Engineering Reports

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Advancements in Biochar Functionalization for Sustainable Adsorption of Sulfur-Containing Gaseous Pollutants

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Received: 20 July 2025 | **Revised:** 16 September 2025 | **Accepted:** 26 September 2025

Keywords: adsorption | biochar | functionalization techniques | gaseous pollutants

ABSTRACT

The continuous emission of gaseous pollutants from the exploration and consumption of fossil-based energy sources has continued to damage the atmosphere, necessitating effective remediation strategies. The utilization of biochar as a renewable material for the adsorption of gaseous pollutants has attracted considerable interest owing to its ease of production, reusability, effectiveness, and eco-friendliness. The study reviews the application of functionalized biochar for the removal of sulfur-containing gaseous pollutants like hydrogen sulfide (H_2S), sulfur dioxide (SO_2), and carbon oxysulfide (COS) from air. The various functionalization techniques for biochar modification and outcomes of recent studies on the deployment of modified biochar for the removal of H_2S, SO_2, and COS are reviewed. The integration of artificial intelligence, case studies, challenges, and future research directions in the research domain is highlighted. The study testifies that functionalization enhances the microstructure, surface area, porosity, surface chemistry, and adsorption capacity of raw biochar for pollutant adsorption. The findings of this review depict functionalized biochar as an efficient material for H_2S, SO_2, and COS removal, thereby mitigating pollution, safeguarding public health, and contributing to environmental sustainability. Interdisciplinary collaboration and a handshake between academic and industry players are needed in overcoming existing challenges and translating research advancements into practical applications.

1 | Introduction

Environmental issues, including pollution, air quality, global warming, and climate change, are among the most pressing challenges affecting human health and the ecosystem globally today. Increasing population growth, overdependence on fossil-based (FB) energy sources, and rising industrial activities have exacerbated environmental pollution, negatively impacted air quality, and posed a significant ecological challenge [1]. Apart from these unwanted consequences, human activities such as urbanization, increased agricultural activities and food production, and improper waste disposal and management continue to release greenhouse gases (GHG) and other anthropogenic gases that threaten the Earth and its inhabitants. The global emission of GHGs such as methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), and so forth, has increased significantly in recent decades due to increased consumption of FB fuels for transportation, heat, and electricity generation, manufacturing, and other human activities [2]. A recent report indicated that the global GHG emissions, which were 8.69 billion tonnes (t) in 1900, rose to 22.13 billion t in 1960 and further to 53.82 billion t in 2023 [3]. The astronomical rise in GHG emissions has led to a rise in global temperature, environmental pollution, changes in weather patterns, and other climate change consequences. During the same period, the global population increased from about 1.6 billion in 1900 to 3.015 billion in 1960 and further to 8.092 billion in 2023 [4]. Figure 1 shows the global population and GHG emissions between 1900 and 2023. In the same vein, the number of disease

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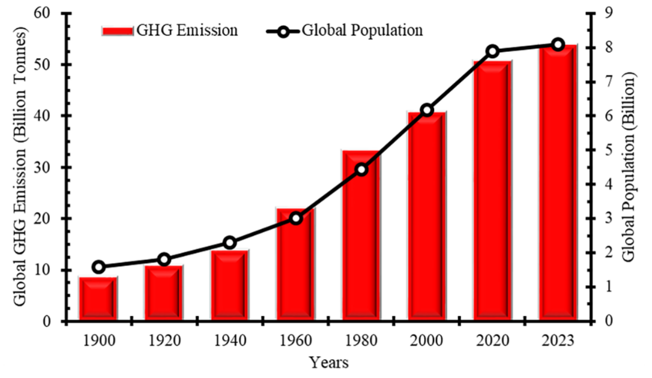


FIGURE 1 | Global population and GHG emission (1900–2023). Data culled from [3, 4].

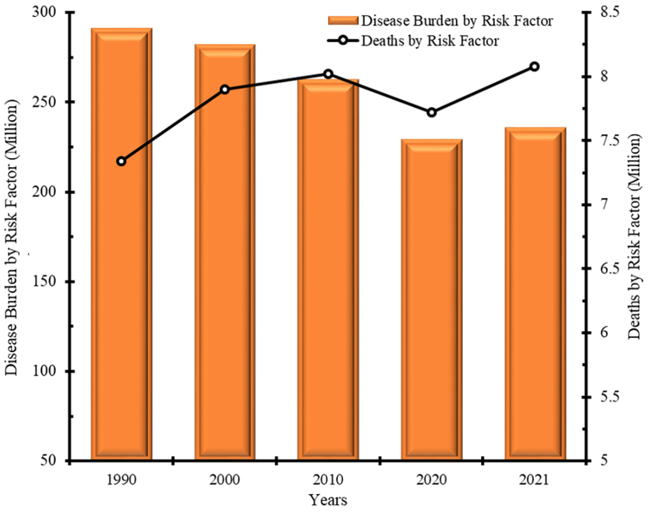


FIGURE 2 | Disease and death risk factors from air pollution (1990–2021). Data culled from [5].

burden from indoor and outdoor air pollution in 2021 was 235.9 million, while the number of deaths arising from indoor and outdoor pollution was 8.08 million in 2021 (Figure 2) [5].

