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REVIEW PAPER

Applications and Contemporary Issues with Adsorption for Water Monitoring and Remediation: A Facile Review

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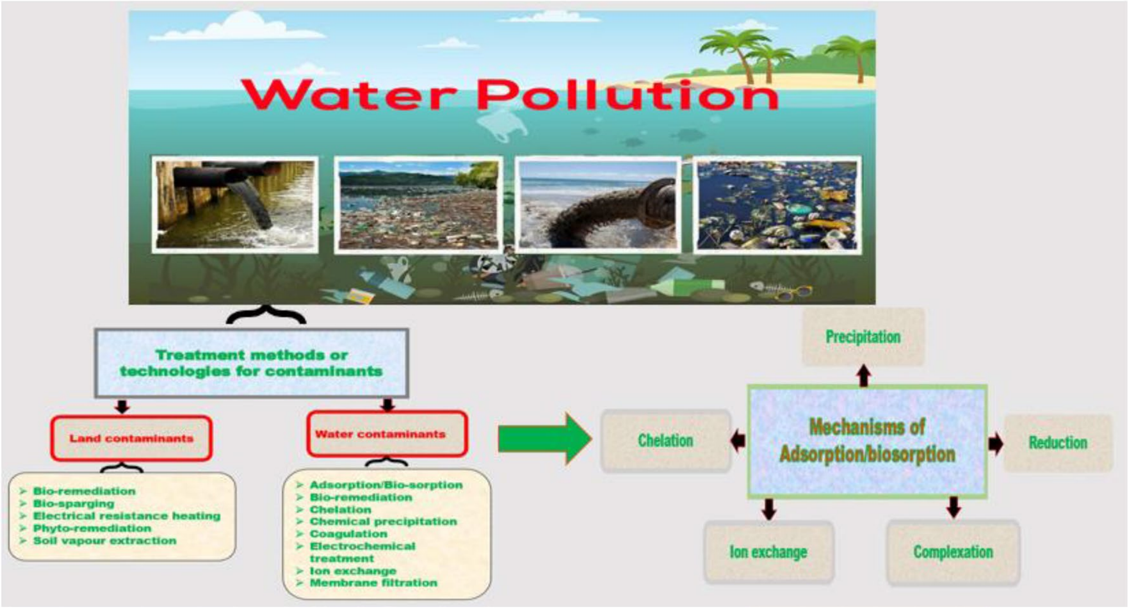
Abstract

Water is necessary for agriculture, industry, and human consumption. Reportedly, freshwater resources are scarce, and it is obvious that industrial and agricultural activities can contaminate water. Consequently, there is a need to continue searching for affordable and environmentally friendly technologies for treating water. Adsorption is a method that saves money and has become popular because it allows for the least amount of garbage to be disposed of. Hence, the contemporary situation and the primary challenges with adsorption as one of the utmost technologies for water monitoring and remediation are briefly discussed in this review article. A number of significant topics that have been extensively covered in the literature, such as adsorbent materials, adsorption operation mode, modelling, regeneration process, and operation procedure using actual samples, are all highlighted in this paper. Conclusively, the paper also outlined what directions, in the form of future prospects, will probably serve as the next steps needed to advance new perspectives and original research in the application of adsorption techniques for treating water vis-à-vis innovative techniques for water monitoring and remediation.

Graphical Abstract



Keywords Adsorption · Agricultural activities · Industrial activities · Wastewater · Technologies

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1 Introduction

Life depends on water, and there is a finite supply of freshwater on earth [1, 2]. According to the World Health Organization [3], about 50% of the world's population is anticipated to reside in water-harassed regions by 2025. Water is necessary for human consumption, but freshwater resources are scarce. Water is necessary for agriculture, industry, and human consumption. It is obvious that industrial and agricultural activities can contaminate water [4, 5]. According to the literature, a variety of contaminants, such as heavy metals (HMs) [6, 7], dyes [8–10], pesticides [11], pharmaceuticals [12–15], personal care products [16], hormones [1], viruses [1], radioactive elements [17], and phenol-derived chemicals [1], can be found in industrial wastewaters, groundwater, and surface water [1]. It is well established in the literature that the presence of these compounds in waters and wastewaters poses a threat to the ecosystem and the general welfare [18–23]. In reality, it is our responsibility as scientists and researchers working in the field of environmental science to create the tools, materials, techniques, and technologies needed to manage, purify, and reuse water.

Globally, the viability of water resources and the safety of the environment are now seriously threatened by surface water pollution [24, 25]. Surface water, however, could not be remedied using conventional concentrated treatment methods, such as conventional coagulation and sedimentation for the polluted surface water, due to its abundance and widespread distribution. (e.g., adsorption, extraction, ion exchange, and membrane separation). Additionally, the total nitrogen and total phosphorus concentrations in contaminated surface waters are typically lower than those in raw wastewater, i.e., 10 mg/L and 1.0 mg/L, respectively. As a result, it may not be practical or cost-effective to use the same treatment methods and machinery used to treat domestic or commercial wastewater [26]. In order to stop the degradation of surface water quality (such as eutrophication) and maintain a healthy aquatic ecosystem, it is essential to develop novel remediation technologies.

Nowadays, water contamination is a worldwide problem that affects the majority of nations. Monitoring water quality is necessary so that officials are made aware of water pollution and can take swift action [27–29]. Thus, a method for monitoring water quality is thought to be the best way to offer early evaluations of contaminants in water. More research is required to determine the advantages and disadvantages of the different traditional and contemporary approaches to water quality monitoring and remediation techniques. The approaches include cyber-physical systems, virtual sensing, optical techniques, artificial intelligence, the Internet of Things (IoT), micro- and nanorobots and other innovative smart systems [28–37]. Thus, a method for monitoring water quality is thought to be the best way to offer early evaluations of contaminants in water [27, 38]. Government, non-public sectors, and society all need to treat water pollution as a significant problem. A reliable system for continuously monitoring water quality in real-time is necessary to help officials decide on the best course of action and to produce useful output data. Thus, there is a need to look into earlier water quality monitoring techniques, contrast traditional and contemporary techniques, and examine various techniques from different nations.

The cyber-physical system is a device that seamlessly integrates physical elements into a computational algorithm. The future of embedded computers is cyber-physical system. Contrary to embedded systems, a full-fledged cyber-physical system is typically designed as a network of cooperating components with physical input and output rather than as stand-alone devices. In the end, cyber-physical system provides more advantages because it manages the intricacy of data points produced by numerous sensor nodes, also referred to as sensor arrays, by using a user-friendly decision support system such as fuzzy logic [39]. Lee [40] asserts that Wiener, who created the technology for aiming and launching anti-aircraft guns during World War II, was the one who created the cyber-physical system. IoT, Industrial 4.0, the Industrial Internet, and machine-to-machine communications are just a few of the modern technologies that make up cyber-physical system. Cyber-physical system can be used for a variety of purposes, including healthcare applications where the system gives patients real-time access to medical experts and services [41]. To create effective working and living conditions, cyber-physical system can also be used in big commercial and residential structures [41]. The four components of cyber-physical system for water sustainability—sensing and instrumentation, communications and networking, computing, and control—have been addressed by Wang [42] along with the opportunities and difficulties they present. Imen and Chang [43] conducted additional research on the cyber-physical system for water sustainability and developed a five-level architecture for the cyber-physical system to manage drinking water infrastructure in a smart and sustainable manner. These levels include smart connection level, data-to-information connection level, cyber level, cognition level, and configuration level. A water quality monitoring device using CPS, which included sensing and computing tools for computational modelling, was developed by Bhardwaj et al. [39]. However, a systematic review by Zainurin et al. [27], describes in detail the improvements in water quality monitoring based on different sensing techniques.

As reported by Wang et al. Wang et al. [44], physical, chemical, and ecological techniques have all been studied

Table 1 Key methods for remediating surface water

Remediation procedure	Procedure principle	Characteristics
Physical technique		
Artificial aeration	Increase the amount of dissolved oxygen in the water body, lower the quantity of dissolved pollutants in the water, and enhance the aquatic creatures' living conditions	High expense, requires combining with other techniques
Sediment dredging	Dredging the entire or a portion of the river with significant deposition to restore the river's usual flow	large-scale mechanical changes that affect current biosystems
Removal of algal mechanically	Utilizing an ultrasonic pulse (wave) to cause an algal cell to burst, shatter, lose its ability to float, and precipitate inside an airbag	Non-sustainable technique
Chemical technique		
Chemical precipitation	Controlling eutrophication by adding iron or aluminium salts results in chemical formation of inorganic phosphate through adsorption or flocculation	
Enhanced coagulation	Decontamination is accomplished through adsorption, chemical precipitation, destabilization flocculation, and adsorption bridging after adding the proper coagulant	The use of chemicals increases costs and causes additional pollution
Acid–alkali neutralization	To balance the pH, satisfy increasing demand, and promote species reproduction in the aquatic ecosystem, substances that are either acidic or alkaline are added to the water body	
Removal of algal mechanically chemically	The result is impressive when you use a chemical algal removal product	damage to the water table, high danger
Ecological method		
Constructed wetlands	uses components from natural wetlands to create artificial wetlands that are similar to the real thing	Bulky floor space
Ecological floating bed	Plants are planted in water employing the principle of the soilless cultivation, and they take nutrients straight from the water	Usually utilized to restore small lakes and rivers
Ecological revetment	River revetment has been artificially altered to fortify or restore its ecological ability, which can safeguard the riverbank and decontaminate the water	Appropriate for the long-term environmental remediation procedure

in recent years to remove contaminants from surface waterways (see Table 1 as adapted from Wang et al. [44],). Surface water pollution can be briefly reduced through physical methods such as dredging sediment, mechanical algal removal, aeration, and water diversion, but these effects are transient [45, 46]. The redox potential and pH of surface water must be changed by chemical agents and adsorbents in order for suspended particles and organic matter to be adsorbed and precipitated [47]. Water pollutants will be separated and recovered by agents and pollutants, or they will be changed into harmless compounds. Although the chemical technique works quickly, it requires the addition of numerous expensive chemical agents that are also likely to result in secondary pollution. (e.g., chemical sludge). Additionally, the sewage treatment plants must treat the produced chemical sludge, which adds a significant quantity of additional work and complicates the operation of sewage treatment plants [44].

