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Chapter 16

Water pollution abatement using waste-derived materials: a sustainable approach

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ABSTRACT

The rapidly growing population has resulted in increased water demand and generation of high volume of solid wastes. Both excess solid waste and poor water reuse efficiency primarily result from improper management. Accordingly, to reduce the associated environmental burdens, the utilization of waste-derived material for water treatment can be considered as a sustainable approach. The current chapter aims to provide a holistic approach to solid waste management by generating value-added materials and their potential application for water pollution abatement. Different classes of waste, including agriculture, industrial, and electronic, and their possible activation methods are discussed. Also, the potential applications of such waste-derived products in different water treatment techniques, such as adsorption, catalysis, and electrochemical application, are detailed. Overall, the possibilities of utilizing waste to derive value-added products that can be employed for pollution abatement of contaminated water and achieve circular economic concepts are reviewed.

Keywords: water treatment, solid waste, activation, adsorbents, catalysts

16.1 INTRODUCTION

Globally, environmental sustainability and conservation are at stake due to rapid urbanization and industrialization. The whole world is confronted with the major challenges of a clean and safe water supply for an increasing population. In recent years, several pollutants, such as dyes, heavy metals, pharmaceuticals, pesticides, detergents, phenols, and oils, have been detected in the waterways. The exposure and accumulation of these contaminants pose serious damage to living bodies and jeopardize natural resources. Water and wastewater technologies, including ion exchange, adsorption, electrochemical oxidation/reduction, membrane separation, catalysis, and reverse osmosis, have been tested to abate the pollutant load (Crini & Lichtfouse, 2019). These technologies require materials such as adsorbents, catalysts, or membranes to facilitate pollutant removal or degradation. In this regard,

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a series of metal oxides, nanomaterials, transition metals, double-layered hydroxides, carbonaceous materials, polymers, and their composites has been developed.

Out of the aforementioned materials, the carbonaceous and metal oxide-based materials appear as attractive options due to their diverse physicochemical properties, abundance as renewable resources, and low cost. Most importantly, these materials can be derived from various classes of waste generated in the environment. For instance, a total of 998 million tonnes of agricultural waste is produced annually, which is highly rich in carbon content. This makes agricultural waste an excellent source for the synthesis of carbon-based materials. In addition to carbon richness, agricultural biomass has abundant functional groups, such as amino, acetamido, carbonyl, alcoholic, phenolic, and sulphhydryl groups. This helps the biomass-derived materials to act as suitable adsorbents for removing different pollutants via complexation, chelation, chemisorption, and ion exchange (Al-Rumaihi *et al.*, 2022). In a similar line, food waste, ash, sewage sludge, distilleries, and bauxite residues (red mud) can aid in the removal of water contaminants. Moreover, the improper management and handling of such waste have led to disposal in landfills, dumpsites, and water bodies, causing threats to living organisms and increasing environmental burdens. Therefore, upcycling such waste into value-added products for water management seems feasible and essential. The current book chapter attempts to give a comprehensive strategy for producing value-added materials from waste with potential applications in water pollution abatement. Modification and activation strategies of different types of wastes are examined. Also, possible uses of such waste-derived materials in various water treatment techniques, such as adsorption, catalysis, and electrochemical applications, are discussed. Overall, the potential for using waste to restore water resources is communicated.

16.2 STRATEGIES FOR MODIFICATION OF WASTE INTO FUNCTIONAL MATERIALS

Solid waste can rarely be utilized directly for water and wastewater treatment due to the leaching of phenolic groups over time, poor regeneration, and stability. Thus, effective strategies are required to turn waste into useful functional materials prior to its use in water and wastewater treatment processes.

16.2.1 Co-precipitation

Co-precipitation is the standard and most straightforward modification technique, whereby metal-based nanomaterials are formed via nucleation, growth, coarsening, and/or agglomeration of metal salt in an alkaline solution. The co-precipitation process primarily extracts metal from electronic waste and loads it on waste-derived carbon materials. For instance, magnetic reed and agriculture biochar can be developed by chemical co-precipitation of iron oxides on the surface of the biomass and subsequent pyrolysis method. Santamaría *et al.* (2022) developed nanomaterials like double-layered hydroxides from the metal extraction of the slag. The primary constraints in using co-precipitation as a modification process are the high probability of metal leaching, poor stability of the developed materials, and non-uniformity in materials (adsorbent or catalyst) structural properties.

