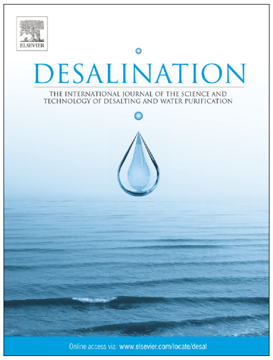

Biochar potential for pollutant removal during wastewater treatment: A comprehensive review of separation mechanisms, technological integration, and process analysis

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Biochar potential for pollutant removal during wastewater treatment: A comprehensive review of separation mechanisms, technological integration, and process analysis

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Abstract

The increasing urbanization and industrialisation worldwide are deteriorating ground and surface water quality. Biochar is derived from the pyrolysis of agro-residues, forestry residues, sewage sludge, fruit peels, poultry manure, and algal biomass. It has emerged as an efficient adsorbent for wastewater treatment. Modified biochar, treated with chemicals like $ZnCl_2$, KOH, and ZnO/ZnS, demonstrates enhanced performance over pristine biochar. Biochar derived from waste biomass stands out as a sustainable and efficient option. This review explores biochar production techniques, pre-treatment methods, and key characteristics that affect its effectiveness, with a focus on studies published over the past decade. Pollutant removal primarily depends on impurity types, with significant contaminants including nitrate, fluoride, phosphorus, ammonia, and heavy metals like Cd, As, Pb, and Cu. Key mechanisms include ion exchange, surface complexation, and physical adsorption, enabled by biochar multi-functional groups, high adsorption capacity, and large surface area. Pyrolytic process conditions, such as temperature and residence time, shape the quality of biochar. Engineered biochar, modified with doped ions, steam/CO_2 activation, or magnetic properties, achieves up to 95% pollutant removal efficiency, combining effectiveness, cost-efficiency, and environmental sustainability. This article offers a thorough summary of the most recent developments in the production of biochar, its uses in wastewater, and the adsorption processes for the removal of pollutants and heavy metals over the previous ten years. Additionally, techno-economic and regeneration studies highlight biochar feasibility. Future research perspectives and challenges emphasise the role of biochar in sustainable waste management practices, offering optimised solutions for environmental remediation.

Keywords: Adsorption; Wastewater; Biochar; Sustainability; Activation; Techno-economic analysis.

1. Introduction

Water pollution, an equally critical issue alongside global warming, primarily arises from industrial activities involving the release of a variety of chemicals, including nitrates, phosphorous, and a range of heavy metals, such as cadmium, arsenic, mercury, lead, and chromium [1], dyes, and cyanides [2], biomedical waste, petroleum and oil spills [3], open defecation [4], marine dumping [5], sewage effluents and agricultural residues [6], into water bodies. Over the years, increased surface water pollution has augmented the dependence on groundwater. However, scanty rainfall and rapid consumption of groundwater have triggered water scarcity issues. In addition, contaminants from surface water gradually percolate through the soil and adversely affect the groundwater quality. In India, major rivers, like Ganga and Yamuna, are polluted due to heavy industrial discharge and other anthropogenic activities, resulting in the scarcity of clean drinking water. The major effects of water contamination are an increase in toxicity and a reduction in dissolved oxygen, rendering loss of terrestrial and aquatic life. It may cause genetic disorders, cholera, typhoid, infant mortality, and respiratory ailments in humans. Moreover, prolonged consumption of crops, fruits, and vegetables grown using polluted water may have adverse impacts on the health of humans and animals. The polluted water causes chronic diseases in humans, including kidney and liver malfunctioning and cancer. For instance, the presence of lead and cadmium results in memory loss, aggression in children, pregnancy issues in women, and affects the brain and kidneys adversely [7]. To overcome the challenges associated with water contamination, depending on the nature of the pollutant, various effective chemical, physical, and biological treatment techniques have been reported in the last few decades [8–10]. Among these ion-exchange [11], adsorption [12], membrane filtration [13], reverse osmosis [14], flotation [15], coagulation-flocculation [16], precipitation, solvent extraction, and electrochemical treatments are most widely adopted. However, reuse and recycling challenges [17], the complex nature of industrial effluents, and the financial estimation of operations are some of the shortcomings of current wastewater management systems. Commercially available technologies include vacuum membrane distillation, multi-effect evaporation [18], free-flowing biodegradable technology [19], crystallisation [20], chemical precipitation [21] for phosphorous removal implemented by industries such as United Phosphorous Limited (UPL). Another promising, scalable, cost-effective and environment-friendly advanced oxidation process includes sonolysis, in which ultrasound is utilised to eliminate the pollutants in sludge pretreatment technology in wastewater treatment plants [22] and production of green hydrogen [23]. Sonolysis has also been used for the degradation of emerging pollutants [24] and the elimination of antibiotics from wastewater [24] that cannot be destroyed using conventional methods.

In developing and under-developed countries, adsorption is adopted because of its feasibility and good pollutant removal efficiency. Various traditional adsorbents, such as silica gel, activated carbon, fuller earth, molecular sieves, zeolites, and ion-exchange resins, are employed for the elimination of organic (dyes, surfactants, phenolic structures) and inorganic pollutants (arsenic, fluoride, iron, nitrate, and heavy metals) [25]. Biochar as an adsorbent is sustainable and eco-friendly [26]. It is produced by thermal decomposition of agricultural residues or forestry biomass in oxygen-deprived conditions at elevated temperature ranges (300-900℃) [27]. Biochar and post-treated biochar possess critical properties for wastewater treatment, but their performance is often inconsistent and application-specific. High surface area (10-500 m^2/g), carbon content (50-90%), porosity (0.1 to 0.5 cm^3/g) and rich oxygen-containing groups (e.g., hydroxyl, carboxyl) enable pollutant adsorption [28]. Still, these attributes are highly dependent on feedstock and pyrolysis conditions, leading to variability. Post-treatments like chemical activation enhance adsorption capacity and add complexity and cost, potentially undermining biochar’s economic viability. Functional group modification improves pollutant selectivity but may reduce biochar’s stability and reusability. Furthermore, regeneration remains a challenge, often leading to diminished adsorption efficiency over cycles [29]. A more standardised approach is needed to optimise biochar properties for large-scale, sustainable wastewater applications reliably. As of December 6, 2024, data from the Scopus database reveals a significant increase in the number of publications on "biochar for water treatment" over the past decade **(Fig. 1**). The increase in publications on biochar for water treatment from 2014 to 2024 can be attributed to growing environmental concerns, the need for sustainable solutions, and advancements in biochar production technology. As awareness of water pollution and contamination escalated, biochar emerged as an effective, low-cost alternative to conventional adsorbents for removing pollutants like heavy metals, organic compounds, and dyes. Additionally, the rising emphasis on circular economy principles and waste valorization has driven research into utilising biochar. Research in material science and environmental engineering has further expanded its potential applications, prompting increased academic interest and publications.

Modification is recommended to improve biochar efficiency and selectivity further. Previous reviews have not undertaken a comprehensive approach that combines critical analysis of conventional water treatment methods, performance of unmodified and modified char for higher removal efficiency, cost analysis, and regeneration and reuse strategies within a single study. This review has covered various adsorbents and highlighted the potential of biochar and adsorption mechanisms. The authors have focused on utilising biochar to remove various inorganic and organic pollutants, such as nitrate, phosphorus, ammonia, and heavy metals. Moreover, particular focus is directed towards biochar modification techniques and the targeted pollutant, aiming to enhance surface properties and overall performance. In a comparative study of techno-economic analysis (TEA), the scalability of biochar as an adsorbent specifically for the treatment of wastewater has been emphasised. The uniqueness of this paper lies in its focus on studies published in the last 10 years, with limited exceptions, offering a fresh perspective compared to existing literature.

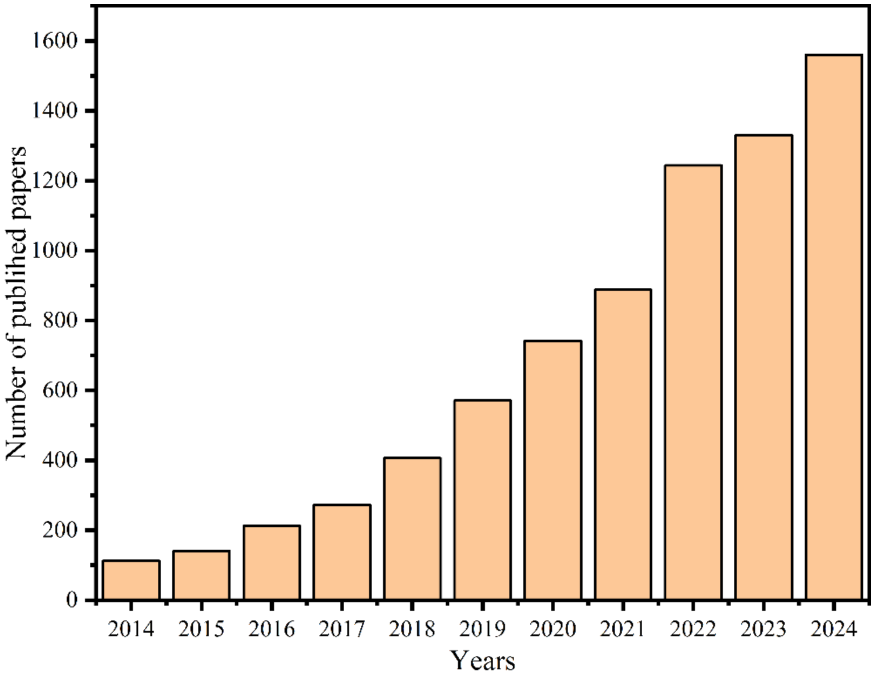


Fig. 1. Number of articles published on biochar from water treatment from 2014-2024 (source: data was obtained from Scopus on 6 December 2024 at 12.39 PM).

2. Biochar production technologies

2.1. *Biochar Pre-treatment Technologies*

The first stage in producing biochar from different raw materials or biomass/agro residues is pre-treatment. The purpose of biochar pre-treatment technologies incorporates improvement in the adsorptive properties of biochar prior to pyrolysis (in the form of biomass), resulting in cost-effective removal of volatile organic compounds, heavy metals [30] and other pollutants by enhancing functional groups, surface area and porosity. These techniques can be broadly divided into three groups: chemical, biological, and physical pre-treatment technologies. The biomass feedstock is usually subjected to physical pre-treatment procedures such as crushing, screening, drying, and washing. Feedstock abundant in lignocellulosic materials is generally ground into smaller particles with a hammer mill and dried to a consistent weight at 105°C. Adding chemical precursors or functional agents to biomass feedstock by treating it with chemicals or functional materials is a popular method of chemical pre-treatment. For instance, pre-treatment with metal ion solutions such as $AlCl_3$, $FeCl_3$, and $MgCl_2$ allows the biomass to be converted into biochar-based nanocomposites with metal oxyhydroxide nanoparticles (e.g., MgO, AlOOH, and Fe_3O_4) stabilised on the carbon surface within pores of the engineered biochar and utilised for removal of heavy metals [31]. Furthermore, biomass can be pre-treated with synthetic nanoparticles and natural colloids like carbon nanotubes, graphene, and clay to create biochar-based nanocomposites effectively (Inyang et al., 2016).Additionally, pre-treating biomass with corrosive substances like acids, alkalis, and oxidants produces tailored biochar with an enhanced surface area, distinct pore structure, and surface functional groups for the removal of metals Ag (II) and Pb (II) [33]. Anaerobic digestion has been used to break down a variety of biomass products, such as animal dung, bagasse, sugar beet tailings, and sludge, into biochar through slow pyrolysis [34]. Applicability of using biological pre-treatment leftovers for biochar formation includes environmentally friendly bioenergy production and lower waste disposal costs [38]. Further transformed a heavy metal hyperaccumulating plant into biochar, suggesting that this approach generates value-added biochar nanocomposites in addition to a safe way to dispose of hyperaccumulators [35].

2.2. Thermal carbonization technologies

The thermal methods of pyrolysis, gasification, hydrothermal carbonisation, and microwave-assisted pyrolysis are used to convert biomass into biochar [36]. These carbonization technologies are compared and summarised in **Table A**. A thermochemical process called pyrolysis that decomposes biomass in anoxic or hypoxic conditions [37]. Slow pyrolysis uses a slow heating rate to produce biochar, biogas, and bio-oil at a low temperature of 10°C/min. Fast pyrolysis decomposes the biomass at elevated temperatures (300-700°C) with a heating rate of 10-200°C/s. The highest temperature range of pyrolysis is flash pyrolysis, operated in the range of 900-1300°C with a higher heating rate of about 1000°C/s [37]. Longer residence time leads to more complete biomass decomposition. Still, it reduces biochar yield and allows for a more thorough thermal decomposition of biomass, resulting in greater conversion of the biomass into gases and liquids, which in turn reduces the overall yield of solid biochar. This is due to the extended exposure to high temperatures breaking down more of the biomass components into volatile substances [38].

Microwave-assisted pyrolysis (MAP) is regarded as a sustainable approach for generating bio-energy products such as bio-oil, biochar and biogas [39]. When compared to conventional techniques, MAP provides more efficient heat transfer, better selective heating, reduced energy requirements, and shorter processing times [40]. Without the requirement for pre-drying, hydrothermal carbonisation (HTC) transforms wet feedstock into biochar at temperatures between 120 and 260°C [36]. As the temperature rises, hydrochar exhibits an abundance of acidic functional groups on its surface, enhancing its contaminant adsorption capacity [41]. Elevating the holding temperature and duration enhances the porous structure of hydrochar, thereby augmenting its potential application as an adsorbent [42]. Gasification is the process of utilising gasification agents to convert biomass into gas fuel. The temperature during gasification is usually higher than 800-1000°C [43].