Ecological remediation is a recent innovative in-situ remediation technique that uses microbes and plants to jointly remove pollutants from the atmosphere [48–51]. Utilizing the metabolic processes of plants and microbes to ingest, assemble, or degrade environmental pollutants is the primary method of in-situ ecological remediation. When compared to other remediation methods, in-situ ecological remediation has a number of benefits, including cheap costs, fewer negative environmental effects, and no secondary pollution production [44]. For the bioremediation of contaminated surface water, numerous in-situ remediation processes, including ecological floating bed techniques and constructed wetlands, have been devised and have shown satisfactory results [48, 50].

An innovative technique for water remediation known as ecological floating beds is based on the conventional constructed wetland, which is characterized by the predominance of terrestrial or aquatic plant growth on the surface of a body of water [44]. Plants absorb pollutants from the water during their development phase and offer attachment sites for microorganisms to grow through their developed plant roots as an essential part of the ecological floating bed [44]. Using water spinach and sticky rice, Sun et al. [52] examined the viability of ecological floating-bed systems for remediation and discovered that the rates of total nitrogen elimination were 92.3% and 81.2%, respectively. In the meantime, adding the right carrier to the ecological floating bed can encourage plant development and enhance their capacity to withstand contamination stress. Green zeolite was found to be the finest substrate for Acorus calamus L. to uptake metals, and removal efficiencies of Cr and Cd were up to 95.24% and 91.8%, respectively, in research using the plant Acorus calamus L. in the ecological floating bed [53].

As reported by Wang et al. [44], the integrated remediation in rural river network area (RRNA) project, sponsored by the China's Ministry of Science and Technology, has been started to achieve the integrated remediation of surface/groundwater and soil in the rural river network area (see Fig. 1 as adapted from Wang et al. [44]). Three Chinese institutions (Tongji University, Central South University, and Donghua University) are partners in the 38-months (that is from 2019 to 2022) integrated remediation in RRNA study. Accordingly, the integrated remediation in RRNA will concentrate on developing key technologies for surface water, underground water, and soil environmental remediation in rural river network areas; implementing the integration of remediation technologies for surface/groundwater and soil in rural river network areas; and applying interdisciplinary and methodological knowledge to clarify the transportation and transformation of pollutants in water and soil during surface/groundwater interaction [44].

As recently reported by Urso et al. [38], micro- and nanorobots are designed to expedite and enhance the water purification process (remediation). The adsorption of heavy metals and soluble organic contaminants at the solid–liquid interface is improved by the mutual interaction between their active motion and material characteristics [38]. However, details on smart micro- and nanorobots for water remediation (purification) are contained a recent study by Urso et al. [38].

Water treatment uses a variety of technologies (see Fig. 2), each with benefits and disadvantages [1]. However, the emphasis in this present review work is on adsorption. A method of contaminant removal known as "adsorption or biosorption" involves the passive binding of contaminants such as HMs and/or dye ions into non-living biomass (biosorbents). The method is similar to bioaccumulation, where pollutants are actively metabolized by living things [54]. It

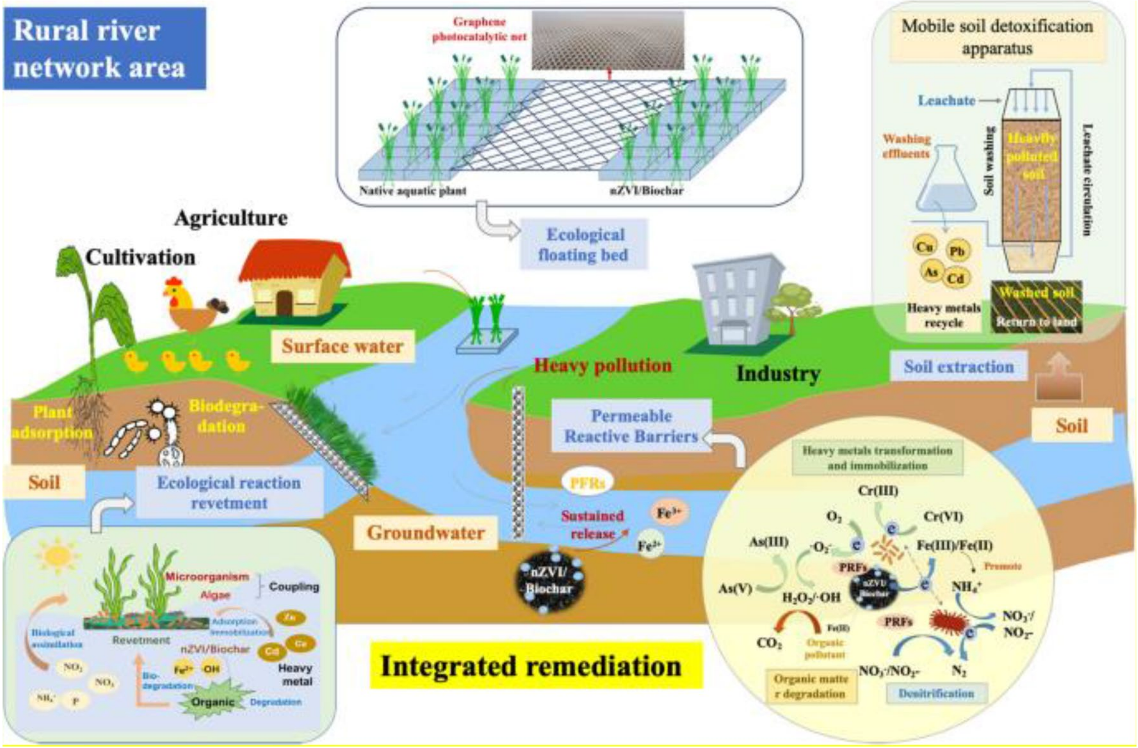

Fig. 1 System for integrated remediation in RRNA for contamination surface water/groundwater and soil

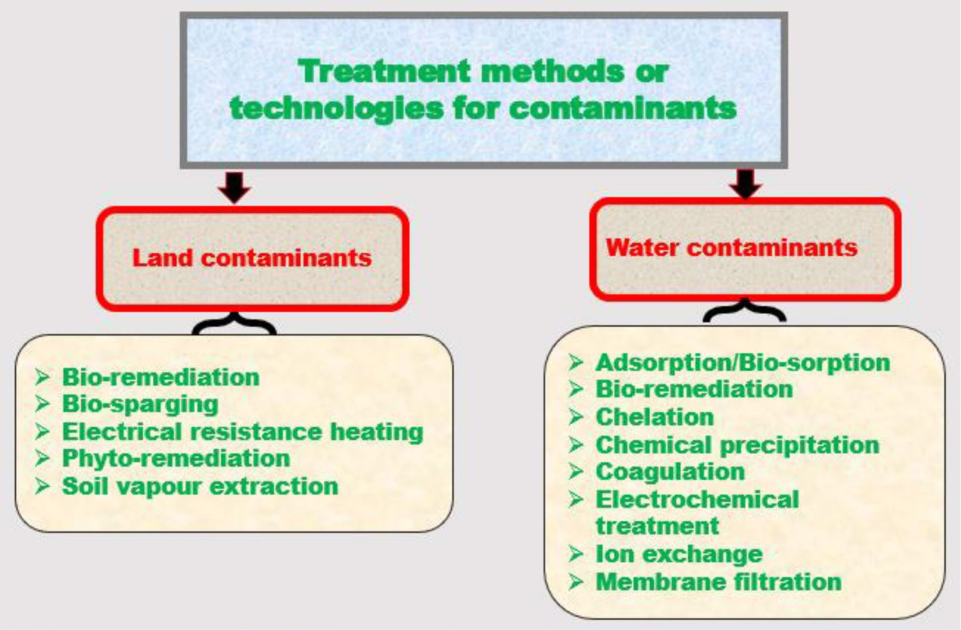

Fig. 2 Treatment methods or technologies for contaminants in water and land

involves the removal of contaminants ions after their binding to both living and non-living biomass. The rate of biosorption is affected by a number of variables, including the size and type of the bio-sorbent, ionic strength, biomass dose, temperature, initial pH, and solvent concentration [55]. A fluid (in this instance, water) and a solid phase are involved in the unit operation of adsorption/bio-sorption (the adsorbent). One or more dissolved contaminants are found in the fluid phase (the adsorbate). Water is purified as the dissolved pollutants are moved from the liquid phase to the adsorbent surface [56–58].

The active binding sites employed, the protein structure, and the functional groups of biosorbents are the variables that affect the solubility of contaminants in solutions. Techniques like surface complexation, chelation, ion exchange, and biologic adsorption are used in the biosorption process to remove trace metals (or HMs) and dyes from contaminated surroundings. Additionally, biosorption is influenced by the environment in which pollutants are present and the particular microbial cell metabolism process in use [2]. Due to the high efficiency of the technique, the capacity to reuse biosorbents, the environmentally friendly nature of the technique, and the capacity to recover the pollutants with little secondary waste, the biosorption of HMs and dyes, especially from polluted water, is widely acknowledged to be effective [55]. Microbial cells, either dead or alive, like those of fungi, algae, and bacteria, are examples of prevalent biosorbents. The cell walls of the microbial biosorbents contain functional groups like carbonyl, hydroxyl, carboxyl, and amino moieties that interact with the pollutants' ions to remove them from contaminated solutions [59]. Toxic trace metals (or HMs) and dyes can be removed by extracellular accumulation and precipitation or by precipitation on the cell membrane, depending on where the pollutant is located. Figure 3 summarizes the biosorption mechanisms based on the configuration of sorbed pollutants and the presence or lack of metabolic activity.