16.2.2 Hydrothermal synthesis

Hydrothermal synthesis is a promising chemical process for converting waste to value-added materials. The chemical reactions are carried out in the aqueous phase (water) at 180–280°C (Yang & Park, 2019). Hydrochar and metal-based functional are the two primary ways of valorization of sewage sludge, food and distillery, and industrial waste. The advantage of the process over thermal modification is that the waste with high moisture content does not require a separate drying procedure. Aside from the nature of waste, the hydrothermal reaction's temperature, solid-to-liquid ratio, pH, and reaction duration have a significant impact on the structural and chemical properties of the material. Hydrothermal synthesis can also be integrated with thermal conversion to prepare hierarchical activated porous carbon microspheres and porous oxides like γ-Al_2O_3 microspheres from red mud. Moreover, it has

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been claimed that the material generated from hydrothermal synthesis has the potential to replace traditional catalysts and electrode materials. However, with limited information on the techno-economics of the process, the scale of the process or integration with other technologies, such as anaerobic digestion, cannot be confirmed.

16.2.3 Thermal conversion

Pyrolysis and calcination of wastes are the two frequently used thermal modification techniques. Pyrolysis is the thermochemical breakdown process that results in the production of carbon-enriched biochar, hydrocarbons (bio-oils), and volatile gases. Unlike pyrolysis, calcination involves heating solid wastes at a high temperature (900°C) in the presence of oxygen. It is typically used to create metal oxide-based valuable products from waste, such as photocatalysts (Al-Rumaihi *et al.*, 2022). In both cases, the physicochemical characteristics of initial waste and reaction temperatures significantly influence the properties and yields of the developed value-added product. For instance, increasing the pyrolysis temperature (>500°C) reported the destruction of the oxygen-containing group, and the production of aromatic thin-layered graphitic structure has been reported. Likewise, the biomass produced from agricultural waste has a low C:N ratio compared to biochar produced from animal waste. Though the biochar produced at high temperatures can be used as a persulphate activator via graphite electron donor-transfer complex, the pore blockage and low yield can adversely affect the probable use of the biochars as an adsorbent. The calcination temperatures also have severe effects on the nanostructure and crystallinity of materials developed from waste. For instance, higher temperatures increase crystallinity and severe particle aggregation. Overall, there is a need to examine the operating parameters for pyrolysis/calcinations and waste characteristics individually to develop biochar with suitable surface chemistry, conductivity, and porosity. In addition, special care should be taken in producing biochar at low temperatures (300°C) due to the formation of harmful environmentally persistent free radicals, which may negatively affect the ecosystems (Bi *et al.*, 2022).

16.2.4 Sol–gel technique

The sol–gel method is commonly used for the valorization of inorganic-rich waste into colloidal suspension of inorganic particles, which transformed into the gelatinous network. The gel formed can be converted into oxide materials by high-temperature calcination. Waste like spent Ni–Cd batteries can be used to develop mixed metal oxide. Similarly, metal-organic frameworks like MIL-53 (Al) have been synthesized using waste aluminium and polyethylene terephthalate bottles (Panda *et al.*, 2020). Although the concept of sol–gel transformation seems appealing, the structures often generated have lower Brunauer–Emmett–Teller (BET) surface areas, lower crystallinity, and chaotic morphologies. Thus, reasonable experimental design and application are highly recommended.

16.3 ACTIVATION METHOD OF WASTE-DERIVED MATERIALS

The modification of solid waste into functional material seems a feasible way to develop engineered materials for water treatment applications. However, poor surface area, inadequate number of functional groups, or high hydrophobicity limits their application in water/wastewater treatment. Moreover, poor stability of metal oxide and leaching is a common problem. It should be noted that often waste materials are carbonized using pyrolysis or calcinations to produce carbon-based adsorbents and nanocomposites. Accordingly, the current section discusses various pre- and post-modification strategies (Figure 16.1) and their suitability for carbon-made materials.