Table A. An overview of popular thermal carbonisation techniques [38,42–49]

Thermal conversion techniques	Key parameters	Temperature/power range	Residence time	Desired product	Advantages
Pyrolysis	Temperature, heating rate; residence time	300-850 ^oC	1-3 h	Biochar	Easy to use, reliable, and affordable; suitable for farm-based and small-scale biochar production.
Intermediate pyrolysis	temperature; heating rate; residence time	450-700 ^oC	10-30 min	Biochar and bio-oil	Simple, cost-effective, and small-scale production
Fast pyrolysis	temperature; heating rate; residence time	500-800 ^oC	2-5 s	Bio-oil	More complicated, sophisticated, and applicable for small and large scales.
Microwave-assisted pyrolysis	microwave power; microwave irradiation time	400-500 W	1-10 min	Biochar and biofuel	Efficient, precise, rapid, and volumetric heating
Hydrothermal carbonization	temperature; residence time; pressure; water-to-biomass ratio	120-260 ^oC	1-16 h	Hydrochar	More appropriate and versatile for feedstock with high moisture content
Gasification	temperature, residence time,	>800	10-20 s	Syngas	Although the gasification yield of

	pressure, particle size, and gasification agent/biomass ratio	Syngas	biochar is lower than that of pyrolysis, the biochar has a high concentration of alkali salts (Ca, K, Si, Mg, etc.).

2.3. Post-treatment technologies

The biochar undergoes post-pyrolysis treatment through physical or chemical modification techniques to enhance its specific surface area (SSA), pore volume, surface chemistry, negative zeta potential, adsorption capacity, and incorporation of surface functional groups (SFG) and composite nanoparticles [37,50]. This review focuses on three post-treatment techniques: magnetic, ball milling, and corrosive treatments (such as acid, alkali, or oxidation). Magnetisation is the process of loading magnetic iron oxides, such as Fe_3O_4, γ-Fe_2O_3, or $CoFe_2O_4$, to biochar to make it magnetic and is utilised for the removal of heavy metals [51]. For instance, the removal rate of Cr^{6+} is higher in magnetic zero-valent iron biochar derived from peanut hulls at 800°C due to its high SSA, pore volume, and reductive iron [52] The production of "biologically activated" biochar with improved characteristics has been demonstrated by bacterial treatments, especially anaerobic digestion or biofuel processes [53]. Using the kinetic energy of moving balls, ball milling is a simple and effective technique that breaks chemical bonds, modifies particle form, and produces nanoscale particles. The ball milling technique is an efficient way to generate unique biochar that has been developed and has improved physicochemical and adsorptive qualities, making it suitable for a range of environmental applications. Chemical modification techniques are often used in corrosive treatments, such as acid, alkali, and oxidation treatments, to modify the surface chemistry of biochar and are widely applicable for the removal of dyes from aqueous solutions [54]. These processes entail altering biochar for various uses by adding corrosive substances such as HCl, HNO_3, KOH, NaOH, $KMnO_4$, and H_2O_2 [70]. H_2O_2-modified manure biochar is widely applicable in wastewater treatment. It has higher oxygen and carboxyl group concentration, which effectively removes heavy metals [55]

3. Biochar properties

The kind of feedstock and process operating parameters, such as temperature, solid residence time, and particle size, determine the properties of the biochar and its surface characteristics.

3.1. Effect of pyrolysis temperature

Given the adsorption performance of biochar, optimum preparation temperature is the key parameter, and it varies with different feed materials. The removal rate and adsorption capacity rise with preparation temperature and reach a maximum value when the temperature [56]. However, a further rise in pyrolysis temperature resulted in a low adsorption capacity and removal rate. This trend may be attributed to enhancing pore geometry and surface functional groups on effective heating, demonstrated in **Table 1a**. With the rise in pyrolysis temperature, Cd^{2+} adsorption potential was noted to increase [57], as shown in **Fig. 2 (a)**. Methylene blue was removed by $ZnCl_2$-modified biochar produced at various pyrolysis temperatures [58], **Fig. 2 (b).** High pyrolysis temperatures will lead to the collapse of pore structure and the decrease of surface functional groups; furthermore, the process of transforming amorphous carbon structure into graphite microcrystalline structure may lead to the decrease of specific surface area. The ecological risk index values or leaching rates significantly decreased after pyrolysis. The studies revealed that the dissolved organic matter (DOM) contents varied with pyrolysis temperatures during pyrolysis is 700°C [59].

The pyrolysis temperature and adsorption capacity are linked to the changes in the physicochemical properties of materials during pyrolysis. Higher pyrolysis temperature leads to the formation of more porous structures and higher surface area in carbon materials. Moreover, at elevated temperatures, micropores and mesopores enhance the ability of material, increase functional groups, improving adsorption capacity. The more reactive surface that develops at higher temperatures increases the adsorption capacity, especially for specific types of adsorbates. The source material's impurities and volatile organic components are removed as the temperature rises, highlighting a pure form of carbon because impurities can inhibit the number of adsorption sites, which makes the adsorbent more effective. With the increase in pyrolysis temperature, the degree of carbonisation increases, resulting in a more graphite-like and stable structure.

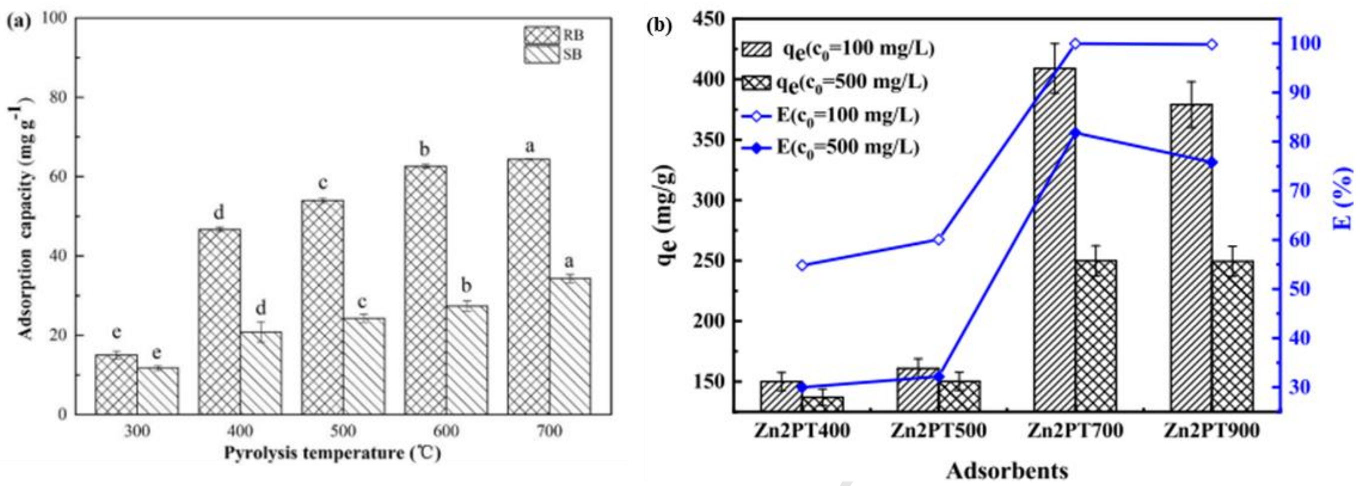


Fig. 2. Effect of pyrolysis temperature on adsorption capacity of **(a)** rice straw and swine manure biochar (300-700 ℃) [57] **(b)** $ZnCl_2$ modified pulp sludge derived biochar (400-900 ℃) [58]

This results in a graphitic-like structure that has an enhanced ability to adsorb different types of molecules due to its more ordered and rigid structure. Pyrolysis at higher temperatures can activate carbon materials, particularly in the presence of activating agents like CO_2 or steam. The structural changes that occur during pyrolysis at higher temperatures make the material more effective at interacting with and adsorbing molecules.

Table 1a. Effect of pyrolysis temperature on the adsorption process.

Adsorbent	Pyrolysis type/ Temp	Adsorbate/Pollutants	Adsorption capacity	Specific findings	References
Corn straw biochar	Slow pyrolysis-400℃	Ammonium, nitrate.	15.45 mg/g	Adsorption of NH_4 +-N was predominantly affected by the cationic exchange capacity of biochar.	[60]
• Modified cornstalk char • Magnetic char	Slow pyrolysis-400-600℃	• Mercury • β-estradiol	269.40 mg/g 98.80 mg/g	The downside of impregnating metal on both the inner and outer surfaces is the possible reduction in surface area and pore volume, as metal particles may obstruct the pores within the biochar structure.	[61]
Sugarcane bagasse-derived biochar	Slow pyrolysis 300-600℃	Nitrate	70% removal efficiency	Biochars' adsorption behaviour resembled that of mesoporous materials more, and the hysteresis effect grew as the pyrolysis temperature rose.	[62]

3.2. Effect of pH

There is a decrease in positively charged sites as pH rises, thereby promoting adsorption while simultaneously increasing negatively charged sites due to electrostatic repulsion. The nitrate and Cr (VI) adsorption on granular materials treated with cationic polymers AC was reported at different pHs (3 to 8) [63], shown in **Fig. 3 (a).** pH plays a vital role in governing the adsorption capacity of methylene blue dyes (MB) by mustard stalk-activated carbon, and **Fig. 3 (b)** depicted that with an increase in pH, the removal efficiency increased from 75 to 97.40% [64]. Species of As (III) adsorption on manganese-modified biochar (MnBC-As (III) and MnBC-As(V)) was influenced negatively by higher anionic surface charge at higher pH values (9<pH<10) shown in **Fig. 3 (c),** followed by unfavourable electrostatic repulsion [65].

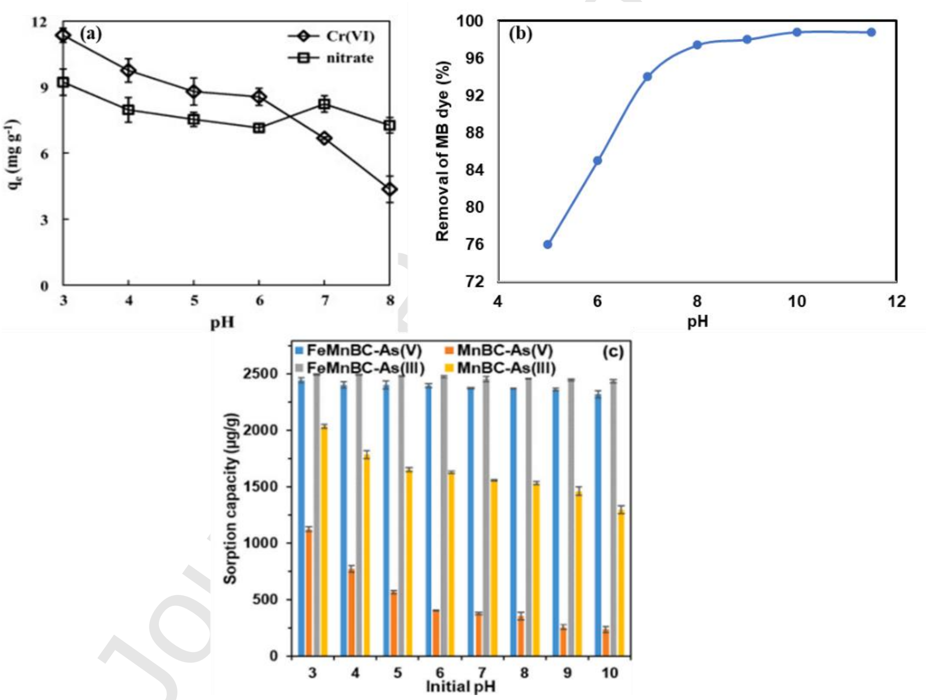


Fig. 3. pH's impact on adsorption of (a) Cr (VI) and nitrate onto cationic polymer modified granular AC [63], (b) MB dye onto Mustard stalk char [64] and (c) As (III) and As (V) onto FeMnBC and MnBC [65].

3.3 Effect of Surface Functional Group

Surface functions are essential to the adsorption process, depending on the chemistry and nature of the adsorbate-adsorbent combination. The adsorption performance of carbon-based adsorbents for heavy metals, nitrate, phosphorous, and ammonium includes functional groups based on oxygen, nitrogen, sulphur, carbonyl, and carboxyl. The carboxyl and hydroxy groups were found to be most suitable for the removal of heavy metals (Cr (VI), Cd (II), Ni (II), Hg (II), and Pb (II)) onto carbon-based adsorbents. Oxygen-containing functional groups have an impact on the hydrophilicity, catalytic attributes, and surface character and reactivity of carbon [66]. Several other functional groups (-C=N-OH, $-CH_2$, -P-O-C, -C=C, $-O-CH_3$) can also be introduced onto an adsorbent to promote adsorption. Sulfuric functional groups significantly enhance heavy metals performance (Cu and Cd ions) adsorption by deposition of elemental sulphur on carbon surfaces by forming hydrogen sulphide ($-H_2S$), sulphates, and thiophenes.