Adsorption is presently used to treat water because it has a number of benefits, including low cost, high efficiency, simplicity in use, the ability to use a variety of solids as

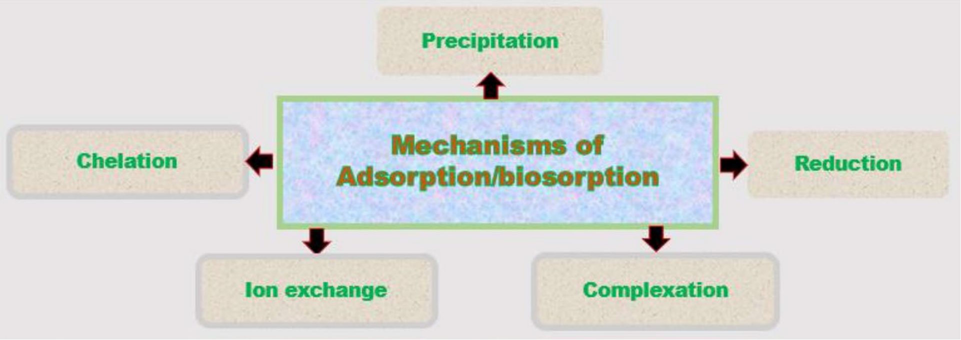

Fig. 3 Mechanisms of adsorption

adsorbent materials, and the ability to recover both the adsorbent and the adsorbate [1, 21, 60].

The competitive and effective nature of adsorption as a polishing process must be emphasized when contaminants are present in water at concentrations between ng L^{-1} and mg L^{-1} [1, 21]. There are many inexpensive materials that can be used as adsorbents to remove pollutants from contaminated land and water. They can be categorized as follows:

- Agricultural waste-based biosorbents
- Industrial waste-based biosorbents
- Natural/organic biosorbents
- Microbial-based biomass biosorbents

According to the literature in the last few years, the selection, development, and characterization of the adsorbent material; the development and optimization of the adsorption mode; the mathematical modelling; the choice and development of the regeneration process; and the application in actual samples are the crucial aspects of being evaluated to apply adsorption for water treatment. Also, the cost analysis (evaluation) is evidently crucial. Cost, however, is a factor in each of the aforementioned aspects and must be taken into account individually. To give you an idea, the costs for most technologies to treat water vary from 10 to 450 US dollars per m^3 of treated water, while those for adsorption are 5.0–200 US dollars per m^3 [1, 21]. The filter is responsible for about 70% of these expenses [61]. Hence, the short review will attempt to briefly discuss all of the aforementioned aspects of adsorption for water treatment. Also, some the major challenges as well as the prospects with adsorption for treating water are highlighted. The implication and rationale for consideration of this present review work is that it will serve as a quick guide to the literature, which will encourage new perspectives and original research in the application of adsorption techniques for treating water vis-à-vis innovative techniques for water monitoring and remediation.

2 Adsorbent/Bio-sorbent Materials

Key considerations in the characterization of an adsorption method for the treatment of water include the selection, development, and characterization of the adsorbent material sources [1, 21]. The following features are necessary for an appropriate absorbent for water treatment sources [1]:

2.1 Cost Effectiveness and Availability

Since the adsorbent accounts for 70% of the operating expenses, a significant quantity of the adsorbent material must be quickly produced or bought and transported to the treatment facilities.

2.2 Stability of the Chemical

This is necessary because various water matrices have different chemical properties (conductivity, pH, strength of the ions, etc.), which can affect the adsorbent.

2.3 Mechanical Stability

Since constant water treatment is carried out in columns, the adsorbent also needs to be stable mechanically to prevent high-pressure drops and preferred pathways.

2.4 Decent Textural and Physicochemical Features

A good adsorbent should have a high surface area, a large pore volume, and functional groups on the surface that can interact with pollutants. It should also have good textural and physicochemical properties. The following three points are impacted by these important traits.

2.5 High Adsorption Capacity

This is required because there must be a high pollutant absorption rate per gram of adsorbent. This reduces the amount of adsorbent needed for the therapy, facilitates phase separation following adsorption, and reduces the amount of physical space needed for the procedure.

2.6 High Efficiency

In accordance with the specific rules, a high percentage of contaminants that are removed from the water and transferred to the adsorbent should be achieved.

2.7 Quick Kinetics

The properties of the adsorbent should enable rapid attainment of high adsorption capacity and effectiveness. As a result, the total treatment time is brief, which has an impact on the treatment plant's size and capital expense.

2.8 Regeneration and Reuse Potential

The adsorbent should, if at all possible, be easily regenerated and used more than once to cut down on operational expenses.

Naturally, it is challenging to create an adsorbent with all of the aforementioned qualities. In this regard, various studies have been conducted to create a number of adsorbents for the treatment of water. For the adsorption-based method of treating water, carbon-derived materials such as chars, biochar, activated carbons, coals, and nanomaterials (NMs) have been created [62–64]. Chitin and chitosan-derived materials are a different class of adsorbents for the treatment of water [1, 65, 66]. Additionally, biosorbents and agro-industrial pollutants are receiving more attention [67, 68]. The inorganic-based materials are a different family that includes zeolites, layered double hydroxides, and geopolymers [69, 70]. Metal–organic frameworks were created with the intention of removing impurities from water [71].

Additionally, silica-based substances are used as adsorbents for the purification of water [1]. The literature is extensive in terms of preparation methodologies and sophisticated characterization techniques for the bulk of these adsorbent materials. In general, we can state that there are a number of suitable, well-developed, and characterized materials for adsorbents for water treatment. There is no question, however, that in order to achieve all of the aforementioned qualities and create more effective adsorption processes for the treatment of water, it is essential to continuously develop novel adsorbent materials sources [1, 21].

3 The Mode of Operation of Adsorption

The mode of operation of adsorption is crucial because it directly impacts the costs of water treatment, the amount of treated water produced, the amount of space needed for the equipment at the treatment plant, and the length of time needed to decontaminate the water sources [1, 21, 72]. Without a doubt, the primary method for treating water described in the publication (batch adsorbers) is discontinuous batch adsorption [1, 21, 73]. In this method of operation, the adsorbent is inserted into a tank filled with contaminated water. The mixture is stirred until it reaches equilibrium, or a capacity that is very near equilibrium. After that, decantation, filtering, or centrifugation are used to separate the solid from the liquid. This is a liquid phase (purified water) and a solid phase (the adsorbent filled with the contaminant) at the conclusion of the process [1, 21]. This method of operation is helpful for optimizing adsorption parameters like adsorbent dosage, concentration of the contaminant, time of contact, time of equilibrium, pH, and others at the laboratory scale [1, 2, 21]. Large volumes of water, on the other hand, necessitate more physical space and extra unit operations for solid–liquid separation, so it is ineffective for the treatment of large volumes of water sources [1]. The primary large-scale treatment application, fixed-bed operation mode, is only ostensibly recorded in the literature [1, 2, 21]. In this instance, the contaminated water is poured into a column that contains the adsorbent. The process continues until the column achieves saturation, where the concentrations of contaminants at the inlet and outlet are equal. Throughout the trial, the contaminant concentration at the column outlet is tracked. With the help of these statistics, the breakthrough curve can be built, allowing the adsorption process to be scaled up [1, 2, 21, 74]. Variables like bed height and flow rate can be assessed through this method of operation [1, 75]. Fixed-bed operation eliminates the need for extra separation processes and enables the treatment of large water volumes in constrained physical spaces. However, fluid-particle interaction does not always work well. Hydro-dynamic restrictions, such as the development of preferential pathways and high-pressure drops, can affect this working mode [1].

In the background of mode of operation of adsorption, we can state that batch adsorbers should be used on a laboratory scale to optimize the experimental adsorption conditions because they are well documented in the literature. In contrast to batch adsorption, operations in a fixed bed are not extensively studied at the laboratory scale, though their design and efficiency are. Evidently, the commercial scale-up of water treatment procedures can be accomplished through fixed-bed operations. The primary issue at hand is the creation and design of alternative operating modes that enable easier phase separation and more effective fluid-particle contact. As a result, we can benefit from factors such as a smaller physical area needed for the treatment, quicker processing periods, the ability to treat larger volumes of water, and lower costs. Studies involving fluidized beds, spouted beds, simulated moving beds, continuous stirred tank reactors, and multi-batch adsorption reactors are encouraged as possible alternatives sources [1, 21].

4 Modelling of the Adsorption Process

The literature has extensively examined the modelling of the adsorption process for the treatment of water. The study of isotherms, kinetics and thermodynamics is frequently used to clarify a defined adsorption process [76–78]. Additionally, mathematical tools such artificial neural networks (ANN), GAMS, fuzzy and neuro-fuzzy networks, and response surface methodology (RSM) can be used to improve the operational parameters [77, 79]. The isotherm curves depict a relationship between the amount of contaminant adsorbed in the adsorbent and the amount of contaminant remaining in the water under thermodynamic equilibrium circumstances [1]. All adsorption systems depend on these curves. Freundlich, Henry, Langmuir, Redlich-Peterson, Sips, Tóth, and other isotherm models are normally used to describe isothermal curves [80].

Additionally, other theories and statistical physics-based models are being created in this regard [81–83]. Although the literature contains all of this information, most of it only pertains to particular systems. The thermodynamic equilibrium constant is typically estimated from the isotherm parameters obtained at various temperatures, which is then used to compute the Gibbs free energy change [84]. The Van't Hoff plot is then utilized to determine the enthalpy and entropy changes [84]. Despite being widely used in the literature, this method's validity was questioned by some writers because of its shaky thermodynamic foundation [1, 85]. Specifically, the difficulties here pertain to the development of isotherm models for multicomponent systems and methods for precisely estimating the thermodynamic parameters.