The continuous generation and release of pollutants in solid, liquid, and gaseous forms contaminates soil, water, and air, necessitating effective remediation strategies. Pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), particulate matter, volatile organic compounds, methane, ozone, and so forth, are generally produced from various human activities and released to the environment they posing devastating threats to plants and other living organisms [6, 7]. For example, CO, a colorless gas, is generated from the incomplete combustion of FB fuels, is toxic and a major constituent of GHG, with grievous health impacts on humans, contributes to air pollution, and is linked to climate change and global warming. The emission of NOx from vehicles and industrial machinery and processes contributes to smog, acid rain, and ozone depletion, and exacerbates the GHG effect. VOCs and other chemicals from industrial processes, power plants, and vehicle emissions pollute air and water bodies, cause unpleasant odors, and impact human health [7, 8]. The emission of pollutants containing sulfur such as hydrogen sulfide (H_2S), sulfur dioxide (SO_2), sulfur trioxide (SO_3), and carbon oxysulfide (COS) from burning of FB fuels, power generation, industrial processes, and volcanic eruptions contributes to acid rain formation, acidification of soil and aquatic ecosystems, interfere with photosynthesis and inhibit plant growth, reduce air quality, and impact human health [9]. The urgent need to ameliorate the deleterious impact of sulfur-containing pollutants has gained traction among researchers and stakeholders in recent times, with concerted efforts ongoing to reduce and mitigate their impacts. To ensure environmental protection, improve human health, mitigate climate change, and ensure clean energy and sustainable industrial processes, efforts at mitigating sulfur-containing emissions should be supported.

At present, the adoption of desulfurization technology and other mitigating efforts, such as the transition to low-sulfur fuels, the adoption of renewable energy, and the implementation of strict sulfur-emission limits and fuel quality standards, has yielded limited results [10]. The challenges of solvent volatilization, high energy consumption, equipment corrosion, difficult scalability, complicated product post-processing, and the high possibility of secondary pollution have made the development and deployment of low-cost and efficient desulfurization technologies inevitable. Scholars have ventured into the development of adsorbents as a viable and efficient desulfurization technique. The use of activated carbon, zeolite, metal oxide, metal organic framework compounds, carbon nanotubes, biochar, and so forth, as adsorbents for sulfur-containing pollutants has gained popularity due to their simplicity, renewability, scalability, efficacy, and absence of wastewater has been relatively successful [11, 12]. However, the development of biochar from crop residues, agricultural waste, and other biomass is simple, economical, and sustainable, and has continued to attract considerable research interest.

Recent studies by Ullah et al. [11], Kong et al. [12], and Gęca et al. [13] on the synthesis, characterization, development, and functionalization of biomass-derived biochar and other composite materials on the adsorption of atmospheric pollutants demonstrated the efficacy of the process. The outcomes of other studies have shown that biochar can effectively absorb H_2S [14], SO_2 [15], CO_2 [16], NOx [17], and inorganic pollutants [18] from the atmosphere, which lends credence to developing prospects in the research area. In the recent past, some review articles have shown research progress of biochar adsorption of gaseous pollutants from the atmosphere to improve air quality. Gwenzi et al. [19], in their recent study, reviewed the properties, removal mechanisms, constraints, and future directions in the application of biochar for the adsorption of H_2S, SO_2, CO_2, NOx, ozone, VOC, and other gaseous pollutants. They concluded that economic consideration, renewability, sustainability, and potential industrial applications as the major benefits of the process. Wei et al. [20] provided an overview of the research situation, principles, techniques, opportunities, and challenges in the removal of COS from blast furnace gas using porous biochar. They identified the impressive surface configuration, pore size, and reasonable alkalinity of the fabricated biochar as important factors that supported COS removal and conversion. Sun et al. [21] reviewed research progress in the application of carbon-based biochar in the desulfurization of H_2S, including the adsorption mechanism, novel modification and activation techniques, and challenges to process scalability. The authors highlighted strategies of deploying biochar as green adsorbents for the removal of pollutants from diverse environments. Other authors, in their separate studies have identified viable challenges, including scarce active sites, inadequate active functional groups, underdeveloped pore structure, high production costs, fear of secondary pollution, and so forth, militating against the development of innovative techniques for sustainable bicohar generation, modification, and application. Strategies to achieve large scale utilization, commercialization, emerging perspectives, limitations, challenges, and future directions for application of bichar as low-cost adsorbents of organic pollutants have been highlighted [22, 23]. Table 1 summarizes some of the research outcomes of the application of biochar as an adsorbent for sulfur-containing pollutants.

From the foregoing, it is clear that the majority of existing reviews were focused on the application and performance of biochar in removing sulfur-containing pollutants with little attention paid to biochar activation and modification techniques. Besides, research into the use of biochar as an adsorbent for sulfur-containing pollutants has gained traction in recent years, resulting in the publication of enormous new information and data. There is a need to publish a new review to update existing information, capture new data, aggregate recent outcomes, and suggest future research directions in the field. This is the motivation behind the current intervention. The aim of the study, therefore, is to review recent advancements in the application of functionalized biochar as sustainable adsorbents for sulfur-containing pollutants. The objective of the study is to aggregate recent research advances, provide updated information, and suggest new insights on the synthesis, activation, modification, and application of biochar as adsorbents for

TABLE 1 | Summary of recent studies on the application of biochar as adsorbents for sulfur-containing pollutants.