16.3.1 Physical activation of waste-derived carbon materials

16.3.1.1 Ball milling

Ball milling is a chemical-free and economical modification strategy whereby mixing two or more solids or solid–liquid is carried under mechanical force. During the process, the dynamic energy of

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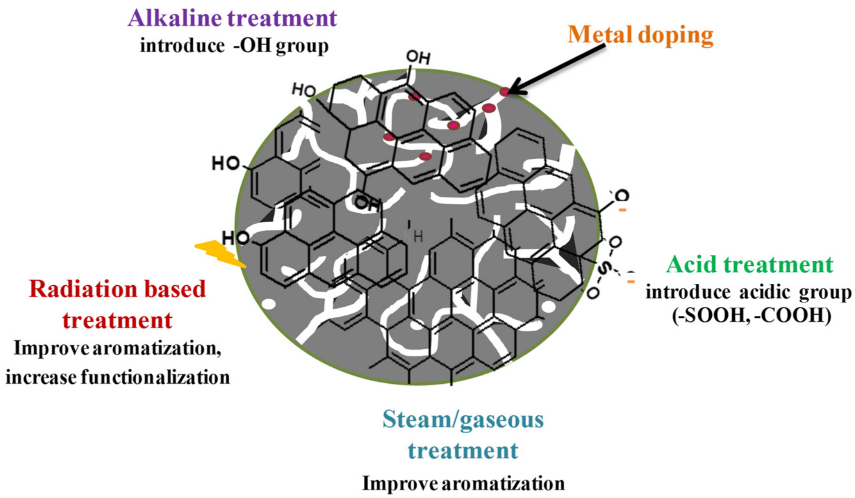

Figure 16.1 Modification method of carbon-based materials.

the moving ball induces chemical and structural changes in the feedstock via grinding and breaking (Amusat *et al.*, 2021). Ball-milling plays a major role in breaking the material down to the nanoscale without damaging the crystal structure. The use of ball-milling for nanoparticle production has been studied widely in recent years because of its low cost, large-scale applicability, and low energy for production. However, the specific relationships between the feedstock, temperature, and other properties with changes in particle size still need to be explored. Moreover, the dispersibility of the nano biochar is adversely affected, restricting its application in water treatment.

16.3.1.2 Gaseous activation

Gas activation using steam, nitrogen, and carbon dioxide has been used to enhance the porosity and specific surface area of the materials. The process also allows the removal of impurities such as ash, organic matter, and products of incomplete combustion from the surface (Sajjadi *et al.*, 2019a). During the steam activation process, the carbonized waste material (like biochar) is subjected to incomplete gasification, the continuous steam supply allows the conversion of CO into CO_2, and the released H_2 weakly combines with carbon to produce a weakly bound carbon–hydrogen complex. Accordingly, this disintegration increases the aromaticity, formation of crystalline carbon, and the opening of embedded porous structures. The steam-activated biochar has the potential to act as a slow-release fertilizer and CO_2 capture. However, the reduction in the carboxylic and phenolic groups on the surface adversely affects the polarity and metal removal potential. Thus, gaseous activation processes are favourable in pre-treatment and improving the porosity of carbon material rather than functionalization.

16.3.1.3 Radiation-based activation

The activation of carbon materials using microwave, ultrasound, and plasma-based radiation is gaining attention. The microwave-based activation forms micropores and increases surface area and polarity ((O + H)/C content). It should be noted that microwave irradiation is not feasible for the pyrolysis of pure biomass; thus, microwave absorbers (e.g., metallic oxides or charcoal) should always be impregnated into biomass structure (Sajjadi *et al.*, 2019a). Unlike microwave heating, sonication (ultrasound treatment) aids in leaching metal salt pores and increasing the internal surface area.

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Additionally, carboxylation, hydrogenation, water splitting, and exfoliation reaction at the surface allow the formation of a graphitic (sp^2) layer and increase the swelling properties of the biochar. Thermal plasma is another promising method for activation or an alternative to pyrolysis. The plasma-based activation and modification strategies provide higher energy density, faster reaction rate, and lower formation of heavy tarry compounds. Moreover, pre-treatment, like chemical washing and prolonged drying, is not required for plasma-based systems. However, the major problem with the process is in introducing oxygen-containing functional groups into a sample surface (Sajjadi *et al.*, 2019a). Overall, the energy throughput of sonication-based treatment is the least (even lower than the traditional methods).

16.3.2 Chemical activation of waste-derived carbon materials

Chemical modification methods like acidic/alkaline treatment, metal salt doping, or modification with oxidizing reagents are the most commonly employed and easy-to-use techniques. The wet chemistry-based methods can improve the functionalization of waste-derived materials (Table 16.1).