Also, kinetic studies are essential for adsorption in water purification. Plots of adsorption capacity versus time or contaminant content versus time can be used to depict kinetic curves in batch systems. The representation in the case of a fixed-bed can be carried out using either dimensionless contaminant concentration at the column output versus time or dimensionless contaminant concentration at the column outlet versus bed volumes [86]. The adsorption rates are effectively modelled by a number of empirical and semiempirical models [6]. For batch adsorption, it can be referenced in pseudo-first order, pseudo-second order, general order, Avrami and Elovich [1], Bangham [6], and for fixed-bed systems (Adams-Bohart, Clark, Thomas, and Yoon-Nelson) [87]. These models are straightforward mathematically, but they are only useful for a limited variety of experiments [6].

The majority of the models mentioned above are unable to estimate basic mass transport parameters, which hinders scale-up. Diffusional mass transfer models, such as the external mass transfer model, uniform surface diffusion model, surface diffusion model, pore volume diffusion model, and pore volume and surface diffusion model, are also helpful in this regard and well-documented in the literature [88–90]. These models are more difficult mathematically, but they can estimate the mass transport properties by taking into consideration the mass transport steps that take place during the adsorption process. Scale-up is therefore feasible [91]. The estimation of mass transfer factors affects the resolution of diffusional models (effective pore diffusion coefficient, external mass transfer coefficient, and surface diffusion coefficient) [1].

There haven't been any fundamentally based correlations to determine the surface diffusion coefficient up until now in the literature. For single systems, diffusional and empirical models are both well established, but there is not enough data to model multicomponent systems. The formation and use of diffusional models for multicomponent systems and the formation of correlations to estimate the surface diffusion coefficient present intriguing challenges in adsorption kinetics for water treatment. The adsorption behaviour for water treatment is also studied using mathematical methods, such as ANN, RSM, fuzzy, and neuro-fuzzy [77, 79]. RSM is used to plan and optimize experiments with the goal of locating an area of interest or the best operating conditions [1]. ANNs are layered algorithms that draw their inspiration from the way the human brain functions. These mathematical tools, which are dependable and strong, can relate nonlinearity between input and output variables from a series of trials [1]. Although fuzzy and neuro-fuzzy neural network models are also based on neural networks, they combine the learning and reasoning effects of ANNs to produce a more accurate outcome [1]. As a result of adjusting a number of input variables, such as contaminant concentration, contact time, temperature, stirring rate, adsorbent dosage, pH, and adsorbent characteristics (surface area, type, point of zero charge), it is possible to optimize a determined response variable (for instance, increasing the adsorption capacity or reducing the contaminant concentration in the liquid phase) (binary component, single component, molecular volume or molecular size). It is believed that these procedures are appropriate for representing multi-component systems where it is challenging to anticipate the interactions as well as variables that are not included in diffusional models (such as pH and specific properties of adsorbate and adsorbent). The difficulties here pertain to any advances in mathematics that can speed up calculations, cut down on the number of experiments needed, and shorten computation time. Studies on mixed models that couple isothermal and kinetic models with RSM, ANN, fuzzy, and neuro-fuzzy neural networks are also encouraged. Consecutive cycles should keep the adsorbent's potential, efficiency, and characteristics, and if at all possible, the adsorbate should be recovered. The renewal of adsorbent materials can be accomplished in a number of ways, including thermal, chemical, and microbiological ones [1].

Chemical reagents, electrical currents, microorganisms or physical waves can all act as regeneration agents. The renewal process can be triggered by leaching or extraction, pH changes, thermal desorption, reaction, or degradation [1]. Although most of these techniques are ineffective for recovering adsorbate, they were effective for regenerating adsorbent. Each of these regeneration techniques, of course, has benefits and disadvantages, and how they are used will rely on the particular adsorption system in question. It is crucial to clarify that regeneration is not always a possibility. For instance, if regeneration produces more waste than the actual adsorption process, if regeneration necessitates more operational effort than adsorption, and if the creation of the adsorbent is simpler than regeneration, therefore, it is preferable to use the refuse treatment techniques of incineration and landfill disposal in these circumstances. The primary issue in this regeneration field is the creation of new, environmentally friendly regeneration methods that reduce waste production, reduce costs, and increase the number of cycles that can be applied to the adsorbent while enabling the recovery of the adsorbate.

This is undoubtedly a significant weak spot in the literature when it comes to the use of adsorption to treat actual water samples. The bulk of aqueous phase adsorption studies are concerned with treating synthetic solutions that only contain one adsorbate and water [92–96]. Two or three adsorbates may occasionally be used [97, 98]. In other situations, effluents with multiple pollutants are used [99, 100]. The remedies, however, are always artificial. The removal of pharmaceuticals and other contaminants of growing concern from complex treated wastewaters has been the subject of several adsorption studies, either alone or in combination with other processes using real or pilot set-ups [1, 101]. These pieces, however, make up a very tiny portion of the literature. The aforementioned factors, including adsorbent substance, operation mode, modelling, and regeneration, are of course crucial in actual water and wastewater treatment systems. Additionally, it is crucial to increase the selectivity of the adsorbents for particular contaminants [1, 21]. In a complicated mixture, this enables the adsorbent to only absorb the desired contaminant. Phase separation following adsorption is a crucial step in effective wastewater remediation.

Depending on the operation mode, decantation, filtration, or centrifugation are necessary for solid–liquid separation. In order to avoid these additional unit operations, there is a progress in the development of magnetic adsorbents, which can be easily separated from the liquid by a simple application of a magnetic field [102–107]. Concerning the application of adsorption to treat real water and wastewater samples, we agree that, initially, studies should be performed in synthetic solutions because the physicochemical and fundamental aspects of adsorption only can be elucidated in controlled conditions. On the other hand, an adsorbent can be excellent in laboratory studies but often inefficient in real cases. Centrifugation, decantation, or filtration may be required for solid–liquid separation, depending on the method of operation. The development of magnetic adsorbents, which can be easily separated from the liquid by a simple application of a magnetic field, has advanced in order to avoid these extra unit operations [102–107]. It is agreed that studies should initially be conducted in synthetic solutions before applying adsorption to actual water and wastewater samples because the physicochemical and basic aspects of adsorption can only be clarified under controlled circumstances. An absorbent, on the other hand, may perform admirably in lab tests but frequently poorly in practical situations. Evidently, adsorption research in laboratory settings is important, and it has been thoroughly recorded and consolidated [1]. However, there aren't many studies that have applications in the actual world. To move forward in this situation, we must first research and perfect adsorption under controlled circumstances before applying it to real-world situations.

5 Regeneration of the Adsorption Process

Adsorption in water purification also relies heavily on the regeneration of the adsorbent and its use with actual water samples [1, 21]. The process's operational expenses and environmental friendliness are directly impacted by the adsorbent regeneration and its repeated use [1, 21]. The characteristics, potential, and efficacy of the adsorbent should be preserved throughout subsequent cycles of the regeneration process, and if at all feasible, the adsorbate must be recovered. The renewal of adsorbent materials can be accomplished in a number of ways, including thermal, chemical, and microbiological ones [1, 21]. Physical impulses, electrical currents, chemical reagents, or microorganisms can all act as regeneration agents. The renewal process may be triggered by leaching or extraction, pH changes, thermal desorption, reaction, or degradation [1, 21].

Although most of these techniques are ineffective for recovering adsorbate, they are effective for regenerating adsorbent. Each of these regeneration techniques has, of course, its benefits and disadvantages, and how they are used will depend on the particular adsorption system in question. It is crucial to clarify that regeneration is not always a possibility. For instance, it is preferable to use the waste treatment techniques of incineration and landfill disposal in situations where regeneration produces more waste than the adsorption process itself, requires more operational work than adsorption, and is simpler to create an adsorbent than regeneration [1, 21].

The primary issue in this regeneration field is the creation of new, environmentally friendly regeneration methods that reduce waste production, reduce costs, and increase the number of cycles that can be applied to the adsorbent while enabling the recovery of the adsorbate. This is undoubtedly a significant weak spot in the literature when it comes to the use of adsorption to treat actual water samples. The bulk of aqueous phase adsorption studies are concerned with treating synthetic solutions that only contain one adsorbate and water [92–95]. Two or three adsorbates may occasionally be used [97, 98]. Other times, effluents with a variety of pollutants are applied [99, 100].

The remedies, however, are always artificial. The removal of pharmaceuticals and other contaminants of growing concern from complex treated wastewaters has been the subject of several adsorption studies, either alone or in combination with other processes using real or pilot set-ups [1, 21, 101]. These pieces, however, make up a very tiny portion of the literature. The aforementioned factors, including adsorbent substance, operation mode, modelling, and regeneration, are

Table 2 analysis of the q_m of some biosorbents/NMs for some selected HMs and dyes in water

Bisorbents	q_m (mg/g)	References
Cr(VI)		
Synthesized triethylenetetramine-pea peels	312.50	[7]
Amine-modified passion fruit peel biosorbent	675.65	[108]
Nano-composites of the functionalized multi-walled carbon nanotubes (MWCNTs)-quartzite nano-composite decorated with the stem bark extract of dacryodes edulis	192.50	[109]
Mango and jackfruit	517.24 and 207.6	[110]
Cu (II)		
Dragon fruit peel, rambutan peel, and passions fruit peel	92.59, 192.31, and 121.95	[111]
Humulus scandens biochars	221.0	[112]
Biochar-NH2	140.85	[56]
Methylene blue dye		
Synthesized sawdust ozone biochar, synthesized sonicated sawdust biochar and synthesized purified sawdust biochar	200.0, 526.3 and 769.23	[8]
Activated carbon from Ulva Lactuca	344.83	[113]
Algae D. Antarctica	702.9	[110]
Activated rice husk biochar	356.99	[114]
Direct blue 106 dye		
Oxidized MWCNTs	500.0	[115]
Acid orange 7 Dye		
Activated biochar gotten from mandarin peels	312.5	[78]
Spherical-shaped nanocarbons	185.18	[116]
Polypyrrole/nanosilica composite	181.40	[117]
Malachite green dye		
Untreated and treated oil palm empty fruit bunch	714.30 and 1250.00	[118]
Activated potassium hydroxide clove leaves	131.58	[58]
Mn-doped CuO-nanoparticles	320.69 and 233.02 for single and binary solutions respectively	[119]

of course crucial in actual water and wastewater treatment systems. Additionally, it is crucial to increase the selectivity of the adsorbents for particular contaminants [1, 21].

