and scalability (Ayati et al. 2019; Karimi-Maleh et al. 2021b; Shahinpour et al. 2022). Adsorption has emerged as a superior approach for pharmaceutical compound removal from aqueous solutions (Ahmed 2017; Huang et al. 2021; Igwegbe et al. 2021; Prasetya et al. 2023).

Extensive research has been conducted on removing ibuprofen from aquatic media through adsorption, leading to the exploration of a wide range of adsorbents with diverse origins. These adsorbents include activated carbons (Labuto et al. 2022; Matějová et al. 2022), polymers (Karimi-Maleh et al. 2021a; Yu et al. 2022), graphene-based materials (Akash et al. 2022; Ndagijimana et al. 2022), biosorbents (Michelon et al. 2022; Priyan and Narayanasamy 2022), and nanoparticles (Wang et al. 2017a). Various modifications to the chemical structures of these adsorbents, such as impregnation, crosslinking, grafting, creating material1@material2@material3 composites, or re-functionalization, and increasing the number of functional groups, have been employed to enhance their performance in ibuprofen adsorption. Researchers are currently focused on obtaining ibuprofen sorbents that exhibit high adsorption capacities, excellent selectivities, and rapid kinetics.

Existing literature has provided insights into various methods for removing ibuprofen from aqueous solutions, focusing on advanced oxidation processes and photocatalysis (Brillas 2022; Choi et al. 2012; Sruthi et al. 2021). However, the potential of adsorption, which offers distinct advantages as a viable approach for ibuprofen removal from aqueous solutions, deserves attention. This review examines the prominent adsorbents reported in the literature for ibuprofen removal and highlights recent advancements in this field. By providing a comprehensive overview, this review aims to assist researchers in exploring innovative strategies for designing efficient and environmentally friendly adsorption processes for treating ibuprofen-contaminated wastewater.

Ibuprofen toxicity and occurrence

Ibuprofen cannot be fully metabolized in humans and animals; therefore, it is excreted in the urine in its pure form and as various metabolites that may be more toxic than their parent molecule (Chopra and Kumar 2020). It has been reported that approximately 85% of the consumed ibuprofen excreted in urine makes up 0.22 µg/L of domestic effluent (Rainsford 2009). Inappropriate waste disposal, industrial and sewage treatment plants, and livestock treatment are other significant sources of ibuprofen entering aquatic environments (Chopra and Kumar 2020). The molecular structure of ibuprofen displays its lower energy conformation with estimated dimensions of approximately 1.03 × 0.52 × 0.43 nm, as illustrated in Fig. 2 (Mestre et al. 2007). This pharmaceutical compound contains functional groups such as carboxylic acids and benzene, which contribute to its heightened mobility while limiting solubility in water. Due to rapid population growth, accelerated urbanization, agricultural demand, and industrial development, the global volume of solid waste has experienced a significant surge. Projections indicate that by 2030, the world's population will reach 8.5 billion, with solid waste production reaching a staggering 2.59 billion tons (Peng et al. 2023). As a result, significant amounts of ibuprofen have been detected in surface water, groundwater, and soil, posing a potential risk to the food web and living organisms. Ibuprofen has been frequently identified in various water bodies, including surface water, groundwater, and wastewater in South Africa (Madikizela and Chimuka 2017), Germany (Huppert et al. 1998), the USA (Wu et al. 2009; Zhang et al. 2007), China (Wang et al. 2013), Taiwan (Fang et al. 2012), and Mexico (Gibson et al. 2010), at concentrations ranging from 3.5 to 8600 ng/L. Despite the high elimination efficiency for ibuprofen and metabolites, in about 90% of wastewater treatment plants (Kermia et al. 2016), the quantitative ibuprofen content in global wastewater treatment plants effluent varies from being undetectable to 140 µg/L (Kermia et al. 2016).

Improper ibuprofen disposal can lead to bioaccumulation and ecological damage, as shown in Fig. 2. To evaluate its acute and chronic toxic effects, ibuprofen toxicity has mainly been studied on fish and daphnia. The studies have shown that it poses an environmental hazard with an actual risk ratio of ≤ 1 (Bouissou-Schurtz et al. 2014), and its toxic effects on various model organisms have been demonstrated (Geiger et al. 2016; Grzesiuk et al. 2020; Gutiérrez-Noya et al. 2020; Mohd Zanuri et al. 2017). Ibuprofen has been reported to interfere with cell reproduction in human embryos (Estevez et al. 2014), adversely affect reproduction in aquatic vertebrates (Collado et al. 2012), exhibit toxicity towards algae (Cleuvers 2003), and disrupt endocrine function in living organisms (Show et al. 2021). This compound tends to bioaccumulate and can cause significant biological harm to organisms, even at very low concentrations over prolonged periods (Cleuvers 2003).

Adsorbents for the removal of ibuprofen

Various remediation techniques have been developed to address the adverse effects of ibuprofen, and their effectiveness has been evaluated. Water treatment technologies focus on removing, containing, and/or reducing ibuprofen

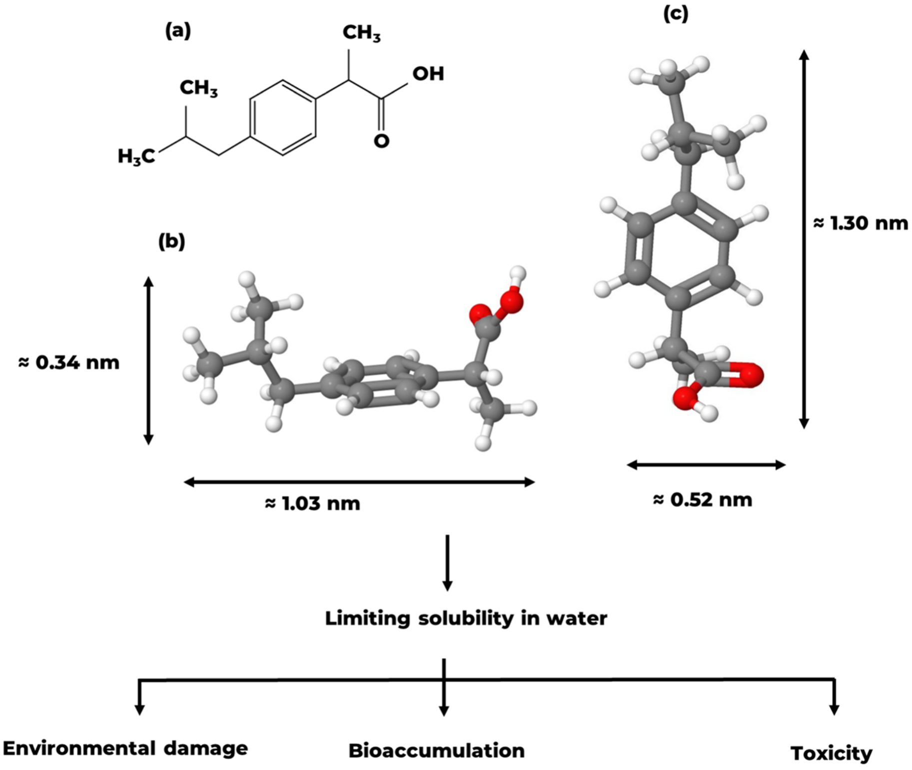

Fig. 2 Ibuprofen molecule structure (**a**), with a molecular weight of 206.28 g/mol. By molecular modeling with Gaussian-03 and using a semi-empirical method of Parametric Method 3 (PM3), the interatomic distances are estimated at 1.03 nm (length, **b**) × 0.52 nm (width, **c**) with a thickness of 0.34 nm. It has enormous daily consumption, and its global consumption is constantly increasing. So, it can enter water bodies and then the living organism's food chain through discharge from households, hospitals, factories, and municipal sewage treatment plants. The improper disposal of ibuprofen can lead to bioaccumulation and ecological damage. The unit nm refers to the nanometer

in wastewater (Chopra and Kumar 2020; Davarnejad et al. 2018) and can be categorized into three groups: chemical, physical, and biological methods (Aryee et al. 2021). Several treatment approaches have been utilized to eliminate ibuprofen from wastewater, including advanced oxidation processes (Brillas 2022), membrane separation (Nasrollahi et al. 2022), extraction (Alitabar-Ferozjah and Rahbar-Kelishami 2022), biodegradation (de Melo Pirete et al. 2022; Hasan et al. 2021), coagulation (Jin et al. 2021), and adsorption (Oba et al. 2021). However, it is essential to note that while each process has unique benefits, many of these methods can be complex, require high maintenance and investment costs, and generate harmful sludge. Among the various removal methods, adsorption has gained significant attention for its advantages in removing pharmaceutical and personal care products. It offers simplicity, potential efficiency, high selectivity at the molecular level, low investment cost, low energy consumption, absence of secondary pollution, and good reversibility (Ayati et al. 2016; Khoshkho et al. 2021; Najafi et al. 2022; Osman et al. 2023a; Titchou et al. 2021).

Adsorption is a surficial phenomenon in which adsorbates accumulate on the surface of an adsorbent or at the interface of two phases via electrostatic attraction, van der Waals forces, ion exchange, ion-pair interactions, cation-π interactions, or hydrophobic hydration (Pakade et al. 2019). Adsorbates can bind weakly to the adsorbent surface through physisorption (van der Waals interactions) or strongly through chemisorption, covalent or ionic interactions (Ma et al. 2019). Adsorption has proven effective in removing a wide range of organic and inorganic contaminants from different types of wastewater (Karimi-Maleh et al. 2021c; Karimi et al. 2022; Ranjbari et al. 2019; Tabrizi et al. 2022; Tanhaei et al. 2019). The adsorbent's nature, type, and surface functional groups influence the primary adsorption mechanism. In recent years, numerous studies have focused on synthesizing and modifying various adsorbents to enhance their adsorption capacity for ibuprofen in aqueous media.

Various types of adsorbents, such as activated carbon, silica, zeolites, graphene-based adsorbents, synthetic polymers, biopolymers, and biosorbents, have been extensively utilized for the removal of ibuprofen from aqueous solutions. When selecting an adsorbent, it is crucial to consider its efficiency in terms of fast removal rate, high uptake capacity, and ease of recovery or separation. The adsorption behavior of different adsorbents can be attributed to their structure, morphology, specific surface area, pore size, surface charge, and intrinsic adsorption affinity (Zheng et al. 2021). Functionalized crosslinking reagents are employed to enhance adsorbents' adsorptive properties, which contribute to the abatement of adsorbates and improve the adsorbent's stability, rigidity, and ruggedness. These crosslinking reagents also serve as scaffolds for additional modification or grafting, further enhancing the adsorbent's performance (Pakade et al. 2019). Incorporating new functional groups through crosslinking or grafting also affects the selectivity of the adsorbent. Therefore, carefully considering and aligning the adsorbent's surface functional group chemistry with the adsorbate is essential for achieving optimal performance.

Carbon-based adsorbents

Over the last two decades, carbonaceous adsorbents have played an essential role in the fate of organic and inorganic water contaminants (Gopinath et al. 2021; Gul et al. 2021; Jain et al. 2021). Among carbon-based materials, activated carbon is the most commonly used adsorbent in water treatment (Rocha et al. 2020; Wong et al. 2018) and air pollution control (Mohamad Nor et al. 2013) due to its well-developed surface, high surface area, abundant micropores, and excellent adsorptive capacity (Ahmed 2017). Additionally, various novel carbonaceous materials, including engineered nanomaterials like graphene-based materials, carbon nanotubes, and C_{60} fullerenes, as well as sustainable and cost-effective materials such as biochar, have been explored (Monisha et al. 2022; Nasrollahzadeh et al. 2021; Thakur and Kandasubramanian 2019; Wang et al. 2019a).

Recent literature review articles have summarized the knowledge available on the application of carbonaceous materials in the remediation of pharmaceutical pollutants (Gopinath and Kadirvelu 2018; Jung et al. 2015; Mansour et al. 2018; Ojha et al. 2021; Rocha et al. 2020; Sandoval-González et al. 2022). This implies that these compounds can be used in ibuprofen removal (Ayati et al. 2023). The performance of activated carbon depends significantly on its characteristics, which are influenced by the precursor material and fabrication methods employed (Torrellas et al. 2015). Typically, activated carbon is produced by directly carbonizing an untreated precursor under an inert gas atmosphere at high temperatures, followed by physical or chemical activation (Adeleye et al. 2021). However, commercial activated carbons can be expensive and non-selective, prompting researchers to explore alternative sources such as waste materials, coal, plant materials, bones, and municipal waste for the synthesis of low-cost activated carbon adsorbents (Álvarez-Torrellas et al. 2016; Ameen et al. 2023; Mansouri et al. 2015; Mestre et al. 2009).

In recent studies, agro-waste materials have emerged as promising precursors for the production of activated carbons used for the removal of ibuprofen from aqueous solutions (Bursztyn Fuentes et al. 2022; Sandoval-González et al. 2022). Various agro-waste materials, such as *Lantana camara* stalk (Ganesan et al. 2021), olive waste cake (Baccar et al. 2012), cork (Mestre et al. 2009), olive stones (Mansouri et al. 2015), coconut shell (Arinkoola et al. 2022; Bursztyn Fuentes et al. 2022), and cocoa husk (Bello et al. 2020b; Villabona-Ortíza et al. 2021) have been investigated as precursors for the synthesis of activated carbons. Table 1 provides examples of these activated carbon materials and their respective sources. The investigated adsorbents have demonstrated remarkable selectivity and high adsorption capacities exceeding 400 g/g for ibuprofen (An et al. 2018; Mestre et al. 2007). The preferential adsorption of ibuprofen occurs within the ultra-micropores of activated carbon (Guedidi et al. 2013). For example, in one study, powdered activated carbon derived from cork waste, treated with potassium carbonate, exhibited an ibuprofen adsorption capacity of approximately 139 mg/g at pH 4.0 and 25 °C. The adsorption capacity was significantly enhanced to around 393 mg/g through chemical and steam activation (Mestre et al. 2007). This finding confirms that the activation method greatly influences the adsorption behavior of activated carbon. In another study, Mestre et al. (2014) compared the ibuprofen adsorption capacities of chemically activated, i.e., potassium hydroxide and potassium carbonate, and physically, i.e., steam, activated cork-based activated carbons. Maximum sorption capacities of 138 mg/g, 119 mg/g, and 93.7 mg/g were achieved for potassium hydroxide-activated, steam-activated, and potassium carbonate-activated activated carbon, respectively, after 6 h of adsorption. Kinetic studies revealed that the initial adsorption rates followed the order of steam more than potassium hydroxide more than potassium carbonate activation, which was directly related to the volume of their micropores. Furthermore, Silva et al. (2005) demonstrated the significance of the number of micropores in the adsorption rate of ibuprofen onto activated carbons.