3.4 Effect of competing ions and ionic strength

The adsorption efficiency of unmodified biochar was low in the case of Pb^{2+} removal. It emphasises the importance of electrostatic interactions of Pb^{2+} onto char, having little effect on both pH and ionic strength on the removal of lead. This may be due to the influence of the precipitation mechanism [67]. The effect of competing ions in the case of sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^+), and using KCl, $MgCl_2$. $CaCl_2$ and NaCl solutions on adsorption of NH^{4+} onto biochar. These ions are commonly found in industrial and municipal wastewater and compete for Cu (II) and Zn (II) to be available at adsorption sites [68,69]. The effect of competing ions focused mainly on sulphate, phosphate, and chloride, with no effect on the carbonate group. Anions with a greater tendency to maintain ion exchange interactions (sulphate and chloride) [70] with active sites of ammonium groups on activated carbon demonstrated a remarkable inhibitory impact, according to the removal efficiencies of nitrate and Cr (VI). Competing cations and anions play a vital role in adsorption, as shown in **Fig. 4.**

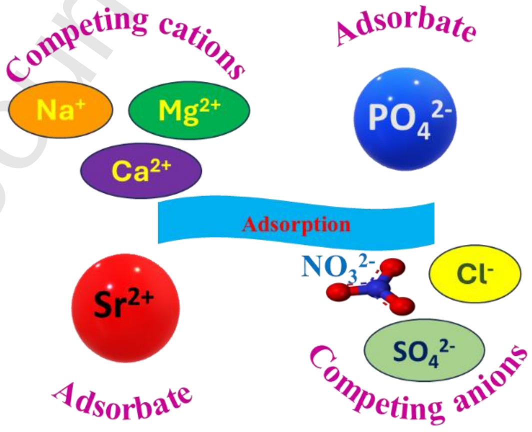


Fig. 4. Effect of competing cations and anions on adsorption of biogenic hydroxyapatite and commercial exchange resins, respectively.

3.5 Effect of adsorbent dosage

The dosage of adsorbent should be optimised for good adsorption results. It was observed that an excessive dosage of adsorbent (Zn2PT350-700) may result in low removal efficiency, and a minimum dose of adsorbent may lead to poor removal performance [58]. Studies demonstrated that for both unmodified and activated biochar, removal rates of Pb^{2+} increased with adsorbent dosage [67]. Unmodified biochar and activated biochar dosage was increased to 20 g/L and 2 g/L, respectively, to achieve similar lead removal efficiency. This concludes that activated biochar is better than raw biochar [87]. The removal efficiency of nitrate rose linearly when the sorbent dosage was increased up to 5 g/L; however, beyond that, the removal efficiency increased, but capacity decreased (due to unsaturated adsorption sites). **Table 1b** lists the effect of different adsorbent dosages on the removal of pollutants.

Table 1b. The impact of the adsorbent doses on biochar's adsorption capabilities.

Adsorbent	Adsorbent dose	Adsorbate/Pollutants	Adsorption capacity	Specific findings	References
Calcium-rich crab shell biochar	0.50 g/L	Malchite green Congo red dye	12502 mg/g 20317 mg/g	The adsorbent's distinct multi-layered structure, high I_D/I_G ratio, high zeta potential, and low C/N ratio may make it easier for dyes to bind to it.	[71]
Cellulose-based adsorbent biocomposite film	30 g/L	Methylene blue dye	146.81 mg/g	Because of the rough surface, the SEM image would function as an adsorption site and robustly transport dye molecules, it could improve the ability of biocomposite films to adsorb substances.	[72]
Date palm fronds biochar	2-20 mg/L	Methyl orange dye Methylene blue Eriochrome black-T Crystal violet	163.13 mg/g 934.57 mg/g 309.59 mg/g 206.61 mg/g	The pH-independent adsorption of cationic dyes suggests the participation of π-π and chemical interactions.	[73]

3.6 Effect of the impregnation ratio

The impregnation ratio is the most crucial parameter in the chemical modification technique. With an increase in impregnation ratios, the shapes of isotherms could change systematically, indicating a significant amount of mesopores in the carbon sample followed by a rise in the hysteresis loop [74]. In a recent study, a detailed analysis of functional groups and FTIR spectra revealed that surface chemical modification of MH-500 (mustard husk procured at 500 ℃) with $ZnCl_2$ impregnation ratios ($ZnCl_2$: char) of 1:1 and 2:1 is reported. Studies revealed that MH-500 (2:1) with acidic functional groups and -C=O moieties are responsible for nitrate adsorption with an efficiency of 45% in 5 h [75]. **Table 1c** lists the impact of the impregnation ratio on biochar's adsorption capabilities.

Table 1c. Effect of impregnation ratio on adsorption performance of biochar.

Adsorbent	Impregnation concentrations/ratio	Adsorbate/Pollutants	Adsorption capacity/ Removal efficiency	Specific findings	References
				.	[76]
Cucumis-derived activated carbon	H_3PO^{4-} 1.50 to 2.50 mol/L	Methylene blue Acid orange 07 dye	99.40 % (MB) 94.20% (AO7)	These low values de CV clearly show that the difference between the experimental and predicted values is slight and confirms the reliability of the models developed.	[77]
MgO-modified rice husk biochar composite	0.6:20 (MgO: biochar)	Cd (II)	Unmodified-6.36 mg/g, Modified-18.10 mg/g	When the MgO-BCR composite merged with water, the MgO on its surface likely underwent hydroxylation.	[78]

3.7 Effect of Initial Concentration

The increase in adsorption potential with initial nitrate concentration ranging from (2.20 to 25.60 mg/g) using modified grape seed biochar. A higher driving force or gradient overcomes mass transfer resistance between solid and liquid phases, which may be achieved by using higher nitrate concentrations [79]. Adsorption removal efficiency (53 to 19%) decreases with a significant increase in initial ammonium concentration. An increase in removal efficiency relates to the saturation of the adsorption active sites of the bentonite surface area. In addition, at very high initial concentrations, the removal capacity remains constant [80]. **Table 1d** lists the Impact of initial adsorbate concentration on biochar adsorption efficiency.

3.8 Effect of Contact Time and Flow Rate

The quantity of 1-butyl-3-methyl-imidazolium chloride that has been adsorbed ([BMIM][Cl]) increases swiftly with time at the primary phase of adsorption, which forwards the mechanism with available sites on the adsorbent surface [81]. For recovery and retentions of the ions Co (II), Mn (II), Ni (II), Cr (III), Cd (II), and Pb (II)) In a recent study, the effect of flow rate on immobilised multi-walled P. aeruginosa biosorbent was examined. All the analytes were retained between the 1-6 mL/min flow rate range [100]. An alternative method for eliminating the neurotoxic Pb (II) (heavy metal) from a flow-through system was examined in a different investigation [82]. The flow rate of 2 and 4 mL/min is maintained; further increase in breakthrough time was shortened due to the flow rate and increased adsorbed rate (Pb) on the unit bed height, which further enhances the mass transfer coefficient, resulting in fast saturation. When the flow rate is increased, the contact time between the adsorbent in the column and the Pb (II) ions is inadequate, resulting in a much lower maximum and equilibrium capacity (32.18 mg/g) compared to the higher capacity (88.86 mg/g) observed with a reduced flow rate [82].

Table 1d. Impact of initial adsorbate concentration on biochar adsorption efficiency

Adsorbent	Initial adsorbate concentration	Adsorbate/Pollutants	Adsorption capacity/ Removal efficiency	Specific findings	References
Wood derived biochar	50 and 75 µg/L	β-endosulfan	223.10 mg/g	The rise in inlet concentration led to a reduction in pesticide adsorption. This method can be scaled up from a laboratory setting to an industrial level.	[83]
Rice straw biochar	0-20 mg/L	Cd (II)	Pristine biochar-12.17 mg/g KOH Modified-41.90 mg/g	The process involves the formation of insoluble cadmium compounds under alkaline conditions, which leads to surface precipitation.	[84]
MgO-modified rice husk biochar composite	20-160 mg/L	Cd (II)	Unmodified-6.36 mg/g Modified-18.10 mg/g	The fitting results showed that the MgO-BCR acceptor site normally accepts one Cd (II) ion at different temperatures, with the number of ions per site ranging from 0.97 to 1.09.	[78]

3.9 Specific surface area (SSA)

Shaddock peel-derived biochar was chemically modified with $ZnCl_2$ (2:1 ratio) and was tested to remove methylene blue dyes. Modified biochar showed pore size (3.05 nm) and the highest specific surface area (2398 m^2/g) with the highest adsorption capacity (869 mg/g) to MB [85]. The specific surface area and porosity have been enhanced by zinc chloride modification. The presence of inorganics and metal compounds in water can interfere with the discharge of volatile materials during the biochar-producing process of pyrolysis. The biochar's specific surface area and active site count may both drop because of this interaction. This interference can result in a reduction of active sites and a decrease in the specific surface area of the biochar. This is important because active sites and specific surface areas are key factors that contribute to the effectiveness of biochar [103]. For supercapacitors, organised graphene aerogel sheets were incorporated into porous carbon foam to maximise the specific surface area. Comprehensive examinations of the morphology, structure, and electrochemical characteristics verified that the specific surface area (682.80 m^2/g) is successfully increased by the addition of graphene aerogels, shown in **Fig 5** [86].

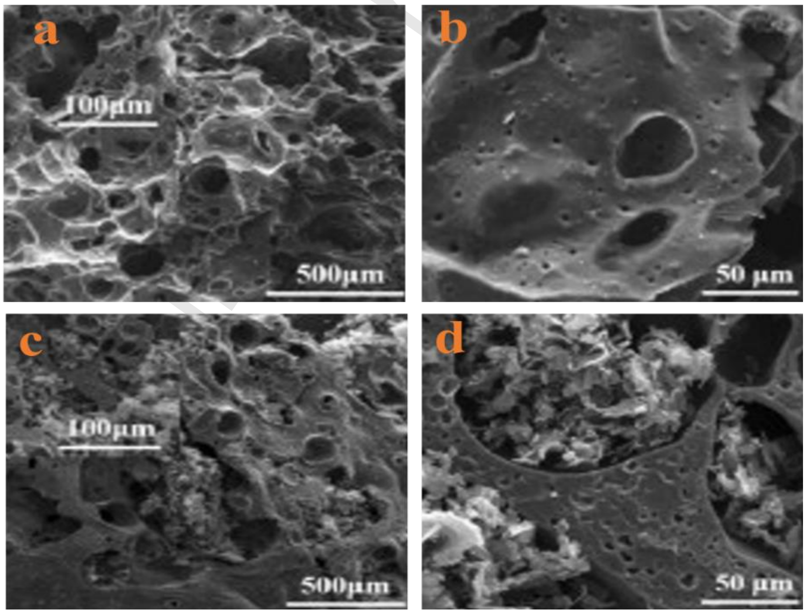


Fig. 5. SEM images of porous graphene aerogel sheets [86].

4. Perspective towards existing and advances in water treatment technologies

Approaches for water treatment technologies have been instrumental in meeting the growing demand for clean water and addressing the elimination of several contaminants. One significant advancement is in membrane filtration technologies. Reverse osmosis (RO) uses semipermeable membranes to remove ions, molecules, and larger particles, making it highly effective in desalination and contaminant removal [87]. Nanofiltration (NF) provides a finer filtration process compared to RO, selectively removing multivalent ions and organic molecules, often used for softening water and removing specific contaminants.

Electrocoagulation uses electric currents to coagulate contaminants into larger particles that can be easily filtered out. Electrodialysis (ED) employs electric potential to move ions through selective membranes, making it useful for desalination and ion removal from water. These methods are gaining attention for their efficiency and effectiveness in various water treatment applications [88]. Biological treatment technologies continue to evolve, offering sustainable solutions for water treatment. Constructed wetlands mimic natural wetlands to treat wastewater through microbial degradation, plant uptake, and natural filtration processes. Nano adsorbents, such as carbon nanotubes and graphene, have high surface areas and reactivity, making them highly effective in adsorbing contaminants. Hybrid systems integrate multiple treatment processes to enhance overall efficiency and adaptability. Integrated treatment systems combine various methods, such as AOPs, biological treatment, and membrane filtration, to provide comprehensive water treatment solutions that can adapt to varying water quality needs. Overall, the treatment technologies of water encompass a broad range of innovative methods, from membrane filtration and advanced oxidation processes to electrochemical methods, biological treatments, nanotechnology, hybrid systems, and biochar-based technologies, **Fig. 6, and Table 2 (a, b and c)** lists the various technologies available to treat waste and wastewater. Soluble contaminants (organics and metals), nutrients, organic matter, and colloids are removed from effluents through these treatments [3].