In a complicated mixture, this enables the adsorbent to only absorb the desired contaminant. Phase separation following adsorption is another crucial component of effective wastewater remediation. Centrifugation, decantation, or filtration may be required for solid–liquid separation, depending on the method of operation. The development of magnetic adsorbents, which can be easily separated from the liquid by a simple application of a magnetic field, has advanced in order to avoid these extra unit operations [102–107]. We concur that studies should initially be conducted in synthetic solutions before applying adsorption to treat actual water and wastewater samples, owing to the fact that the physicochemical and basic aspects of adsorption can only be clarified under controlled circumstances. An absorbent, on the other hand, may perform admirably in laboratory tests but frequently poorly in practical situations. Undoubtedly, laboratory adsorption studies are important, and they have been thoroughly documented and consolidated. Table 2 contains analysis of the maximum sorption capacity (q_m) of some studies on biosorbents for some selected HMs and dyes in water. However, there aren't many research studies that have practical applications. Here, we must move forward; that is, we must research and improve adsorption under controlled circumstances before using it in actual situations sources [1, 21].

6 Conclusion

The generation and treatment of effluents are an increasing concern today due to increased urbanization and industrialization. To address the problem of rising environmental risks, a variety of effluent treatment techniques, including physical, chemical, and biological (primary to secondary treatment) methods, are used. The potential for producing secondary pollution is increased by the use of various cleaning techniques. The use of different materials as adsorbents is the most efficient way to treat effluents with the least amount of secondary pollution generation. Adsorption is a vital

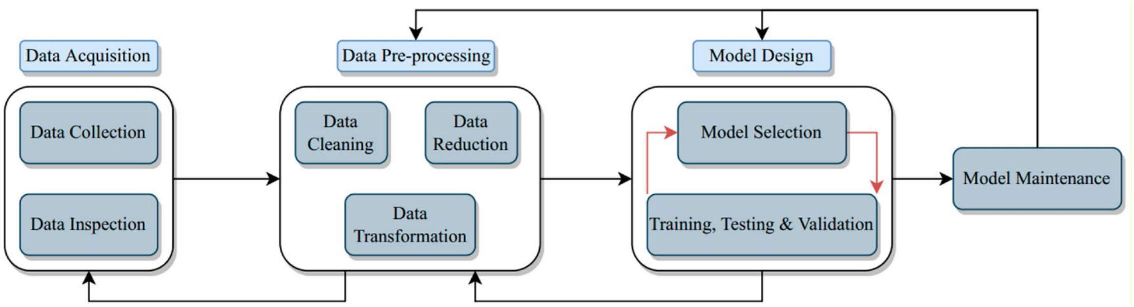

Fig. 4 An outline of virtual sensing development stages

process that is both effective and affordable. This technique primarily employs the adsorption procedure and mechanism to remove toxicants from effluents. Along with any possible techniques of adsorption for water treatment, some of the major challenges as well as the prospects for adsorption for treating water are highlighted. This also makes it clearer how these sorbents can be modified or given special treatment to increase their efficacy.

The significant study gaps and potential directions for future research on adsorption vis-à-vis innovative techniques for water monitoring and remediation are also highlighted in the next section. However, the main goal of this present review study was to explore the issues and potential benefits of adsorption applications for treating water vis-à-vis environmental safety. This study specifically addressed the present situation and the main challenges with the adsorption applications for environmental safety in relation to water purification. As a result, this review serves as a convenient reference for fresh ideas and original studies in the field. Finally, the review suggests what ought to be the subsequent actions required to advance this aspect.

7 Future Insights on Adsorption Vis-à-Vis Innovative Techniques for Water Monitoring and Remediation

Nevertheless, contemporary adsorption technologies are urgently needed to ensure high-quality water, reduce chemical and biological contaminants, and enhance agricultural and industrial production processes for environmental safety [1, 120–122]. Up to this point, the majority of research findings have involved modest laboratory tests. The lack of knowledge about pilot-scale systems is the main weakness of substituting cost-effective adsorbents for activated carbon and other costly treatment technologies [21]. Before promoting the widespread use of unconventional adsorbents, more study is required. Nanotechnology, which includes the adsorption of contaminants using NMs, is one of the best techniques for contemporary contamination treatment processes [68, 123, 124].

It has been effective to conduct research on the treatment of contaminants, and numerous different NMs have been developed. These include a few that are noteworthy; photocatalysts, electrocatalysts, nanofilms, and nano-adsorbents based on the metals [1, 21, 120, 125]. These NMs can also be introduced to biological processes to improve the effluent treatment procedure's efficiency (like microbial fuel cells, algae membranes, and anaerobic fermentation). Each technology varies in how well it removes contaminants and has advantages of its own [1, 21, 120, 125, 126]. Nano-adsorbents can be used to filter out potentially hazardous substances from wastewater [123, 127]. With the help of NM photocatalysts, harmful contaminants can now be treated without the use of expensive synthetic UV radiation, thanks to the modification of the catalyst substance.

As previous stated, there is a need to look into earlier water quality monitoring techniques, contrast traditional and contemporary techniques, and examine various techniques from different nations. As reported by Zainurin et al. [27], there is a thorough overview of various approaches for monitoring water quality, including the cyber-physical system approach, electronic sensing methods, virtual sensing systems, IoT approach, and optical techniques. According to the Zainurin et al. [27], cyber-physical systems are appropriate and suitable for use in water quality monitoring systems. In addition, a cyber-physical system connects the physical and digital realms by using software and data to communicate with sensors, environments, and people in the physical world. Figure 4 shows an outline of virtual sensing development stages as adapted from Zainurin et al. [27]; Paepae et al. [128].

The potential of early warning in the water quality management system is made possible by the indirect real-time monitoring of water quality [25]. As a result, it is possible to identify water pollution and evaluate the water's quality before it is suitable for consumption. Future monitoring methods will be able to combine advanced optical techniques with cyber-physical system technology to produce systems with high reliability and sensitivity because current monitoring techniques have trouble getting accurate measurements of water quality parameters in real-time and are not cost-effective with continuous data collection [44]. There have been some tool limitations in the past that have necessitated improvements to the current water quality evaluations.

Also, as previously mentioned, micro- and nanorobots are designed to expedite and enhance the water purification process (remediation). Self-propulsion has added an engineering component to micro- and nanomaterials, enabling the creation of groups of intelligent, small-scale machines that move in reaction to exterior cues and collaborate to carry out specific tasks. Micro- and nanorobots have proven successful in water remediation applications, where the effectiveness and speed of the purification process are important. This is because of the interaction between active motion and programmed contaminant removal and degradation processes achieved through material design. Although the effectiveness of micro- and nanorobots against contaminants varying in type and size (from mm- to atomic-scale) is wide, there are still a number of obstacles to overcome for practical uses. For uses involving water remediation, self-propelled micro- and nanorobots are more effective than static materials. For all the contaminants examined, the elimination and degradation efficiencies are also insufficient. As an illustration, it is especially difficult to completely decompose plastic debris because polymers contain UV stabilizers to increase their stability. Combining various degradation processes in a single robot or programming it to specifically target the most enduring contaminant are two feasible solutions. These characteristics increase complexity and manufacturing costs because they call for the integration of numerous components. Thus, in order to satisfy the demands of mass production, the design of micro- and nanorobots must be kept as basic as feasible, for example, by utilizing high-throughput fabrication techniques (for example, 3D bioprinting) [38]. The increase in small-scale machines in the environment should be considered a danger. Utilizing readily available, safe, and impermanent natural materials like microalgae is a desirable choice in this situation. The widespread use of toxic chemicals in agriculture to increase agricultural output puts soil and plants at high risk of contamination. Micro- and nanorobots can be used to clean up these areas. Small-scale machines that are biocompatible and environmentally benign could break down poisons into harmless substances on the spot. The robots require a liquid medium, just like in water remediation, to allow their active movement as well as the removal and degradation of pollutants. Under sunny conditions, the pesticides could be broken down at the water-soil and water-plant interfaces by suspending the robots in water sprinkled on the soil or plant surfaces. They could also be made to specifically target bugs, taking the place of harmful poisons [38]. The enormous promise of using micro- and nanorobots for water remediation has been demonstrated in numerous studies. To satisfy market demands, however, the development of this technology into practical uses requires the combined efforts of scientists from various disciplines.

Since NMs are still more expensive than conventional materials, future studies should concentrate on effective processes that only require small concentrations of NMs (such as activated carbon) [123, 126]. Furthermore, more work is needed to develop low-cost methods of NM synthesis and to conduct large-scale efficiency assessments for practical field uses. The following research voids must be filled in the future:

- Understanding how adsorbents function in wastewater filtration requires research at the cellular and molecular levels.
- More work needs to be done on pilot-scale and field-scale experiments in addition to laboratory testing.
- Cost-effect benefits need to be estimated and computed prior to performing pilot-scale experiments.
- It is crucial to look into how well the adsorbents mentioned here work in conjunction with other treatment modalities, especially carbon-based adsorbents.
- Investigating microbial interactions in aquatic environments is crucial.
- It is necessary to conduct more research on how geo-environmental factors affect sorption processes.

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Declarations

Conflict of interest There is no conflict whatsoever to declare.