ToP (YoP)	Research highlights	Remark	KPM	CC	Ref.
Research (2020)	Kinetic study of adsorption of H_2S using macroalgae biochar	Biochar demonstrated enhanced adsorption capacity after activation	RE up to 99%; Q = 582–5800 mg/kg; ORC = Calcination at 800°C BY = 26.1 30.2%	78	[24]
Research (2020)	Surface characterization of corn straw biochar for the removal of HCN, COS, and CS_2	Biomass-based biochar exhibited excellent pollutant removal	RE = 100%; ORC = 600°C–800°C, 360–480 min, using CO_2	25	[25]
Review (2022)	Application of 2D materials as adsorbents for environmental decontamination	Limited to the application of 2D materials for polluted air filtration	RE up to 99%; Q = VOCs: 150–300 mg/g (VOCs), 50–120 mg/g (Heavy metals); ORC = 25°C–40°C, 30–90 min	34	[26]
Review (2022)	Synthesis, modification, mechanisms, and performance of biochar for air pollutant removal	Economic and high removal efficiency of pollutants by fabricated biochar	RE up to 99%; Q = 50–150 mg/g (SO_2), 20–80 mg/g (NH_3), and 0.5–1.5 mmol/g (Hg^0); ORC = 25°C–60°C, 30–120 min	67	[27]
Research (2024)	Synthesis, characterization, and application of biochar for environmental remediation	Effective and low-cost removal of sulfur dioxide	Activation increased RE by 45%; ORC = 800°C and 16 wt%	2	[28]
Research (2024)	Bamboo-derived biochar for the adsorption of CO_2 and PM	Pollutant removal efficiency of 91.23% and 89.19% for CO_2 and $PM_{2.5}$, respectively.	BY = 34.25%; RE = 89.19%–91.23%; ORC = 700°C, 60–120 min	12	[29]
Research (2024)	Microalgal biochar for the removal of PM and VOC	Over 90% removal efficiency achieved with minimal waste generation	RE = 99%; ORC = 500°C, and pore size 9.85–11 nm	9	[30]
Research (2024)	Modified biochar for the adsorption of SO_2	Biochar modification enhanced the pollutant removal efficiency	RE = 98–100%; Q = 75.598–100.181 mg/g; ORC = 783°C–788°C, 47–57 min	10	[31]
Review (2024)	Polymer-based biochar for environmental remediation	Biochar demonstrated high regenerability and adsorption efficiency	Re = 98 5; Q = 50–300 mg/g; ORC = 25°C–45°C, pH 5–7, 60–180 min	5	[32]
Review (2024)	Application of biochar for the removal of environmental pollutants	Effective use of biochar for pollutant removal and environmental remediation	RE = 99%; Q = 150–300 mg/g (Pb^{2+}), 50–100 mg/g (${NH_4}^+$), 20–80 mg/g (pesticides); ORC = 25°C–45°C, 60–180 min, and 5–8 pH	14	[33]
Review (2025)	Progress, challenges, and perspectives of biochar as adsorbents for sulfur-based pollutants	Modification of biochar contributed to improved performance	RE = 99%; Q = 50–150 mg/g (H_2S), 100–200 mg/g (SO_2), 30–90 mg/g (COS); ORC = 25°C–60°C, 30–120 min	2	[34]
Review (2025)	Sewage sludge biochar for adsorption of pollutants	Low-cost and environmentally sustainable pollutant removal technology	RE = 95%; Q = 80–250 mg/g (Pb^{2+}), 50–150 mg/g (Methylene blue), 20–100 mg/g (Antibiotics); ORC = 25°C–60°C, 60–180 min, and pH 5–8	Nil	[35]

Abbreviations: BY, Biochar yield; CC, citation count; KPM, key performance metrics; ORC, optimal removal conditions; Q, adsorption capacity; RE, removal efficiency; ToP, type of publication; YoP, year of publication.

sulfur-containing pollutants to ensure environmental sustainability. The novelty of this review lies in its comprehensive analysis of biochar pretreatment and modification strategies, particularly the novel green-solvent-based pretreatment techniques and advanced and hybrid functionalization techniques as well as the synergistic integration of Artificial Intelligence (AI) and other machine learning (ML) algorithms in optimizing biochar performance for the adsorption of sulfur-containing pollutants. By consolidating implications, case studies, practical examples, and modeling approaches, the review highlights how AI-driven frameworks enhance predictive accuracy, material design, and process control. Unlike similar review articles on the subject, the current study also addresses current challenges, including variability in biochar feedstocks, limited mechanistic understanding of sulfur adsorption pathways, and so forth, and outlines future research directions focused on real-time AI-assisted monitoring systems, hybrid adsorbent development, and intelligent solution for sulfur pollution mitigation. The inclusion of visual representations and illustrative figures to improve clarity and enhance the readers' understanding presents an innovative approach. In this review, separate sections are dedicated to the overview of biochar feedstock, generation, and activation, biochar functionalization techniques, interrogation of recent research outcomes on the application of biochar as an adsorbent for sulfur-containing pollutants, and the application of AI in the absorption of sulfur-containing pollutants by biochar. Challenges in the synthesis and application of biochar as an adsorbent for sulfur-containing pollutants are identified, while future research directions are suggested. The scope of this review is limited to the review of synthesis, activation, modification, and application of biochar for the removal of H_2S, SO_2, and COS from polluted air using information available in recently published peer-reviewed literature. The outcome of this study will update existing information and provide new insights, guidance, and motivation for researchers, environmentalists, and other stakeholders in air pollution remediation research areas to develop innovative, low-cost, and sustainable biochar-based desulfurization adsorbents. The study is expected to instigate further study on the deployment of AI and other innovative digital technologies to enhance the desulfurization process.