An assessment of several existing water treatment technologies indicates that much research is needed to improve the efficiency and sustainability of existing technologies and address the challenges in water quality. With futuristic perspectives, there is a need to bridge a gap between existing and emerging water treatment technologies. Advanced techniques that combine green nano remediation, improved remediation using integrated methods, UV photo-Fenton processes, advanced phytoremediation, and biocatalysts have achieved significant success in removing polycyclic aromatic hydrocarbons (PAHs) from solid waste and leachates, which have overcome the currently available methods of treatment such as extraction, chemical oxidation, bioremediation, and photocatalytic degradation. Remediation methods can involve integrated chemical-physical (e.g., chemical oxidation, solvent extraction), biological-physical (e.g., bioremediation, solvent extraction), and biological-chemical (e.g., bioremediation, chemical oxidation) processes. Therefore, through the synthesis of nano-oxidizers for PAH oxidation, green nano remediation should be researched and merged with well-established techniques like chemical oxidation and the Fenton process, developing the potential for commercialisation. Currently, technologies for treating Acid mine drainage (AMD) are categorised into source prevention and final treatment [112]. Advances in physical and physicochemical techniques offer several advantages such as compatibility with various dyes, straightforward design, ease of operation, compatibility with various dyes, minimal chemical usage, and no inhibitory effect in the presence of toxic or harmful compounds with limitations such as the production of hazardous byproducts. Adsorption has always achieved attention when compared with conventional water treatment processes because of its least initial investment, recovery and recycling of adsorbents, high efficacy, and simplicity of operation. However, challenges persist in additional research due to industrial scale uses, such as evaluating the operating lifespan and the capacity to regenerate adsorbent materials. For handling dye-containing wastewater, the biological microbiological method makes use of bacteria, fungi, algae, and yeast outperforms physical, physicochemical, and chemical approaches. It is generally recognised, economical, and ecologically acceptable, even if it calls for longer hydraulic retention periods (HRT) [89]. Further research into optimising various combinations of biological-chemical or biological-physicochemical technologies could yield significant future benefits, enhancing treatment efficiency, reducing operational costs, and minimising environmental impact. To improve the efficiency of existing treatment processes, these technologies utilise novel physio-chemical, biological, and modified oxidation processes [90]. However, future research could integrate fluorescent spectrometry since no technique can currently remove pharmaceutical contaminants from wastewater successfully., Recent advances in anaerobic processes include the construction of unconventional bioreactors, such as bio-electrochemical systems (BES), and the integration of pre-and post-treatment methods with chemical and biological additives to enhance bioreactor performance. Treatment of wastewater, which is more sustainable and efficient, results from integrating these advancements with conventional anaerobic bioreactors. Also, research is explored on reverse osmosis (RO) processes integrated with pressure retarded osmosis for capturing energy from waste. Technological advancements in membrane-based desalination and water treatment have improved the sustainability of these systems [91].

Probable advances in physical treatment technologies are proposed: innovation in optimising electrocoagulation techniques by combining them with plasma technology to enhance the scalability of the process for broader applications [92]. A recent study has addressed the advances in the application of low-temperature plasma technology integrated with the oxidation process for wastewater treatment [93]. On critical assessment, a few suggestions to overcome these gaps for future research in this direction can be: Considering reactor geometry, residence time and kinetics, fluid dynamics, and operational controls Thus, there is a need for the implementation of these strategies tailored to specific operating parameters to achieve a uniform reaction mechanism.

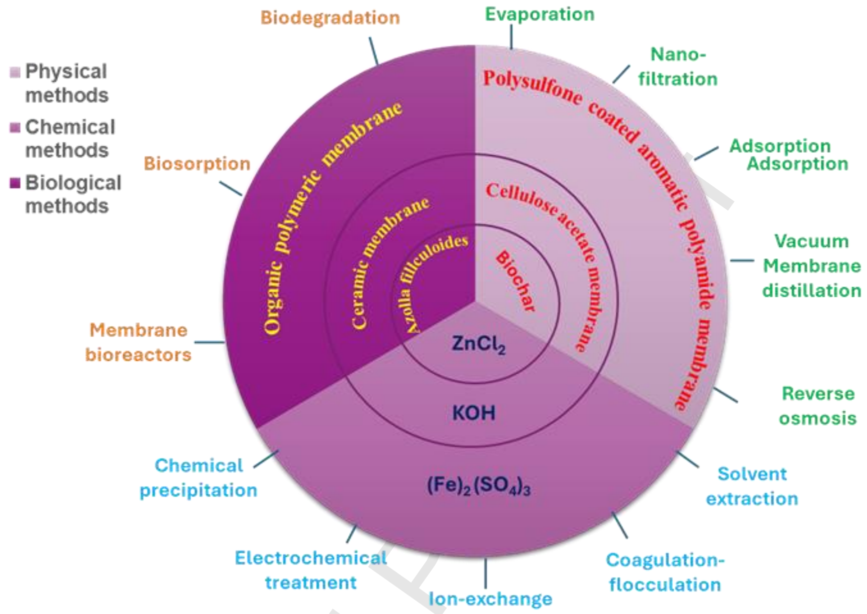


Fig. 6. Classification of potential pollutant removal technologies.

Table 2a. Physical treatment technologies for the removal of pollutants.

Treatment methods	Pollutants	Findings	Limitations	References
Nano membrane technology	Chromium	• The nano-zero valent ion lowered the pH and redox potential of the prepared solution. • High removal efficiency with low waste production.	• The bandgap dependency and interfacial charge transfer would limit the removal effectiveness of Cr (VI).	[13]
	Phosphorous	• Hybrid nanotechnology results in low cost and high recovery efficiency up to 75%.	• Limited phosphorus selectivity because wastewater contains competing anions, primarily sulphates. • The economic feasibility of regeneration is limited by the high chemical requirements and the low potential for solution valorization. • Lacks in designing the area.	[11]
Vacuum membrane distillation	Hypersaline water	• A superhydrophobic membrane based on polydopamine nanoparticles has excellent anti-pollution and resistant properties, making the membrane more abrasive.	• The feed solution contains numerous impurities that may precipitate on the membrane surface and cause membrane	[94]

		• The hydrophobic PDMS layer increases the membrane's hydrophobicity and secures the nanoparticles in place.	wetting. • The method for coating nanoparticles entails intricate multi-step procedures and difficult process control, as well as an unstable bond between surface particles and the membrane substrate.	
	Heavy metals (Zn, Cu, Ni, and Ca)	• VMD process resulted in good acid resistance (pH >0). • Calcium and EDTA influenced the performance of VMD.	• Calcium and EDTA content need to be controlled.	[18]
Reverse osmosis	Nicosulfuron, naphthalene trisulfonic acid, and naphthalene disulfonic acid (Micropollutants).	• Neutral chemicals' transit was inversely related to their size. In contrast to neutral hydrophilic MPs, this association was weaker for neutral hydrophobic MPs. • One-way analysis of variance (ANOVA) evaluated their passage of the relationship between the physical and chemical properties of MPs. • By increasing the average passage of	• It has been established that determining the MP removal rate is a high-priority issue when it comes to contaminated drinking water. • The passage varied for several molecules with molecular weight less than 140 Da.	[95]

		MPs by 6.5%, water temperature rises from 5 to 19 °C.		
	Cr (III)	• Pollution-free, high removal efficiency, and lower energy consumption.		[13]
Evaporation	Organic dyes	• The porous network structure of the rGCPP (Reduced graphene composite solar steam generator offers more active catalytic sites for photocatalysis and water evaporation with high efficiency for dye degradation. • The rGCPP-based interfacial solar-driven steam production system achieves a high evaporation rate of 1.87 kg m^2/h and a solar-to-vapour efficiency of 81.07% under 1 sun irradiation by merging photocatalysis and solar steam generation.	• Complicated manufacturing methods in addition to the material's efficiency.	[96]
	Pb-Ag alloy	• No chemicals added • Simple assembly with convenient	• High energy (Pumping energy to convert the liquid to vapors)	[97]

	operations	• Waste disposal and scale formations. • Requirements of large space.

4.1. The perspective towards physical water treatment technologies

Conventional physical methods have always been prioritised before the recent technological advancements were implemented. Our vision and knowledge about the removal of emerging contaminants in conventionally treated wastewater have enhanced expeditiously in the past few decades. One of these technologies, nanomembrane filtration, can be merged with reverse osmosis, a physical adsorption process, with other technologies like ion exchange and flocculation process for a hybrid water treatment approach. The vacuum membrane distillation technique is widely used in heavy metal removal at low energy consumption. Still, due to issues such as possible failure in operating semi-solids and solid extracts, it is necessary to equip the process with a tool that deals with solids **(Table 2a)**.

4.2 The perspectives towards chemical water treatment technologies

The selection of an appropriate treatment method relies on the level of contamination of wastewater **(Table 2b)**. Ozonation [98], Fenton's process [99], H_2O_2/pyridine/Cu system, ultrasonic irradiation, and photocatalysis are some of the advanced oxidation processes (AOP) (physiochemical methods). Various constraints include cost management, feasibility, reliability, efficiency, practical approaches, environmental impact, sludge and scale formation, operational management, pre-treatment necessities, and formation of highly toxic by-products [3]. However, AOP is an excellent technique for degrading colours from wastewater because of its affordability, efficiency, reduced pollutant load, and higher water reusability [89]. AOPs are based on the hydroxyl axis and other radicals that oxidise non-biodegradable and toxic by-products. They are costly due to the chemical costs but are economically feasible. UV/H_2O_2 process can readily destroy the Cu-EDTA and has been proven to be more effective than direct photolysis [100]. Still, many hybrid and individual chemical treatment technologies lack applicability in industrial wastewater treatments.

Research indicates that adsorption technology has addressed some of the drawbacks, like lower removal efficiency of metal ions at low concentrations, operational difficulties, disposal problems, high sludge formation, high cost, and energy use associated with the conventional treatment processes. More importantly, more insights regarding the transformation processes occurring in conventional wastewater treatment are needed to understand the potential of different techniques in the removal of various contaminants. The assessment of treatments such as coagulation, flocculation, chlorination, and other AOPs indicated stability issues when a part of a hybrid system; therefore, before full-scale treatment plant stabilisation, it is essential to gain a proper understanding of the system by working in laboratory scale.

4.3 The perspectives towards biological water treatment technologies

Biological treatment technologies mainly include membrane bioreactors, biosorption, biodegradation, and microbial fuel cell technology. A summary of a few studies is reported in **Table 2c**. To increase the effectiveness of microorganisms in the biodegradation method, there is a need to optimise various key factors. i) Regular monitoring to ensure temperature, pH levels, and nutrient availability, which supports the efficiency and growth of the microbial community, ii) optimisation of reactor's hydraulic retention time (HRT) by increasing the contact time between the microbes and contaminants and (iii) adjusting the flow rate to promote and fasten the microbial activities. Moreover, these strategies may enhance the overall efficiency of the biodegradation process, and much research is needed to explore new microbial strains or pathways for enhancements in these promising technologies and examine the sensitivity of contaminants and operational complexities for the biological treatment processes. In several biological and chemical methods, slow kinetics, low biodegradability of dye molecules, and poor decolourisation reduce its applicability. High dependence on pH, low throughput, formation of by-products, energy-intensive and high-pressurised conditions, and excess quantity of concentrated sludge produced limits these processes.

Table 2b. Chemical wastewater treatment processes.

Treating methods	Pollutants	Findings	Limitations	References
Ion-exchange	Pb and Cd	• Mg-modified biochar has a higher affinity for removal than unmodified biochar. • Q_e for Pb^{2+}/Cd^{2+} is 50 times that of unmodified biochar.	• Economic constraints initial cost, regeneration time-consuming.	[25]
	Phosphorous	• Hybrid ion-exchange nanotechnology results in low cost and high recovery efficiency up to 75%.	• High environmental risk during regeneration of ion-exchange bed.	[11]
Coagulation/ flocculation	Cu, Hg, and Cr.	• Cu, Hg, and Cr were removed by 60%, 50-80, and 87% respectively.	• Non-reusable coagulants, flocculants, and chemicals are required. • Increased sludge/waste volume generation • Treatment and operating costs are high.	[16]
	Natural organic matter residuals	• The efficiency of organic matter increased to 37.40% following the addition of polyelectrolyte under a cold environment. • The PACl dose had a significant negative influence on the NOM concentration when the	• (MACs) are found on average. • Furthermore, for iron and turbidity, the highest reported readings were about five times higher than the MACs.	[101]

		mixing circumstances were optimal, and the coagulant aid was present. • The change in coagulant dosage had a considerable effect on the amount of residual aluminium in the water when it was cold. • Coagulation-flocculation tests conducted in less-than-ideal mixing circumstances had an efficiency similar to coagulation trials conducted without coagulant help, according to principal component analysis.		
Electrochemical treatment	Cr	• Simple, productive, and easy to operate for removal of Cr. • Efficiency with the electrochemical treating process is 3 times higher than the chemical coagulation.	• High initial equipment and maintenance costs (anodes and cathodes). • Sludge deposition on the electrodes inhibits the electrolytic process in continuous operation. • Increase in anode passivation	[13]
Chemical precipitation	Zn (II) and Cu (II)	• The precipitating agent soda ash can be a reasonably priced solution for Cu (II) and Zn (II) in the cable industry's industrial effluent.	• Chemical precipitation generates precipitates that must be removed in a subsequent treatment step. • Possibility of metals precipitating or	[102]

		- Copper has higher removal efficiency than zinc.	binding to solid particles during the co-precipitation process with calcite formation at high pH and low solubility.	

Table 2c. Biological wastewater treatment processes.