The literature has shown that the reactivation, functionalization, and modification of native activated carbons enhance their adsorption performance. Activated carbon post-treatment is another approach used to introduce or increase the number of functional groups in the structure or change the functional groups to other forms, e.g., thiol to amino (Pakade et al. 2019). It can also improve activated carbon’s physical features, such as surface area and pore characteristics. Suitable reduction or oxidation treatments can enhance adsorption behavior (Guedidi et al. 2013). Chemical oxidation of activated carbon can introduce oxygen-containing functional groups, such as carbonyl or carboxyl, lactonic, phenolic, and hydroxyl groups, positively impacting ibuprofen adsorption (Guedidi et al. 2013). Various oxidizing agents, including phosphoric acid (Álvarez-Torrellas et al. 2016; Bello et al. 2020a; Bursztyn Fuentes et al. 2022), sulfuric acid (Al-Kindi and Al-Haidri 2021), and potassium carbonate (Al-Kindi and Al-Haidri 2021), as well as activating agents like zinc chloride (Villabona-Ortíza et al. 2021), have been employed for the oxidative post-treatment of activated carbon to enhance its adsorptive removal of ibuprofen. For example, the oxidation treatment of activated carbon in hydrogen peroxide with/without ultrasonic irradiation slightly increases its adsorption capacity. This enhancement can be attributed to the donor–acceptor mechanism between the π aromatic ring of ibuprofen and the resulting carbonyl groups, also

Table 1 Carbon-based adsorbents for ibuprofen removal

Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Cork	Potassium carbonate (K_2CO_3)	891	7.5	145	298 K, pH 4, 20–120 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	Mestre et al. 2009
Cork	Heat	1060	9.9	378	298 K, pH 4, 20–120 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	
Olive stones	Carbon dioxide (CO_2)	1055	5.6	178	298 K, pH 4, 5–100 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	Mansouri et al. 2015
Olive stones	Phosphoric acid (H_3PO_4)	1106	9.5	313	298 K, pH 4, 5–100 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	
Olive stones	Ammonium persulfate $(NH_4)_2S_2O_8$	903	3.4	160	298 K, pH 4, 5–100 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	
Moringa oleifera seeds	Sulfuric acid (H_2SO_4)	720	Not reported	Not reported	293 K, pH 2, 100–625 mg/L	Pseudo-first order	Freundlich	Not reported	Not reported	Al-Kindi and Al-Haidri 2021
Olive waste cake	Not reported	793	5.03	10.8	298 K, pH 4.1	Pseudo-second order	Langmuir	Not reported	Not reported	Baccar et al. 2012
Artemisia vulgaris	Not reported	358	5.05	16.9	298 K, pH 2, 10–50 mg/L	Pseudo-first order	Langmuir	Endothermic	1.745–5.728	Dubey et al. 2010
Cork waste	Potassium carbonate (K_2CO_3)	891	7.5	139	298 K, pH 4, 20–120 mg/L	Pseudo-firs order	Langmuir	Not reported	Not reported	Mestre et al. 2007
Cork waste	Potassium carbonate (K_2CO_3) and steam	1060	9.9	393	298 K, pH 4, 20–120 mg/L	Pseudo-first order	Langmuir	Not reported	Not reported	
Babassu coconut husk	Not reported	641	Not reported	115	328 K, pH 2, 25–150 mg/L	Pseudo-second order	Sips	Endothermic	8.2–10.9	Fröhlich et al. 2018a
Babassu coconut husk	Sonication	732	Not reported	134	328 K, pH 2, 25–150 mg/L	Pseudo-second order	Sips	Endothermic	9.7–13.1	
Albizia lebbeck seed	Not reported	1548	Not reported	79.5	37.48 K, pH 7.82, $50–250 \times 10^{-3}$ mg/L	Avrami	Smith	Exothermic	44.3–52.8	Sivarajasekar et al. 2018

Table 1 (continued)

Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Date palm leaflets	Potassium hydroxide (KOH)	823	5	68	308 K, pH 7, 5–200 mg/L	Pseudo-second order	Langmuir	Endothermic	Not reported	Ali et al. 2019
Date palm leaflets	Potassium hydroxide (KOH)	34	3.24	81.3	308 K, pH 7, 5–200 mg/L	Pseudo-second order	Langmuir	Endothermic	Not reported	
Date palm leaflets	Potassium hydroxide (KOH)	4	8.2	47.8	308 K, pH 7, 5–200 mg/L	Pseudo-second order	Langmuir	Endothermic	Not reported	
Date palm leaflets	Potassium hydroxide (KOH)	9.9	8.2	63.7	308 K, pH 7, 5–200 mg/L	Pseudo-second order	Langmuir	Endothermic	Not reported	
Nauclea diderrichii	Potassium hydroxide (KOH)	33.2	8	70.9	328 K, pH 12, 5–40 mg/L	Pseudo-second order	Langmuir	Exothermic	0.37–3.11	Omorogie et al. 2021
Babassu coconut husk	Not reported	640	Not reported	85	298 K, pH 2, 25–150 mg/L	Not reported	Redlich–Peterson	Not reported	Not reported	Fröhlich et al. 2018b
Babassu coconut husk	Sonication	731	Not reported	107	298 K, pH 2, 25–150 mg/L	Not reported	Redlich–Peterson	Not reported	Not reported	
Kola nut husk	Phosphoric acid (H_3PO_4)	712	5.32	39.2	303 K, 10–50 mg/L	Pseudo-second order	Langmuir	Endothermic	64.04–164.48	Bello et al. 2020a
Bean husks	Phosphoric acid (H_3PO_4)		4.75	50.5	303 K, pH 4.75, 20–100 mg/L	Pseudo-second order	Langmuir	Endothermic	16.29–26.67	Bello et al. 2019
Prunus domestica L	Not reported	1230		23.3	299 K, pH 2	Pseudo-second order	Freundlich	Not reported	50.6–53.4	Turk Sekulic et al. 2019
Cherry kernels	Phosphoric acid (H_3PO_4)	791	About 3.2	21.8	295 K, pH 2, 1–50 mg/L	Elovich	Freundlich	Endothermic	Not reported	Pap et al. 2021
Peach stones	Phosphoric acid (H_3PO_4)	1521	3	111	303 K, pH 3, 10–100 mg/L	Pseudo-second order	Guggenheim–Anderson–de Boer	Not reported	Not reported	Álvarez-Torrellas et al. 2016
Rice husk	Phosphoric acid (H_3PO_4)	278	3.4	240	303 K, pH 3, 10–101 mg/L	Pseudo-second order	Guggenheim–Anderson–de Boer	Not reported	Not reported	

Table 1 (continued)

Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Agave sisalana	Potassium carbonate (K_2CO_3)	1906	3.8	278	303 K, pH 5, 5–150 mg/L	Pseudo-second order	Langmuir and Freundlich	Not reported	Not reported	Mestre et al. 2019
Agave sisalana	Potassium hydroxide (KOH)	1419	4.9	309	303 K, pH 5, 5–150 mg/L	Pseudo-second order	Langmuir and Freundlich	Not reported	Not reported	
Quercus brantii (Oak) acorn	Potassium hydroxide (KOH)	298	10	15.9	298 K, pH 2, 5–149 mg/L	Pseudo-second order	Freundlich	Endothermic	0.76–1.67	Nourmoradi et al. 2018
Quercus brantii (Oak) acorn	Phosphoric acid (H_3PO_4)	234	2	22.7	298 K, pH 3, 5–150 mg/L	Pseudo-second order	Freundlich	Endothermic	Not reported	
Erythrina speciosa	Zinc chloride ($ZnCl_2$)	795	Not reported	98.1	328 K, pH 3, 50–200 mg/L	Linear driving force	Freundlich and Langmuir	Endothermic	23.79–29	Franco et al. 2022
Cocoa husk	Zinc chloride ($ZnCl_2$)	Not reported	Not reported	123	20–40 mg/L	Pseudo-first order and Pseudo-second order	Freundlich	Not reported	Not reported	Villabona-Ortíza et al. 2021
Sludge of the beverage industry	Zinc chloride ($ZnCl_2$)	642	7.8	105	298 K, pH, 40–100 mg/L	Pseudo-second order	Sips	Not reported	21.95–22.63	Streit et al. 2021
Coconut husk	Phosphoric acid (H_3PO_4)	Not reported	Not reported	76.9	303 K, 10–50 mg/L	Pseudo-second order	Langmuir	Endothermic	6.94–7.06	Bello et al. 2020b
Holm oak	Not reported	1339	7.8	18.5	293 K, pH 5, 15–50 mg/L	Pseudo-second order	Freundlich	Not reported	0.86–3.21	Delgado-Moreno et al. 2021
Schumannianthus dichotomus	Phosphoric acid (H_3PO_4)	1058	6.1	243	303 K, pH 2	Pseudo-second order	Langmuir	Exothermic	Not reported	Reza and Ahmaruzzaman 2020
Iron-based metal-framework	Not reported	199	4.2	206	318 K, pH 3, 5–20 mg/L	Pseudo-second order	Langmuir	Exothermic	Not reported	Van Tran et al. 2019a
Zeolitic imidazolate framework-8	Not reported	1855	4.9	320	298 K, pH 5, 5–21 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	Bhadra et al. 2017

Table 1 (continued)

Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Iron-based metal-framework	Not reported	225	5.8	144	298 K, pH 3, 5–20 mg/L	Pseudo-second order	Langmuir	Not reported	29.7–33.01	Van Tran et al. 2019b
Metal azolate framework-6	Potassium hydroxide (KOH)	3123	Not reported	408	298 K, pH 4.4	Pseudo-second order	Langmuir	Not reported	Not reported	An et al. 2018

The sorption behavior of these adsorbents is greatly influenced by crucial parameters such as the raw material, synthesis approach, and activation method. Furthermore, the reactivation, functionalization, modification, and post-treatment of activated carbons enhance their adsorption performance. Various physical and chemical activation methods have been employed to activate these adsorbents. In the adsorption process, hydrophobic and π-π interactions between the carbon surface and ibuprofen molecules play a significant role. Activated carbon stands out as the most commonly utilized adsorbent for removing ibuprofen

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present in carboxylic and lactonic groups (Guedidi et al. 2013). On the other hand, reducing the surface functionality of activated carbon, e.g., through annealing, also increases its adsorption capacity, independent of pH. This effect is due to the slight oxidation of carbon after aging, which promotes dispersive interactions.

While some treatments can enhance the adsorption of ibuprofen onto activated carbon, others may have adverse effects. For example, treating activated carbon with sodium hypochlorite is not beneficial for ibuprofen adsorption due to the absence of carbonyl sites and the formation of phenolic groups (Haydar et al. 2003). Recently, metal–organic framework-derived carbons have gained attention for removing pharmaceuticals from wastewater (Chen et al. 2020). These carbons, derived from metal–organic frameworks, exhibit high porosities, well-defined pore structures, and, in some cases, nitrogen doping (in nitrogen-containing metal–organic frameworks) (Liu et al. 2022; Van Tran et al. 2019b). Pyrolysis has enhanced their surface areas and porosities and broadened their applications (Yu et al. 2021). Among them, porous activated carbon derived from the pyrolysis of metal–organic framework-6 and activated with potassium hydroxide has demonstrated a high sorption capacity for pharmaceutical compounds, including ibuprofen (An et al. 2018). Moreover, highly porous nitrogen-/oxygen-doped porous carbons obtained from the zeolitic-imidazolate framework-8, namely ZIF-8, have shown effective performance in the adsorptive removal of antibiotics, such as ciprofloxacin (Li et al. 2017), diclofenac (Bhadra et al. 2017), and ibuprofen (Bhadra et al. 2017). Bhadra et al. (2017) found that H-bonding interactions, mainly through the phenolic group, are responsible for ibuprofen adsorption using zeolitic imidazolate framework-8-derived carbon, with carbon acting as the hydrogen-bond donor and ibuprofen as the H-bond acceptor.

The adsorption capacity of activated carbon was also improved by other parameters, including activation time (Ulfa et al. 2020b) and activator concentration (Ulfa et al. 2020a). One study demonstrated that increasing the activator concentration improved adsorption capacity by precipitating impurities, increasing the surface area, and increasing the functional groups (Ulfa et al. 2020a). Other advanced treatments, such as ozonation (Guillossou et al. 2019) and sonication, have been found to effectively enhance the ibuprofen adsorption capacity of activated carbons (Fröhlich et al. 2018a; Ondarts et al. 2018). These treatments form new binding sites on the activated carbon surface (Yazidi et al. 2019). For example, Fröhlich et al. (2018b) demonstrated that ultrasound-modified activated carbon exhibited a 25% higher adsorption capacity than unmodified activated carbon.

In the adsorption of ibuprofen onto activated carbon, hydrophobic and π-π interactions between the carbon surface and micro-pollutants play a significant role in the adsorption mechanism. While hydrophobic interactions may not be directly responsible for the adsorption of ibuprofen onto activated carbon, their influence cannot be ignored (Kaur et al. 2018; Zhao et al. 2016). In acidic media, dispersive π–π and donor–acceptor interactions occur between the carbonyl groups in activated carbon and the aromatic ring of ibuprofen (Fröhlich et al. 2018b). As expected, ibuprofen adsorption is higher in monopollutant systems than in wastewater effluent due to particle pore blocking and competition for adsorption sites (Guillossou et al. 2020). While the small size of ibuprofen molecules allows for its fast and high sorption, its molecular configuration and adsorbent size will affect adsorption efficiency (Turk Sekulic et al. 2019).

The surface functionalization or crosslinking of activated carbon presented a promising solution for removing pharmaceuticals (Ali et al. 2019; Tian et al. 2022). These modifications can affect both the adsorption kinetics and adsorption capacity. Recent studies have demonstrated the effectiveness of ethylamine- and ethylenediamine-functionalized activated carbon, which possesses basic and hydrophobic surfaces, respectively, in the Langmuir monolayer adsorption of ibuprofen through endothermic and spontaneous processes (Ali et al. 2019). Following the pseudo-second-order model, the equilibrium adsorptions were faster on the functionalized activated carbons than on unmodified activated carbon. However, the maximum sorption capacity was observed to be in the order of activated carbon more than ethylenediamine-functionalized activated carbon more than ethylamine-functionalized activated carbon (An et al. 2018; Fröhlich et al. 2019). In one study, a magnetic nickel ferrite ($NiFe_2O_4$)/activated carbon composite with a high surface area of 564 m^2/g showed great potential for ibuprofen removal with a maximum adsorption capacity of 261 mg/g (Fröhlich et al. 2019). In such cases, activated carbon serves not only as a support but also actively participates in ibuprofen uptake through physisorption, attributed to its high surface area, or chemisorption, which is facilitated by the presence of heteroatoms on the surface (Pakade et al. 2019). Wasilewska and Deryło-Marczewska (2022) successfully enhanced the adsorption capacity of activated carbon by immobilizing it in calcium alginate. They achieved maximum sorption capacities of 0.873 mmol/g for diclofenac and 0.381 mmol/g for ibuprofen drugs. The samples with higher activated carbon content exhibited increased hygroscopicity, polarity, and superior adsorption rate and capacity. The higher sorption capacity for diclofenac can be attributed to the disparities in adsorbate solubilities. In contrast, the faster removal rate of ibuprofen is attributed to the variance in the molecular sizes of the drugs.

As presented in Table 1, several studies have shown that maximum ibuprofen adsorption occurs under acidic conditions, particularly between pH 2 and 4. This may be due to the repulsion between the negatively charged activated carbon surface in alkaline media and the negatively charged ibuprofen molecules, which hinders adsorption (Dubey et al. 2010). In acidic solutions, excess hydrogen ions neutralize the negative charges on the adsorbent surface, facilitating the diffusion of ibuprofen molecules. Combining activated carbon adsorption systems and biological treatment or hybrid membrane systems was also proposed to remove ibuprofen (Ferrer-Polonio et al. 2020; Kim et al. 2019; Zhang et al. 2019). For example, granular activated carbon has been efficiently used in the pilot- and full-scale hybrid adsorption columns and membrane systems to remove ibuprofen from aquatic media (Jamil et al. 2020; Zhang et al. 2019). Numerous research studies have been conducted to analyze the thermodynamics of ibuprofen adsorption on activated carbons. As shown in Table 1, the presence of negative ΔG° values confirms the viability and spontaneous nature of ibuprofen sorption onto activated carbons. Moreover, highly negative ΔG° values indicate a significant level of favorability in terms of adsorption (Ahmed 2017).

Apart from activated carbon, other carbon-based materials, such as biochar and hydrochar obtained through the pyrolysis and hydrothermal carbonization of biomass wastes, including agricultural waste, have also been investigated for their potential in ibuprofen adsorption (Delgado-Moreno et al. 2021; Osman et al. 2023c; Patel et al. 2022). Table 2 provides an overview of some specific examples of these adsorbents. Several natural waste sources, such as date palm leaflets (Ali et al. 2019), wood waste (Van Limbergen et al. 2022), *Cocos nucifera* shell (Chakraborty et al. 2019), date palm fiber wood (Van Limbergen et al. 2022), date seeds (Chakraborty et al. 2020), bamboo waste (Reza et al. 2014), waste coffee residue (Shin et al. 2022), almond shells (Show et al. 2021), *Quercus brantii* (oak), coffee bean husk (Van Limbergen et al. 2022), sugarcane bagasse (Chakraborty et al. 2018b), tamarind seeds (Show et al. 2022a), *Albizialebbeck* seeds (Sivarajasekar et al. 2018), and kola nut husk (Bello et al. 2020a), have been used as ibuprofen-adsorbent biochars. The main adsorption mechanism involves a combination of acid/base sorbate equilibria and the interaction of carboxylic acid and phenolic hydroxyl sites with varying pH levels (Essandoh et al. 2015).