16.3.2.1 Acid and alkali treatment

The acid and alkali modification of waste-derived materials like biochar and carbon nanocomposite mainly alters the oxygen-containing functional groups. Strong acids like H_3PO_4 and H_2SO_4 alter the elemental composition and surface area of the materials, but treatment using high concentrations (2% sulphuric acid) can sometimes cause a reduction in the surface area. While weak acids such as oxalic acid and citric acid can introduce the carboxyl group on the surface through esterification. Accordingly, optimization of the nature of acid and concentration to increase functional groups and specific surface area is highly essential (Wang & Wang, 2019). Similar to acid modification, alkaline modification involves the usage of strong bases like sodium hydroxide (NaOH) and potassium hydroxide (KOH). On treatment with the alkali, the aromaticity of the carbon composite is increased due to the formation of a positive charge, and hydroxyl functional groups are easily incorporated (Sajjadi *et al.*, 2019b). It should be noted that the effect of acid/alkaline modification relies on the feedstock and preparation methods. Hence, it is too difficult to obtain a consistent result.

16.3.2.2 Oxidizing agents

Chemical oxidants like hydrogen peroxide, potassium permanganate, and zinc chloride have been used to increase the number of lactones, carboxylic, and hydroxyl groups and the decomposition of the aromatic carbons (Wang & Wang, 2019). It should be noted that the decrease in aromaticity of the structure can often weaken the π–π interaction and adversely affect the sorption of hydrophobic compounds. Thus, the properties of targeted pollutants should be considered before using the modification methods.

16.3.2.3 Metal doping

The doping of metal oxides/nanoparticles such as iron oxide, nZVI, and metal chloride salts onto feedstock/biochar has been studied owing to the benefit of increased surface area, adsorption capacity, catalytic and magnetic properties, and ease of separation (Figure 16.1). Additionally, using substrates like rice straw or char prevents the agglomeration of nanomaterials. It should be noted that most of the waste-derived material had lower pK_a ($\sim$2). Accordingly, the high negative charge on the surface makes the adsorption of anionic pollutants like phosphate and dyes difficult. Thus, modification with metal/metal oxides adjusts the surface charge and allows the effective removal of negatively charged contaminants (Wang *et al.*, 2019). The magnetic modification method provides a solution for adsorbent recovery. However, significant increases in the adsorption capacity are not always noted. Overall, the incorporation of metal/metal-oxide/nanomaterials depends on the use of

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Table 16.1 Summary of physiochemical properties of activated waste-derived carbon material.

Feedstock	Carbonization Technique	Activation Type	Properties	Remarks
Peanut hull	Pyrolysis	Acid activation	$S_{BET} = 952.6\ m^2/g$ Pore vol. $= 0.88\ cm^3/g$	• The biochar found rich in oxygenated functional groups • The adsorption capacity was reported at 149.25 mg/g
Rice husk	Microwave pyrolysis		$S_{BET} = 1165\ m^2/g$ Pore vol. $= 0.78\ cm^3/g$	• Acid treatment increases S_{BET} from 752 to 1165 m^2/g • Significant adsorption capacity was reported at 441.52 mg/g
Cinnamomum camphora	Pyrolysis	Alkali activation	$S_{BET} = 75.92\ m^2/g$Pore Vol. $= 0.13\ cm^3/g$	• Alkali treatment jointly with ultrasound increases S_{BET} from 29.86 to 75.92 m^2/g, and the pore vol. increased from 0.056 to 0.128 cm^3/g • Significant surge in adsorption capacity was reported from 39.06 to 98.33 mg/g
Sugarcane waste	Pyrolysis		$S_{BET} = 291.8\ m^2/g$ Pore vol. $= 0.24\ cm^3/g$	• Alkali treatment has improved oxygenated functionalities and microporosity • Acid treatment reduced the ash content.
Peach stone	Hydrothermal	Gaseous activation	$S_{BET} = 1247\ m^2/g$ Pore vol. $= 0.12\ cm^3/g$	• Microporosity was almost absent • Very low functional groups attached • Very high surface area was achieved
Eucalyptus globulus	Pyrolysis		$S_{BET} = 801.2\ m^2/g$ Pore vol. $= 0.08\ cm^3/g$	• Richness in functional groups is maintained after pyrolysis • The biochar possesses more micropore structures
Bamboo	Solvothermal	Irradiation activation	$S_{BET} = 88.52\ m^2/g$ Pore vol. $= 0.18\ cm^3/g$	• 2D and 3D graphene was synthesized • 100% removal of pollutants was achieved • This material showed bioimaging application
Willow	Steam pyrolysis		$S_{BET} = 443.2\ m^2/g$ Pore vol. $= 0.242 cm^3/g$	• Microwave activation showed high potential in toxicity reduction • Ash content was reduced, and the carbon content increased drastically
Microalgae	Hydrothermal	Doping	$S_{BET} = 62.2\ m^2/g$ Pore vol. $= 0.1\ cm^3/g$	• TiO_2 is doped over microalgae biochar • 99.2% removal of pollutants was achieved • Reusability up to the 8th cycle noted to be 80%
Jute fibres	Pyrolysis		$S_{BET} = 62.2\ m^2/g$ Pore vol. $= 0.1\ cm^3/g$	• ZnO was dispersed over jute biochar • 99% of degradation achieved • Reusability till three cycles for 78.6% degradation