Treating methods	Pollutants	Findings	Limitations	References
Biosorption	As (V) and As (III)	- Eggshell and java plum seeds have the best capacity to extract As species from drinking water polluted with As, according to a pilot-scale study. - Using biosorbents is a more cost-effective choice than activated carbon (U $1500/ton), as their production costs might vary and go up to U $386/ton. - Fast kinetics with developing an affordable, long-lasting, and efficient filtering system.	- Negatively charged biosorbent, which causes its sorption to decrease as pH rises (8-10).	[103]
	Cu and Pb	- The concentrations of the electrolytes in the solution affect the adsorption of both metal ions. - Wood biochar is considered the most promising low-cost and effective biosorbent for treating	- Requires management and maintenance of physiochemical pretreatments.	[104]

		these toxic elements.		
Membrane bioreactors	Phosphorous	• The total P-removal rate in batch-moving bed membrane bioreactors was approximately 84%. • P-removal using granular sludge in a single system under anaerobic-anoxic conditions.	• Lack of achievement of high efficiency with minimal use of chemicals and energy sources.	[105]
	Sewage sludge	• Second-stage microbes participate in the efficient removal of contaminants. • Membrane bioreactors permit oxygen to permeate into the biofilm and promote the growth of organisms that dissolve organic and inorganic matter.	• Operation cost is high.	
Biodegradation	Organic contaminant	• Biodegradation of microorganisms is simple, cost-effective, and widely applicable. • Microbial organisms transform organic matter through metabolic processes.	• Low biodegradability • Excess generation of biological waste/sludge and degraded products.	[3]

5. Adsorption-Burgeoning technology

Factors that affect the sorption process incorporate (i) initial adsorbate concentration and its nature (ii) solution pH, (iii) specific surface area of solid (SSA), (iv) Dose and nature of adsorbent, (v) temperature and other operating conditions [57]. To remove heavy metals and other contaminants, initial sorption capacity was enhanced significantly after oxidation with Alkali-HNO_3, NaOH, $KMnO_4$, NaClO, and numerous other chemical solutions.

5.1. Adsorbents

Adsorbents are extensively utilised to eliminate nutrients, hazardous metals, and organic contaminants from wastewater [106]. An adsorbent is a substance that binds and holds molecules of gases, liquids, or dissolved solids on its surface. It is widely used in environmental cleanup, purification, and separation due to its high surface area and ability to selectively remove contaminants or impurities [106]. In general, adsorbents are categorised into the following types.

5.1.1. Biochar

Biodegradable organic waste materials such as agro-residues, fruit peels, straw, husk, wood pulp, bagasse, seaweed, manures [107,108], kitchen waste [109], jackfruit, rice husk, maize cob, hazelnut shell [13] and organic MSW [110] were used as feedstock for producing biochar. Biochar is an environment-friendly (biodegradable), effective, stable, biocompatible, highly aromatic, and low-cost adsorbent with high surface area and significant surface functional groups highlighted in **(Table 3)** [111]. Chemical modification of biochar may improve its sorption ability compared to unmodified biochar. In general, activation can be achieved by controlling pyrolytic operating conditions and physiochemical modification [112]. So far, several studies have been carried out to compare unmodified and modified char obtained from agro-residues, which hindered commercial application as an adsorbent along with activated carbon [113]**.** Biochar yield is maximum in slow pyrolysis configuring heating rate of 20-30℃, residence time for many hours [107]. Activation methods for engineered biochar concerning their adsorption phenomena are alkali-treated biochar and gas/steam-activated biochar, which cover pristine biochar to engineered ones on chemical modification [143]. Engineered biochar has a higher surface area, adsorption capacity, and high quantity of surface functional groups (SFG) than pristine and unmodified biochar [106]. In a recent study by Jang and Kan, the authors used alfalfa hay-derived biochar to extract tetracycline (TC) from water [114]. For effective and economical phosphate (PO_4^{3-}) removal, biochar can be modified magnetically by slow pyrolysis [145]. An abundant amount of oxygen functionalities leads to good adsorption. Eggshell biowaste-based sorbent is used to remove nitrate from groundwater. The results showed the highest nitrate removal capacity (8.25 mg/g) with 1500 mg/L of initial nitrate concentration in both batch and column studies at a drying temperature of 45℃ and particle size between 90 and 710 μm [9].

5.1.2. Activated carbon

Activated carbon (AC) is a carbon-rich adsorbent material with an extensive adsorption capacity range and effective removal rate [147]. To date, thousands of articles have reported research in adsorption using biochar and activated carbon (synthesised and commercial) as adsorbents. It was observed that at a higher pH range, the adsorption capacity for AC is better, and for a lower pH range, biochar proved better in glyphosate adsorption (temperature above 40-50 °C). Biosorption for heavy metals removal is a promising process with significant benefits like low cost and excellent efficacy. Sources of biosorbents are (1) microbial biomass (fungi, yeast, and bacteria), (2) algal feedstock, and (3) non-living biomass such as eggshell, lignin, shrimp, bark, etc [115]. Bacteria includes *Escherichia coli, Pseudomonas aeruginosa, Bacillus cereus* [89]. Biomass of *Rhizopus nigricans, Oscillatoria anguistissima, Streptomyces sp, Aspergillus niger, Penicillium chrysogenum, and Bacillus firmus.* have reported the highest metal (Ni, Cr, Cd, Pb, Zn, Cu) adsorption capacity in range 500-600 mg/g. **Table 3** demonstrates that research has explored the potential of biochar as an adsorbent for a variety of pollutants found in wastewater. Though biochar is seen as an alternative to conventional activated carbon, it needs to be further explored for numerous pollutants. In addition, from the studies reported for using chemically modified biochar in water treatment, it can be inferred that using activation agents such as H_3PO_4, $ZnCl_2$, KOH, Al, and NaOH could result in high sorption capacity because of the existence of oxygen and -OH functional group.

Saturated AC regeneration is essential for reducing product waste and operating expenses. Because the separation and recovery steps of powdered AC are costly, time-consuming, and inefficient, they are not appropriate for industrial applications, which makes the reusability of synthesised AC after regeneration extremely difficult [116]. The service life of the ACs is also short when it is bonded or filled with contaminants [117]. ACF has better adsorption rates and more porosity than other types of ACs. The type of reactor to be used determines whether one of the two AC formulations, powder (PAC) or granular (GAC), is most suitable. Despite being suitable for column (fixed-bed) and stirred-tank reactors, GAC is employed to remove organic compounds from water and wastewater. Future research needs to be focussed on identifying routes to produce carbon-based adsorbents cost-effectively.

Table 3. Significant contributions highlight the application of biochar as an adsorbent to remove nitrogen, phosphorous, heavy metals and other pollutants from aqueous solutions.

Adsorbate	Adsorbent	Operating Conditions	Specific findings	References
Nitrogen, Phosphorous, and heavy metals	Agricultural residue-derived biochar	Pyrolysis temp – 450 ℃ Dose (biochar)- 1 g/L Initial adsorbate concentration- 100 mg/L	Engineered biochar has a significant surface area, adsorption capacity of 435.70 mg/g, and carboxyl and oxygen-containing Surface functional groups (SFG).	[106]
Humic acid, fulvic acid, and tyrosine-like substances	Wetland biomass-derived biochar	Temperature- 20 ℃ Biochar dose- 1 gm Extraction fluid- 20 mL, 150 rpm, Muffle furnace temp- 500-700 ℃	At moderate pyrolysis temperatures (300-500 °C), larger DOM was liberated from biochars than at elevated pyrolysis temperatures (600-700 °C).	[59]
Copper, Zinc, Lead, Arsenic, Chromium, etc.	Waste adsorbent	Specific UV adsorption- 254 nm, Adsorption capacity- 79.90- Initial adsorbate concentration -148.00 mg/L Surface area- 1150.00 m^2/g Time of adsorption- 0.50-48 h Membrane filter- 0.45 µm	Due to the constant availability of raw materials, blending different waste materials for absorption purposes may be more appealing for industrial uses.	[118]

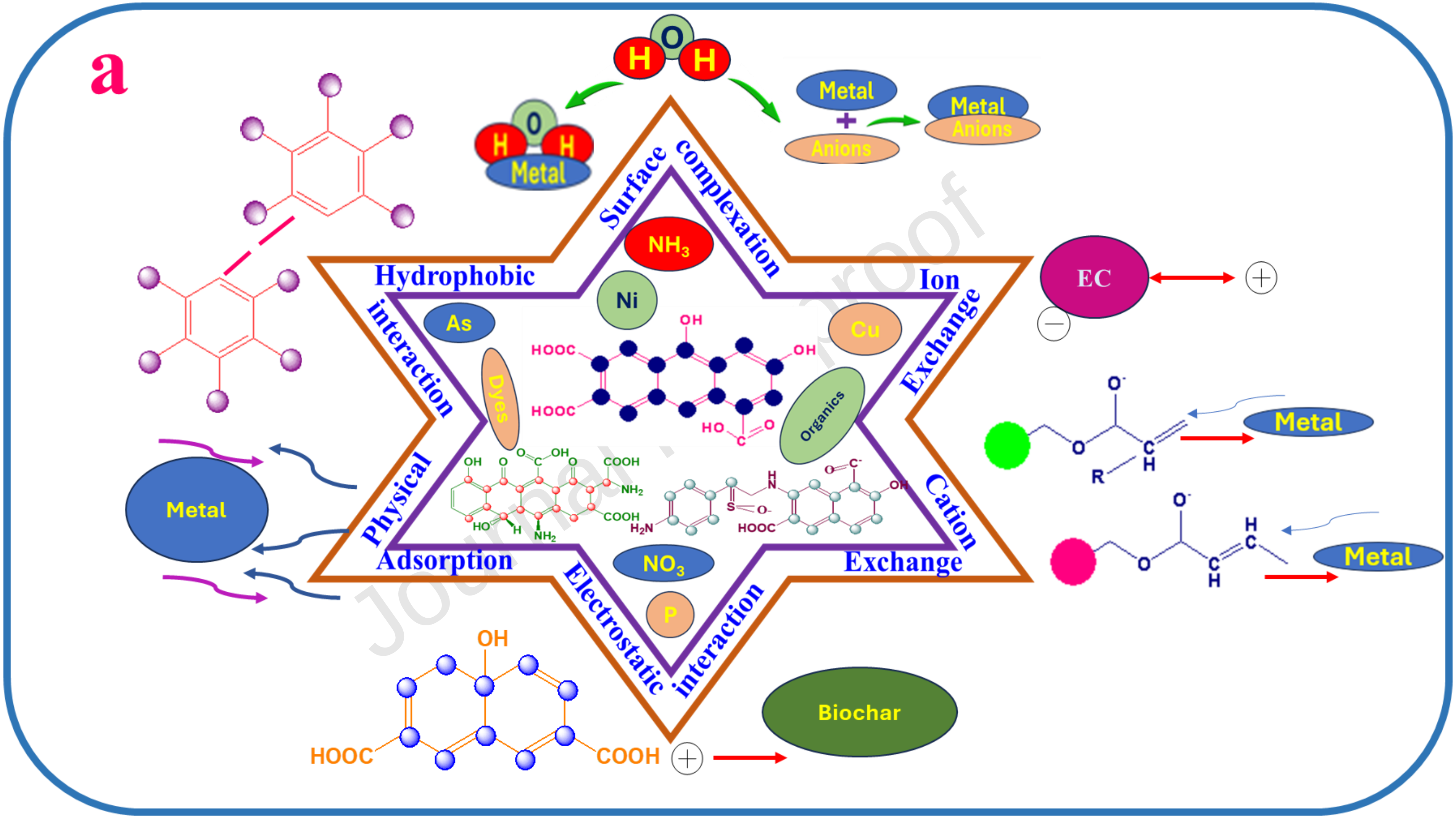
Manganese (Mn)	Bio waste derived biochar	Adsorption condition pH- 6 Temp. -298 K Contact time - 3 h	A tessellated carbon surface is seen in crater-like structures.	[119]
Cr (VI)	*Enteromorpha prolifera-derived* biochar	Langmuir model- 88.17 mg/g Removal efficiency -97.71%, Initial adsorbate concentration - 100 mg/L Muffle furnace temp.-400 or 600 °C Rate - 10 °C min^{-1}, 2 h. Room temperature - 25 °C	The surface of the modified biochar was less porous and included numerous γ-Fe2O3 particles. The Langmuir model yielded a maximum adsorption capacity and was best fitted among other isotherm models.	[120]
Cadmium (Cd), lead (Pb), and dibutyl phthalate (DBP).	Bamboo- and pig-derived biochars.	Methanol solution- 200 mL DBP - 900 mg of every 3 kg of soil. Initial concentration - 300 mg DBP with Soil- 1 kg Incubation temp- (25 ±1°C)	Given that Pb has a larger specific surface area, surface alkalinity, pH, and mineral content than BB. It may be more effective than BB for minimizing the leaching of DBP, Cd, and Pb in the LOC soil.	[121]
		pH ranging from 6.2-6.8, Solubility (water) ~34 mg/L		[122]
Food waste	Wood waste	Rpm- 900 rpm (2 h) Pyrolysis-	The surface chemistry of the catalyst had an impact	[123]

	biochar	400-700 °C for 2 h, Energy consumption (Ball mill) - 0.50 kWh, Annealed at 500, 750, 900 °C under N_2, 1000 °C. Heating rate (Argon atmosphere)-10 °C/min	on how Sn interacted with the carbonaceous supports. SnO_2 was visible following annealing at 500 °C, and at elevated temperatures, it changed into metallic Sn.	
Heavy metals (Cu and Zn).	Swine manure biochar	Muffle furnace- 550 °C Heating rate -10 °C/min, 2h (anaerobic), Shaking -170 rpm- 24 h, Temperature- 400 °C, Gas Flow rate (Desolvation)- 600 L/h; Flow speed of cone gas: 50 L/h	Mn-BC was highly effective in removing Zn and Cu. Using Mn-BC, it was possible to observe removal efficiencies of 83.98%, 83.76%, and 77.34% for arsenic, sulfadimidine, and tylosin, respectively.	[124]
Cadmium (II)	Mango peel waste-derived biochar	Initial adsorbate conc. - 10–300 mg /L Contact time- 2880 min, pH range- 2–8 Biochar dosage-1–20 g /L Adsorption capacity-13.28 mg/g, adsorption efficiency-	There was a drop in the molar ratios of H/C, O/C, and (O + N)/C. This study employed batch adsorption tests for Cd (II) adsorption. Pseudo-second-order kinetics and the Langmuir isotherm models fit the data better than other alternative models.	[125]

		67.70%.		