2 | Overview of Biochar Feedstock, Generation, and Activation

2.1 | History and Definition of Biochar

Biochar has its historical roots in the Amazon Basin of South America, where indigenous people created a dark, charcoal-rich soil to improve soil fertility over 2500 years ago. However, modern-day renaissance and scientific understanding of biochar came with the work of Justus von Liebig around the mid-nineteenth century. The work of the German chemist laid the foundation and renewed scientists' interest in research into the production and potential application in areas other than agriculture and soil improvement [36]. Other historical information has shown that biochar was applied for agricultural purposes in Japan, Korea, and other Asian countries. Subsequently, the awareness of biochar increased with many countries forming National Biochar Societies to initiate, champion, and expand the frontiers of research in biochar. Since the first meeting of the International Biochar Advocacy Organization held in Australia in 2007, the quantum and intensity of biochar research has increased in all its ramifications [36, 37]. Today, with the surging population, an increase in human activities, rising industrialization, and technological advancements, research into the raw materials, production techniques, and utilization avenues of biochar has increased tremendously.

According to the International Biochar Initiative, biochar is a solid carbonaceous residue generated through the thermochemical degradation of various biomass at elevated temperature in an oxygen-controlled environment [38]. In their recent study, Awogbemi and Kallon [39] defined biochar as a solid, hard, charcoal-like, and carbon-rich residue obtained from the high-temperature decomposition of biomass under a controlled environment. According to Hagemann et al. [40] and Wiinikka et al. [41], biochar is different from charcoal and activated carbon. Charcoal is described as a solid carbon-rich woody material usually produced from woody biomass and other waste materials as feedstock and used as fuel and reducing agent in metallurgical and metal processing. Activated carbon, also a carbonaceous solid residue produced from biomass materials like coal, lignite, tar pitch, and other similar feedstocks. Comparatively, biochar is obtained during the pyrolysis of biomass, while activated carbon is produced from physical or chemical modification of biochar. Charcoal is a product of wood carbonization and is commonly used as a renewable solid fuel [39, 42].

2.2 | Biochar Feedstock and Generation

Primarily, biochar can be produced from any carbon-rich organic material. However, to align with the concept of circular bioeconomy, recycling, and for economic and environmental sustainability, lignocellulose biomass such as agricultural waste, crop residues, food leftovers, animal bones and horns, animal wastes, mill residues, algae, and so forth, have been used as feedstock to manufacture biochar [43]. The construction of biochar from waste biomass supports sustainable waste management, reduces the cost of waste disposal, helps divert waste from landfills, reduces the need for open burning of waste, and minimizes the emission of toxic gases from open burning. The conversion of waste materials to useful biochar supports job creation, creates additional income to farmers and households, and helps in meeting some of the United Nations Sustainable Development Goals (SDGs) [44]. Prominent waste materials that have been used as feedstock for biochar production can be categorized as forest waste, crop residues, domestic waste, and animal waste, as shown in Figure 3. The choice of this waste biomass as feedstock for biochar production supports food security, prevents the food versus fuel debate, and cost-effective production of biochar.

Conversion of feedstock to useful biochar involves a series of processes including collection and sorting of waste biomass, preparation and pretreatment, selection of conversion technique and processing parameter, feedstock conversion, and product separation. Feedstock for biochar is collected from farms, households, industries, abattoirs, and other locations where they are sorted and separated before being transported to the location of the conversion plant. At the conversion site, the feedstocks are

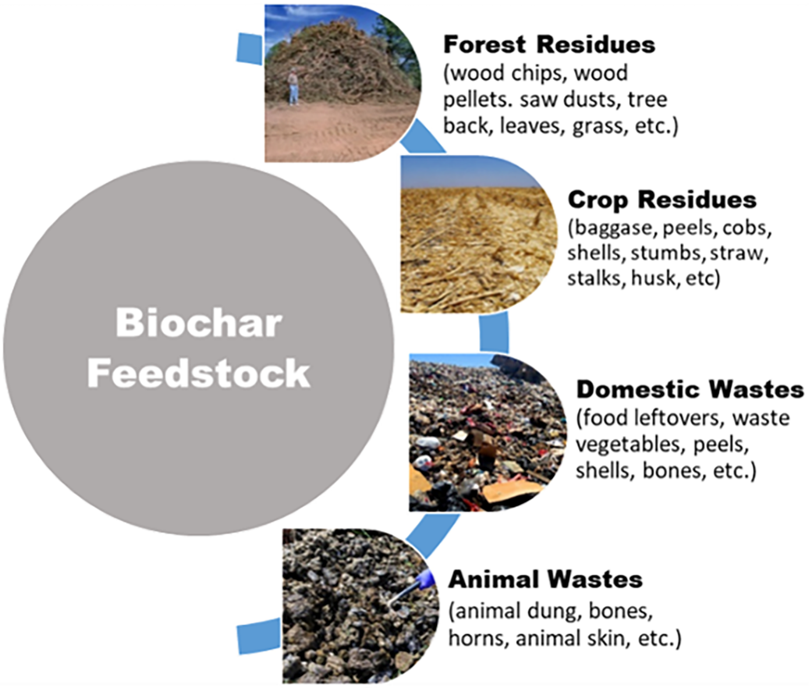
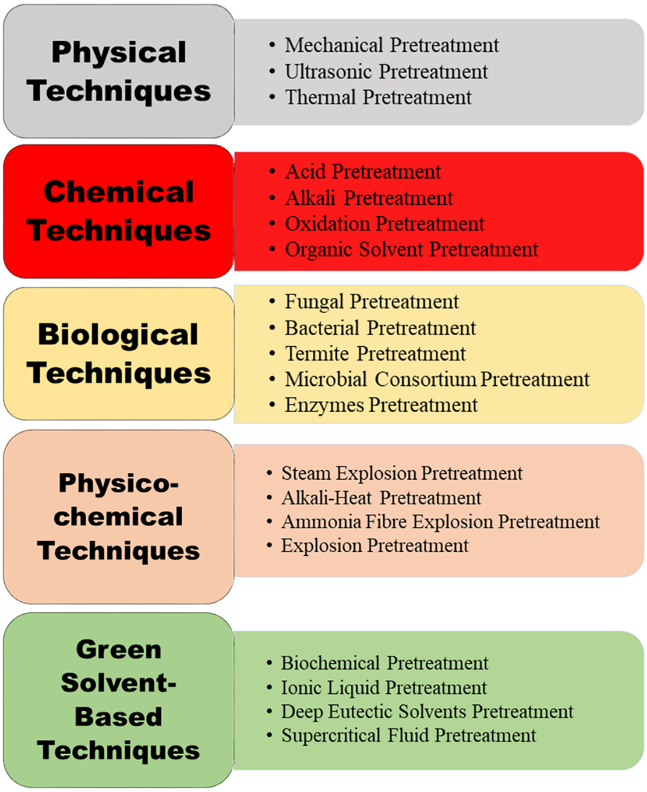