To enhance the sorption capacity of biochars in the removal of ibuprofen, various pre- and post-treatment methods have been explored (Shin et al. 2021). These methods include physical modifications like ball milling (Chakraborty et al. 2020; Luo et al. 2020), composite formation (Moreno-Pérez et al. 2021), chemical oxidation (Ali et al. 2019), and acid/base modification (Shin et al. 2020). For example, Shin et al. (2021) demonstrated that the reinforced aromatic structure of sodium hydroxide-activated biochar obtained from spent coffee waste facilitated π–π interaction, significantly improving its adsorption capacity. In another

Table 2 Biochar and hydrochar as adsorbents for removing ibuprofen

Adsorbent	Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Biochar	*Tropical almond* shells	Sodium hydroxide	Not reported	7.6	9.5	308 K, pH 2, 5–50 mg/L	Pseudo-second order	Langmuir	Exothermic	1.02–2.05	Show et al. 2021
Biochar	*Tropical almond* shells	Phosphoric acid	Not reported	6.3	8.8	308 K, pH 2, 5–51 mg/L	Pseudo-second order	Langmuir	Exothermic	5.45–5.54	Show et al. 2021
Biochar	*Lantana camara* stem	Nitric acid	Not reported	Not reported	106	pH 3	Pseudo-second order	Langmuir	Not reported	Not reported	Ganesan et al. 2021
Biochar	Wood chips	Not reported	841	3.5	132	298 K, pH 6, 25–500 mg/L	Pseudo-second order and Elovich	Langmuir Freundlich	Not reported	Not reported	Luo et al. 2020
Biochar	Pinewood	Not reported	1.35	2	10.7	308 K, pH 3, 25–100 mg/L	Pseudo-second order	Langmuir	Not reported	23.5–24.8	Essandoh et al. 2015
Biochar	Wood waste	Not reported	78.2	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	
Biochar	Coffee bean	Not reported	2.11	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	
Biochar	Date palm fiber wood	Not reported	32.9	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	
Biochar	Pepper stems	Not reported	727	6.3	570	293 K, pH 4, 20–300 mg/L	Pseudo-second order and Avrami	Langmuir	Not reported	Not reported	Naima et al. 2022
Biochar	*Parthenium hysterophorus*	Sodium hydroxide	308	7.4	3.7	293 K, pH 2, 5–100 mg/L	Pseudo-second order	Langmuir	Exothermic	9.59–11.6	Mondal et al. 2016a
Biochar	*Alternanthera philoxeroides*	Not reported	857	Not reported	172	298 K, pH 4, 10–100 mg/L	Pseudo-second order	Freundlich	Exothermic	Not reported	Du et al. 2021
Biochar	Chili seeds	Not reported	0.18	7.7	Not reported	298 K, pH 7, 53–229 mg/L	Pseudo-second order	Langmuir	Endothermic	1.76–4.76	Ocampo-Perez et al. 2019
Biochar	Tamarind seed	Not reported	Not reported	Not reported	8.6	313 K, pH 2, 1–50 mg/L	Pseudo-second order	Langmuir	Exothermic	1.58–8.57	Show et al. 2022a
Biochar	Tamarind seed	Phosphoric acid	Not reported	Not reported	10.6	308 K, pH 2, 1–50 mg/L	Pseudo-second order	Langmuir	Exothermic	Not reported	Show et al. 2022a
Biochar	Date seed	Phosphoric acid	342	5.1	12.2	293 K, pH 3, 5–50 mg/L	Pseudo-second order	Langmuir	Exothermic	0.701–4.42	Chakraborty et al. 2020
Biochar	Date seed	Steam	513	5.8	9.7	293 K, pH 3, 5–50 mg/L	Pseudo-second order	Langmuir	Exothermic	0.05–4.46	Chakraborty et al. 2020

Table 2 (continued)

Adsorbent	Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Biochar	Coffee	Not reported	62.0	Not reported	4.2	298 K, pH 7, 2–10 mg/L	Pseudo-second order	Freundlich	Endothermic	18.91–20.26	Shin et al. 2021
Biochar	Coffee	Sodium hydroxide	655	Not reported	16.5	298 K, 2–10 mg/L	Pseudo-second order	Langmuir	Endothermic	1.54–3.83	Shin et al. 2021
Biochar	Wood apple	No reported	4.4	7.2	5	288 K, pH 3, 1–45 mg/L	Pseudo-second order	Langmuir	Exothermic	2.13–7.61	Chakraborty et al. 2018a
Biochar	Wood apple	steam	308	7.2	12.7	293 K, pH 2, 1–45 mg/L	Pseudo-second order	Freundlich	Exothermic	Not reported	Chakraborty et al. 2018a
Biochar	Coconut shell	Steam	726	6.3	9.7	288 K, pH 2, 1–50 mg/L	Pseudo-second order	Langmuir	Exothermic	1.45–1.88	Chakraborty et al. 2019
Biochar	Coconut shell	Phosphoric acid	805	6.8	12.2	288 K, pH 2, 1–50 mg/L	Pseudo-second order	Langmuir	Exothermic	2.198–4.46	Chakraborty et al. 2019
Biochar	Mung bean husk	Steam	308	7.4	59.8	293 K, pH 2, 5–100 mg/L	Pseudo-second order	Langmuir	Exothermic	4.38–6.15	Mondal et al. 2016b
Biochar	Bamboo waste	Microwave	722	5.2	278	298 K, pH 2–3, 50–100 mg/L	Pseudo-second order	Langmuir	Exothermic	Not reported	Reza et al. 2014
Biochar	Holm wood	Not reported	151	9.2	2.5	293 K, pH 5, 15–50 mg/L	Pseudo-second order	Freundlich	Not reported	Not reported	Delgado-Moreno et al. 2021
Biochar	Tree pruning	Not reported	215	10.1	2.5	293 K, pH 5, 15–50 mg/L	Pseudo-second order	Freundlich	Not reported	Not reported	Delgado-Moreno et al. 2021
Biochar	Palm bunch	Phosphoric acid	60.3	4.2	38.8	Room temperature, pH 6, 0.1–10 mg/L	Pseudo-second order	Sips	Endothermic	11.2–13.6	Choudhary and Philip 2022
Hydrochar	Olive stone	Not reported	1.17	7.6	2.5	293 K, pH 5, 15–50 mg/L	Pseudo-second order	Freundlich	Not reported	Not reported	Delgado-Moreno et al. 2021
Hydrochar	Olive tree pruning	Not reported	207	10.4	3.3	293 K, pH 5, 15–50 mg/L	Pseudo-second order	Freundlich	Not reported	Not reported	Delgado-Moreno et al. 2021
Hydrochar	Pitted and reprocessed wet olive mill waste	Not reported	7.6	5.4	10.0	293 K, pH 5, 15–50 mg/L	Pseudo-second order	Freundlich	Not reported	Not reported	Delgado-Moreno et al. 2021
Hydrochar	Green tea waste	Not reported	6.4	5.1	63.7	303 K, pH 4, 50–250 mg/L	Pseudo-second order	Langmuir	Endothermic	Not reported	Khalaf et al. 2013

Table 2 (continued)

Adsorbent	Raw material	Activation agent/method	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
ZnAl/biochar	Bovine bones	Not reported	0.17	7.3	1032	298 K, pH 5, 25–125 mg/L	Not reported	Freundlich	Not reported	14.94–16.10	Moreno-Pérez et al. 2021
Magnetic biochar	Orange peel	Not reported	665	4.4	28.7	298 K, pH 4.5, 0.5–100 mg/L	Pseudo-second order	Langmuir	Not reported	5.88–13.07	Ai et al. 2020
Magnetic methanol-modified biochar	Orange peel	No reported	857	4.4	58.1	298 K, pH 4.5, 0.5–100 mg/L	Pseudo-second order	Langmuir	Not reported	Not reported	Ai et al. 2020
Magnetic Douglas fir biochar	Commercial	Sodium hydroxide	322	8.1	39.9	298 K, pH 8, 0–750 mg/L	Not reported	Langmuir	Endothermic	Not reported	Liyanage et al. 2020
Magnetic chitosan/activated biochar	Commercial	Sodium hydroxide	502	5.2	21.2	298 K, pH 6, 0.5–3 mg/L	Not reported	Langmuir Freundlich	Not reported	Not reported	Mojiri et al. 2019
Ammonium (NH_4) adsorbent materials biochar and zeolite	Commercial	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	de Boer et al. 2018
Activated charcoal	Commercial	Not reported	Not reported	Not reported	64.5	pH 4, 50–1000 mg/L	Not reported	Langmuir	Not reported	Not reported	Khalaf et al. 2013

Biochar and hydrochar have been extensively investigated as effective adsorbents for removing ibuprofen. Researchers have utilized a range of natural waste sources to fabricate biochar specifically designed for ibuprofen adsorption, with the raw material playing a critical role in determining its performance. Physical and chemical pre- and post-treatments of biochars and hydrochars have been explored to enhance the sorption capacities. The carboxylic acid and phenolic hydroxyl sites are mainly responsible for the ibuprofen adsorption onto biochar

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study, Chakraborty et al. (2019) presented a study highlighting the effective performance of activated biochar derived from *Cocos nucifera* shells, which underwent physical and chemical modifications, in the adsorption of ibuprofen. The modified activated biochar demonstrated maximum sorption capacities of 9.7 mg/g and 12.2 mg/g, respectively. Recently, Moreno-Pérez et al. (2021) explored the adsorption potential of a zinc aluminium alloy (ZnAl)/biochar composite for pharmaceutical compounds. Following the Henry isotherm model, they achieved a remarkable adsorption capacity of 1032 mg/g for ibuprofen. The primary mechanism of transport was identified as surface flux within the particles. Activated carbons also exhibited promise as adsorbents due to their numerous surface functional groups, large surface area, and well-developed pore structures, making them suitable for removing ibuprofen molecules from aqueous environments. Notably, commercial activated carbon (Zhao et al. 2018) and activated carbon derived from primary pulp mill sludge (Coimbra et al. 2019) exhibited remarkable behavior in the adsorptive removal of ibuprofen.

Graphene-based materials, such as pristine graphene and graphene oxide, represent a fascinating category of carbonaceous adsorbents with significant promise for removing ibuprofen. Recent studies have revealed the exceptional characteristics of these materials, including their remarkable hydrophobicity, high adsorption capacity, extensive surface area, low toxicity, and recyclability. The nanostructured porous nature of graphene lends itself well to effective ibuprofen adsorption, making it an ideal choice for this application (Amiri et al. 2019; Khalil et al. 2021, 2020; Lou et al. 2020; Nawaz et al. 2020; Park et al. 2018; Wazzan 2021). The utilization of graphene oxide as an optimal sorbent has been limited in current research due to the presence of surface functional groups, such as –OH, –COOH, and –C=O, and its pronounced hydrophilic properties resulting from hydrogen bonding. These characteristics pose challenges in recovering graphene oxide from the solution following adsorption. To address this issue, researchers have employed graphene oxide as a foundational component in composite adsorbents (Pakade et al. 2019). For example, Liu et al. (2019) developed a superparamagnetic genipin-crosslinked chitosan/graphene oxide-SO_3H composite, exploiting electrostatic interactions to remove ibuprofen and tetracycline. The composite exhibited maximum adsorption capacities of 138 mg/g and 473 mg/g, respectively. However, a notable research gap exists in investigating the adsorption behavior of different crosslinked graphene oxides and their composites concerning ibuprofen. This aspect deserves further comprehensive exploration.

Carbon nanomaterials have shown immense promise for treating water containing ibuprofen. They possess numerous advantages, such as high surface area, wide pore size, various functional groups, good thermal stability, and low mass transfer resistance (Afifeh et al. 2019; Ahmadpour et al. 2014; Gopinath et al. 2021; Mashkoor et al. 2020). Single-walled carbon nanotubes, multi-walled carbon nanotubes, and functionalized carbon nanotubes showed promise as potential adsorbents in ibuprofen removal due to their high surface areas, structural diversity, and good stabilities (Al-Khateeb et al. 2021; El-Sheikh et al. 2019). Cho et al. (2011) demonstrated that ibuprofen exhibited stronger adsorption onto single-walled carbon nanotubes than multi-walled carbon nanotubes. This disparity in adsorption behavior was attributed to the larger surface area of single-walled carbon nanotubes and the significant presence of oxygen on the surface of oxidized multi-walled carbon nanotubes.

Oyetade et al. (2018) achieved maximum adsorption of 12.2 mg/g for ibuprofen using carboxylated carbon nanotubes. The size of the nanotubes was found to be crucial in determining their adsorption behavior. El-Sheikh et al. (2019) investigated the adsorption of various anti-inflammatory drugs on magnetic carbon nanotubes, including ibuprofen, diclofenac, and ketoprofen. They observed that longer nanotubes outperformed shorter nanotubes in adsorption efficiency, and the optimal external diameter range was 60–100 nm. The magnetite-to-carbon nanotube ratio was identified as another influential parameter in the uptake of these compounds. The best mixing ratio was determined to be 1:1 for magnetite and carbon nanotubes. One advantage of magnetic carbon nanotubes is their effortless and rapid separation using an external magnet, affecting their surface areas and adsorption capacities. In one example, a carbon aerogel, a nanostructured sponge-like carbon material with a diameter of smaller than 50 nm and unique properties like well-proportioned porosity, a high surface area of 790 m^2/ g, and low density, also exhibited multilayer chemical ibuprofen adsorption in a heterogeneous system (Abolhasani et al. 2019). Recently, fullerene C_{60} (Alipour et al. 2019; Parlak and Alver 2019) and carbon nanocapsules (Ávila et al. 2020) have emerged as other effective carbonaceous nanostructures for ibuprofen adsorption. These carbon-based nanomaterials exhibit notable adsorption capacities, demonstrate no toxicity, and display high selectivity, even at trace concentrations. Such carbonaceous nanomaterials hold significant value due to their ability to effectively adsorb ibuprofen while maintaining favorable properties.

Silica-based adsorbents

Silica-based adsorbents have gained significant attention in water treatment applications due to their notable features, including high specific surface areas, large pore sizes, cost-effectiveness in manufacturing, and the ability to incorporate various surface functional groups to achieve exceptional selectivity (Diagboya and Dikio 2018; Wang et al. 2022). the utilization of silica-based adsorbents for removing ibuprofen from water is still limited. Some examples of such adsorbents include mesoporous silicas (Delle Piane et al. 2014; Kamarudin et al. 2013; Ulfa et al. 2018a, b; Wang et al. 2019b) and their modified composites (Peralta et al. 2021). Among these, mesoporous silica structures, such as MCM-41 and Santa Barbara Amorphous-15 have demonstrated remarkable ibuprofen adsorption capabilities (Barczak 2019; Bui and Choi 2009; Trzeciak et al. 2020; Ulfa et al. 2019a, b). In this context, the present discussion highlights the significant findings and recent contributions utilizing silica-based adsorbents. Table 3 provides an overview of some of these adsorbents and their characteristics. In one study, integrating carbohydrate polymers into mesoporous silica (MCM-48) considerably improved its role as an ibuprofen

Table 3 Silica-based ibuprofen adsorbents. Silica-based adsorbents are promising adsorbents for the removal of ibuprofen from an aqueous solution

Adsorbent	Precursor	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Adsorption conditions and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	References
Mesoporous silica	Starch of waste rice	Not reported	Not reported	120	298 K, 75 mg/L	Not reported	Langmuir	Not reported	Ulfa et al. 2018a
Mesoporous silica	Batik sludge	118	Not reported	34.96	298 K, pH 7, 25–200 mg/L	Pseudo-second order	Freundlich	Not reported	Choong et al. 2019
Natural silica	Starch of waste rice-gelatin	Not reported	Not reported	66.7	298 K, 100 mg/L	Pseudo-second order	Langmuir	Not reported	Ulfa et al. 2018b
Santa barbara amorphous-15	Tetraethyl orthosilicate	737	4	0.41	298 K, pH 5, 0.01–300 mg/L	Pseudo-second order	Freundlich	Not reported	Bui and Choi 2009
Aluminated mesoporous silica nanoparticles	Not reported	722	Not reported	Not reported	1000–8000 mg/L	Not reported	Not reported	Not reported	Kamarudin et al. 2015
$MgO–SiO_2$/lignosulfonate	Not reported	71	Not reported	Not reported	298 K, pH 8, 0.5–1.5 mg/L	Pseudo-second order	Langmuir	Not reported	Ciesielczyk et al. 2019
Amine functionalized $NiFe_2O_4$@SiO_2	Not reported	Not reported	Not reported	59	pH 7, 6–14 mg/L	Pseudo-second order	Langmuir	Not reported	Chandrashekar and Balakrishnan 2021
Mesoporous SBA-3 silica	Tetraethoxysilane	Larger than 1000	Not reported	Not reported	298 K	Not reported	Langmuir	Not reported	Sandberg et al. 2018
Organo silica nanosheets with gemini	Not reported	638	1.74	64.19	298 K, pH 4, 40–200 mg/L	Pseudo-second order	Hill	Exothermic	Zeng et al. 2018
Polyamidoamine/silica	Not reported	714	9	124	298 K, pH 9, 50–200 mg/L	Pseudo-second order	Langmuir	Endothermic	Lotfi et al. 2019
3-aminopropyltriethoxysilane grafted pumice-derived silica aerogel	Pumice	407	7.4	39.95	298 K, pH 7, 2–10 mg/L	Not reported	Khan	Not reported	Mohseni-Bandpei et al. 2020
Zirconia/silica	Not reported	52	Not reported	6.13	278 K, pH 7.2, 1000 mg/L	Not reported	Not reported	Not reported	Ciesielczyk et al. 2018
N-(3 trimethoxisilylpropyl) diethylenetriamine modified magnetic SiO_2	Not reported	42.2	3–9	72.6	298 K, pH 6, 10–250 mg/L	Pseudo-second order	Langmuir	Not reported	Kittappa et al. 2020

These adsorbents can be customized by incorporating abundant surface functional groups to achieve remarkable selectivity towards ibuprofen. Their effectiveness as ibuprofen sorbents is significantly influenced by surface chemistry, porous structure, component ratio, and post-treatment processes. In particular, the introduction of amine functional groups through modification enhances their sorption capacity. The positive surface charge of amino-functionalized mesoporous silicas creates a strong electrostatic attraction between the anionic ibuprofen molecules and the adsorbent surface, further enhancing their adsorption capability

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carrier (Abukhadra et al. 2020), and the maximum loading capacity of MCM-48 increased from 328 mg/g to 479 mg/g, 360 mg/g, and 420 mg/g by integrating chitosan, starch, and β-cyclodextrin, respectively. Ibuprofen loading onto the MCM-48/chitosan composite was found to be monolayer, while that of the starch/β-cyclodextrin composite was multilayer. A recent study by Choong et al. (2019) demonstrated that impregnating mesoporous silica derived from batik sludge with aluminum hydroxide ($Al(OH)_3$) markedly enhanced its affinity for ibuprofen. This improvement was primarily attributed to hydrogen bonding and electrostatic attraction, resulting in a maximum adsorption capacity of 34.9 mg/g. Another investigation by Kamarudin et al. (2015) revealed that the adsorption behavior of mesoporous silica nanoparticles towards ibuprofen could be enhanced by loading aluminum onto the material. Adding 1, 5, and 10 wt.% of aluminum resulted in respective increases in adsorption of 35%, 58%, and 79%. The excellent adsorption performance of mesoporous silica nanoparticles was attributed to its abundance of surface silanol groups. The introduction of aluminum increased the Brönsted acidity of the material, providing additional acidic sites for holding the ibuprofen molecules (Kamarudin et al. 2013, 2015).