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chemicals for modification, activation, and function. Aside from the fact that it is a costly method, the high chances of re-introduction of toxic waste from the chemicals used are a cause for concern.

16.4 APPLICATION OF WASTE-DERIVED MATERIALS AS ADSORBENT

The adsorption technique is widely employed to remove the trace/low concentration of contaminants from water. This section will discuss the different forms of waste-derived absorbents and their suitability for water and wastewater remediation.

16.4.1 Biochar and hydrochar

The popularity of biochar arises due to some key advantages, such as it restricts greenhouse gases during biomass decomposition and the richness of physical and chemical properties such as high surface area, various functionality, and so on. Compared to biochar, the abundance of hydrogen and oxygen makes hydrochar more suitable for adsorption. The diverse physicochemical properties of biochar and hydrochar mediate a broader range of reactions over its surfaces and facilitate higher sorption capabilities than activated carbon. A meta-analysis conducted by many research groups to compare the economic and ecological implications of biochar/hydrochar and activated carbon showed that biochar is more efficient in pollutant removal, with the additional advantage of lower greenhouse gas emissions. For instance, 97 MJ/kg of energy is required for activated carbon synthesis, while just 6.1 MJ/kg is needed for biochar. In addition, Choudhary and Philip (2022) conducted a sustainability assessment of biochar and granular activated carbon and found that the total environmental impact of biochar was 20 times less than commercial carbon. This brings one of the key motivations to switch existing adsorbents with low-cost waste-derived carbonaceous materials like biochar and hydrochar. A significant amount of studies are reported on the uses of such biochars for removing organic (polyaromatic hydrocarbons, carbofuran, polychlorinated dibenzo-*p*-dioxins, perfluoroctane, pentachlorophenol) and inorganic (Cd^{2+}, Zn^{+}, As, Cr, Pb^{2+}) pollutants from water and wastewater. All earlier studies showed the removal efficiency of 30–100% at an adsorbent dose of 0.03–10 g/L, which promotes the extensive use of such carbonaceous materials in the remediation of water and wastewater (Amalina *et al.*, 2022). Therefore, it can be affirmed that biochar/hydrochar can be a sustainable, low-cost alternative to commercial activated carbon.

16.4.2 Nanomaterials

With advancements in nanoscience and nanotechnology, a large class of nanomaterials has been developed using waste materials. Broad applications of waste-derived nanomaterials have been reported due to their high thermal, mechanical stability, optical, and electrical properties. The critical aspects of nanomaterials are a very high surface-to-volume ratio, high porosity, and small size, making these materials superior adsorbents. Particularly engineered carbon-based nanomaterials have attracted attention as sensors, energy storage devices, and air pollution control due to their tunable and multifunctional nature. The application of carbon-based nanomaterials in wastewater remediation has also shown high potential. The nanomaterials like nanotubes, nanofibres, nanoparticles, quantum dots, and nanosheets have been synthesized from rice husk, wheat straw, sugarcane bagasse, and so on., and showed very high adsorption potential for water and wastewater abatements (Jun *et al.*, 2018). These functionalized nanomaterials are highly prone to the adsorption of organic contaminants via electrostatic interactions, hydrogen bonding, π–π interactions like electron donor–accepter mechanism, and Van der Waals interactions (Figure 16.2). These nanomaterials have proven to be more effective adsorbents than traditional materials such as zeolites, clays, and polymers. Also, few studies reported the development of two-dimensional (2D) and three-dimensional (3D) graphene nanomaterials using bamboo biomass and their promising applicability in water and wastewater remediation (Mubarik *et al.*, 2021). Therefore, it would be a great opportunity for upcycling waste and its applications in water and wastewater purification.