6. Mechanism of heavy metals/ pollutants removal

Depending on the aqueous solution's ionic phenomena, pH, adsorbate type, heterogeneity, chemistry, and reaction mechanism on the carbon surface, the intermolecular interactions between heavy metals and functionalities are complex [126]. The processes of ion exchange, physical adsorption, surface complexions, and precipitation are involved in the adsorption of heavy metals on carbon sorbents [66]. The mechanism for the removal of emerging contaminants is highlighted in **Fig. 7 (a) and (b)**. Using an in-situ sorption-reduction-precipitation technique, specific high-valent metal ions, such as Cr (VI), can be reduced to low-valent metals, such as Cr (III), and precipitate on biochar. It is possible to ascertain the precise mechanism of the binding activity by comparing the surface functional groups of biochar before and after the adsorption of metal ions. A nano-magnetite-modified biochar material system was developed via microwave in-situ rapid synthesis, achieving an elevated Cr (VI) sorption capacity of 9.92 mg/g, significantly surpassing the original biochar's capacity of 8.03 mg/g [127]. In another study, the authors examined cations such as Ca and Mg released from the biochar into the solution, and the sorption of Cr (III) was linked to cations. This suggests that the cation exchange process was the primary mechanism for sorption. Also, the surface complexation mechanism was dominant in Hg sorption from water by hickory chips and bagasse-derived biochar [128].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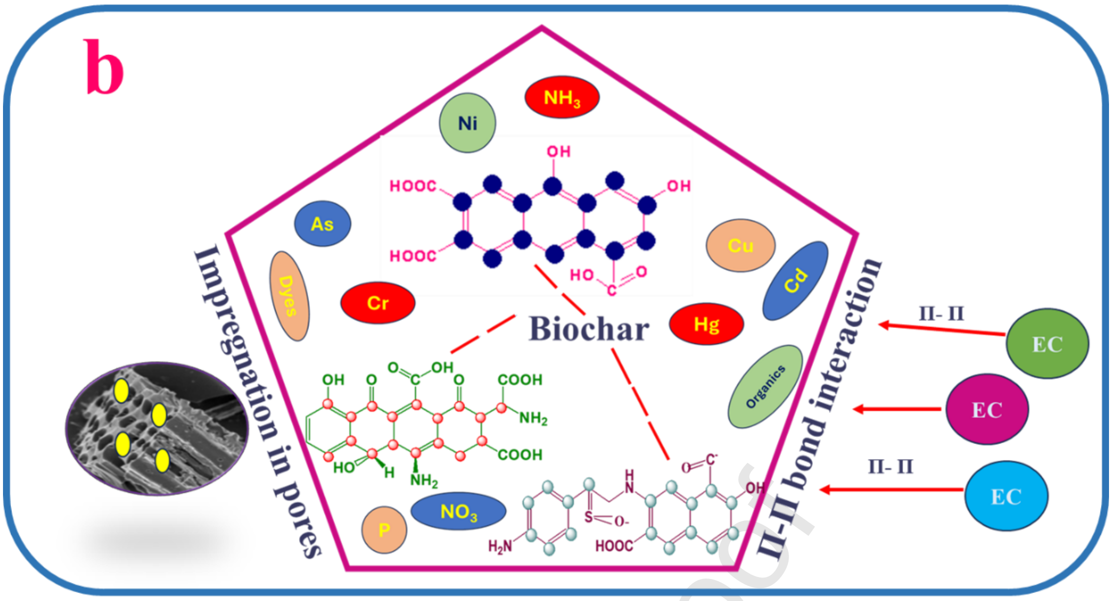

Fig. 7 (a) and (b): Schematic illustration of the processes used by biochar to remove emerging contaminants (EC) (heavy metals, nitrate, phosphorous, ammonia, and organics).

6.1. Ion-exchange

Ion exchange is the mechanism by which dissolved metals are exchanged for ionised cations and protons on the surface of biochar. This exchange depends significantly on the functional groups of the metal's size and the biochar. During this process, positively charged ions on the biochar surface are replaced by the target metals. Essential factors in this exchange include bond characteristics, charge differences, and ionic radii [129]. Biochar's potential to extract ions from soil, including heavy metals, is determined by its cation exchange capacity (CEC), which is impacted by surface functional groups [171]. At temperatures exceeding 350 °C, biochar exhibits a lower cation exchange capacity (CEC) compared to biochar produced at 300-350 °C, which has higher CEC values. Ion exchange significantly enhanced the increase in cadmium (Cd) adsorption from 20 to 40 mg/g through the exchange of Cd for exchangeable calcium ions in biochar made from municipal sludge [130]. One of the primary processes for the adsorption of heavy metals such as Zn (II), Hg (II), Cd (II), Cu (II), Pb (II), and As (III) is ion-exchange [131].

The mechanism is explained as follows-

$$–COOH + M^{2+} \rightarrow –COOM^{+} + H^{+} \quad (1)$$

$$–OH + M^{2+} \rightarrow –OM^{+} + H^{+} \quad (2)$$

$$–2COOH + M^{2+} \rightarrow –COOMOOC– +2H \quad (3)$$

$$–2OH + M^{2+} \rightarrow –OMO- +2H^{+} \quad (4)$$

Solution pH is a crucial factor that affects ion exchange. In acidic conditions, more protons

(H+) are available to occupy metal binding sites, and their release from sorbents where metals are adsorbed can change the pH of the solution [66,132].

6.2 Surface complexation

GO-Zr-P (graphene oxide-zirconium-phosphate) nanocomposite material (NCMs) exhibits adsorptive ability for divalent zinc (II), copper (II), and lead (II). The surface functionalities and morphology of GO-Zr-P were investigated through XRD, XPS, SEM, TEM, and zeta-potential analysis [176]. High concentrations of carboxylic, oxygen-related groups, -C=O stretching and -C-C vibrations (aromatic), and carbonyl (-C=O) functional groups in mustard husk-derived modified biochar favoured nitrate adsorption [75]. Metal complexation involves forming multi-atom complexes through interactions with specific metal ligands. Oxygen-containing functional groups, such as carboxyl, phenolic, and lactonic groups, exhibit excellent binding effectiveness to heavy metals in low-temperature biochar [129]. Animal-based biochar, particularly that obtained from dairy manure and chicken litter, helps lead bind to phosphate ligands to form complexes like pyromorphite. The high adsorption capabilities of cadmium (Cd) (1.76 mmol/g) and copper (Cu) (1.63 mmol/g) with N-doped biochar were shown to be caused by complexation and cation-π bonding [133]. The maximum adsorption of Cd (101.00 mg/g) and Cu (64.90 mg/g) with ferromanganese binary oxide-biochar (FMBC) were demonstrated by X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR) analysis [134,135]. These results were attributed to surface complexation and ion-exchange.

7. Modified sorbents

Orange peel powder was pyrolyzed at 600°C to prepare a methanol-modified magnetic biochar (CH_3OH-OP-char/Fe_3O_4). The modified biochar was used to eliminate the drugs ibuprofen and sulfamethoxazole from wastewater. The highest adsorption capacities of SMX (sulfamethoxazole) and IBP (ibuprofen) on CH_3OHOP-char/Fe_3O_4 were 60.90 mg/g and 58.12 mg/g, respectively. This represents an increase of roughly 102.72% to 163.18% in comparison to the untreated biochar (OP-char) [136]. In-situ generation of Fe_2O_3-produced super magnetic modified char is effective in recycling plastic char from water by separating composites of magnetic plastic waste and metal oxide from the reaction solution. The findings indicated that the low-cost, reusable Fe_2O_3/plastic char can remove antibiotics from water efficiently and quickly. Char is associated with the possibility of removing metal ions from wastewater through its high sorption ability. Strong inner-sphere surface complexes are formed when the surface functional groups come together in the presence of metal ions. Certain varieties of modified plastic char can start the formation of solidification on the char because of the reduction of high valent metal ions to low valent metal ions [137]. Another study examined the removal of As (V) and Sb (II) from contaminated neutral drainage (CND) via column testing, utilising two-Fe-loaded biochar by precipitation (P-product) and evaporation (E-product) [138]. It was critically analysed that both Fe-loaded biochar showed efficient Sb (III) removal but for batch testing only. However, it is recommended that additional studies be conducted to examine the possibilities for As stability, sorbent recovery, and reuse. On modification SSA, reaction activity, negative zeta potential, pore volume, and oxygen-based functional groups are enhanced, which further results in high adsorption potential of heavy metals, nitrate, ammonia, phosphorous, and other organic and inorganic pollutants, with environmental and economic aspects. **Fig. 8** summarises the modification compounds of various char with the adsorption potential of adsorbates at different pyrolysis temperatures. On $ZnCl_2$ modification, different modified activated carbons processed from lignite granules, tamarind wood, mustard stalk and tomato solid wastes were utilised for the removal of nitrate, methylene blue, metal yellow dye and chromium at different pyrolysis temperatures and adsorption capacities as mentioned in the figure [139–143]. Contaminants such as cadmium, tetracycline, nitrate and phosphorous at around 300-600℃ of pyrolysis temperature were removed by modifying biochar, phragmites, montmorillonite, sesame straw and potassium-rich biochar composites with KOH, $MgCl_2.6H_2O$, MgO, $ZnCl_2$-KOH, K_2SO_4, K_2SiO_3 [144–149]. The soybean and peanut shell waste, biochar-based nanocomposites, and industrial waste biochar were employed for the removal of ammonium, nitrate, cadmium, phosphorous, chromium, cadmium, and phosphate on Mg-Al, polyethene, phosphate, Mg-Fe, Fe_2SO_4 and NaOH modification [150–156]. On modification with ZnO/ZnS, HNO_3, humic acid, $H_3PO_4/ZnCl_2$, $KMnO_4$-KOH, the heavy metals (Pb, Cu, lead and nickel) and methylene and Congo dyes were removed by biochar [157–161]

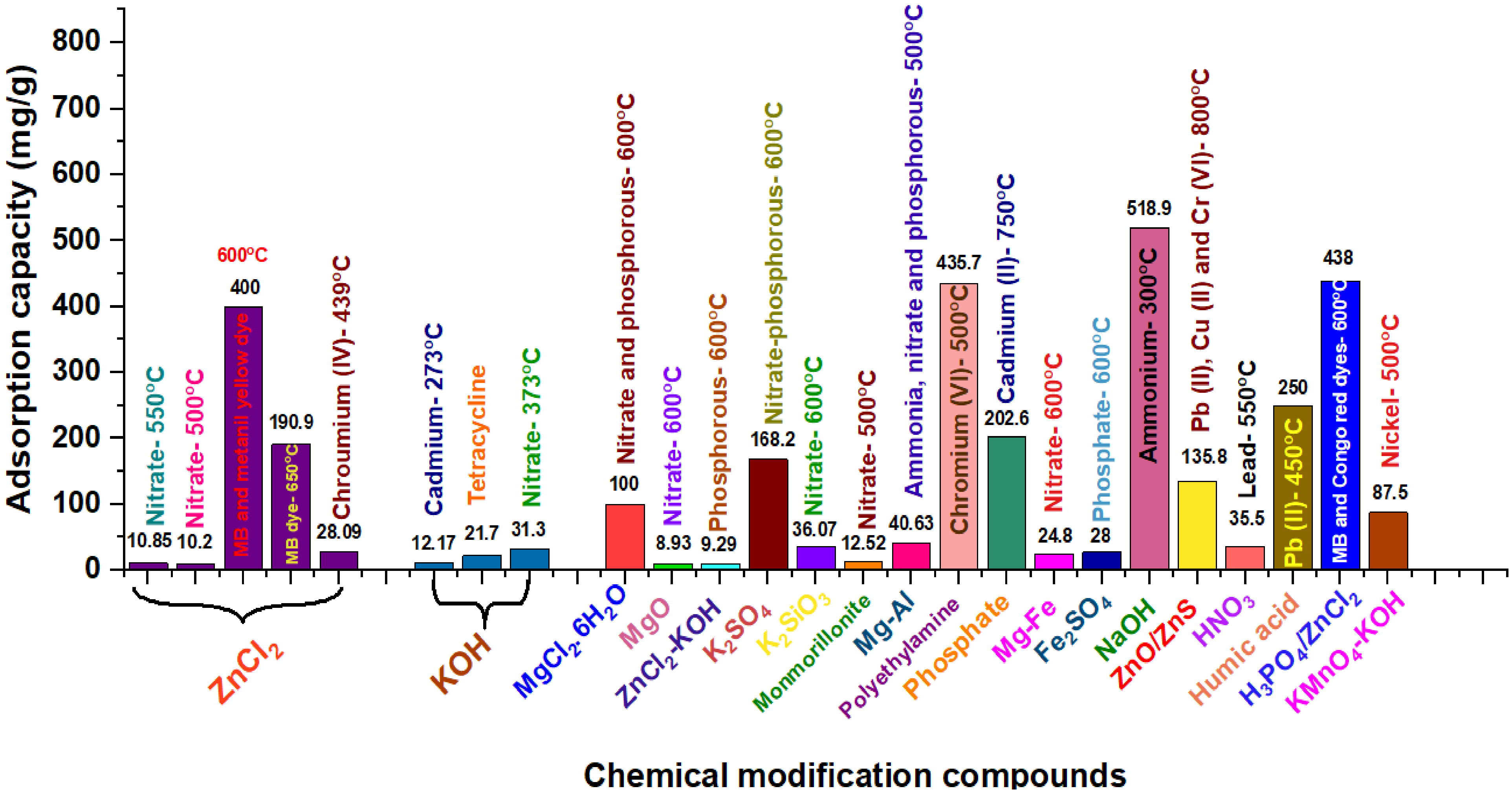

Fig. 8. Review of adsorption capacities of various chemically modified char for removal of nitrate, phosphorous, heavy metals, dyes, and other organics at different pyrolysis temperatures.