FIGURE 3 | Categories of biochar feedstock.

screened to remove any unwanted materials and prevent contamination of the feedstock, preparatory to loading them into the conversion chamber. Most feedstocks, due to their composition, nature, types, and so forth, are recalcitrant, intractable, and difficult to convert; hence, they need to be pretreated. Pretreatment of biochar feedstock is a series of processes deployed to adjust, modify, and transform raw biomass before its actual conversion. The pretreatment techniques alter the moisture content, composition, physical, chemical, surface, and biological characteristics of the biomass [45]. Recent studies by Awogbemi and Kallon [46], Ramos et al. [47], and Prasad et al. [48] classified biomass pretreatment approaches into physical, chemical, biological, physicochemical, and green solvent-based techniques and extensively discussed the major examples, benefits, and drawbacks of each pretreatment technique. Figure 4 shows the major biomass pretreatment techniques. Unlike the previous studies, the current review article introduced green-solvent based pretreatment techniques for biochar treatment. The novel green-solvent-based pretreatment techniques offer a sustainable and tunable pathway for enhancing biochar surface functionality, porosity, and pollutant affinity under mild conditions. Their low toxicity, recyclability, and compatibility with diverse biomass feedstocks position them as a transformative approach for next-generation biochar engineering. Generally, pretreatment of feedstock enhances the feedstock quality, improves the structural properties, reduces contaminants, and prepares the feedstock for the conversion process. In some cases, wet biomass is dehydrated to reduce the moisture content and reduce decay or insect infestation, while other biomass may be cut into smaller pieces to increase the surface contact during conversion [49, 50]. Though the cost of pretreatment adds to the production costs and needs extra energy, manpower, machinery, and other logistics, pretreatment enhances the digestibility and biodegradability of the feedstock and ensures the generation of quality products. When compared with untreated feedstock, pretreated feedstock requires less time, energy, and cost for conversion, demonstrates higher conversion efficiency, and ensures improved biochar yield [51].



Physical Techniques	• Mechanical Pretreatment • Ultrasonic Pretreatment • Thermal Pretreatment
Chemical Techniques	• Acid Pretreatment • Alkali Pretreatment • Oxidation Pretreatment • Organic Solvent Pretreatment
Biological Techniques	• Fungal Pretreatment • Bacterial Pretreatment • Termite Pretreatment • Microbial Consortium Pretreatment • Enzymes Pretreatment
Physico-chemical Techniques	• Steam Explosion Pretreatment • Alkali-Heat Pretreatment • Ammonia Fibre Explosion Pretreatment • Explosion Pretreatment
Green Solvent-Based Techniques	• Biochemical Pretreatment • Ionic Liquid Pretreatment • Deep Eutectic Solvents Pretreatment • Supercritical Fluid Pretreatment

FIGURE 4 | Major biochar pretreatment techniques.

2.3 | Biochar Properties

The key properties of biochar are the characteristics that determine and make it valuable for various applications, including agriculture, environmental remediation, and energy storage. The properties of biochar depend on the feedstock type, pyrolysis temperature, and residence time. The properties of biochar are categorized as physical properties and chemical properties [52]. Among the favorable physical properties of biochar is density, particle size, pore size and volume, structural porosity, specific surface area, grindability, thermal conductivity, heat capacity, hydrophobicity, and water retention capacity. The required chemical properties of biochar include carbon content, volatile matter, ash content, pH, electrical conductivity, reactivity, functionality, proportion of atoms, and cation exchange capacity (CEC) [53, 54]. The presence of essential nutrients like phosphorus and nitrogen in biochar influences its utilization area. The limiting potential property of biochar allows it to act as a liming agent, alter soil pH, and improve the soil microbial activity. Biochar's electrochemical conductivity is an important property that influences soil redox reactions, affecting nutrient availability and microbial interactions [55]. Figure 5 explains some physical and chemical properties of biochar while Table 2 shows some of the properties of biochar.