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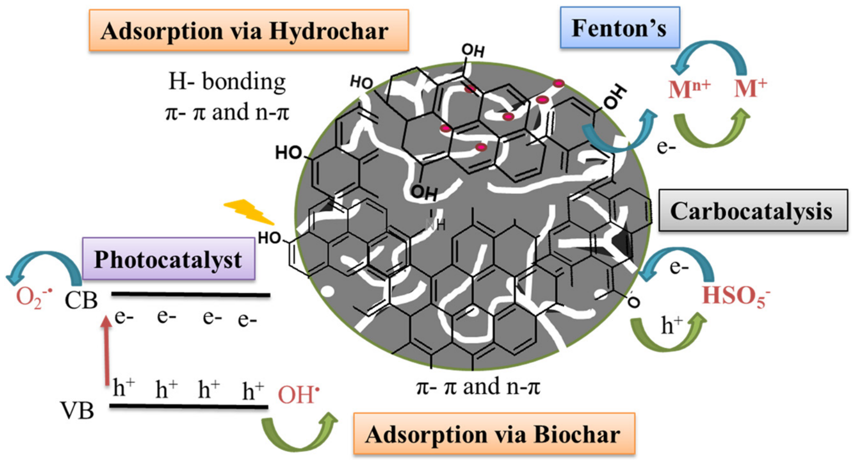

Figure 16.2 Schematics of sorption and degradation mechanism using waste-derived carbon materials and composite.

16.5 APPLICATION OF WASTE-DERIVED MATERIALS AS CATALYSTS

Low-cost waste-derived carbonaceous materials have recently been tested for catalytic application in water treatment, fuel cells, and soil abatements. However, an understanding of the practical uses in respective fields is still unclear. In this section, we will discuss the use of waste-derived materials as a potential catalyst in water treatment applications.

16.5.1 Fenton-like catalysts

The Fenton processes like conventional Fenton, electro-Fenton, and photo-Fenton are among the oldest advanced oxidation processes where Fe^{2+} is used as a catalyst to activate the oxidant (H_2O_2). However, this process is identified with key demerits like non-recycling of catalyst, large production of sludge, and lower operational pH (<3). In recent years, the 'Fenton-like' catalysts have been getting attention to overcome the limitations of the classical Fenton's systems. This utilizes reusable and recyclable catalysts and different oxidants like H_2O_2 and $S_2O_8^{2-}$. The porous carbon materials and composites are a preferred option as they can enrich the pollutants and disperse the reactive species, resulting in better efficiencies. Additionally, such porous structures facilitate mass transfer owing to shorter diffusion pathways. Despite lower catalytic efficiencies reported for pristine carbon materials towards H_2O_2 activation, the doping/modification of carbon materials with metal catalysts can enhance the crystallinity and performance of the composite catalysts. Moreover, carbon-based composite provides radical and non-radical pathways for degradation, which alleviates the performance in real wastewater. It should be noted that carbon composite developed from high-temperature carbonization shows improved oxygen reduction reaction and $S_2O_8^{2-}$ activation due to the richness in carbon defects. While mild temperature carbonization results in the distribution of oxygen functionalities and promotes the generation of hydroxyl radicals. Thus, the generation of diverse reactive radical species enhances the degradation and mineralization of a wide range of organic pollutants from water and wastewater (Pan & Qian, 2022).

16.5.2 Photocatalysts

Photocatalysis is proven to be a very effective in-situ water treatment technology in the last few decades. The process efficiency is significantly dependent on the photocatalyst used. Generally,

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semiconducting metals are recommended as photocatalysts; however, quick recombination of electron–hole pairs and poor response towards visible lights adversely affects the performance. Moreover, due to scarce semiconducting metals, such catalysts put an extra burden on the treatment technology. So, considerable efforts have been made to develop metal oxides and non-metal-based photocatalysts. Such developed catalysts are reported to reduce band gap and improve photo absorbance. However, photo corrosion, thermal instability, and dopant leaching are the major drawbacks that still need to be tackled. Various non-metallic and composite catalysts are being studied these days. In this regard, modified carbonaceous materials such as TiO_2-coconut shell, TiO_2-reed straw, TiO_2-corn cob, and TiO_2-bamboo are focused on due to their structure tunability, electronic conductivity, and good absorptive nature. Moreover, the surface functionality of biochar has shown active participation in reactions and promoted catalytic efficiency. For instance, the larger surface area can facilitate better absorption, due to which the pollutants could be prone to attack by short-lived radical species. Carbonaceous material also helps in suppressing the recombination of electron–hole pairs and narrowing the band gap to improve photo-absorption by forming a bridge and acts as a photosensitizer, charge carrier, and electron transport (Li *et al.*, 2022).