8. Application of biochar in water treatment technologies

Wastewater generation due to numerous commercial, agricultural, industrial, and domestic practices has been a global concern. This section incorporates the potential applications of biochar by providing future directions in each sector.

8.1. Groundwater treatment

In a recent study, a new inorganic/hybrid fibrous polymer with hydrated ferric oxide (HFO) was used as an adsorbent to remove natural toxic species As (V) and As (III) removal **(Table 4).** A recent study reported the treatment of groundwater from the Jhunjhunu district of Rajasthan containing non-carcinogenic species (nitrate approx. 10.22-520.64 ppm and fluoride 6 ppm) that had numerous concerns related to human health [162]. About 86% and 54% of nitrate and fluoride exceeded the BIS and EPA permissible limits. Biochar was noticed as a potential sorbent for nitrate adsorption in the reported literature. Coagulation, sand filtration, and sedimentation are the steps in a specific drinking water treatment process that are crucial for eliminating particulate matter [90]. Freshwater scarcity, industrial water utilisation, and agricultural requirements have made access to pure water challenging. Using seas and oceans for low-cost freshwater recovery is a solution, but it must be environmentally sustainable [91]. Date palm biochar's impact on the modified bio-sand filter (MBSF) versus BSF was investigated to remove total coliform, turbidity, colour, and Cu, Zn, Fe, Mn, NH^{4+}, PO_4^{3-}, NO_3^{2-}, SO_4^{2-}, Cl^-, Na, Mg, K from synthetic groundwater (mainly utilised for drinking purpose). By placing biochar at the bottom of the filter media in MBSF(D), Mn and Fe were effectively removed. The pilot-scale MBSF(D) encountered earlier clogging (43 days) and exhibited reduced contaminant treatment efficiency compared to the lab-scale MBSF(D), except for total coliform removal (100%). Following regeneration, the pilot-scale MBSF(D) was operational for 32 days and the lab-scale MBSF(D) for 82 days, both of which met WHO drinking water criteria [163]. The activated biochar produced in the presence of H_3PO_4, KOH, and (CO_2/Steam) at elevated temperature (900°C) resulted in an improvement in porosity, aromaticity, and optimum pH, which enhances the adsorption efficiency of organic pollutants [164].

Table 4. Contaminants from groundwater and their adverse effects.

Pollutants	Sources	Harmful effects	References
Fecal waste	Open defection to drinking	Water-borne diseases like diarrhea by ingesting polluted water	[4]

	water		
Arsenic	Groundwater	• An overview of real-time monitoring techniques that can be combined with biochar for upscaling and evaluating adsorption studies is given. • SIP (spectral Induced parameter) provides high-resolution spatial and temporal imaging, with its sensitivity to arsenic (As) sorption.	[165]
Trichloroethylene (TCE)	Groundwater	• Examined the organic degradation efficiency to elucidate possible synergistic interactions between nanoscale zero-valent ion (nZVI) and biochar.	[166]
Fluoride, nitrate, lead, iron, and boron.	Groundwater	• Analysis indicates that Pb and NO_3 are high energy-intensive and low energy-intensive parameters, respectively. • Lowers energy costs and suggests a scientific method for reducing energy depletion that incorporates a renewable energy product in relation to the water-energy nexus.	[167]

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8.2 Industrial wastewater treatment

In India, 13,500 million litres of industrial wastewater per day was generated and disposed of into water sources (rivers, lakes, ponds, etc.) without any suitable treatment, leading to environmental deterioration. Moreover, high adsorbent costs may impact the circular economy and commercialisation of the techniques. Industrial wastewater sources include smelting, chemical industries, dyes, leather and battery manufacturing, pharmaceutical industries, mining, and others. The two primary contaminants found in industrial effluent are organic chemicals and heavy metals **(Table 5)**. Insoluble chromate compound Cr (VI) was recovered from the wastewater of Hindustan Motor Limited (HML), located in Hooghly, West Bengal, India. Thus, biochar has wide applications in treating industrial wastewater, but it needs to be tested on a large scale. Nitrate adsorption onto biochar was discussed in these outlines [167]. Dyes, pharmaceuticals, and heavy metals are the primary hazardous pollutants in industrial water, which have been treated by adsorption and photocatalytic degradation utilising biochar-based nanocomposites; further, biochar achieved elevated photocatalytic and adsorption efficiency, improved reusability, and more straightforward recovery [168].

Table 5. Contaminants from industrial wastewater and their adverse effects

Pollutants	Sources	Harmful effects	References
Organic matter and heavy metals	Industrial wastewater	• Metal ions or metal oxide modification improves the adsorption, magnetic, and catalytic capacity. • Conversion of sewage sludge to biochar can yield high adsorption efficiency by modifying it with carbonaceous materials (nanotubes, graphene).	[169]
Lead (Pb), Mercury (Hg), Copper (Cu), Nickel (Ni), Cadmium (Cd), and Chromium (III).	Oil refineries, metal piping, and mining industries.	• Water pollution and scarcity. • Adversely affecting the health of animals, plants, and humans.	[104]
	Dyeing, petroleum, electroplating, and paint industries.	• Toxic for microorganisms, plants, humans, and animals.[170] • Human toxicity includes	[171]

		liver, kidney, lung, and gastric cancer. • Hazardous impact on the environment.	
Inorganic and organic contaminants	Industrial wastewater	• Industrial dyes exhibited strong adsorption on biochar, up to 80%. • Examined the process by which photocatalytic materials accompanied by biochar break down organic pollutants in wastewater.	[172]

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More pesticides and hazardous heavy metals are released onto land because of the accelerated development in agricultural industrialisation sectors [106] **(Table 6)**. Fertilisers (NPK- Nitrogen, phosphorous, and potassium) result in agricultural contamination and are resolved by modified biochar forms. Studies reported the removal of a common pesticide (atrazine) in agriculture derived from dairy-manure residue. The biochar produced via low-temperature pyrolysis was noticed to be six times more effective in atrazine and lead adsorption. Soybean and corn straw-derived biochar showed that atrazine removal capacity depends mainly on pore volume, biomass utilised, and pH of char [122]. Adsorption mechanisms using agricultural waste-derived biochar included cationic-π bonding, ion exchange, intermolecular and electrostatic interactions, π- π bonding, and surface complexation.

Table 6. Contaminants from agricultural wastewater and their adverse effects

Pollutants	Sources	Harmful effects	References
Antibiotics (tetracycline, quinolines, macrolides and sulfonamides)	Agricultural and animal husbandry (medicines).	• Alters microbial ecological functions and causes bacterial resistance. • Reduces human immunity causing hormonal	[173]

		imbalance and interfering physiological functions. • Carcinogenic and teratogenic in nature.	
Phosphate	Agricultural waste- Fertilizers.	• Affects the aquatic ecosystem. • Excess phosphate causes digestive problems.	[174]
Pentachlorophenol and atrazine	Agriculture waste- pesticides.	• Low fetal weight during pregnancy, urinary, heart, and limb defects. • Carcinogenic and causes liver cancer in humans and animals. • Breathing, chest and abdomen pain and weakness in humans.	[106]

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8.4 Municipal wastewater treatment

The pyrolysis of digested sludge at 450 °C was used to produce biochar, which was then utilised as an adsorbent to remove ammonium from municipal wastewater. Besides chemisorption, the biochar's increased surface area and higher density of functional groups were observed to contribute to its maximum removal capacity. Biochar produced from municipal solid waste had a high porosity and many active sites on the surface, acting as a biofilter. Remarkable removal of COD, TP, TSS, and TKN from wastewater was noticed passing through biofilter (biochar) [110]. Municipal wastewater underwent treatment with biochar during the biofiltration stage. Using standard techniques, changes in pH, total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total phosphates (TP), and chemical oxygen demand (COD) were determined before and after biochar treatment [110]. Digested sludge was pyrolyzed to improve ammonium adsorption capacity [34]. Batch reactors and fixed-bed columns employed pristine biochar to remove Cu^{2+}, Fe^{2+}, $Ni^{2+}$and Zn^{2+} derived from heating date palms at 500°C [175]. Another study demonstrated that engineered biochar has great potential in treating municipal wastewater, as it can reduce phosphorus levels in discharge, benefiting the environment. Additionally, it can reclaim phosphorus for use as an agricultural fertiliser, enhancing phosphorus biogeochemical cycling and sustainability [176].

9. Regeneration and recyclability of adsorbents with cost analysis approach

The regeneration and disposal of spent sorbent safely and eco-friendly, focusing on the significant gaps and future research directions, should be emphasised. Moreover, this area has been of interest in the past few decades to reduce the potential risk associated with the disposal of waste adsorbent. Regeneration solution for adsorbents incorporates $NaNO_{3,}$ HCl, NaOH, H_2SO_4, CH_3COONa, and $NaHCO_{3,}$ which addresses the adsorption-desorption/recyclability cycles. Surprisingly, very few studies reported the recovery of desorbed and adsorbed metals from regenerated and saturated sorbents. It summarised the suitable recovery techniques of heavy metals and contaminants from both desorbing solvents and used sorbents. The study of feasible reuse of desorbing agents and their recyclability ratios (**Table 7)** contributes to the same [17]. Activated carbon, calcium-enhanced bentonite clay, and βcyclodextrin were combined to create a hybrid composite adsorbent (βCD-AC-CA Bent) through chemical synthesis. Activated carbon, βcyclodextrin, and calcium-enhanced bentonite clay were combined to generate a hybrid composite adsorbent (βCD-AC-CA Bent) through chemical synthesis. Adsorbents reported a significant efficiency for Pb removal after regeneration, indicating an assured potential in a sustainable approach. Capacities at 1.00 g/L of dosage showed 174.50 mg/g, and at 0.25 g/L, there were 434.70 mg/g Pb removal efficiencies in 1 h [177]. Several of the latest versions of the adsorbents and resins have been developed. Nano-structured and biologically regenerated materials (nano-zeolites and nano-synthetic materials) are widely used as cationic adsorbents. In most chemical regeneration techniques, a major concern is the toxicity of the by-products generated. High pressure is required for supercritical regeneration extraction, which raises expenses. While biological regeneration holds promise for the restoration of depleted adsorbents, its restricted rate of regeneration mainly limits its usage in dye treatments. Furthermore, specific adsorbents require reagents, such as cationic surfactants, to enhance their exchange capabilities; however, these reagents are not appropriate for biological regeneration since they might be detrimental to bacteria. A single technique is insufficient to maintain or increase the adsorption effectiveness of all adsorbents successfully. Therefore, a combination of multiple methods might be necessary to stimulate used adsorbents effectively [89]. The rising concern about recyclable water necessitated the need to use cost-effective technologies, such as biowaste-derived sorbents for water treatment, which will have a resistive impact soon. Adapting the biosorbents as an ultimate cost-effective, optimum, and feasible solution is needed. However, it is at the primary stage in Indian industries. Fixing the pilot plant of bio-sorbents in CETP's is required as a cost-effective, viable option with suitable technological upgrades, which are financially assisted by state and central governments [178]. The most important factors that affect the feasibility and economy of the adsorption process are removal efficiency (adsorption capacity) and spent adsorbent cost. Numerous adsorbents, such as fly ash, scrap metal, carbon-based adsorbents, biosorbents, activated carbon, etc., are available, and their recyclability can be established based on their cost comparison shown in **(Table 8).** Studies reported in the literature have reviewed the cost and applicability of numerous adsorbents for treating wastewater. Additionally, variation in the cost performance of adsorbents is demonstrated in 3 ranges (between 1 and 200 $/g (optimum cost), <1$/g (cheap adsorbents) and >200 $/g (costly)). Hence, the investigation of these studies will help determine the exact cost estimation and relevance in the areas of their applicability [178]**.** Fly ash is available in power plants for free, and the primary cost for transportation, laying, and rolling is added. Waste slag can be used to produce fly ash at $ 0.002/kg, and the final product costs around $0.009/kg, including the expenses associated with transportation, electrical energy, chemicals, etc., involved in the process. The cost of activated carbon exceeds $3 due to two parameters: a) original cost of adsorbent. b) adsorption efficiency. Blast furnaces, industrial scrap metal waste, and fertilisers cost approximately <$0.10/kg [115].