3 | Biochar Functionalization Techniques

The raw biochar manufactured through the pyrolysis or carbonization of biomass exhibits inappropriate properties and lower quality in physical, chemical, compositional, and structural characteristics such as reduced pores, smaller surface area, and fewer surface functional groups. These inadequacies impact the properties and performance of biochar during application, necessitating the need for modification. Biochar functionalization refers to the process of modifying the surface chemistry of biochar to enhance its properties for specific applications. While raw biochar has inherent porosity and adsorption capabilities, functionalization further enhances its effectiveness in environmental and industrial applications. This involves introducing functional groups, metals, non-metals, or polymers to improve its reactivity, adsorption capacity, and catalytic performance. Biochar functionalization can be achieved through physical techniques, chemical techniques, biological techniques, and advanced and hybrid techniques (Figure 6). The novelty of the current approach is the inclusion of advanced and hybrid techniques for biochar functionalization, which enable precise control over surface chemistry, porosity, and catalytic behavior, surpassing traditional biochar limitations. Table 3 highlights the operating conditions, benefits, limitations, and areas of application of various biochar functionalization techniques. The aim of the functionalization techniques is to improve the physicochemical properties, electrochemical characteristics, and surface active sites of raw biochar, leading to improved performance across various applications.

3.1 | Physical Biochar Functionalization Techniques

Physical biochar functionalization involves modifying the surface properties of biochar through mechanical, thermal, or structural treatments without the use of chemicals. These techniques enhance biochar's porosity, surface area, and adsorption capacity, making it more effective for environmental and industrial applications [88]. Physical functionalization of biochar is achieved through ball milling, thermal treatment, microwave irradiation, and ultrasonic treatment. During ball milling, biochar

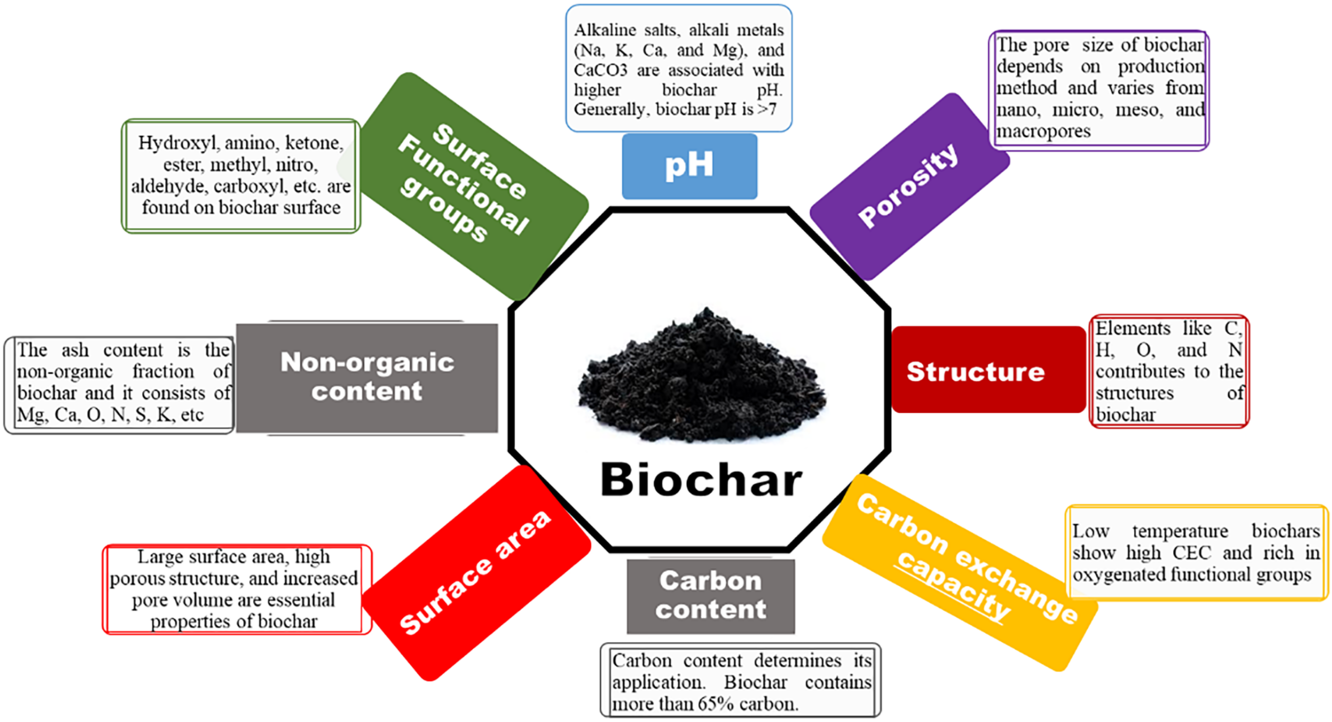


FIGURE 5 | Physicochemical properties of biochar.

TABLE 2 | Properties of biochar.