16.5.3 Carbonaceous catalysts

The term carbocatalyst describes the use of carbonaceous materials in catalysis as a catalyst. Few carbon forms, primarily graphene, carbon nanotubes, and fullerenes, have been focused in the field of catalysis. However, in recent years, other carbonaceous materials have emerged as better alternatives. Biochar, which is widely available and inexpensive, has shown chemical and physical properties similar to traditional carbon catalysts. Furthermore, differing electronic structures of edges or defects can be created by post treatment of biochar/carbonaceous materials. The important criterion for defining the use of biochar as carbocatalyst is the presence of an sp^2 network. This rigid carbon framework provides high chemical stability and assists in free electron generation. The carbonaceous interface allows an effective transfer of reagents for oxidation and offers sufficient space around functional groups to act as landing sites (adsorption space). The inertness of the carbon allows a spill-over mechanism for the reactive species (active radicals) without getting attacked by them (Schlögl, 2021). In addition, the anisotropic nature of carbonaceous materials makes them easily regenerable in case of deactivation or contamination, which is absent in the case of metal-based catalysts.

16.5.4 Electrochemical catalyst

In the past few years, electrochemistry-based water and wastewater treatment technologies have attracted huge attention due to their lower chemical consumption, high efficiency, ease in handling, and low emissions. Metal-based materials are extensively used as electrocatalysts, and all such catalysts have shown excellent effectiveness. But the constant exploitation of natural resources has limited its large-scale application due to the high cost of catalysts, by-product formation, metal leaching, and so on. Therefore, green and low-cost materials are needed as electrodes. Electrochemical catalysts have shown tremendous potential due to their multitude applications, such as energy storage, electro-sorption, and electrocatalytic oxidation/reduction (Alkhadra *et al.*, 2022). Agricultural wastes like straw, lotus leaves, hemp stem, Platanus fruit, peels, and rice husk are among the common low-cost green materials used for electrode development. For instance, carbonized cornstalk and modified biochar with Fe and Zn resulted in effective nitrobenzene degradation in less time than the pure metal electrode. Electrocatalytic performance is also demonstrated to be highly dependent on electronic properties, surface area, and nano-structure of electrode materials. Accordingly, dopants such as Pd, Co, Pt, S, and N on biochar have been studied. The presence of dopant and carbon substrate enhances the adsorption of pollutants and allows effective reduction/oxidation by providing electron transport channels and enhancing the radical species generation (Macchi *et al.*, 2022). Overall, electrochemical technology offers the advantage of modular design and effective removal of contaminants; however

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more efforts in the direction of developing and optimising the performance of waste-derived electrode and electrocatalyst are needed.

16.6 SUMMARY

This chapter systematically presented the overview of waste-derived water and wastewater treatment materials. The conversion of common wastes to valuable products such as metal oxide, double-layered hydroxides, nanomaterials, biochar, and hydrochar provides an option for the treatment of wastes and contributes towards environmental sustainability. Different activation methods can be selected to modulate the physiochemical properties of waste-derived carbon material (specifically biochar). In terms of performance, waste-derived adsorbents and catalysts show a wide prospect. However, most studies have been conducted in a laboratory scale. To facilitate the application of these adsorbents and catalysts in the real field: (1) optimization of activation/ modification methods, (2) study in wastewater and mixed systems, (3) investigation of the stability of produced materials, and (4) reuses and post-treatment of spent materials are needed.

REFERENCES

Alkhadra M. A., Su X., Suss M. E., Tian H., Guyes E. N., Shocron A. N., Conforti K. M., de Souza J. P., Kim N. and Tedesco M. (2022). Electrochemical methods for water purification, ion separations, and energy conversion. *Chemical Reviews*, **122**(16), 13547–13635, https://doi.org/10.1021/acs.chemrev.1c00396

Al-Rumaihi A., Shahbaz M., Mckay G., Mackey H. and Al-Ansari T. (2022). A review of pyrolysis technologies and feedstock: a blending approach for plastic and biomass towards optimum biochar yield. *Renewable and Sustainable Energy Reviews*, **167**, 112715, https://doi.org/10.1016/j.rser.2022.112715

Amalina F., Abd Razak A. S., Krishnan S., Sulaiman H., Zularisam A. W. and Nasrullah M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications – a review. *Journal of Hazardous Materials Advances*, **7**, 100134, https://doi.org/10.1016/j.hazadv.2022.100134