Modifying silica-based materials with compounds containing amine functional groups resulted in a powerful sorbent capable of capturing both positively and negatively charged contaminants (Jadach et al. 2019; Kittappa et al. 2020; Mohseni-Bandpei et al. 2020). Barczak (2019) showed the strong electrostatic attraction between anionic pharmaceutical compounds and the positively charged surface of different amino-functionalized mesoporous silicas with different pore structures and morphologies. They observed the development of porous structure in the presence of amine groups in the case of amorphous silica xerogels, and its functionalization efficiency value was the highest among all groups. Unlike the minimal effect of porous structure, the number of surface amine groups significantly affected sorption.

The presence of surface amine groups accessible through the porous structure is crucial for achieving high adsorption of pharmaceuticals, regardless of the specific surface area, pore size, or volume. A comparison of various silica-based materials revealed that Santa Barbara Amorphous-15 and mesocellular silica foams outperformed amorphous silica xerogels and porous silica nanotubes in terms of ibuprofen adsorption, primarily due to their favorable porous structures (Barczak 2019). Another effective adsorbent is spherical pumice-derived silica aerogel particles, which possess a particle size larger than 25 nm and a specific surface area of 407 m^2/g. These particles are grafted with a multilayer of high-stability and high-density amine groups. The ibuprofen adsorption capacity of this adsorbent is attributed to dominant hydrogen bonding and hydrophobic interactions, which encompass both electrostatic and non-electrostatic interactions. Remarkably, this adsorbent exhibited a maximum sorption capacity of 39.9 mg/g at pH 7, with the adsorption isotherm following the Khan isotherm model (Mohseni-Bandpei et al. 2020).

Silica nanosheets were effectively modified by Zeng et al. (2018) using gemini surfactants. Their study highlighted that longer alkyl chains in the surfactants facilitated the modification process and resulted in enhanced ibuprofen adsorption. The primary mechanisms involved in this physical adsorption phenomenon were electrostatic interactions and the partition effect. Remarkably, the organo-silica nanosheets exhibited a high sorption capacity of 64.2 mg/g within a rapid timeframe of 5 min. This impressive adsorption performance was achieved at a low surfactant concentration of 0.42 mmol/g silica nanosheets. The adsorption process was found to be exothermic and followed the pseudo-second-order kinetic model and Hill isotherm equation. It was demonstrated that the concentration of modified silica functional groups could control the amount of adsorbed model drug (Barczak 2019).

A dendritic polyamidoamine/silica nanohybrid, an interesting material synthesized by grafting a chelating agent on silica nanoparticles, was introduced as a promising and effective sorbent for the removal of different pharmaceuticals from aqueous media (Lotfi et al. 2019). In an endothermic process, it showed a good maximum Langmuir adsorption capacity of 124 mg/g toward ibuprofen at pH 9 and 298 K. In another study, the high efficacy of an active magnesium oxide and silicon dioxide ($MgO–SiO_2$)/lignosulfonate hybrid for ibuprofen removal was proven, with an efficiency exceeding 70% in the first 3–5 min of the process (Ciesielczyk et al. 2019); however, the highest drug removal was achieved in an acidic environment (pH 2). The pharmaceutical binding to the adsorbent surface may have resulted from the condensation of −OH groups existing in the ibuprofen structure and the adsorbent surface and hydrogen bonds.

The effectiveness of sorbents can be significantly influenced by surface chemistry, porous structure, component ratio, and post-treatment processes such as calcination (Osman et al. 2023b). A notable example is the study of a binary oxide composite, Zirconium dioxide- silicon dioxide ($ZrO_2–SiO_2$), synthesized via the sol–gel approach for the adsorption and release of ibuprofen and paracetamol (Ciesielczyk et al. 2018). The research findings demonstrated that the composite's adsorption capacity and release ability strongly depended on the zirconia-to-silica molar ratio and the calcination process. Calcinating the oxide system reduced the surface area and porosity of the adsorbent, promoting the condensation reaction of Zr–O and Si–O groups to form siloxane bridges and Zr–O–Si groups. This decreased the number of active sites on the oxide surface, leading to lower adsorption and subsequent release of the pharmaceutical compounds under study. Figure 3 illustrates the potential interaction between calcinated and uncalcinated inorganic carriers and ibuprofen molecules. Notably, the highest adsorption of ibuprofen molecules was observed at high zirconia percentages, which can be attributed to the larger pore sizes. Regarding ibuprofen release, the oxide materials with excess zirconium and excess silicon at approximately 70% exhibited the largest release after 24 h. The release process occurred in two steps: the rapid release of adsorbed molecules on the outer surface of ZrO_2–SiO_2 followed by the slower release of molecules located within the pores.

Magnetic silica-based adsorbents have demonstrated remarkable potential for ibuprofen adsorption, as highlighted in a few studies (González-Hurtado et al. 2018). For instance, superparamagnetic silica-based nanocomposites modified with aminosilane exhibited a high removal efficiency of 97% for ibuprofen within the first 15 min, with a maximum sorption capacity of 59 mg/g at pH 7 (Chandrashekar and Balakrishnan 2021). These nanocomposites, specifically nickel–iron oxide encapsulated silicon dioxide-3-aminopropyltriethoxysilane, also displayed excellent reusability for up to four cycles without significant loss in their overall efficiency. Silica-based materials have also been extensively applied in drug delivery (Suttiruengwong et al. 2018). It is worth noting that the silica surface exhibits a greater affinity for water compared to ibuprofen (Delle Piane et al. 2014). Consequently, water and ibuprofen compete for the available surface silanols. Further research focused on removing ibuprofen using silica-based adsorbents for potential application in wastewater treatment is necessary to expand our understanding in this area.

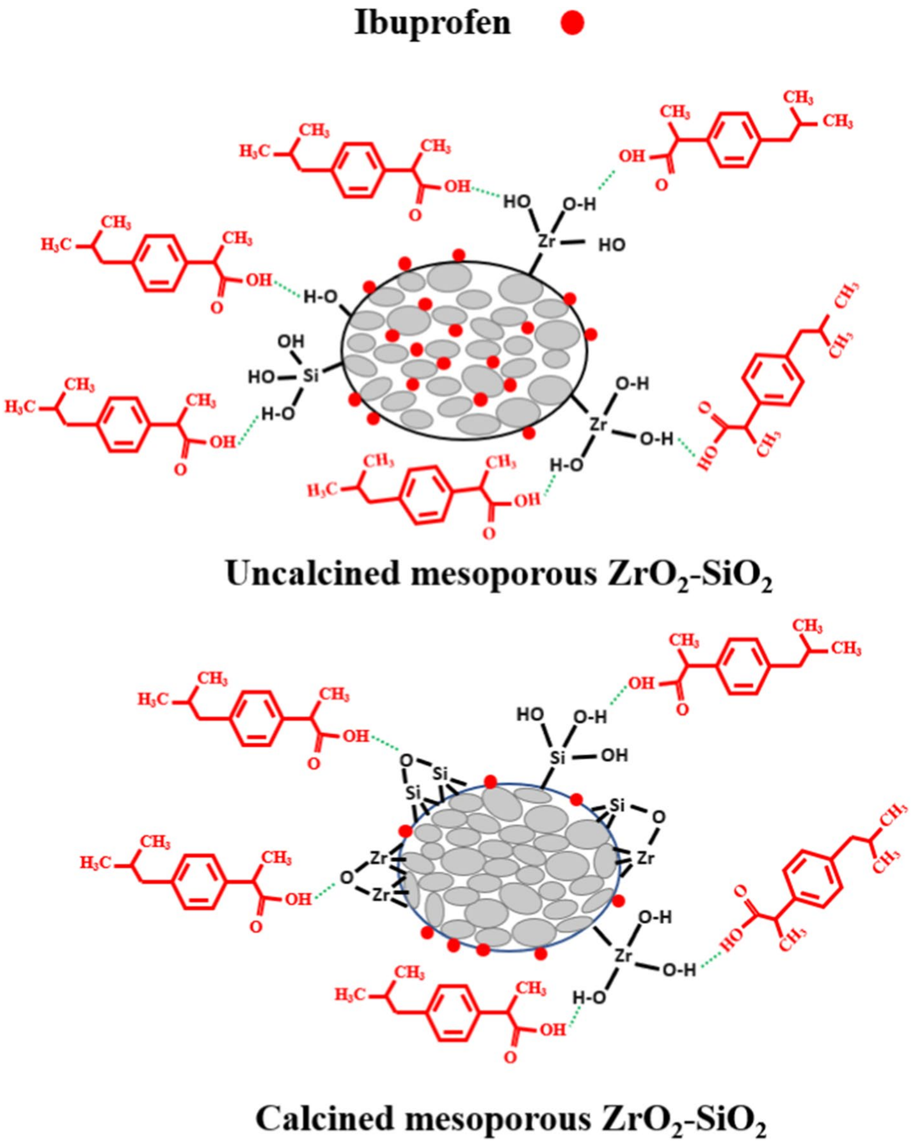

Fig. 3 Adsorption of ibuprofen in calcinated and uncalcinated inorganic carriers. The calcination process highly influences the adsorption capacity and mechanism of ZrO_2-SiO_2 binary oxide. Calcination reduces the surface area and porosity of the adsorbent, leading to the condensation reaction of Zr-O and Si–O groups, forming siloxane bridges and Zr-O-Si groups. This reduction in active sites results in a lower adsorption capacity, with adsorption predominantly occurring on the outer surface of the calcined oxide material. Conversely, contrasting results are observed with uncalcined ZrO_2-SiO_2 materials with well-developed porosity and surface area. In such cases, ibuprofen molecules can be adsorbed on the surface and inside the pores. Notably, a higher percentage of zirconia in the binary oxide is associated with larger pore sizes, facilitating increased ibuprofen molecule adsorption. Reprinted with permission of Elsevier (Ciesielczyk et al. 2018). ZrO_2 and SiO_2 refer to zirconium dioxide and silicon dioxide, respectively

Metal–organic frameworks

Metal–organic frameworks, which are advanced porous materials, have gained significant attention as remarkable and promising adsorbents (López et al. 2021). Their synthesis is straightforward, and they possess high surface areas, exceptionally large pore volumes, tunable chemical properties, and well-defined geometric structures (Akbari Beni et al. 2020; Lee et al. 2023). Metal–organic frameworks are composed of organic linkers and metal ions connected through coordination bonds (Abbasnia et al. 2022), resulting in coordinatively unsaturated sites and open metal sites that serve as active sites for hosting adsorbate molecules (Ejeromedoghene et al. 2022; Jun et al. 2019; Wang et al. 2017b). Although metal–organic frameworks exhibit relatively low stability in water(Bhadra et al. 2017), hydrophobic or specially functionalized metal–organic frameworks have been developed to enhance their performance as adsorbents. The porous structure of metal–organic frameworks allows for physically trapping pharmaceutical molecules through π–π interactions or interactions with the metal centers (Huxford et al. 2010; Lestari et al. 2018; Tabatabaeian et al. 2020). As a result, certain metal–organic frameworks have demonstrated higher removal capacities than commercial activated carbon (Jun et al. 2019; Lin et al. 2018). In addition to their adsorption capabilities, metal–organic frameworks have attracted attention in drug delivery applications, serving as hosts for controlled release (Chávez et al. 2021). This discussion highlights the significant findings and recent contributions in metal–organic framework-based adsorbents, and some noteworthy examples are presented in Table 4.

The adsorption of ibuprofen onto metal–organic frameworks can be attributed to several potential interaction mechanisms. These mechanisms include the formation of Lewis acid/base complexes between the coordinatively unsaturated sites of the metal ions in metal–organic frameworks and the dissociated ibuprofen molecules. Another mechanism involves hydrogen bonding between the carboxyl group of ibuprofen and oxygen atoms within the structure of the metal–organic framework. Additionally, π–π electron donor–acceptor interactions between the metal–organic frameworks and ibuprofen molecules have been considered (Álvarez-Torrellas et al. 2016; Sun et al. 2019). Furthermore, anion-π interactions between the benzene ring of the metal–organic frameworks and the dissociated carboxyl group of ibuprofen are also possible (Ghasemi et al. 2022; Scheytt et al. 2005; Sun et al. 2019; Wei et al. 2018). Sun et al. (2019) conducted density functional theory calculations to analyze the binding energies and typical structures of ibuprofen adsorbed onto zirconium-based metal–organic framework, namely UiO-66, and amino zirconium-based metal–organic framework, namely UiO-66-NH_2, metal–organic frameworks. They comprehensively considered all possible interaction mechanisms involved in pharmaceutical adsorption. They found that the binding energies followed the order of π–π interactions more than hydrogen bonding more than Lewis acid/base more than anion-π interactions. Specifically, hydrogen bonding was identified as the primary pharmaceutical adsorption mechanism, including ibuprofen and oxybenzone, onto the iron-based metal framework, namely MIL-101 (Seo et al. 2016).

Most studies on the adsorption of ibuprofen onto metal–organic frameworks focused on MILs types (Cao et al. 2020; Horcajada et al. 2008; Rajab Asadi et al. 2018). For example, a chemically stable metal–organic framework of iron-based metal–framework, namely MIL-53(Fe), efficiently adsorbed ibuprofen molecules with a removal efficiency above 80% under optimal conditions (Nguyen et al. 2019). In another study, Jun et al. (2019) investigated the effectiveness of aluminium terephthalate, namely MIL-53(Al), as an adsorbent for removing ibuprofen. They observed that the aluminum metal in aluminium terephthalate likely formed coordination bonds with the anionic ibuprofen molecules, contributing to hydrophobic and electrostatic interactions. Additionally, they found that the positive surface charge of aluminium terephthalate decreased gradually as the solution pH increased from 3.5 to 9.5. This reduction in surface charge resulted in enhanced hydrophobic interactions between aluminium terephthalate and ibuprofen molecules.

Furthermore, divalent cations, which act as counterions for ibuprofen, have been found to enhance the electrostatic interaction between ibuprofen and metal–organic frameworks by bridging the two entities. On the other hand, divalent anions that coexist with ibuprofen can suppress this electrostatic interaction. The proposed adsorption mechanisms for ibuprofen and carbamazepine are depicted in Fig. 4. Remarkably, the copper-doped iron-based metal–organic framework demonstrated a high adsorption capacity for ibuprofen across a wide pH range, with a maximum sorption capacity of 497 mg/g (Xiong et al. 2021). Furthermore, this adsorbent exhibited reusability and could be easily regenerated using ethanol.