	Feedstock							
Properties	**Date palm**	**Rice husk**	**Swine manure**	**Orange pomace**	**Soybean straw**	**Turkey litter**	**Timothy grass**	**Grass**
pH	8.92	9.5	11	9.9	11.3	10.9	NR	NR
Electrical Conductivity (dS/m)	3.98	2.56	NR	NR	NR	NR	NR	NR
Volatile matter (%)	NR	NR	35.5	32.3	14.7	NR	7.5	26.8
CEC	NR	NR	65.6	35.2	59.2	24.4	NR	NR
C (%)	60	NR	74.9	56.8	82.0	15.6	67.5	77.3
O (%)	NR	NR	NR	NR	NR	4.4	28.2	16.7
H (%)	3.44	NR	NR	NR	NR	0.83	2.3	4.7
N (%)	0.24	0.10	NR	NR	NR	0.78	1.9	1.24
Surface area (m2/g)	237.8	NR	4.9	1.2	14.7	21.8	17.9	8.7
Ash (%)	25.70	NR	4.8	11.3	17.2	6.4	3.5	16.3
Reference	[56]	[57]	[52]	[52]	[52]	[58]	[58]	[58]

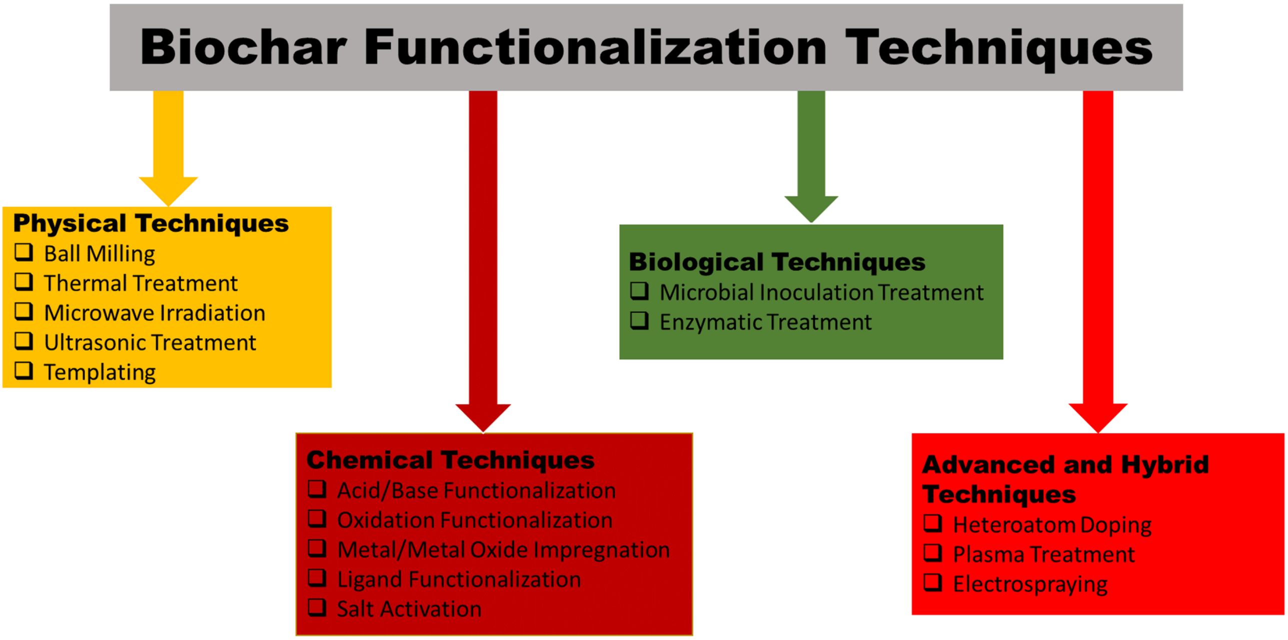


FIGURE 6 | Major biochar functionalization techniques.

is pulverized into finer particles using mechanical milling to increase the surface area and improve its adsorption properties. Though ball milling biochar functionalization appears simple and easily achievable, the biochar quality depends on milling type, ball size, vibrational amplitude, rotational type, milling medium, speed, duration, feedstock-to-balls, and other operational parameters. To improve the quality of the product, the high-energy ball milling technique can be employed at elevated temperatures and pressures for the synthesis of micro- and nano-sized biochar particles [89, 90]. The ball milling technique of biochar functionalization exemplifies a greener, cost-effective, and eco-friendly approach for producing biochar-based nanomaterials from biomass resources. However, the challenges of inaccurate measurement of process parameters, lack of control over particle morphology, and possible formation of agglomerates require process optimization and other theoretical investigations [59, 60].

Thermal treatment is a physical biochar functionalization technique that modifies biochar's pore structure and surface properties by exposing it to controlled elevated temperatures. This process enhances porosity, surface area, and surface chemistry, making biochar more effective for various applications. The modification can occur during the biochar production when pyrolysis temperature, heating rate, and residence time are adjusted and optimized to fine-tune biochar's structural properties [91]. Kim and Jung [60] reported that biochar manufacture at 600°C–800°C demonstrated increased surface area and microporosity, making it ideal for adsorption of pollutants. Post-pyrolysis heat treatment is a form of modification where biochar is subjected to

TABLE 3 | Summary of biochar functionalization techniques.