Amusat S. O., Kebede T. G., Dube S. and Nindi M. M. (2021). Ball-milling synthesis of biochar and biochar-based nanocomposites and prospects for removal of emerging contaminants: a review. *Journal of Water Process Engineering*, **41**, 101993, https://doi.org/10.1016/j.jwpe.2021.101993

Bi D., Huang F., Jiang M., He Z. and Lin X. (2022). Effect of pyrolysis conditions on environmentally persistent free radicals (EPFRs) in biochar from co-pyrolysis of urea and cellulose. *Science of the Total Environment*, **805**, 150339, https://doi.org/10.1016/j.scitotenv.2021.150339

Choudhary V. and Philip L. (2022). Sustainability assessment of acid-modified biochar as adsorbent for the removal of pharmaceuticals and personal care products from secondary treated wastewater. *Journal of Environmental Chemical Engineering*, **10**(3), 107592, https://doi.org/10.1016/j.jece.2022.107592

Crini G. and Lichtfouse E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters*, **17**(1), 145–155, https://doi.org/10.1007/s10311-018-0785-9

Jun L. Y., Mubarak N. M., Yee M. J., Yon L. S., Bing C. H., Khalid M. and Abdullah E. C. (2018). An overview of functionalised carbon nanomaterial for organic pollutant removal. *Journal of Industrial and Engineering Chemistry*, **67**, 175–186, https://doi.org/10.1016/j.jiec.2018.06.028

Li Z., Li K., Du P., Mehmandoust M., Karimi F. and Erk N. (2022). Carbon-based photocatalysts for hydrogen production: a review. *Chemosphere*, **308**, 135998, https://doi.org/10.1016/j.chemosphere.2022.135998

Macchi S., Denmark I., Le T., Forson M., Bashiru M., Jalihal A. and Siraj N. (2022). Recent advancements in the synthesis and application of carbon-based catalysts in the ORR. *Electrochem*, **3**(1), 1–27.

Mubarik S., Qureshi N., Sattar Z., Shaheen A., Kalsoom A., Imran M. and Hanif F. (2021). Synthetic approach to rice waste-derived carbon-based nanomaterials and their applications. *Nanomanufacturing*, **1**(3), 109–159, https://doi.org/10.3390/nanomanufacturing1030010

Pan Z. L. and Qian X. F. (2022). Porous carbons for use in electro-Fenton and Fenton-like reactions. *Xinxing Tan Cailiao/New Carbon Materials*, **37**(1), 180–195, https://doi.org/10.1016/S1872-5805(22)60578-X

Panda D., Patra S., Awasthi M. K. and Singh S. K. (2020). Lab cooked MOF for CO_2 capture: a sustainable solution to waste management. *Journal of Chemical Education*, **97**(4), 1101–1108, https://doi.org/10.1021/acs.jchemed.9b00337

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Sajjadi B., Chen W.-Y. and Egiebor N. O. (2019a). A comprehensive review on physical activation of biochar for energy and environmental applications. *Reviews in Chemical Engineering*, **35**(6), 735–776, https://doi.org/10.1515/revce-2017-0113

Sajjadi B., Zubatiuk T., Leszczynska D., Leszczynski J. and Chen W. Y. (2019b). Chemical activation of biochar for energy and environmental applications: a comprehensive review. *Reviews in Chemical Engineering*, **35**(7), 777–815, https://doi.org/10.1515/revce-2018-0003

Santamaría L., Korili S.A. and Gil A. (2022). Layered double hydroxides from slags: Closing the loop. *Journal of Environmental Chemical Engineering*, **10**(1), 106948.

Schlögl R. (2021). Quo vadis carbocatalysis? *Journal of Energy Chemistry*, **61**, 19–27.

Wang J. and Wang S. (2019). Preparation, modification and environmental application of biochar: a review. *Journal of Cleaner Production*, **227**, 1002–1022, https://doi.org/10.1016/j.jclepro.2019.04.282

Wang L., Wang Y., Ma F., Tankpa V., Bai S., Guo X. and Wang X. (2019). Mechanisms and reutilization of modified biochar used for removal of heavy metals from wastewater: a review. *Science of the Total Environment*, **668**, 1298–1309, https://doi.org/10.1016/j.scitotenv.2019.03.011

Yang G. and Park S.-J. (2019). Conventional and microwave hydrothermal synthesis and application of functional materials: a review. *Materials*, **12**(7), 1177, https://doi.org/10.3390/ma12071177

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