In a recent study by Sompornpailin et al. (2022), aluminium terephthalate demonstrated a remarkable adsorption capacity for three non-steroidal anti-inflammatory drugs, namely ibuprofen, naproxen, and ketoprofen, surpassing that of activated carbon. The dominant interactions between aluminium terephthalate and ibuprofen were attributed to hydrogen bonding between the carboxylic group of the metal–organic framework's terephthalic acid, Al–OH(OH_2) node, and ibuprofen's carboxylic groups. The authors also investigated the adsorption behavior of polyvinylidene fluoride/aluminium terephthalate metal–organic framework and aluminium terephthalate/alginate beads in batch and dynamic systems. Although aluminium terephthalate

Table 4 Metal–organic framework-based adsorbent for ibuprofen

Adsorbent	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum conditions and ibuprofen concentrations	Kinetics	Isotherm	References
Iron-based metal–organic framework (MIL-53(Fe))	5.5	Not reported	10. 7	Room temperature, pH 2.6, 1.6–18.4 mg/L	Pseudo-second order	Langmuir	Nguyen et al. 2019
Copper-doped iron-based metal–organic framework (MIL-101(Fe))	15.5	Not reported	497	Room temperature, pH 3, 1–60 mg/L	Pseudo-second order	Langmuir	Xiong et al. 2021
Zirconium 1,4-dicarboxybenzene metal–organic framework (UiO-66)	1171	6.4	62.5	298 K, pH 4.4, 1–10 mg/L	Pseudo-second order	Langmuir	Sun et al. 2019
Zirconium 1,4-dicarboxybenzene metal–organic framework (UiO-66)	1507	Not reported	606	298 K, pH 6, 0–400 mg/L	Pseudo-second order	Langmuir	Lin et al. 2018
Zirconium 1,4-dicarboxybenzene metal–organic framework (UiO-66)	1317	5.5	213	298 K, pH 4, 15–40 mg/L	Pseudo-first order	Langmuir Freundlich	Fayyazi et al. 2022
Amino zirconium 1,4-dicarboxybenzene metal–organic framework (UiO-66)UiO-66-NH_2	1277	4.7	96.7	298 K, pH 4, 15–40 mg/L	Pseudo-first order	Langmuir Freundlich	Fayyazi et al. 2022
Amino zirconium 1,4-dicarboxybenzene metal–organic framework (UiO-66-NH_2)	646	4.6	21.7	298 K, pH 4.4, 1–10 mg/L	Pseudo-second order	Langmuir	Sun et al. 2019
Zirconium-based metal–organic framework@5% Metal–organic framework-199 (UiO-66@5% HKUST-1)	1277	5	147	298 K, pH 4, 15–40 mg/L	Pseudo-first order	Langmuir Freundlich	Fayyazi et al. 2022
Metal–organic framework-808	1314	Not reported	268	298 K, pH 6, 0–400 mg/L	Pseudo-second order	Langmuir	Lin et al. 2018
Amino covalent-organic framework (COF-NO_2)	679	Not reported	94	Room temperature, 50 mg/L	Pseudo-second order	Not reported	Liang et al. 2021

Table 4 (continued)

Adsorbent	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum conditions and ibuprofen concentrations	Kinetics	Isotherm	References
Amino covalent-organic framework (COF-NO_2)	282	Not reported	Not reported	Room temperature, 50 mg/L	Pseudo-second order	Not reported	Liang et al. 2021
Nickel@ metal–organic framework-74(Ni)	467	Not reported	4.1	Room temperature, 465 mg/L	Pseudo-second order	Not reported	Xu et al. 2018
Fluorine-bearing covalent organic framework TpBD-$(CF_3)_2$	870	Not reported	119	pH 2, 20 mg/L	Not reported	Not reported	Mellah et al. 2018
Copper-BTC@ iron oxide	Not reported	Not reported	13.4	Room temperature, pH 4, 10–60 mg/L	Pseudo-second order	Langmuir	Chang et al. 2022
Aluminum Raschig ring supported iron-based metal–organic framework	858	Not reported	300	Room temperature, 0.5–21 mg/L	Pseudo-second order	Langmuir	Wu et al. 2022
Zirconium-based metal–organic framework (UiO-67(Zr))	2900	4.7	213	298 K, pH 7, 25 mg/L	Not reported	Langmuir	Mondol et al. 2022

Metal–organic frameworks have emerged as highly promising materials for the adsorptive removal of ibuprofen and other pharmaceutical compounds. Their well-defined geometric structures and open metal sites provide active sites for hosting adsorbate molecules. Additionally, metal–organic frameworks have shown potential in drug delivery applications, acting as hosts for pharmaceutical agents. The adsorption of ibuprofen onto metal–organic frameworks involves various interaction mechanisms, with hydrogen bonding being a predominant mechanism observed in some instances, particularly for pharmaceuticals like ibuprofen and oxybenzone. The application and significance of metal–organic frameworks in ibuprofen adsorption are summarized here, highlighting their potential in wastewater treatment and drug delivery

K Kelvin

metal–organic framework/alginate adsorption capacities were 2.2–2.5 times lower than pristine aluminium terephthalate, it exhibited higher selectivity for ibuprofen in hospital wastewater. The experimental breakthrough curves were well-described by the multi-layer log-Thomas model. In a study by Lin et al. (2018), the exceptional adsorption ability of zirconium(IV)-based metal–organic frameworks, i.e., metal–organic framework-808, metal–organic framework-802, and zirconium 1,4-dicarboxybenzene metal–organic framework, namely UiO-66, with incomplete-coordinated zirconium clusters were demonstrated for the capture and separation of non-steroidal anti-inflammatory drugs from water. The authors highlighted the strong affinity of metal–organic frameworks towards anionic pharmaceuticals, attributed to the interaction between the drug's carboxyl groups and primary amine groups with the cationic zirconium sites in the metal–organic framework clusters via chemical adsorption. Due to its narrow pores, metal–organic framework-802, namely MOF-802, exhibited the lowest pharmaceutical uptake. The higher uptake of zirconium 1,4-dicarboxybenzene metal–organic framework, namely UiO-66, was attributed to its greater number of functional groups (benzene rings) for π–π interactions. Lately, Mondol et al. (2022) used a zirconium-based metal–organic framework, namely UiO-67, with several defects, adjusted by benzoic acid, for the adsorption of ibuprofen and carbamazepine. They showed that the molar ratio (x, %) of benzoic acid/zirconium chloride in the synthesis of zirconium-based metal–organic framework, namely UiO-67(Zr))-benzoic acid, x value significantly impacted its surface area and sorption capacity, and the highest surface area, 2900 m^2/g, and maximum sorption capacity, i.e., 294 mg/g and 213 mg/g toward carbamazepine and ibuprofen, respectively, were obtained at x equal to 10. They explained the efficient adsorption onto zirconium-based metal–organic framework at a wide pH range through the

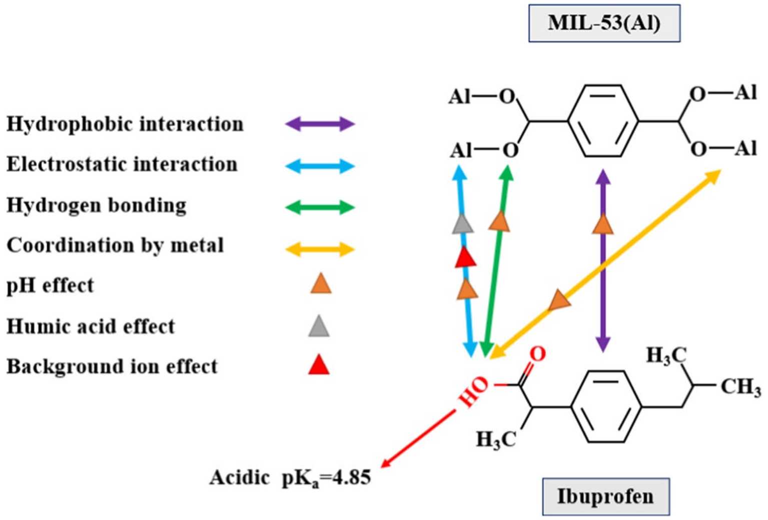

Fig. 4 Electrostatic interaction between ibuprofen and aluminium terephthalate metal–organic framework, namely MIL-53(Al). The divalent cations can facilitate the electrostatic interaction between ibuprofen molecules and aluminium terephthalate. The proposed adsorption mechanisms show that hydrophobic and electrostatic interactions have the strongest role in the ibuprofen adsorption onto MIL-53(Al). The carboxylic groups in the aluminium terephthalate structure provide the dominant interactions with ibuprofen molecules. The hydrogen bonding and coordination by metal can also show a minor effect on ibuprofen adsorption. pH of the solution is the most influential parameter in all the interactions above. Besides pH, it was revealed that the electrostatic interaction can be promoted by humic acid or ionic strength/background ions, as illustrated by triangles. pK_a refers to the acid dissociation constant. Reprinted with permission of Elsevier from Jun et al. (2019)

synergistic effects between defect sites and porosity via van der Waals, π–π, and H-bonding interactions.

Functional group tuning and the chosen synthesis method can significantly influence the adsorption behavior of metal–organic frameworks. Liang et al. (2021) demonstrated this effect by enhancing the selective adsorption of pharmaceuticals from aqueous effluent using crystalline porous covalent-organic framework and amino covalent-organic framework polymers. It was observed that the higher specific surface area of the amino covalent-organic framework, namely COF-NO_2, (679 m^2/g), made it an excellent adsorbent for capturing ibuprofen, ketoprofen, and naproxen, although without significant selectivity among them. On the other hand, the amino covalent-organic framework exhibited selective adsorption behavior and had a twice higher adsorption capacity for ketoprofen compared to the other compounds studied. Functional group tuning was also studied using amino zirconium 1,4-dicarboxybenzene metal–organic framework, namely UiO-66-NH_2, toward ibuprofen and naproxen (Sun et al. 2019), which followed the pseudo-second order kinetic and Langmuir isotherm models. The adsorption of ibuprofen onto these metal–organic frameworks was higher than that of naproxen due to its larger binding energies with the adsorbents. The amino group in amino zirconium 1,4-dicarboxybenzene metal–organic framework provides one more binding site, which can form hydrogen bonding with the ibuprofen molecule. On the other hand, the binding sites of the zirconium-based metal–organic framework were more than the amino zirconium 1,4-dicarboxybenzene metal–organic framework due to its larger surface area. The higher competitive adsorption between naproxen and ibuprofen and onto zirconium-based metal–organic framework compared to the amino metal–organic framework was also explained by a higher amount of adsorption sites and the type of binding sites.

Various strategies have been explored to enhance the adsorption performance of metal–organic frameworks, including composite formation and structural modifications. For example, it was shown that the incorporation of graphene oxide and iron oxide could increase the ibuprofen adsorption capacity of metal–organic frameworks by up to 94.12% through a physical interaction involving hydrogen bonding, π-π interactions, and van der Waals interactions with the ibuprofen carboxylic acid group (Lestari et al. 2020). In another study, a Ni@metal–organic framework-74(Ni) composite, where Ni acted as a metal source for the formation of metal–organic framework-74(nickel), was introduced as an efficient candidate for ibuprofen adsorption (Xu et al. 2018). Wu et al. (2022) recently developed a supported iron-based metal–organic framework structure on a micro-structured alumina Raschig ring. The unique structure of the alumina Raschig ring facilitated easy access to water contaminants, leading to a significant increase in the ibuprofen adsorption capacity, reaching 300 mg/g.

For the adsorption of ibuprofen onto metal–organic frameworks, solution pH is a critical factor that strongly influences the surface features, e.g., hydrophobicity and surface charge, of both the adsorbent and adsorbate. At the pH_{pzc} of a metal–organic framework, surface charges are predominant by changing the pH. For example, ibuprofen adsorption onto aluminium terephthalate meta-organic framework (Jun et al. 2019) and zirconium-based metal–organic framework (Sun et al. 2019) markedly decreased with increasing solution pH. Sun et al. (2019) explained the decrease in ibuprofen adsorption onto zirconium-based metal–organic framework with increasing pH by the facilitation of metal–organic framework aggregation at pH lower than pH_{pzc}, whereas electrostatic repulsion between the ibuprofen molecules and metal–organic frameworks increased at pH more than pH_{pzc}. The carboxyl group in the ibuprofen molecules with pK_a of 4.91 can dissociate at pH more than pK_a and acts as Lewis base sites to anchor zirconium (Zr) Lewis acid sites in metal–organic frameworks (Hasan et al. 2013; Sun et al. 2019).

Clays

Clays have emerged as promising materials for ibuprofen adsorption and have been extensively studied. They offer numerous advantages, including availability, low cost, i.e., 20 times cheaper than activated carbon, safety, layered structures, high specific surface areas, high ion exchange potentials, high stabilities, and suitability for large-scale applications (Malvar et al. 2020; Tabrizi et al. 2022). These exceptional properties make clays highly attractive for ibuprofen removal. The adsorptive capabilities of clays, whether modified or unmodified, are influenced by their inherent nature, properties, and the specific operating conditions employed. Various studies have investigated the potential of clays for ibuprofen adsorption, and their findings are summarized in Table 5. Studies have examined the adsorption capacity of unprocessed mineral clays, such as kaolinite, montmorillonite, goethite, and bentonite, for ibuprofen removal. However, these clays demonstrated a limited affinity for ibuprofen compared to activated carbon. In a comparative study, the adsorption capacities of these clays decreased in the following order: activated carbon, 28.5 mg/g more than montmorillonite, 6.1 mg/g more than kaolinite, 3.1 mg/g more than goethite, 2.2 mg/g. The higher adsorption capacity of montmorillonite was attributed to its higher organic matter content of 7.8% and surface area of 34.3 m^2/g in comparison to kaolinite, as much as 3.1% and 2.3 m^2/g, respectively, and goethite, as much as 3.75% and 2.8 m^2/g, respectively (Behera et al. 2012).

In the study by Hounfodji et al. (2021), the adsorption mechanism of various pharmaceuticals onto kaolinite was investigated using density functional theory calculations. They found that the adsorption of these compounds onto kaolinite was more favorable than water. The adsorption process was spontaneous and exothermic and did not result in the formation of dangerous by-products or water acidification. The researchers observed that the molecules primarily adsorbed onto the basal aluminol-terminated surface of kaolinite rather than the siloxane surface. The adsorption was facilitated by π-π and London interactions, hydrogen bonding, and dispersion interactions, with dispersion interactions playing a significant role.

Among the different studied pharmaceutical molecules, ibuprofen was the most weakly adsorbed molecule, with an adsorption energy of – 154.8 kJ/mol, while the paracetamol adsorption energy was – 159.4 kJ/mol. Interestingly, the planar adsorption of ibuprofen was significantly favored over vertical adsorption. In the vertical configuration, ibuprofen attaches to the adsorbent via two hydrogen bonds, namely the carboxylic group of the molecule and a surface oxygen atom/hydroxyl group, and the remaining chain does not bond to the adsorbent surface. In the planar configuration, in addition to hydrogen bonds between the non-aromatic hydrogen atoms of the molecule and some surface oxygen atoms, the oxygen atom of the carboxyl group interacts with the surface hydroxyl group via a hydrogen bond.

Surface modification and combining clay with other materials were efficient strategies to improve clay adsorption capacity. For example, Show et al. (2022b) studied ibuprofen adsorptive removal using amalgamated calcium chloride-caged acid-activated tamarind seed and bentonite alginate beads in a fixed bed upward flow column reactor, in which the maximum sorption uptake was 17.5 mg/g at 20 cm, which was found to be the optimum height of the column bed. The surface features of natural clays can be easily improved with organic cations via ion exchange (Kurczewska et al. 2020; Shahinpour et al. 2022). Most of these studies were carried out on surfactant-modified clays, which may be attributed to the presence of non-polar alkyl chains, their hydrophobization, or interlayer space expansion (Awad et al. 2019; Martín et al. 2019; Obradović et al. 2022).