References

1. Dotto G, McKay G (2020) Current scenario and challenges in adsorption for water treatment. J Environ Chem Eng 8(103988):1–6
2. Aigbe U, Ukhurebor K, Onyancha R, Okundaye B, Pal K, Osibote O, Esiekpe E, Kusuma H, Darmokoesoemo H (2022) A facile review on the sorption of heavy metals and dyes using bionanocomposites. Adsorpt Sci Technol 8030175:1–36

3. WHO (2019) World Health Organization: drinking water. WHO, Geneva, Switzerland.
4. Denchak M (2018) Water pollution: everything you need to know. NRDC Guide. NRDC
5. Ukhurebor K, Aidonojie P (2021) The influence of climate change on food innovation technology: review on topical developments and legal framework. Agric Food Secur 10(50):1–14
6. Aigbe U, Ukhurebor K, Onyancha R, Osibote O, Darmokoesoemo H, Kusuma H (2021) Fly ash-based adsorbent for adsorption of heavy metals and dyes from aqueous solution: a review. J Market Res 14:2751–2774
7. El-Nemr M, Aigbe U, Ukhurebor K, Onyancha R, El Nemr A, Ragab S, Osibote O, Hassaan M (2022) Adsorption of Cr6+ ion using activated pisum sativum peels-triethylenetetramine. Environ Sci Pollut Res 2022:1–25
8. Eldeeb T, Aigbe U, Ukhurebor K, Onyancha R, El-Nemr M, Hassaan M, Ragab S, Osibote O, El Nemr A (2022) Adsorption of methylene blue (MB) dye on ozone, purified and sonicated sawdust biochars. Biomass Convers Biorefinery 2022:1–23
9. Onyancha R, Aigbe U, Ukhurebor K, Kusuma H, Darmokoesoemo H, Osibote O, Pal K (2022) Influence of magnetism-mediated potentialities of recyclable adsorbents of heavy metal ions from aqueous solutions—an organized review. Results Chem 4:100452
10. El-Nemr M, Aigbe U, Hassaan M, Ukhurebor K, Ragab S, Onyancha R, Osibote O, El Nemr A (2022) The use of biochar-NH2 produced from watermelon peels as a natural adsorbent for the removal of Cu(II) ion from water. Biomass Convers Biorefinery
11. Souza R, Seibert D, Quesada H, Bassetti F, Fagundes-Klen M, Bergamasco R (2020) Occurrence, impacts and general aspects of pesticides in surface water: a review. Proc Saf Environ Prot 135:22–37
12. Carmalin S, Lima E (2018) Removal of emerging contaminants from the environment by adsorption. Ecotoxicol Environ Saf 150:1–17
13. Kaur H, Raveendran A, Athwal S, Verma M, Mutreja V, Ukhurebor K, Kusuma H (2023) Assessment of diabetes biomarker monitoring via novel biosensor activity. Results Chem 5(100777):1–9
14. Kerry R, Ukhurebor K, Kumari S, Maurya G, Patra S, Panigrahi B, Majhi S, Rout J, Rodriguez-Torres M, Das G, Shin H-S, Patra J (2021) A Comprehensive review on the applications of nano-biosensor based approaches for non-communicable disease detention. Biomater Sci 9:3576–3602
15. Ukhurebor K, Onyancha R, Aigbe U, UK-Eghonghon G, Kerry R, Kusuma H, Darmokoesoemo H, Osibote O, Balogun V (2022) A methodical review on the applications and potentialities of using nanobiosensors for diseases diagnosis. BioMed Res Int 168250:1–20
16. Yang Y, Ok YS, Kim K, Kwon K, Tsang Y (2017) Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: a review. Sci Tot Environ 596(303–320)
17. Zhang X, Gu P, Liu Y (2019) Decontamination of radioactive wastewater: state of the art and challenges forward. Chemosphere 215:543–553
18. Taheran M, Naghdi M, Brar S, Verma M, Surampalli R (2018) Emerging contaminants: here today, there tomorrow! Environ Nanotechnol Monitor Manag 10:122–126
19. Wilkinson J, Hooda P, Barker J, Barton S, Swinden J (2017) Occurrence, fate and transformation of emerging contaminants in water: an overarching review of the field. Environ Pollut 231:954–970
20. Ukhurebor K, Aigbe U, Onyancha R, Nwankwo W, Osibote O, Paumo H, Ama O, Adetunji C, Siloko I (2021) Effect of hexavalent chromium on the environment and removal techniques: a review. J Environ Manag 280:111809
21. Gkika D, Mitropoulos A, Kyzas G (2022) Why reuse spent adsorbents? The latest challenges and limitations. Sci Total Environ 822:153612
22. Neolaka Y, Riwu A, Aigbe U, Ukhurebor K, Onyancha R, Darmokoesoemo H, Kusuma H (2023) Potential of activated carbon from various sources as a low-cost adsorbent to remove heavy metals and synthetic dyes. Resul Chem 5:100711
23. Aigbe U, Onyancha R, Ukhurebor K, Obodo K (2020) Removal of fluoride ions using polypyrrole magnetic nanocomposite influenced by rotating magnetic field. RSC Adv 10(1):595–609
24. Pekel J, Cottam A, Gorelick N, Belward A (2016) High-resolution mapping of global surface water and its long-term changes. Nature 540(7):418–422
25. Anani A, Adama K, Ukhurebor K, Habib A, Abanihi V, Pal K (2023) Application of nanofibrous protein for the purification of contaminated water as a next generational sorption technology: a review. Nanotechnology 34(23200):1–18
26. Domagalski J, Morway E, Alvarez N, Hutchins J, Rosen M, Coats R (2020) Trends in nitrogen, phosphorus, and sediment concentrations and loads in streams draining to Lake Tahoe, California, Nevada, USA. Sci Total Environ 752:141815
27. Zainurin S, Wan Ismail W, Mahamud S, Ismail I, Jamaludin J, Ariffin K, Kamil WA (2022) Advancements in monitoring water quality based on various sensing methods: a systematic review. Int J Environ Res Public Health 19(4)
28. Mahajan P, Shahane P (2021) An IoT based system for water quality monitoring. SSRN Electron 489–495
29. Pasika S, Gandla S (2020) Smart water quality monitoring system with cost-effective using IoT. Heliyon 6:e04096
30. Ighalo J, Adeniyi A, Marques G (2020) Artificial intelligence for surface water quality monitoring and assessment: a systematic literature analysis. Model Earth Syst Environ 7:669–681
31. Lin H, Liu J, Dong Y, He Y (2019) The effect of substrates on the removal of low-level vanadium, chromium and cadmium from polluted river water by ecological floating beds. Ecotox Environ Safe 169:856–862
32. Zhou J, Wang Y, Chen Y, Li X, Xie Y (2021) Water quality prediction method based on multi-source transfer learning for water environmental IoT system. Sensors 21(7271)
33. He Y (2021) Design of water quality monitoring platform based on embedded system. IOP Conf Ser Earth Environ Sci 631:012020
34. Chang H-C, Hsu Y-L, Hung S-S, Ou G-R, Wu J-R, Hsu C (2021) Autonomous water quality monitoring and water surface cleaning for unmanned surface vehicle. Sensors 21:1102
35. Li Y, Wang X-K, Zhang H-Y, Wang J-Q, Li L (2021) An integrated regional water quality assessment method considering interrelationships among monitoring indicators. Environ Monit Assess 193(223)
36. Manoj M, Kumar V, Arif M, Bulai E-R, Bulai P, Geman O (2022) State of the art techniques for water quality monitoring systems for fish ponds using IoT and underwater sensors: a review. Sensors 22:2088
37. Zhang H, Zhang L, Wang S, Zhang L (2022) Online water quality monitoring based on UV–Vis spectrometry and artificial neural networks in a river confluence near Sherfield-on-Loddon. Environ Monit Assess 194:630
38. Urso M, Ussia M, Pumera M (2023) Smart micro- and nanorobots for water purification. Nat Rev Bioeng 2023
39. Bhardwaj J, Gupta K, Gupta R (2018) Towards a cyber-physical era: Soft computing framework based multi-sensor array for water quality monitoring. Drink Water Eng Sci 11:9–17
40. Lee E (2015) The past, present and future of cyber-physical systems: a focus on models. Sensors 15:4837–4869