Table 7. Desorption efficiency of various adsorbents with regeneration cycles**.**

Adsorbent used	Adsorbate	Removal Efficiency/desorption Capacity	Recyclability/Regeneration cycles (n)	References
Immobilized Biomass (Garcinia cambogia)	As (III)	95% (0.20 M NaOH)	n=5	[179]
Magnetized wheat straw	As(III), As(V),	24.14 mg/g Fe_3O_4 80 % (NaOH)	n=10	[180]
Nano-zero valent iron (Activated	As (III)	100% (0.10 M NaOH)	n=8	[181]

carbon)				
Nanoparticles of TiO_2	Zn(II), Pb(II), and Cu(II)	92% (EDTA)	n=4	[182]
Maghemite (γ-Fe_2O_3)	Cr(VI)	87.7% (0.01 M NaOH)	n=6	[183]

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Table 8: Cost-analysis of various adsorbents

Targeted contaminants/Adsorbate	Adsorbent used	Adsorption efficiency (mg/g)	Cost ($/g)	Authors
Cadmium and lead,	Cherry kernels biochar	92.42 and 94.48	0.041	[184]
Zinc	Rice straw biochar	35.71	0.002	[185]
Copper	Alkali-activated steel slag	161.29	0.0001	[186]
Nickel	Cation-exchange resin	63.00	0.0000006	[187]
Nitrophenol	Nano-zeolite	156.60	0.030	[188]
Phosphorous	Chitosan-calcite	21.36	0.264	[20]
Malachite green	Gasification waste-based activated carbon	226.06	0.0002	[189]
Acid blue -92	Tomato seeds	36.23	0.118	[190]

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10. Techno-economic analysis (TEA) of biochar as an adsorbent in water treatment

A technique for assessing a project's, process's, or investment's technological and financial viability is techno-economic analysis (TEA). A techno-economic analysis (TEA) of biochar as an adsorbent in water treatment evaluates the financial feasibility and technical performance of biochar-based systems. The analysis typically compares biochar's cost-effectiveness, adsorption capacity, and regeneration potential with conventional materials like activated carbon or post-treated biochar. While biochar offers significant cost savings due to lower production expenses, its adsorption capacity can vary depending on feedstock and activation methods. Critical challenges include optimising biochar production processes and ensuring consistency in quality. Although biochar presents a promising alternative, further research is needed to refine its scalability and long-term economic viability for widespread industrial applications. To ascertain the feasibility and possible return on investment (ROI) of a project, a thorough analysis that considers both technical and economic factors is performed. Key components of TEA include technical, economical, cost-benefit analysis, and risk assessment. Research findings and several case studies offer insightful information about the techno-economic viability of using biochar as an adsorbent **(Table 9)**. These investigations provide insightful information about the performance and economic feasibility of biochar-based adsorption systems for wastewater treatment, emphasising their potential as affordable and environmentally friendly approaches to problems with water quality [191]**.** A comprehensive summary of techno-economic analysis (TEA) research on biochar as a sorbent for the treatment of wastewater is included in **Table 10.** Studies emphasise the potential economic and environmental benefits of biochar, but they also point out specific difficulties, such as feedstock unpredictability, scalability, and adsorption capacity optimisation. The study of Techno-economic assessment of swine manure biochar production in large-scale piggeries in China evaluated the rise in the selling price of biochar from 154 to 193 USD/ton which summarised the profitable large-scale production of biochar with high demand highlights the economic viability and potential large scale biochar production with a highest benefit-cost ratio of 1.476 at 8 ton/ha biochar application rate [192,193]. Certain studies highlight the advantages that biochar has over conventional adsorbents and highlight its application in the treatment of industrial and decentralised wastewater [194]. Biochar will become known as a reliable and affordable option for solving problems with water quality worldwide. The global biochar market size was valued at $184.90 million in 2022 and is projected to grow from $204.69 million in 2023 to $450.58 million by 2030. The study addressed the perspective on barriers and opportunities of scaling up biochar production. Challenges such as economic difficulties resulting in expenses, financing, and market stability; governance concerns including policy and permits; technological obstacles involving tools and techniques; and the need for more research and the problem of biochar's supply and demand are faced [195]. However, very few studies have been reported on biochar scale-up to an industrial level. A few literature studies of TEA, which conducted a comparative analysis and evaluated the economic viability and adsorption performance with a life cycle cost analysis for wastewater treatment, are highlighted in **Table 10**.

Table 9. TEA of biochar in the water treatment process.

Biochar	Adsorbate	Operating Condition	Economic Evaluation/operating parameters-cost	References
Orange peel waste biochar	Crystal violet dye	Pyrolysis temperature- 550 ℃ (2 h) Stirring rate-400 rpm (30 min) Adsorption temperature- 25 ℃	Electricity- 155 USD/month Chemical consumption- 85 USD/month Water consumption- 60 USD/month Cost (operator salary- 45 USD/month) Biochar feedstock- 26 USD/month Other- 25 USD/month	[191]
Biosorbents • Coconut shell (CS) • Groundnut shell (GS) • Rice husk (RH)	Basic Red 09 dye	Pyrolysis temperature- 500 ℃ Stirring rate-400 rpm (6 h) Adsorption temperature- 25-50 ℃	Feedstock cost + feedstock transport + drying cost + pyrolysis + grinding cost (Rs.) CS- 37.84, GS- 35.44, RH- 35.64 Chemicals (Rs.) - CS-7.56, GS-7.00, RH-7.12 Total Cost (Rs.) - CS-45.40, GS-42.52, RH-42.76	[196]
Biochar-based char slurry (CS) with Rice straw (RS)	-	Pyrolysis temperature- 700-1000 ℃	Electricity- A$ 0.28/kWh Natural gas- A$ 15.80/GJ Operator costs- A$100,000/year RS feedstock- A$ 40/tonne	[197]

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Table 10. A literature review of TEA of biochar in water treatment process.

Description	Specific findings	Remarks	Case Study
Conducted a comparative examination of activated carbon and biochar for heavy metal removal in industrial wastewater treatment processes.	Evaluated the economic viability and adsorption performance of engineered and pristine biochar and activated carbon adsorbents.	The economic viability of biochar adsorption: Biochar exhibited heavy metal removal efficiencies similar to activated carbon but at a significantly lower cost, making it a cost-effective alternative for heavy metal remediation in industrial water treatment plants. The study emphasised the potential of biochar-based adsorption technologies to reduce treatment costs and improve the sustainability of wastewater treatment operations in industrial settings.	[198]
Conducted a life cycle cost analysis of biochar adsorption for nutrient removal in agricultural runoff treatment.	Assessed the economic and environmental impacts of biochar-based treatment compared to conventional methods.	Life cycle cost analysis: Biochar adsorption achieved a 30% reduction in overall treatment costs and reduced nutrient runoff from agricultural fields. The study emphasized the potential for biochar-based adsorption technologies to mitigate nutrient pollution in water bodies and improve the sustainability of agricultural practices, promoting environmental stewardship and resource conservation.	[67]
Conducted a techno-economic assessment of biochar adsorption for pharmaceutical pollutant	Evaluated the cost-effectiveness and environmental benefits of biochar adsorption compared to	Cost-effectiveness of biochar adsorption: Biochar-based treatment led to a 30% reduction in treatment costs and a smaller environmental footprint in wastewater treatment	[120]

removal in municipal wastewater treatment plants.	conventional treatment methods.	operations. The study highlighted the significance of optimising biochar production processes and adsorption parameters to improve treatment efficiency and lower overall operational costs in municipal wastewater treatment facilities.	
Examined the techno-economic feasibility of large-scale biochar production for wastewater treatment applications.	Investigated the cost-effectiveness and scalability of biochar production and adsorption technology deployment.	Scalability of biochar production: Large-scale biochar production facilities achieved economies of scale, reducing production costs by 25% and enabling cost-competitive wastewater treatment solutions. The study highlighted the potential for biochar-based adsorption technologies to address emerging water quality challenges and meet stringent regulatory requirements in municipal and industrial wastewater treatment sectors.	[199]
Investigated the techno-economic feasibility of using biochar for the removal of organic pollutants in municipal wastewater treatment.	Evaluated the economic viability and adsorption efficiency of biochar compared to conventional treatment methods.	Economic feasibility of biochar adsorption: Biochar-based treatment demonstrated a 25% reduction in operational costs and achieved efficient organic pollutants removal from wastewater. The study highlighted the potential for biochar utilisation in improving water quality and reducing treatment costs in municipal wastewater treatment plants, contributing to sustainable urban water management practices.	[200]
Techno-economic analysis of biochar production from	Demonstrated potential cost-effectiveness of biochar	Cost-effectiveness of portable slow pyrolysis system: Initial investment cost was reduced by 30%, and operational costs	[201]

agricultural waste using portable slow pyrolysis system.	production compared to traditional activated carbon methods.	decreased by 20%. Moreover, the study highlighted the potential of utilising waste biomass from agricultural activities, such as crop residues and animal manure, as feedstock for biochar production, promoting circular economy principles and waste valorization.	
Examined the use of biochar as a sustainable alternative for water filtration in developing countries.	Biochar filtration systems demonstrated cost-effective and efficient removal of pathogens and contaminants from water sources.	Cost-effectiveness and efficiency of biochar-based water filtration systems: Biochar filters reduced water treatment costs by 50% and removed 95% of bacterial contaminants. The study also emphasised the importance of considering local context, socio-economic factors, and community engagement in implementing biochar-based water treatment technologies, promoting equity, inclusivity, and sustainability in addressing water quality challenges in resource-constrained settings.	[202]
Investigated the feasibility of biochar-based adsorption for wastewater treatment in industrial settings.	Analysed the economic viability and performance of biochar adsorption compared to conventional treatment methods.	The economic viability of biochar adsorption: Biochar-based treatment demonstrated a 20% reduction in operational costs and achieved comparable pollutant removal efficiencies to traditional methods. The study highlighted the potential for biochar utilization in decentralized wastewater treatment systems, offering cost-effective and sustainable solutions for industrial wastewater management.	[203]

11. Conclusion and future recommendation

Biochar is a promising, efficient adsorbent and holds great potential for applications in water treatment research. Among various wastewater treatment technologies, adsorption stands out for its ability to produce high-quality treated effluent, flexibility in operation, and recyclability due to the reversible nature of adsorbent regeneration. The pH of the aqueous solution significantly influences the removal of heavy metals through ion exchange. In contrast, the removal of nitrates, owing to their strong solubility and stability in aqueous media, is particularly challenging. Functional groups such as carbonyl (-C=O), carboxyl, and hydroxy groups in carbon-based sorbents have been found effective in removing heavy metals like Cr(VI), Cd(II), Ni(II), Hg(II), Pb(II), and nitrates. Modified biochar, achieved through chemical or thermal enhancements, significantly outperforms unmodified biochar in adsorption efficiency, though the latter remains a more cost-effective option. The adsorption capacity is influenced by factors such as the choice of feedstock, its chemical and physical properties, pyrolysis conditions, and chemical composition, including hemicellulose, lignin, proteins, and lipids. Groundwater treatment for removing nitrate, fluoride, and arsenic highlights the need to develop effective and environmentally sustainable adsorbents. Cost analysis reveals a wide range of sorbent costs, from $1/g to $200/g, with nano-resins offering a cost-effective solution for metal removal. However, the choice of adsorbent depends on the specific adsorption process, targeted pollutants, and economic feasibility. Despite its potential, the biochar market in India faces challenges, including limited market knowledge, difficulty in securing long-term agreements, and the financial constraints of Indian farmers. Biochar's primary applications, such as removing pollutants from municipal sewage, agricultural waste, industrial wastewater, and groundwater, underscore the need for research to address gaps in production techniques and operational strategies to optimise its performance and disposal.

Although this area has been applied, considerable research activities are ongoing to bring out further innovations and improvements in cost, efficiency, and more. Hence, to contribute, this review suggests some efforts to be made in this direction. Novelty in this area lies in compiling studies on sorbent types (modified and unmodified), their mechanisms, applications, cost-effectiveness, and regeneration solutions. Additionally, the review highlights the progress in water treatment technologies aimed at resolving the significant challenge of water contamination, with a focus on areas that still need to be fully investigated. The pragmatic shift towards developing economically viable adsorbents underscores the importance of ongoing research and innovation in addressing the global challenge of water contamination. Through collaborative efforts and interdisciplinary approaches, advancements in waste material management and water treatment can lead to tangible solutions that benefit both the environment and society at large.

Data availability

The datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request.

Conflict of interest

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

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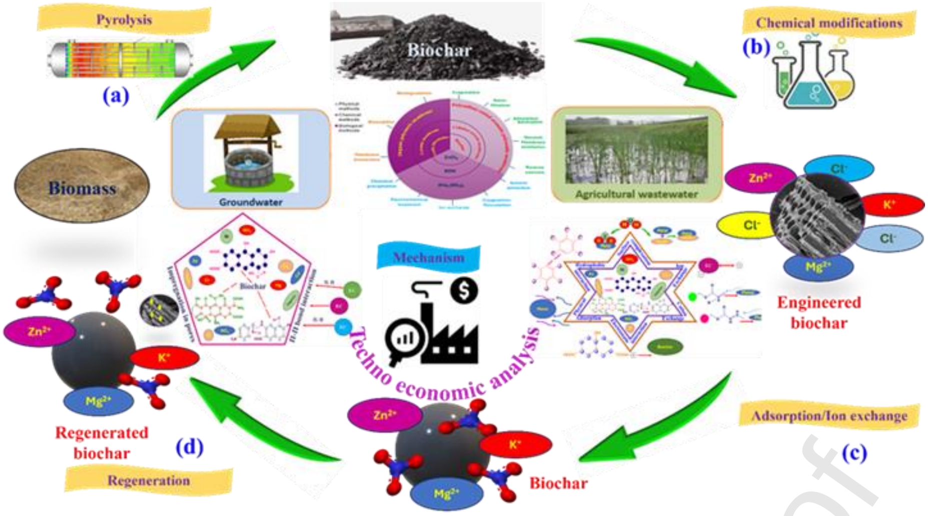
Graphical abstract



Highlights

- **Higher surface area and removal efficiency can be seen with engineered biochar.**
- **Biochar for the removal of pollutants from wastewater may lead to sustainability.**
- **Comparative analysis of treated char and their mechanism in water treatment.**
- **Cost analysis of adsorbents for removal of targeted pollutants.**