In such cases, the adsorbed surfactant's chemical nature strongly affected organoclay materials' adsorption properties (Ghemit et al. 2019). For example, organoclay derivatives of Na^+-exchanged montmorillonite, which contained benzyldimethyltetradecylammonium as a cationic surfactant and polyoxyethylene (20)oleyl-ether as a non-ionic surfactant, exhibited a certain versatility in the removal of diverse pharmaceuticals from the effluent of a rural wastewater facility in France (De Oliveira et al. 2020). It was proposed as a filter between the transitions from different settling tanks in wastewater treatment plants to improve the removal efficiency (De Oliveira et al. 2020). Benzyldimethyltetradecylammonium- montmorillonite showed a remarkable affinity for anionic pharmaceutical compounds, while cationic pharmaceutical compounds were better adsorbed onto polyoxyethylene (20)oleyl-ether-montmorillonite and

Table 5 The potential of clays for ibuprofen adsorption

Adsorbent	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Optimum adsorption condition and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	References
Montmorillonite	34.3	2.15	6.1	298 K, pH 3, 60 mg/L	Not reported	Not reported	Not reported	Behera et al. 2012
Kaolinite	2.31	4.13	3.1	298 K, pH 3, 60 mg/L	Not reported	Not reported	Not reported	Behera et al. 2012
Goethite	2.82	6	2.2	298 K, pH 3, 60 mg/L	Not reported	Not reported	Not reported	Behera et al. 2012
Bentonites	79.3	6.95	9.4	Room temperature, pH 2, 2–200 mg/L	Pseudo-second order	Langmuir–Freundlich	Not reported	Kusmierek et al. 2020
Mono-tosyl b-cyclodextrin functionalized cloisite 15A	Not reported	Not reported	1.1	Room temperature, pH 6, 3–10 mg/L	Elovich	Freundlich, Fritz–Schlunder, Redlich–Peterson, Radke–Prausnitz, Sip, Toth, Khan	Not reported	Rafati et al. 2018
Hexadecyltrimethylammonium-modified montmorillonite	25.4	1.9	12	298 K, pH 7, 9–90 mg/L	Not reported	Freundlich, Langmuir, Dubinin-Radushkevich, and Polanyi-Dubinin-Manes	Not reported	Choi and Shin 2020
Octadecylamine modified montmorillonite	Not reported	6.5	41	Room temperature, pH 4, 0.5–80 mg/L	Pseudo-second order	Langmuir	Endothermic	Martín et al. 2019
Octadecylamine modified mica	Not reported	6.5	15	Room temperature, pH 4, 0.5–80 mg/L	Pseudo-second order	Freundlich	Endothermic	Martín et al. 2019
Octadecylamine modified montmorillonite	Not reported	Not reported	64	293 K, pH 6.5, 50–80 mg/L	Pseudo-second order	Langmuir	Endothermic	Malvar et al. 2020
Polyamidoamine -halloysite dunino hybrid	33.7	Not reported	68	298 K, pH 6, 20–100 mg/L	Pseudo-second order	Langmuir	Endothermic	Malvar et al. 2020
Cetyltrimethylammonium bromide-modified bentonite	3	6.5	195	296 K, pH 7, 10–1000 mg/L	Pseudo-second order	Langmuir and Freundlich	Not reported	Ghemit et al. 2019
Zirconium-based metal–organic framework/sepiolite aerogel	41.3	Not reported	10	293 K, pH 7, 1–150 mg/L	Pseudo-second order	Langmuir	Exothermic	Njaramba et al. 2023

Certain clays have been investigated as potential adsorbents for ibuprofen removal. Surface modification techniques or their combination with other materials have been explored to enhance their adsorption capacity. The effectiveness of modified and unmodified clays in adsorbing ibuprofen depends on their inherent properties and characteristics. Notably, the adsorption of ibuprofen onto clays is significantly influenced by pH and ionic strength variations. However, it should be noted that the adsorption performance of clays for ibuprofen is generally lower compared to carbon-based adsorbents

K Kelvin

Na^+-exchanged montmorillonite, with its dual hydrophobic-hydrophilic nature via compensating Na^+ cations and the non-ionic surfactant. The intercalation of surfactants within the interlayer space of organoclays created a hydrophobic environment that adsorbed numerous pharmaceuticals through weak π–π and/or van der Waals interactions. Mainly, electrostatic interactions controlled the adsorption of drugs onto the Na^+-exchanged montmorillonite, nonionic polyoxyethylene (20)oleyl-ether-montmorillonite, and cationic benzyldimethyltetradecylammonium- montmorillonite organoclay adsorbents.

The cationic octadecylamine surfactant modification of clays, such as Na^+-exchanged mica (Martín et al. 2018) and montmorillonite (Malvar et al. 2020), significantly increased their affinity for ibuprofen molecules. Hydrophobic interactions between the surfactant alkyl chains of modified clay and organic compounds play a major role in adsorption, and the incorporation of ibuprofen occurred on the external surface and in the interlayers (Martín et al. 2018). Martín et al. (2019) compared ibuprofen adsorption to octadecylamine-modified montmorillonite and Na^+-exchanged mica. While adsorption was faster onto modified montmorillonite, smaller than 5 min, than modified Na^+-exchanged Mica, smaller than 60 min, both adsorption kinetics followed the pseudo-second order, indicating chemisorption. Furthermore, the adsorption isotherm of modified montmorillonite corresponded to the Langmuir model, while that of modified Na^+-exchanged mica fitted better to the Freundlich model, indicating a difference in the types of adsorption.

In addition to ibuprofen molecules, the efficient adsorption performance of octadecylamine-modified montmorillonite was also demonstrated in the removal of primary ibuprofen metabolites, including 1-hydroxyibuprofen, 2-hydroxyibuprofen, and carboxyibuprofen, from aqueous solution (Malvar et al. 2020). It was mainly due to electrostatic interaction and partitioning in the adsorption mechanism. The maximum adsorption capacities toward ibuprofen and all its primary metabolites within 20–30 min were 64 mg/g, 20 mg/g, 63 mg/g, and 19 mg/g, respectively (Malvar et al. 2020). It should be noted that the sorption capacities were considerably lower in mixture solutions due to competition for adsorbent active sites.

Hexadecyltrimethylammonium is another surfactant used to modify montmorillonite and zeolite to efficiently absorb ibuprofen and salicylic acid at pH 7 (Choi and Shin 2020). Due to the higher organic carbon content of modified montmorillonite, a higher adsorption capacity compared to that of modified zeolite was observed; furthermore, because of the higher hydrophobicity and molar volume of ibuprofen molecules, it showed higher uptake than salicylic acid. Since the anionic speciation of ibuprofen is more prolific at pH 7, higher than pK_a, its adsorption onto modified montmorillonite mainly occurs via two-dimensional surface adsorption onto the pseudo-organic medium in the adsorbent, while bonding to the positively charged "head" of hexadecyltrimethylammonium is responsible for modified zeolite. The adsorption isotherms corresponded well to the Polanyi-Dubinin-Manes model, indicating that pore-filling was the dominant adsorption mechanism.

Cetyltrimethylammonium bromide, a cationic surfactant with long alkyl chains, creates a suitable organic–inorganic framework for pharmaceutical compound adsorption. It was found to be suitable for synthesizing organobentonite adsorbents with high ibuprofen and diclofenac molecule adsorption capacities of 194 mg/g and 600 mg/g, respectively (Ghemit et al. 2019). The higher potential for the uptake of pharmaceutical contaminants was attributed to the larger interlayer space within organobentonites. The chemical nature of bentonite changes from hydrophilic to hydrophobic by intercalating cationic surfactants through ion exchange, and consequently, hydrophobic interactions play an essential role during adsorption. Both ibuprofen and diclofenac molecules were divided into the organic phase of the interlayer space made by the surfactant. The amount of ibuprofen and diclofenac adsorbed gradually increased with increasing surfactant concentration. In the competitive adsorption of ibuprofen and diclofenac, their monolayer adsorption decreased to 83 mg/g and 188 mg/g, respectively.

Functionalizing clays with amines was also investigated for ibuprofen adsorptive removal. For example, the amine-functionalized nano-clay Cloisite 15A was successfully used for the adsorptive removal of ibuprofen in both batches (Rafati et al. 2018) and continuous fixed-bed column (Rafati et al. 2019) systems. Rafati et al. (2019) showed that the adsorption capacity of the fixed-bed column depended on ibuprofen concentration and bed depth. The Thomas, bed-depth service time, Yoon-Nelson, and Clark mathematical models accurately predicted the breakthrough curves. The strong hydration of the inorganic counter ions in the interlayer space of expandable clay minerals made them hydrophilic and, therefore, often weak adsorbents toward hydrophobic organic compounds (Gámiz et al. 2015).

In another study, polyamidoamine dendrimer was grafted onto halloysite clay mineral (Kurczewska et al. 2020) with an intermediate 3- aminopropyltrimethoxysilane functionalization step. Electrostatic interactions between protonated amine groups on halloysite surfaces in both 3- aminopropyltrimethoxysilane functionalized and polyamidoamine dendrimer grafted halloysite, and the carboxyl groups in pharmaceutical molecules significantly affect adsorption efficiency. However, Tan et al. (2013) indicated that the holloysite-3-aminopropyltriethoxysilane surface had 25% higher ibuprofen loading than the unmodified halloysite. More reactive functional groups were provided by the polyamidoamine dendrimer for favorable adsorption toward ibuprofen and naproxen than organosilane (Kurczewska et al. 2020). Halloysite surfaces bearing covalently attached organic units demonstrated a higher affinity for pharmaceutical molecules than the unmodified mineral, and the ibuprofen and naproxen loading efficiencies increased to high adsorption capacities of 68 mg/g and 5.9 mg/g, respectively, at pH 6.

In a study conducted by Li et al. (2019), the adsorption mechanism of ibuprofen onto a zeolite/sepiolite nano-heterostructure and an organically modified sepiolite called Tetranyl® B-2MTH, namely stearyl dimethyl benzyl ammonium chloride, sepiolite was investigated. The study utilized isotherm studies to propose a pore-filling mechanism, indicating the formation of one or more adsorbed layers. Notably, the results revealed that the bonding of ibuprofen molecules on both adsorbents occurred in both horizontal and non-horizontal, temperature-dependent orientations. This suggests the presence of multi-docking and multi-molecular adsorption, respectively. At higher temperatures, specifically 60 °C, ibuprofen molecules in solution tended to aggregate primarily through dimer formation, with an approximate capture of two ibuprofen molecules. The organically modified sepiolite exhibited a higher adsorption capacity than the zeolite/sepiolite across all studied temperatures. The primary factors influencing the mechanism of ibuprofen adsorption were identified as the adsorption energies and the density of receptor sites. Recently, Njaramba et al. (2023) introduced a novel three-dimensional mesoporous aerogel by incorporating sepiolite and zirconium 1,4-dicarboxybenzene metal–organic framework UiO-66, a zirconium-based metal–organic framework, into gelatin. This innovative aerogel was proposed as a promising alternative adsorbent for efficiently removing ibuprofen and naproxen. The adsorption process was found to be exothermic, and it followed both the pseudo-second-order kinetics and the Langmuir isotherm models. The maximum sorption capacities for ibuprofen and naproxen were determined to be 10 mg/g and 8.5 mg/g, respectively.

The adsorption process onto clay is highly influenced by pH and is susceptible to changes in ionic strength. Behera et al. (2012) observed that the adsorption of ibuprofen onto clays increased as the ionic strength increased. This phenomenon was attributed to the partial neutralization of the positive charge on the surface of the adsorbent, which led to the contraction of the electric double layer due to the presence of chloride ions. Furthermore, chloride ions were found to enhance the adsorption of ibuprofen by effectively pairing their charges. This pairing mechanism reduced repulsion between ibuprofen molecules already adsorbed on the surface, thereby facilitating the adsorption of additional positively charged ibuprofen ions.

Polymer-based adsorbents

Polymeric materials have garnered significant attention as adsorbents for pharmaceutical applications, with chitosan being one of the most extensively studied polymers (Hamidon et al. 2022; Tseng et al. 2022; Yu et al. 2022; Zare et al. 2022). Chitosan, a cationic amino polysaccharide, is widely utilized in drug release and pharmaceutical adsorption due to its non-toxic, biodegradable, and biocompatible nature (Balakrishnan et al. 2023; Farrokhi et al. 2019; Moghaddam et al. 2019; Pereira et al. 2020; Souza et al. 2020). Its structure contains multiple amino and hydroxyl groups, which make it amenable to grafting and chemical modifications (Rahimzadeh et al. 2022; Ranjbari et al. 2022).

Previous research has focused on enhancing chitosan's physical solubility and electric charge through grafting and chemical modification, showing promising outcomes in removing ibuprofen (Ferrah et al. 2022; Sahin et al. 2020). Two effective grafting agents for chitosan include acrylic monomers of ammonium hydroxide (Farrokhi et al. 2019) and β-cyclodextrin (Bany-Aiesh et al. 2015). These modifications have demonstrated improved adsorption behavior of chitosan towards ibuprofen, particularly in acidic media. Bany-Aiesh et al. (2015) revealed that ibuprofen adsorption occurred through multilayer physisorption onto β-cyclodextrin-grafted chitosan, with the adsorption rate controlled by intraparticle diffusion. Phasuphan et al. (2019) developed an efficient adsorbent by incorporating chitosan onto tire crumb rubber waste to remove ibuprofen, naproxen, and diclofenac anti-inflammatory drugs. Maximum adsorption capacities of 70 mg/g, 2.3 mg/g, and 18 mg/g were achieved for ibuprofen, naproxen, and diclofenac, respectively, at pH 6.

The amino groups in chitosan play a crucial role in facilitating electrostatic interactions with the carboxyl groups of drugs. O-carboxymethyl-N-laurylchitosan/γ-Fe_2O_3, a magnetic polymer, has also exhibited a high adsorption capacity for ibuprofen (Chahm and Rodrigues 2017). At pH 7 and 25 °C, the maximum sorption capacity was determined to be 395 mg/g. However, it was observed that the adsorption capacity decreased above pH 5. This can be attributed to the electrostatic repulsion between the negatively charged –COO-groups of O-carboxymethyl-N-laurylchitosan/γ- iron oxide (II) and the deprotonated ibuprofen. The presence of functional groups such as $–NH_2$ and –COOH, as well as the aliphatic chain of the adsorbent, significantly influenced its affinity for ibuprofen molecules. The adsorption of ibuprofen onto O-carboxymethyl-N-laurylchitosan/γ-iron oxide (II) was primarily physical, and the process was characterized by an activation energy of 37.9 kJ/mol. Through the use of response surface methodology, it was determined that the initial concentration of ibuprofen was the most influential parameter affecting the adsorption process.

Polypyrrole-modified carboxymethyl cellulose has recently emerged as a polymeric adsorbent for removing ibuprofen from aqueous solutions. Optimal conditions for ibuprofen adsorption were achieved at pH 7, resulting in an adsorption capacity of 72 mg/g. The adsorption process was well described by the Elovich kinetic and Langmuir isotherm models (Kumar et al. 2022). In the realm of biopolymers, chitin and lignin have gained significant attention across various fields (Gellerstedt and Henriksson 2008). When modified with Kraft lignin, chitin becomes an effective adsorbent with a surface rich in functional groups (Żółtowska-Aksamitowska et al. 2018). The Kraft lignin-modified chitin adsorbent exhibits both negative charges (attributed to lignin functional groups) and positive charges (derived from chitin's protonated acetylamino groups) on its surface (Żółtowska-Aksamitowska et al. 2018). Notably, this adsorbent demonstrated the highest adsorption capacity for ibuprofen among the studied polymeric adsorbents, with a capacity of approximately 400 mg/g, as shown in Table 6. The effective adsorption is attributed to hydrophobic interactions, π-π interactions, and electrostatic interactions between the protonated acetylamino groups. This allows for efficient monolayer ibuprofen loading and multilayer acetaminophen loading between pH 2 and 6. The adsorbent's surface exhibited a combination of negative and positive charges, enabling interactions with the target compounds' anionic and cationic forms. In the case of ibuprofen, which exists predominantly in its anionic form, the primary interactions involved hydrophobic, π-π, and electrostatic interactions. However, it was observed that the adsorption effectiveness of the adsorbent decreased in alkaline solutions. This can be attributed to the lower hydrophobicity of the ibuprofen anion compared to acetaminophen. The main mechanisms for acetaminophen adsorption onto chitin/lignin were electrostatic interactions, hydrogen bonds, and ion–dipole interactions. These interactions facilitated the binding of acetaminophen molecules to the surface of the adsorbent.