41. Mohamed N, Al-Jaroodi J, Jawhar I (2020) Cyber–physical systems forensics: today and tomorrow. J Sens Actuator Netw 9:37
42. Wang Z, Song H, Watkins DW, Ong KG Xue P, Yang Q Shi X (2015) Cyber-physical systems for water sustainability: challenges and opportunities. IEEE Commun Mag 53:216–222
43. Imen S, Chang NB (2016) Developing a cyber-physical system for smart and sustainable drinking water infrastructure management. In: Proceedings of the 2016 IEEE 13th international conference on networking, sensing, and control (ICNSC), Mexico City, Mexico, 2016.
44. Wang H, Wang T, Xue G, Zhao J, Ma W, Qian Y, Wu M, Zhang Z, Gao P, Su C. Zong B, Yu J. Guo J, Wang Y (2021) Key technologies and equipment for contaminated surface/groundwater environment in the rural river network area of China: integrated remediation. Environ Sci Eur 33(5)
45. Wu J, Xu Z, Li H, Li P, Wang M, Xiong L, Zhang J (2019) Long-term effect of water diversion and CSOs on the remediation of heavy metals and microbial community in river sediments. Water Sci Technol 79(12):2395–2406
46. Adapa L, Azimi Y, Singh S, Porcelli D, Thompson I (2016) Comparative study of chemical and physical methods for distinguishing between passive and metabolically active mechanisms of water contaminant removal by biofilms. Water Res 101:574–581
47. Camacho F, Sousa V, Bergamasco R, Teixeira M (2017) The use of Moringa oleifera as a natural coagulant in surface water treatment. Chem Eng J 313:226–237
48. Song J, Li Q, Dzakpasu M, Wang X, Chang N (2020) Integrating stereo-elastic packing into ecological floating bed for enhanced denitrification in landscape water. Bioresour Technol 299(122601)
49. MacArthur M, Naylor L, Hansom J, Burrows M (2020), Ecological enhancement of coastal engineering structures: passive enhancement techniques. Sci Total Environ 740:139981
50. Irwin N, Irwin E, Martin J, Aracena P (2018) Constructed wetlands for water quality improvements: benefit transfer analysis from Ohio. J Environ Manag 206:1063–1071
51. Wang H, Li Z, Han H (2017) Comparison of different ecological remediation methods for removing nitrate and ammonium in Qinshui River, Gonghu Bay, Taihu Lake. Environ Sci Pollut R 24(2):1706–1718
52. Sun S, Sheng Y, Zhao G, Li Z, Yang J (2017) Feasibility assessment: application of ecological floating beds for polluted tidal river remediation. Environ Monit Assess 189(12):609
53. Lin J-Y, Tsai H-L, Lyu W-H (2021) An integrated wireless multisensor system for monitoring the water quality of aquaculture. Sensors 21:8179
54. Kumar G, Rao K, Yadav A, Kumar M, Sarathi T (2018) Biosorption of copper (II) and manganese (II) from waste water using low-cost bio adsorbents. J Indian Chem Soc 95:1–8
55. Priya A, Gnanasekaran L, Dutta K, Rajendran S, Balakrishnan D, Moscoso M (2022) Biosorption of heavy metals by microorganisms: evaluation of different underlying mechanisms. Chemosphere 307:135957
56. Eleryan A, Aigbe U, Ukhurebor K, Onyancha R, Eldeeb T, El-Nemr M, Hassaan M, Ragab S, Osibote O, Kusuma H, Darmokoesoemo H, El Nemr A (2022) Copper (II) ion removal by chemically and physically modified sawdust biochar. Biomass Convers Biorefinery 2022:1–38
57. Eldeeb T, Aigbe U, Ukhurebor K, Onyancha R, El-Nemr M, Hassaan M, Osibote O, Ragab S, Okundaye B, Balogun V, El Nemr A (2022) Biosorption of acid brown 14 dye to mandarin-biochar-CO-TETA derived from mandarin peels. Biomass Convers Biorefinery 2022:1–21
58. Kusuma H, Aigbe U, Ukhurebor K, Onyancha R, Okundaye B, Ama O, Darmokoesoemo H, Widyaningrum B, Osibote O, Balogun V (2023) Biosorption of methylene blue using clove leaves waste modified with sodium hydroxide. Results Chem 5(100778):1–15
59. Cheng S, Show P, Lau B, Chang J, Ling T (2019) New prospects for modified algae in heavy metal adsorption. Trends Biotechnol 37:1255–1268
60. Cherkasov N (2020) Liquid-phase adsorption: common problems and how we could do better. J Mol Liq 301:112378
61. Li W, Mu B, Yang Y (2019) Feasibility of industrial-scale treatment of dye wastewater via bioadsorption technology. Bioresour Technol 277:157–170
62. Diraki A, Abdala A, McKay G, Mackey H (2019) Removal of emulsified and dissolved diesel oil from high salinity wastewater by adsorption onto graphene oxide. J Environ Chem Eng 7:103106
63. Streit A, Côrtes L, Druzian S, Godinho M, Collazzo G, Perondi D, Dotto G (2019) Development of high-quality activated carbon from biological sludge and its application for dyes removal from aqueous solutions. Sci Tot Environ 660:277–287
64. Zazycki M, Perondi D, Godinho M, Oliveira M, Collazzo G, Dotto G (2020) Conversion of MDF wastes into a char with remarkable potential to remove Food Red 17 dye from aqueous effluents. Chemosphere 250:126248
65. Kwok K, Koong L, Ansari TA, McKay G (2018) Adsorption/desorption of arsenite and arsenate on chitosan and nanochitosan. Environ Sci Pollut Res 25:14734–14742
66. Santos J, Pereira C, Foletto E, Dotto G (2019) Alternative synthesis for $ZnFe_2O_4$/chitosan magnetic particles to remove diclofenac from water by adsorption. Int J Biol Macromol 131:301–308
67. Mo J, Yang Q, Zhang N, Zhang W, Zheng Y, Zhang Z (2018) A review on agro-industrial waste (AIW) derived adsorbents for water and wastewater treatment. J Environ Manag 227:395–405
68. Escudero L, Quintas P, Wuilloud R, Dotto G (2019) Recent advances on elemental biosorption. Environ Chem Lett 17:409–427
69. Zubair M, Daud M, McKay G, Shehzad F, Al-Harthi M (2017) Layered double hydroxides nano-hybrids for water purification: a review. Appl Clay Sci 143:279–292
70. Briao G, Foletto E, Jahn S, et al (2018) Adsorption of crystal violet dye onto a mesoporous ZSM-5 zeolite synthesized using chitin as template. J Colloid Interface Sci 508:313–322
71. Haldar D, Duarah P, Purkait M (2020) MOFs for the treatment of arsenic, fluoride and iron contaminated drinking water: a review. Chemosphere 251:126388
72. Sudarni D, Aigbe U, Ukhurebor K, Onyancha R, Kusuma H, Darmokoesoemo H, Osibote O, Balogun V, Widyaningrum B (2021) Malachite green removal by activated potassium hydroxide clove leaves agro-waste biosorbent: characterization, kinetics, isotherms and thermodynamics studies. Adsorpt Sci Technol 1145312:1–15
73. Tien C (2018) Introduction to adsorption. Elsevier, New York
74. Patel P (2019) Fixed-bed column adsorption study: a comprehensive review. Appl Water Sci 9:45
75. Schio R, Salau N, Mallmann E, Dotto G (2019) Fixed bed adsorption of Allura Red dye on chitosan/polyurethane foam. Chem Eng Technol 42:2434–2442
76. Miraboutalebi S, Nikouzad S, Peydayesh M, Allahgholi N, Vafajoo L, McKay G (2019) Methylene blue adsorption via maize silk powder: Kinetic, equilibrium, thermodynamic studies and residual error analysis. Proc Saf Environ Prot 106:191–202
77. Karimifard S, Moghaddam M (2018) Application of response surface methodology in physicochemical removal of dyes from wastewater: a critical review. Sci Tot Environ 640–641:772–797
78. Eleryan A, Hassaan M, Aigbe U, Ukhurebor K, Onyancha R, El Nemr M, Ragab S, Hossain I, El Nemr A (2023) Kinetic and isotherm studies of acid orange 7 dye absorption using sulphonated