Microgranular crosslinked cationic starch, an economical and natural polymer, has shown significant potential for binding ibuprofen (Navikaite-Snipaitiene et al. 2022). This polymer can be modified with different degrees of substitution of quaternary ammonium groups, and it has been found to exhibit high levels of ibuprofen binding. The adsorption process primarily relies on the electrostatic interaction between the carboxylic groups of ibuprofen molecules and the quaternary ammonium groups of the modified starches. The study showed starches with varying degrees of substitution of quaternary ammonium groups, i.e., 0.42 and 0.21, demonstrated sorption capacities of 345 mg/g and 232 mg/g, respectively. The adsorption capacity of the modified starch granules was further enhanced to 574 mg/g and 579 mg/g, respectively, through ultrasonic activation. This activation method induced the formation of cracks and fissures on the exterior surface of the starch granules, facilitating increased adsorption. Moreover, corn starch nanoparticles also exhibited a significantly high adsorption capacity toward ibuprofen, with an adsorption capacity of 65 mg/g (Priyan and Narayanasamy 2022).

In recent studies, crosslinked β-cyclodextrin has emerged as an effective adsorbent for ibuprofen removal (Skwierawska et al. 2022; Wang and Yang 2021). Wang and Yang (2021) specifically developed a highly efficient adsorbent by crosslinking 2-hydroxypropyl-β-cyclodextrin polymers with poly(acrylic acid). The adsorption process was primarily driven by hydrogen bonding between ibuprofen and the hydroxyl groups present in the polymer. Additionally, the authors proposed that the primary mechanism of adsorption involved the encapsulation of ibuprofen molecules within the cavities of the crosslinked polymer through host–guest inclusion interactions. The adsorption capacity of the crosslinked polymer increased with higher concentrations of ibuprofen and elevated temperatures. The adsorption process followed the pseudo-second-order kinetic and Langmuir isotherm models, indicating favorable adsorption behavior. Remarkably, the polymer demonstrated good reusability, maintaining its original adsorption capacity even after being used up to 10 times in a 5% ethanol/water solution.

In a study by Zhao et al. (2019), porous aromatic frameworks, namely PAF-45, were covalently anchored onto electrospun polystyrene fiber membranes to significantly increase their surface area from 9 to 262 m^2/g. Aromatic seed layers of polyaniline were utilized in the process. This polymeric material exhibited remarkable adsorption capacities of 613 mg/g, 384 mg/g, and 429 mg/g for three pharmaceutical chemicals: ibuprofen, N, N-diethyl-meta-toluamide, and chloroxylenol, respectively. The adsorbent displayed good recyclability, and pore capture, π-π interactions, and hydrophobic interactions primarily drove the bonding between the sorbates and the polymeric adsorbent. These interactions played a crucial role in the adsorption process. In another study by Kebede et al. (2019), nanofibers composed of Moringa seed protein/poly(vinyl alcohol) were employed for the efficient adsorption of non-steroidal anti-inflammatory drugs. When applied to real wastewater treatment, the nanofibers demonstrated a high removal efficiency of 96.1%. The maximum sorption capacity ranged from 31.2 mg/g to 333 mg/g and 125 mg/g for ibuprofen. The interaction between the nanofibers and the drugs occurred through multilayer physicochemical adsorption on heterogeneous surfaces. Jian et al. (2019) showed the adsorption activity of polyaniline toward pharmaceuticals with two aromatic rings, which have lower polarities than those with one aromatic ring, such as ibuprofen. The adsorption and desorption performance of a core–shell polyaniline/polyacrylonitrile nanofiber mat towards hydrophilic non-steroidal anti-inflammatory drugs was also demonstrated in static and dynamic

Table 6 Polymers for removal of ibuprofen

Adsorbent	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Adsorption optimum condition and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Kraft lignin modified chitin	Not reported	8.5	400	298 K, pH 2	Pseudo-second order	Langmuir	Exothermic	1.68–1.87	Żółtowska-Aksamitowska et al. 2018
Chitosan-modified waste tire crumb rubber	Not reported	6.01	70	298 K, pH 6 30 mg/L	Pseudo-second order	Freundlich	Not reported	Not reported	Phasuphan et al. 2019
Epichlorohydrin-crosslinked chitosan microsphere	Not reported	Not reported	Not reported	pH 7.4	Pseudo-second order	Langmuir	Not reported	Not reported	Pereira et al. 2020
β-cyclodextrin (β-CD) grafted chitosan	Not reported	Not reported	Not reported	310 K, pH 4.9, 10–50 mg/L	Pseudo-first order	Freundlich	Exothermic	Not reported	Bany-Aiesh et al. 2015
Chitosan/alginate-polyethyleniminemethylene phosphonic acid	49.2	7.5	122	289 K, pH 5.5, 50 mg/L	Pseudo-second order	Langmuir	Exothermic	4.13–5.01	Ferrah et al. 2022
O-carboxymethyl-N-laurylchitosan/γ-Fe_2O_3	Not reported	Not reported	395	298 K, pH 7, 5–75 mg/L	Pseudo-second order	Sips	Exothermic	0.29–1.77	Chahm and Rodrigues 2017
Electrospun nanofibers	Not reported	Not reported	125	300 K, pH 5.5, 0.65–6 mg/L	Pseudo-second order	Freundlich	Exothermic	Not reported	Kebede et al. 2019
Quaternized polyacrylic polymer	0.41	Not reported	266	318 K, pH 4.17, 31 mg/L	Pseudo-first order	Langmuir model and the Freundlich	Endothermic	Not reported	Zhang et al. 2020
Polyaniline/polyacrylonitrile nanofibers mat	10.6	Not reported	49.8	298 K, pH 7, 1–45 mg/L	Pseudo-second order	Langmuir	Endothermic	21.21–26.01	Jian et al. 2019
Magnetic polypyrrole	Not reported	4	53.7	Room temperature, pH 4, 80 mg/L	Pseudo-second order	Langmuir–Freundlich	Langmuir–Freundlich	1.47–1.66	Pires et al. 2020
2-hydroxypropyl-b-cyclodextrin crosslinked by poly(acrylic acid)	Not reported	Not reported	87.5	298 K, pH 5, 10–50 mg/L	Pseudo-second order	Langmuir	Endothermic	5.60–5.63	Wang and Yang 2021
Microgranular cross-linked cationic starch	Not reported	Not reported	345	298 K, 100–1000 mg/L	Not reported	Langmuir	Not reported	Not reported	Navikaite-Snipaitiene et al. 2022

Table 6 (continued)

Adsorbent	Surface area (m^2/g)	Point of zero charge	Theoretical maximum adsorption capacity (mg/g)	Adsorption optimum condition and ibuprofen concentrations	Kinetics	Isotherm	Thermodynamics	− ΔG (Gibbs free energy) (kJ/mol)	References
Ultrasound-activated cross-linked cationic starch	Not reported	Not reported	579	298 K, 100–1000 mg/L	Not reported	Langmuir	Not reported	Not reported	Navikaite-Snipaitiene et al. 2022
Polypyrrole-modified carboxymethyl cellulose	Not reported	7.32	72.3	293 K, pH 7, 5–120 mg/L	Elovich	Langmuir	Exothermic	0.74–6.67	Kumar et al. 2022

The applications of a few studied polymers in literature for the adsorptive removal of ibuprofen from an aqueous solution are summarized here. Grafting and chemical modification of polymers with organic ligands have been widely explored to enhance their characteristics for ibuprofen removal. Chitosan and starch have demonstrated the highest affinity for ibuprofen molecules among these polymers. The interactions of π-π stacking and hydrogen bonding have been identified as the main mechanisms for the adsorption of ibuprofen onto these polymeric materials. These interactions are crucial in binding ibuprofen molecules to the polymer surfaces, facilitating their removal from aqueous solutions. Additionally, electrostatic attraction has been identified as another potential mechanism for ibuprofen adsorption onto polymeric adsorbents

K Kelvin

adsorption/desorption systems. The potential interactions of π–π stacking and hydrogen bonding between the polyaniline and pharmaceutical structures were discussed for this phenomenon. In addition, electrostatic attraction is a potential interaction mechanism between polyaniline/polyacrylonitrile nanofibers mat and drugs.

Magnetic polymers have attracted the attention of several researchers. For example, a magnetic anion exchange resin with a polyacrylic matrix efficiently adsorbed ibuprofen within 150 min in an endothermic process (Zhang et al. 2020). In addition to the critical role of electrostatic interactions in ibuprofen uptake onto magnetic anion exchange resin, hydrogen bonding between the –COOH groups of ibuprofen and -OH groups on the surface of anion exchange resin also significantly contributed to the interactions. The authors showed that the coexisting salts sodium chloride and sodium sulfate reduced the amount of ibuprofen adsorbed. Another study reported rapid adsorption, up to 180 s, of pharmaceutical compounds, i.e., ibuprofen, caffeine, and bupropion from aqueous solutions on mesoporous magnetic polypyrrole (Pires et al. 2020). Maximum adsorption was observed at pH 4 for ibuprofen and caffeine and pH 7 for bupropion, with maximum adsorption capacities of 53.6 mg/g, 16.7 mg/g, and 24.7 mg/g, respectively. The adsorption data followed the dual-site Langmuir–Freundlich isotherm and pseudo-second-order kinetic models.

Numerous studies have investigated the adsorption of ibuprofen onto microplastics. Elizalde-Velázquez et al. (2020) conducted a comparative study on the adsorption behavior of various microplastics, such as polyethylene, polystyrene, and polypropylene, towards three pharmaceutical compounds: ibuprofen, naproxen, and diclofenac. The researchers found that the highest adsorption of these drugs onto microplastics occurred under acidic conditions, i.e., pH 2, primarily through hydrophobic interactions. Furthermore, the adsorption pattern of the studied pharmaceuticals followed the sequence diclofenac ≈ ibuprofen more than naproxen, which is consistent with their respective log K_{ow} values: ibuprofen, i.e., 3.97, diclofenac, i.e., 4.51, and naproxen, i.e., 3.18. This suggests that the adsorption affinity onto microplastics increases with the increasing hydrophobicity of the pharmaceutical compounds. The size of microplastic particles has a significant impact on the adsorption of pharmaceuticals, including ibuprofen. It has been observed that adsorption increases as the particle size decreases. In the study by Elizalde-Velázquez et al. (2020), different microplastics were compared, and the trend in adsorption capacity from highest to lowest was found to be: ultra-high molecular weight polyethylene more than average molecular weight medium density polyethylene more than polystyrene more than polypropylene. Interestingly, despite its semi-crystalline structure, polypropylene showed a distinct behavior in pharmaceutical adsorption. This can be attributed to its perfectly spherical shape, large particle size, and the presence of long aliphatic chains in polypropylene monomers, which primarily contribute to weak van der Waals molecular forces. These factors influence the adsorption interaction with pharmaceutical compounds.

Salinity was also found to have a slight effect on the adsorption of pharmaceuticals onto microplastics in the mentioned study. Additionally, biofilms in nutrient-enriched waters and extensive biofouling were identified as significant factors affecting the adsorptive removal of pharmaceuticals from plastics (Magadini et al. 2020). High adsorption capacities and selectivity have been achieved by researchers using polymeric adsorbents. To further enhance ibuprofen removal, a promising avenue is carefully selecting magnetic nanoparticle integrated monomers immobilized on various supports such as carbon-based materials, graphene oxide, nanoparticles, and other polymers. Carbonaceous and silica-based adsorbents have shown promising results, making them candidates for future high-efficiency ibuprofen removal applications.

Bio-adsorbents

Researchers have continuously explored biosorbents as a cost-effective solution for the adsorption of non-steroidal anti-inflammatory drugs (Nguyen et al. 2022a; Pereira et al. 2019; Qamar et al. 2022). Various plant-based materials have been investigated for their adsorption potential, benefiting from their abundance, low cost, and biodegradability (Singh et al. 2020; Tee et al. 2022; Varghese et al. 2022). Studies have successfully utilized biosorbents from different sources to adsorb pharmaceuticals, employing diverse molecular interactions such as electrostatic interactions, surface complexation, π-π bonding, hydrogen bonding, hydrophobic interactions, and van der Waals forces (Gothwal and Shashidhar 2015; Rovani et al. 2014). However, the unprocessed form of biosorbents faces limitations, including low sorption capacity, low surface area, and high chemical and biological oxygen demand (Tee et al. 2022). Several treatment methods have been proposed in the literature to overcome these drawbacks.

Green algae, rich in cellulosic polysaccharides containing various functional groups such as carboxyl, hydroxyl, amino, and sulfate, have shown great potential in biosorption treatment (Farghali et al. 2023). Studies have highlighted the significant role of green microalgae, specifically *Scenedesmus* (Silva et al. 2020) and alkaline-modified *Scenedesmus* (Ali et al. 2018), in exhibiting high biosorption capacity for various pharmaceuticals, including ibuprofen. The adsorption capacities of *Scenedesmus* and alkaline-modified *Scenedesmus* for ibuprofen were reported as 12 mg/g and 42 mg/g, respectively. Another biosorbent, cellulose-based Sisal fiber derived from the *Agave sisalana* plant, was modified with polypyrrole-polyaniline nanoparticles to form a bio-composite material for ibuprofen adsorption. This bio-composite achieved an impressive efficiency of 88% under optimized conditions (Khadir et al. 2020). The adsorption isotherm followed the Sips model, and it was observed that higher temperatures activated more binding sites, resulting in increased adsorption capacity.

A novel approach to enhance the adsorption performance of biomass, including cocoa shells and cellulosic biomass, involves their functionalization through plasma pretreatment. Several studies, such as Jean-Rameaux et al. (2021) and Takam et al. (2020), have explored plasma pretreatment's use to modify biomass's surface properties. Plasma pretreatment induces surface oxidation of the biomass, incorporating additional functional groups such as hydroxyl, carbonyl, and carboxyl groups (Jean-Rameaux et al. 2021). This modification of functional groups enhances the adsorption capabilities of the biomass. Additionally, plasma pretreatment has been shown to increase the porosity of biomass (Al-Yousef et al. 2021a). Al-Yousef et al. (2021a) investigated the adsorption behavior of dyes and pharmaceutical molecules on plasma-modified cocoa shell biomass. They found that the non-flat orientation of the molecules, coupled with exothermic reactions, facilitated interactions with functional groups on the surface of the plasma-modified cocoa shell. The maximum biosorption capacities for ibuprofen and ampicillin were determined to be 12 mg/g and 6.7 mg/g, respectively. Multiple mechanisms, including π–π bonding, electrostatic interaction, the hydrophobic effect, and van der Waals forces, were identified to be involved in the adsorption process. The Avrami fractional kinetic model and Liu isotherm model well described the biosorption of antibiotics onto plasma-treated cocoa shells. Theoretical calculations further supported the notion of inclined orientation for physically adsorbed ibuprofen molecules on unmodified and plasma-modified cocoa shell surfaces (Al-Yousef et al. 2021b). The grafting of glycine onto plasma-pretreated cocoa shells also resulted in loading nitrogen-containing functional groups and polar oxygen, which increased ibuprofen adsorption to 39 mg/g (Jean-Rameaux et al. 2021). Double-layer adsorption of ibuprofen onto cocoa shell biomass was observed both with and without glycine and plasma functionalization (Al-Yousef et al. 2021b).

In a study conducted by Quintelas et al. (2020), activated sludge biomass demonstrated effective removal of paracetamol and ibuprofen from aqueous solutions. The biomass exhibited high resistance to the xenobiotic effects of pharmaceuticals, making it a promising alternative for this purpose. The researchers employed quantitative image analysis to identify and quantify filamentous and aggregated microorganisms. Interestingly, they observed a significant impact of ibuprofen on bacterial biomass, leading to deflocculation. Although agro-based byproducts, such as shells and kernels, possess diverse functional groups that highlight their potential for biosorption of various water contaminants, their application in ibuprofen removal has been largely overlooked. Consequently, further investigation is needed to enhance the behavior of different biosorbents, coupled with modifications tailored specifically for ibuprofen removal.

Other nanomaterials

Nanomaterials have garnered significant interest as potential adsorbents for pharmaceutical removal due to their high surface area-to-volume ratios (Ayati et al. 2011; Kumar et al. 2021; Madhura et al. 2019; Madima et al. 2020; Marcelo et al. 2021). However, removing bare nanoparticles from aqueous solutions has been challenging after treatment (Tanhaei et al. 2015). In one study, zinc oxide nanoparticle-coated natural piezoelectric quartz demonstrated enhanced physical adsorption of ibuprofen molecules, exhibiting adsorption energy ranging from − 7.93 to − 9.5 kJ/mol (Yang et al. 2022). A multimolecular sorption mechanism was proposed, suggesting that three or four ibuprofen molecules bonded vertically to the surface.

Steric studies have revealed interesting findings regarding the adsorption capacity and active site density of zinc oxide nanoparticle-coated piezoelectric quartz for ibuprofen (Yang et al. 2022). It was observed that as the temperature increased, both the adsorption capacity and active site density decreased. The highest values were obtained at 25 °C, with an adsorption capacity of 145 mg/g and an active site density of 38 mg/g. Interestingly, unlike many carbonaceous adsorbents, this particular adsorbent exhibited a significant increase in sorption capacity at higher pH values, specifically at pH 6, where a 133 mg/g capacity was achieved. This behavior was attributed to the partial dissolution of zinc oxide under acidic conditions, leading to increased hydrophilicity of ibuprofen at higher pH levels. The increased hydrophilicity enhanced the solubility of ibuprofen and its uptake as dissolved molecules.

The adsorption pH dependency of zinc oxide nanoparticle-coated piezoelectric quartz exhibited an interesting trend beyond pH 6. This behavior can be attributed to the repulsion between the deprotonated carboxylate functional groups of ibuprofen and the negative charges present on the surface of the adsorbent. As a result, the adsorption capacity of ibuprofen decreased at pH values higher than 6. In the case of natural zeolites, these abundant minerals have been extensively investigated for their adsorptive removal of various organic and inorganic compounds (Al-rimawi et al. 2019). However, their negatively charged nature limits their adsorption capacity for positively charged species, including some pharmaceuticals. Researchers have proposed surface modification strategies using cationic reagents to overcome this limitation. One such approach is the modification of zeolites with cationic surfactants, which can alter the surface charge of the zeolite to neutral or even positive (Smiljanić et al. 2021), depending on the surfactant used. This surface modification technique has been applied to zeolites to enhance their adsorption capacity and selectivity for ibuprofen. Several studies have explored the use of surface-modified zeolites as carriers for ibuprofen, demonstrating their potential for effective adsorption (Gennaro et al. 2017; Izzo et al. 2019; Mercurio et al. 2018; Pasquino et al. 2016; Smiljanić et al. 2021). In one study, Smiljanić et al. (2021) used the cationic surfactants Arquad® 2HT-75 and cetylpyridinium chloride, to modify the surfaces of two natural zeolites, namely phillipsite and clinoptilolite, and studied the resulting monolayer and bilayer surfactant-covered zeolites for the removal of ibuprofen and naproxen. They found that the hydrophobicity of the pharmaceutical is one of the main factors influencing the adsorption behavior. The sorption capacity of all adsorbents mentioned above toward ibuprofen and naproxen was obtained in the range of 3–20 mg/g, and the highest capacity was found on the bilayer-modified zeolite composites. It indicated that ion exchange and hydrophobic partitioning were involved in adsorption. Also, bicarbonates and sulfates resulted in a minor change in drug removal using monolayer-modified zeolites, whereas it was considered onto the bilayer-modified zeolite.

Hydroxyapatite, a multifunction nanomaterial in medicine with improved biocompatibility properties, has been used as a drug carrier (Placente et al. 2018). In one study, hydroxyapatite provided an efficient platform for the adsorption/desorption of ibuprofen and ciprofloxacin at 37 °C through the electrostatic interactions between the Ca^{2+} and PO_4^{3-} ions of nanoparticles and the drug molecules (Benedini et al. 2019). The amino acid L-arginine functionalization of hydroxyapatite nanoparticles, which resulted in it being positively charged, improved their electrostatic interactions with ibuprofen molecules. The desorption/release of drugs followed a pH-responsive release, and the highest ibuprofen adsorption was observed at pH 7.4, whereas the release percentage was the lowest at pH 6.

Shen et al. (2022) have used the quinoline-based gemini surfactant to modify vermiculite to enhance its hydrophobicity and adsorption performance toward pharmaceuticals. Efficient adsorption of ibuprofen, i.e., 240 mg/g, and mefenamic acid, i.e., 123 mg/g, were achieved at an extremely low gemini surfactant dosage. The drug adsorptions were satisfactorily fitted to the Freundlich isotherm and pseudo-second-order kinetic models and were exothermic. The authors intensely studied the multiple interactions involved in the process, and their results revealed that, despite the remarkable strength of various active sites provided by quinoline. i.e., CH–π, NH–π, and π–π interactions), electrostatic interaction/intraparticle diffusion dominated the adsorption process. The intraparticle diffusion effect directly depends on the molecular flexibility of adsorbates. Also, π–π stacking between isolated aromatic rings is more robust than between parallelly connected ones.

To enhance the adsorption ability of nanocomposite membranes, imprinting has been introduced as an effective approach. Yan and Wu (2020) demonstrated the successful imprinting of porous polyvinylidene fluoride membranes with ibuprofen, improving selective recognition and separation capabilities for ibuprofen removal. The ibuprofen-imprinted membranes exhibited high recognition specificity for ibuprofen molecules, with imprinting factors of up to 4.68 for ibuprofen and less than 1.44 and 1.28 for naproxen and ketoprofen, respectively. In their study, the authors integrated the ibuprofen-imprinted membranes with polydopamine-modified titanium dioxide functional microspheres, significantly enhancing their rebinding capacity, i.e., 42.1 mg/g, perm selectivity, and regeneration performance. This improvement was attributed to the increased surface area resulting from integrating polydopamine-modified titanium dioxide nanoparticles and the formation of stereo complementation-specific recognition sites for ibuprofen molecules. Combining the benefits of imprinting and nanocomposite materials, the developed membranes exhibited enhanced adsorption characteristics and showed promising potential for selective removal and separation of ibuprofen from aqueous solutions.

Limited research has been conducted on the adsorption of ibuprofen using various nanoparticles, including zinc oxide nanoparticles (Ulfa and Iswanti 2020), zinc sulfide nanoparticles (Ulfa et al. 2019a, b), iron oxide@silver nanoparticles (Vicente-Martínez et al. 2020), iron nanoparticles (Yin et al. 2018), graphitic carbon nitride/soot nanocomposites (Liao et al. 2018), and titanium dioxide nanocomposites (Lin et al. 2019). For example, Lin et al. (2019) demonstrated that combining titanium dioxide nanofibers with boron nitride increased ibuprofen adsorption capacity by 14 mg/g. The synergistic effect of the nanocomposite also improved its photocatalytic behavior towards ibuprofen. In another study, Yin et al. (2018) achieved an ibuprofen adsorption capacity of 3.5 mg/g using recycled rusted iron nanoparticles, which was 4.8 times higher than that of α-FeOOH. These studies highlight the potential of different nanoparticles for the adsorptive removal of ibuprofen, offering opportunities for further exploration and optimization of these nanomaterials in wastewater treatment applications.

Adsorption kinetic study

Kinetics study is an essential index to explore adsorbent applicability. The adsorption process can involve three different stages: (i) external diffusion or film diffusion, in which the adsorbate diffuses to the adsorbent structure; (ii) surface or inner pore diffusion, containing the diffusion into the adsorbent through the pores; and (iii) interaction of adsorbate and adsorbent and increasing adsorbate concentration on the adsorbent surface (Eizi et al. 2023). The interaction stage is usually fast, so the first two stages mainly control the adsorption rate (Pakade et al. 2019).

The kinetics of ibuprofen adsorption have been extensively studied using various models, including the pseudo-first order, pseudo-second order, Elovich, and intraparticle diffusion models. The results of these studies are summarized in Tables 1, 2, 3, 4, 5, and 6. The pseudo-second-order model was the dominant kinetic model of ibuprofen adsorption, demonstrating that it is mainly controlled by chemical adsorption. Indeed, active functional groups on adsorbent surfaces provide chemical interactions that are less reversible than physical adsorption (Gupta and Bhattacharyya 2011). Therefore, the chemisorption that the pseudo-second-order kinetics model claims can be attributed to functional groups in most adsorbents. In some cases, such as cherry kernel-derived activated carbon (Pap et al. 2021), wood chip-derived biochar (Essandoh et al. 2015), and polypyrrole-modified carboxymethyl cellulose (Kumar et al. 2022), the adsorption kinetic followed the Elovich model.

Adsorption isotherm studies

Adsorption isotherms play a crucial role in characterizing the equilibrium performance of adsorbents under constant temperature conditions. These isotherms are influenced by several factors, including the properties of the adsorbate species, the characteristics of the adsorbent materials, and the conditions of the adsorption process, such as solution pH, temperature, and ionic strength (Al-Ghouti and Da'ana 2020). The great significance of adsorption isotherms is attributed to designing porous solids and industrial adsorption processes. It has often been studied in the adsorption of ibuprofen onto different adsorbents, as summarized in Tables 1, 2, 3, 4, 5, and 6. The Freundlich and Langmuir adsorption isotherm models were the most common, whereas the Sips and Langmuir–Freundlich models were infrequent. As seen, the data most frequently fit the Langmuir model during the modeling of ibuprofen adsorption isotherms, suggesting that the ibuprofen molecules occupied homogeneous sites on the surfaces of different adsorbents, resulting in the subsequent formation of an ibuprofen monolayer (Tabrizi et al. 2022). Restricted ibuprofen adsorption onto some adsorbents, such as octadecylamine-modified mica (Martín et al. 2019), *Quercus brantii* (Oak) acorn-derived activated carbon (Nourmoradi et al. 2018), holm oak -derived activated carbon (Delgado-Moreno et al. 2021), showed the multilayer adsorption of ibuprofen molecules on heterogeneous sites.

The Sips model is the most often used three-parametric studied isotherm for the monolayer adsorption of ibuprofen. A combination of the Langmuir and Freundlich models can describe heterogeneous systems and is valid for localized adsorption without adsorbate–adsorbate interactions. For example, in one study, the adsorption of different pharmaceutical compounds onto acid-modified biochar followed the Sips model (Choudhary and Philip 2022). Sips model is a hybrid model combining Langmuir and Freundlich models, which can describe homogeneous or heterogeneous systems (Amrhar et al. 2021). The value of the Sips exponent, namely β, was lower than 1, showing the heterogenous surface of this adsorbent with multiple active sites that can assist in drug adsorption. The separation factor, namely R_L, for ibuprofen adsorption was calculated in the range of 0.57–0.40, less than unity, indicating a high degree of heterogeneity and favorable adsorption. Furthermore, the Sips model was the best isotherm representing experimental equilibrium data for ibuprofen and ketoprofen adsorption onto sonicated activated carbon (Fröhlich et al. 2018a). Other isotherms also modeled ibuprofen adsorption, such as the Guggenheim-Anderson-de Boer model for the adsorption of ibuprofen onto activated carbon derived from peach stones and rice husk (Álvarez-Torrellas et al. 2016), the Redlich-Peterson model for the adsorption of ibuprofen onto babassu coconut husk-derived activated carbon (Fröhlich et al. 2018b) and mono-tosyl b-cyclodextrin-functionalized Cloisite 15A (Rafati et al. 2018), and the Hill model for ibuprofen adsorption onto organo-silica nanosheets with gemini (Zeng et al. 2018).

Reusability of ibuprofen adsorbents

The reusability of adsorbents is a crucial economic aspect that can significantly impact the overall cost of the adsorption process. It reduces the expense of preparing new adsorbents and minimizes the need for proper waste management and disposal of used sorbents, thereby mitigating potential environmental concerns (Tanhaei et al. 2020, 2019). Many studies have reported that most adsorbents used for ibuprofen removal can be effectively regenerated and reused through simple treatment with dilute acids or alkaline solutions. These regeneration methods aim to desorb the adsorbed ibuprofen molecules from the adsorbent surface, allowing the adsorbent to regain its adsorption capacity. The adsorbent nature, surface functional groups, bonding interaction, and adsorption mechanism are key factors affecting the selection of an appropriate desorbing agent (Pakade et al. 2019). Distilled water, hydrochloric acid, sodium hydroxide, sodium bicarbonate, nitric acid, and sodium carbonate are some of the most common desorbing agents, but sodium hydroxide is the most popular. For example, porous graphene, genipin-crosslinked chitosan/graphene oxide-SO_3H composite (Liu et al. 2019), and modified multi-walled carbon nanotubes (Hanbali et al. 2020) have been efficiently regenerated using dilute sodium hydroxide. In another study, acetaldehyde showed the highest percentage of desorption, about 95.34%, in acid-modified activated carbon when compared to sodium hydroxide, hydrochloric acid, and acetic acid, and ibuprofen adsorption remained high without significant variation, with about 3% decrease, after four cycles (Bello et al. 2020a).

Sodium hydroxide is a favorable desorption agent for removing ibuprofen on different activated carbon materials. Studies have shown that sodium hydroxide exhibits higher desorption efficiency than distilled water (Álvarez-Torrellas et al. 2016). Acetone has also successfully regenerated ibuprofen from hydrochar (Yudha et al. 2019) and metal–organic framework-derived porous carbon (Bhadra et al. 2017). Acetone as a desorption agent has shown promising results in these studies. Hydrogen peroxide at pH 3 has regenerated magnetic activated carbon, demonstrating its effectiveness in desorbing ibuprofen (Vargues et al. 2021). In the case of metal–organic framework-derived mesoporous carbon, a sodium hydroxide/methanol solution has been utilized as a "green and available" eluent for the regeneration process (Van Tran et al. 2019b).

Lung et al. (2021) showed that eluent volume does not affect the desorption and regeneration degree of carbon nanotubes-COOH/manganese dioxide/magnetite, except for hydrochloric acid, where the ibuprofen desorption degree increased with increasing eluent volume. In their study, hydrochloric acid, ethylenediaminetetraacetic acid, and ethanol exhibited the highest desorption efficiencies, whereas sulfuric acid and sodium hydroxide had the lowest ibuprofen desorption, less than 20%. Regeneration of the adsorbent with 0.1 M hydrochloric acid showed no significant decrease in ibuprofen uptake after five cycles. Methanol stripping was an effective desorption process for the reuse of biochars (Essandoh et al. 2015; Reza et al. 2014; Show et al. 2022a). Methanol desorbed 81% and 74% of ibuprofen from biochar derived from wood apple and its steam-activated analog, respectively (Chakraborty et al. 2018a).

Perspective

The extensive use of ibuprofen and its potential health risks to the aquatic environment necessitate further research on its removal from aqueous solutions. Despite the significant progress made in the study of ibuprofen adsorption, several knowledge gaps still need to be addressed in this field. One crucial concern is the systematic investigation of ibuprofen removal from real or simulated wastewater. While numerous studies have been conducted, only a few have focused explicitly on real wastewater samples. It is crucial to consider variables such as the actual concentration range of ibuprofen, pH levels, presence of competitive pollutants, and temperature conditions that mimic real wastewater scenarios. Furthermore, most studies have been conducted on a laboratory scale, and the efficacy of these sorbents in real-world industrial-scale applications remains uncertain. The applicability of these sorbents in treating real samples, such as industrial and hospital wastewater, as well as groundwater, where higher concentrations of ibuprofen are expected, needs to be better understood.

The inability of some adsorbents to be reused poses a challenge regarding their sustainability and cost-effectiveness. Furthermore, there is a limited focus on dynamic adsorption systems in the existing literature. Therefore, it is essential to assess the capability of adsorbents to remove ibuprofen in dynamic adsorption systems, such as at the point of use, to evaluate their practical applicability. Substantial research is needed to develop low-cost, high-performance adsorbents that remove ibuprofen in wastewater treatment plants. This can open up opportunities for their application in domestic water filters and residential settings.

Additionally, the cost analysis of the adsorption process should be considered, as it is an essential factor that has often been neglected in previous investigations. Future research should also address disposing of spent adsorbents after prolonged use, focusing on environmentally sustainable and friendly techniques. Moreover, combining mechanical or biological treatment methods with adsorption systems should be studied to enhance the overall removal performance of ibuprofen in wastewater treatment processes. By addressing these areas of concern, advancements can be made in developing and applying effective and sustainable ibuprofen removal technologies.

Conclusion

The presence of ibuprofen in wastewater has recently emerged as a significant environmental and human health concern. Among the various methods employed to remove ibuprofen, adsorption has gained significant attention, particularly in the past five years. The review has demonstrated that functionalized or modified adsorbents perform superior to pristine materials for removing ibuprofen. Various strategies, such as grafting, crosslinking, and material combinations, have been employed to enhance the adsorption capacity of these materials. The review highlighted that activated carbons and biochar are the most widely studied materials for ibuprofen removal, while metal–organic framework structures have also shown promising performance. The adsorption process was found to be influenced by the solution pH, with higher adsorption typically observed under acidic conditions, i.e., pH 3. The dominant mechanisms involved in ibuprofen adsorption were electrostatic and π-π interactions and hydrogen bonding. However, despite the progress made in understanding ibuprofen adsorption, this field is still evolving, and several aspects require continuous investigation and improvement. Essential factors such as cost, safety, and compatibility with industrial conditions must be thoroughly examined to ensure the practical applicability of these adsorbents. Further research is necessary to address these gaps and advance the development of efficient and cost-effective adsorbents for ibuprofen removal.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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