mandarin biochar treated with TETA. Biomass Convers Biorefinery 2023:1–12

79. Ghaedi A, Vafaei A (2017) Applications of artificial neural networks for adsorption removal of dyes from aqueous solution: a review. Adv Colloid Interface Sci 245:20–39
80. Kalra A, Hadi P, Mackey H, Ansari TA, McKay G (2018) Sorption of heavy metal ions onto e-waste derived ion-exchange material—selecting the optimum isotherm. Des Water Treat 126:196–207
81. Yazidi A, Sellaoui L, Soetaredjo F, Ismadji S, Erto A, Bonilla-Petriciolet A, Dotto G, Lamine AB (2020) Adsorption of amoxicillin and tetracycline on activated carbon prepared from durian shell in single and binary systems: experimental study and modeling analysis. Chem Eng J 379:122320
82. Zhang L, Sellaoui L, Franco D, Dotto G, Bajahzar A, Belmabrouk H, Bonilla-Petriciolet A, Oliveira M, Li Z (2020) Adsorption of dyes brilliant blue, sunset yellow and tartrazine from aqueous solution on chitosan: analytical interpretation via multilayer statistical physics model. Chem Eng J 382:122952
83. Rodrigues F, Salau N, et al (2019) New insights about reactive red 141 adsorption onto multi-walled carbon nanotubes using statistical physics coupled with Van der Waals equation. Sep Purif Technol 224:290–294
84. Lima E, Hosseini-Bandegharaei A, Moreno-Piraján J, et al (2019) A critical review of the estimation of the thermodynamic parameters on adsorption equilibria. Wrong use of equilibrium constant in the Van't Hoof equation for calculation of thermodynamics parameters of adsorption. J Mol Liq 273: 425–434
85. Fenti A, Iovino P, Salvestrini S (2019) Some remarks on a critical review of the estimation of the thermodynamic parameters on adsorption equilibria. Wrong use of equilibrium constant in the Van't Hoof Equation for calculation of thermodynamic parameters of adsorption. J Mol Liq 276:529–530
86. Tran H, You S, Bandegharaei A, Chao H (2017) Mistakes and inconsistencies regarding adsorption of contaminants from aqueous solutions: a critical review. Water Res 120:88–116
87. Ahmed M, Hameed B (2018) Removal of emerging pharmaceutical contaminants by adsorption in a fixed-bed column: a review. Ecotoxicol Environ Saf 149:257–266
88. Ma A, Abushaikha A, Allen S, McKay G (2019) Ion exchange homogeneous surface diffusion modelling by binary site resin for the removal of nickel ions from wastewater in fixed beds. Chem Eng J 358:1–10
89. Fröhlich A, Ocampo-Pérez R, Diaz-Blancas V, Salau N, Dotto G (2018) Threedimensional mass transfer modeling of ibuprofen adsorption on activated carbon prepared by sonication. Chem Eng J 341:65–74
90. Pauletto P, Dotto G, Salau N (2020) Diffusion mechanisms and effect of adsorbent geometry on heavy metal adsorption. Chem Eng Res Des 157:182–194
91. Costa C, Rodrigues A (1985) Intraparticle diffusion of phenol in macroreticular adsorbents: modelling and experimental study of batch and CSTR adsorbers. Chem Eng Sci 40:983–993
92. Alyasi H, Mackey H, Loganathan K, McKay G (2020) Adsorbent minimisation in a two-stage batch adsorber for cadmium removal. J Ind Environ Chem 81:153–160
93. Vargas V, Paveglio R, Pauletto P, Salau N, Dotto G (2020) Sisal fiber as an alternative and cost-effective adsorbent for the removal of methylene blue and reactive black 5 dyes from aqueous solutions. Chem Eng Commun 207:523–536
94. Barbosa T, Foletto E, Dotto G, Jahn S (2018) Preparation of mesoporous geopolymer using metakaolin and rice husk ash as synthesis precursors and its use as potential adsorbent to remove organic dye from aqueous solutions. Ceram Int 44:416–423
95. Zazycki M, Godinho M, Perondi D, Foletto E, Collazzo G, Dotto G (2018) New biochar from pecan nutshells as an alternative adsorbent for removing Reactive Red 141 from aqueous solutions. J Clean Prod 171:57–65
96. Peres E, Slaviero J, Cunha A, Bandegharaei A, Dotto G (2018) Microwave synthesis of silica nanoparticles and its application for methylene blue adsorption. J Environ Chem Eng 6:649–659
97. Loganathan P, Shim W, Sounthararajah D, Kalaruban M, Nur T, Vigneswaran S (2018) Modelling equilibrium adsorption of single, binary, and ternary combinations of Cu, Pb, and Zn onto granular activated carbon. Environ Sci Poll Res 25:16664–16675
98. Sellaoui L, Mendoza-Castillo D, Reynel-Ávila H, Bonilla-Petriciolet A, Ben Lamine A, Erto A (2018) A new statistical physics model for the ternary adsorption of Cu2+, Cd2+ and Zn2+ ions on bone char: experimental investigation and simulations. Chem Eng J 343:544–553
99. Lima D, Gomes A, Lima E, Umpierres C, Thue P, Panzenhagen J, Dotto G, El-Chaghaby G, Alencar W (2019) Evaluation of efficiency and selectivity in the sorption process assisted by chemometric approaches: removal of contaminants from water. Spectroscopy 218:366–373
100. Georgin J, Franco D, Drumm F, Grassi P, Netto M, Allasia D, Dotto G (2020) Powdered biosorbent from the mandacaru cactus (cereus jamacaru) for discontinuous and continuous removal of Basic Fuchsin from aqueous solutions. Powder Technol 364:584–592
101. Michael S, Michael-Kordatou I, Beretsou V, Jäger T, Michael C, Schwartz T, Fatta-Kassinos D (2019) Solar photo-Fenton oxidation followed by adsorption on activated carbon for the minimisation of antibiotic resistance determinants and toxicity present in urban wastewater. Appl Cat B 244:871–880
102. You N, Wang X, Li J, Fan H, Shen H, Zhang Q (2019) Synergistic removal of arsanilic acid using adsorption and magnetic separation technique based on Fe_3O_4@ graphene nanocomposite. J Ind Eng Chem 70:346–354
103. Santos J, Pereira C, Pinto L, Frantz T, Lima E, Foletto E, Dotto G (2019) Synthesis of a novel $CoFe_2O_4$/chitosan magnetic composite for fast adsorption of indigotine blue dye. Carbohydr Polym 217:6–14
104. Fröhlich A, Foletto E, Dotto G (2019) Preparation and characterization of $NiFe_2O_4$/activated carbon composite as potential magnetic adsorbent for removal of ibuprofen and ketoprofen pharmaceuticals from aqueous solutions. J Clean Prod 229:828–837
105. Foletto V, Ferreira A, Severo E, Collazzo G, Foletto E, Dotto G (2017) Ironbased adsorbent prepared from Litchi peel biomass via pyrolysis process for the removal of pharmaceutical pollutant from synthetic aqueous solution. Environ Sci Pollut Res 24:10547–10556
106. Netto M, Rossatto D, Jahn S, Mallmann E, Dotto G, Foletto E (2020) Preparation of a novel magnetic geopolymer/zero-valent iron composite with remarkable adsorption performance towards aqueous Acid Red 97. Chem Eng Commun 2020
107. Rossatto D, Netto M, Jahn S, Mallmann E, Dotto G, Foletto E (2020) Highly efficient adsorption performance of a novel magnetic geopolymer/Fe_3O_4 composite towards removal of aqueous acid green 16 dye. J Environ Chem Eng 8:103804
108. Zhao X, Zheng J, You S, Liu C, Du L, Chen K, Liu Y, Ma L (2021) Selective adsorption of Cr (VI) onto amine-modified passion fruit peel biosorbent. Processes 9(5):790
109. Amaku J, Ogundare S, Akpomie K, Ibeji C, Conradie J (2021) Functionalized MWCNTs-quartzite nanocomposite coated with Dacryodes edulis stem bark extract for the attenuation of hexavalent chromium. Sci Rep 11(1):1–15
110. Guarin J, Moreno-Pirajan J, Giraldo L (2018) Kinetic Study of the bioadsorption of methylene blue on the surface of the biomass obtained from the Algae D. Antarctica. J Chem 2124845
111. Phuengphai P, Singjanusong T, Kheangkhun N, Wattanakornsiri A (2021) Removal of copper (II) from aqueous solutions using

chemically modified fruit peels as efficient low-cost biosorbents. Water Sci Eng 14(4):286–294
112. Bai X, Xing L, Liu N, Ma N, Huang K, Wu D, Yin M, Jiang K (2021) Humulus scandens-derived biochars for the effective removal of heavy metal ions: Isotherm/kinetic study, column adsorptions and mechanism investigations. Nanomaterials 11:3255
113. El Nemr A, Shoaib A, El Sikaily A, Mohamed A, Hassan A (2021) Evaluation of cationic methylene blue dye removal by high surface area mesoporous activated carbon derived from Ulva Lactuca. Environ Process 8(1):311–332
114. Nworie F, Nwabue F, Oti W, Mbam E, Nwali B (2019) Removal of methylene blue from aqueous solution using activated rice husk biochar: adsorption isotherms, kinetics and error analysis. J Chilean Chem Soc 64:4365–4376
115. Sobhanardakani S, Zandipak R (2015) Removal of anionic dyes (direct blue 106 and acid green 25) from aqueous solutions using oxidized multi-walled carbon nanotubes. Iran J Health Sci 3(3):48–57
116. Krishnappa B, Shivanna JM, Naik M, Padova P, Hegde G (2021) Acid orange-7 uptake on spherical-shaped nanocarbons. Nanomater Nanotechnol 11
117. Sillanpää M, Mahvi A, Balarak D, Khatibi A (2021) Adsorption of acid orange 7 dyes from aqueous solution using polypyrrole/nanosilica composite: experimental and modelling. Int J Environ Anal Chem 2021.
118. Mustapha R, Ali A, Subramaniam G, Zuki A, Awang M, Harun M, Hamzah S (2021) Removal of malachite green dye using oil palm empty fruit bunch as a low-cost adsorbent. Biointerface Res Appl Chem 11(6):4998–15008
119. Sharifpour E, Dil E, Asfaram A, Ghaedi M, Goudarzi A (2019) Optimizing adsorptive removal of malachite green and methyl orange dyes from simulated wastewater by Mn-doped CuO-Nanoparticles loaded on activated carbon using CCD-RSM: mechanism, regeneration, isotherm, kinetic and thermodynamic studies. Appl Organomet Chem 33(3):e4768
120. Younas F, Mustafa A, Farooqi Z, Wang X, Younas S, Mohy-Ud-Din W, Hameed MA, Abrar MM, Maitlo A, Noreen A, Hussain M (2021) Current and emerging adsorbent technologies for wastewater treatment: trends, limitations, and environmental implications. Water 13:215
121. Adetunji C, Olaniyan O, Anani O, Inobeme A, Ukhurebor K, Bodunrinde R, Adetunji J, Singh K, Nayak VPW, Singh R (2021) Bionanomaterials for green bionanotechnology. In: Singh R, Singh K (eds) Bionanomaterial for green bionanotechnology. IOP Publishing, London, pp 1–24
122. Aigbe U, Ukhurebor K, Onyancha R, Ama M, Okundaye B, Esiekpe E, Osibote O, Kusuma H, Osifo P (2021) Utility of bionanocomposite for wastewater treatment. In: Singh R, Singh K (eds) Bionanomaterials for environmental and agricultural applications. IOP Publishing, London, pp 1–25
123. Onyancha R, Aigbe U, Ukhurebor K, Osibote O, Balogun V, Kusuma H (2022) Current existing techniques for environmental monitoring. In: Singh R, Ukhurebor K, Singh J, Adetunji C, Singh K (eds) Nanobiosensors for environmental monitoring: fundamental and applications. Springer, Berlin pp 239–262.
124. Wong J, Tan H, Lau S, Yap P-S, Danquah M (2019) Potential and challenges of enzyme incorporated nanotechnology in dye wastewater treatment: a review. J Environ Chem Eng 7:103261
125. Aigbe U, Ukhurebor K, Onyancha R, Ama M, Osibote O, Kusuma H, Okanigbuan P, Azi S, Osifo P (2022) Dendrimers for environmental remediation. In: Sabu T, et al. (eds) Nanotechnology for environmental remediation. Wiley, New York.
126. Aigbe U, Ukhurebor K, Onyancha R, Okundaye B, Osibote O (2023) Green nanomaterials in wastewater treatment. In: Pal K (ed) Green nanoarchitectonics. Jenny Stanford Publishing, Boca Raton
127. Aigbe U, Ukhurebor K, Onyancha R, Ama M, Okundaye B, Esiekpe E, Osibote O, Kusuma H, Osifo P (2021) Utility of bionanocomposite for wastewater treatment. In: Singh R, Singh K (eds) Bionanomaterials for environmental and applications. IOP Publishing, London, pp 1–25
128. Paepae T, Bokoro P, Kyamakya K (2021) From fully physical to virtual sensing for water quality assessment: a comprehensive review of the relevant state-of-the-art. Sensors 21:6971

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