Biochar functionalization technique	Operating conditions	Benefits	Limitations	Areas of application	Remarks	References
Physical functionalization techniques						
Ball milling	• TR: 400°C–700°C • Ball milling time: 30 to 240 min • Ball-to-Material ratio: 50:1 • Milling speed: 300 rpm	• Enhanced surface area and porosity • Cost-effective and ecofriendly • Improved reactivity	• Feedstock selection challenges • Requires process optimization • Potential environmental risks	• Water and soil remediation • Catalysis and energy storage • Agriculture	• Further study of milling process optimization • Conduct environmental impact assessment • Expand R&D on applications	[59, 60]
Thermal Treatment	• TR: 300°C–800°C • Atmosphere: Oxygen-limited environment • RT: 1–2 h • Feedstock type: Lignocellulosic and non-lignocellulosic biomass.	• Improved surface area and porosity • Boosts graphitization • Cost-effectiveness	• Yield reduction • High energy consumption • Potential pollutants generation • Variable performance	• Energy storage • Chemical reactions and environmental remediation • Carbon Sequestration	• Optimize temperature between 600°C and 700°C • Combine with other techniques • R&D into application-specific adjustments	[61, 62]
Microwave irradiation	• TR: 300°C–900°C • Microwave power: Usually 500–2000 W • RT: 5–30 min • Atmosphere: Inert gas environment	• Improved adsorption • Environmental sustainability • Cost-effectiveness • Lower energy consumption	• High cost of specialized microwave reactors • Limited scalability • Feedstock sensitivity • Potential byproducts	• CO_2 capture • Catalysis • Energy storage • Wastewater treatment • Carbon sequestration • Environmental remediation	• Optimize microwave parameters • Adopt use of RE for microwave heating • Implement hybrid activation methods • Future research on industrial scale development • Carry out application-specific adjustments	[63, 64]
Ultrasonic treatment	• Ultrasound frequency: 20 kHz–40 kHz • Power input: 100 W to 1000 W, • RT: 30 s to several min • Adsorption capacity: 238.7 mg/g	• Rapid and uniform activation • Enhanced porosity and adsorption capacity • Sustainability and energy efficient	• Limited scalability • High cost of ultrasonic reactors • Feedstock dependency	• Environmental remediation • Catalysis for biomass conversion • Agriculture and soil improvement	• Optimization of ultrasound parameters • Implement hybrid activation methods • Future research in scalability and industrial scale development	[65, 66]
Templating	• TR: 400°C–900°C • Template materials: Surfactants, block copolymers, silica, zeolites, and metal oxides. • RT: Few minutes to several hours	• Enhanced porosity and adsorption • Energy efficiency • Optimization of material performance • Improved catalytic properties	• High cost of specialized templating materials • Complex synthesis • Technical challenges • Complex template removal	• Environmental remediation • High performance energy storage • Carbon sequestration	• Optimization of template selection • Combine templating with other techniques • Further research on scalability and commercialization	[67, 68]
Chemical functionalization techniques						
Acid/base functionalization	• Acid type: H_2SO_4, HNO_3, and H_3PO_4 • Type of base: NaOH, KOH, $Ca(OH)_2$, etc. • Concentration: 0.1 M–2 M • TR: 50°C–150°C • RT: 30 min–h	• Enhanced organic pollutants adsorption • Improved catalytic properties • Increased surface area and porosity • Better chemical stability	• Acid residue may cause pollution • Biochar structural damage • High costs of some acids • Environmental and disposal concerns	• Wastewater treatment • Catalysis • Enhancement of soil fertility and nutrient retention • Production of supercapacitors and batteries • CO_2 adsorption	• Optimize acid concentration to balance functionalization and structural integrity • Explore green functionalization methods for sustainability • Perform detailed characterization to assess modifications	[68, 69]

(Continues)

TABLE 3 | (Continued)

Biochar functionalization technique	Operating conditions	Benefits	Limitations	Areas of application	Remarks	References
Oxidation functionalization	• Oxidizing agents: HNO_3, H_2O_2, O_3, or piranha solution • Concentration: 0.1 M to 2 M • TR: 50°C–150°C • RT: few hours to several days	• Effective adsorption of pollutants • Improved catalysis • Increased surface area • Greater stability and resistant to environmental degradation.	• Oxidizing agent residue • Excessive oxidation degrades biochar structure • High cost of some oxidizing agents • Environmental concerns on disposal of oxidized biochar	• Removal of heavy metals and organic pollutants • Oxidation reactions and environmental remediation. • Soil fertility and nutrient retention • Energy storage • Carbon capture	• Optimize oxidizing agent concentration • Conduct thorough washing to remove excess oxidizing agents • Explore alternative oxidation methods for sustainability • Perform detailed characterization	[70, 71]
Metal/Metal oxide impregnation	• Type of metal/metal oxide: Fe_3O_4, TiO_2, ZnO, CuO, MnO_2, etc. • Impregnation method: Wet impregnation, sol–gel synthesis, precipitation, hydrothermal treatment. • Metal concentration: 1wt%–20wt% • TR: 50°C–300°C • RT: few hours to several days.	• Superior adsorption capacity • Improved catalysis • Suitable for batteries, supercapacitors, and fuel cells	• Potential of metal leaching • Structural damage and degradation • High cost of metals and complex synthesis methods • Environmental concerns:	• Electrocatalysis • Energy storage • Biorefinery • Removal of heavy metals and organic pollutants	• R&D of metal/nonmetal concentration to balance functionalization and structural integrity • Devise cost reduction strategies • Explore alternative impregnation methods	[72, 73]
Ligand Functionalization	• Type of ligand: NH_2, SH, COOH, and PO_4 • Functionalization method: Covalent bonding, electrostatic interactions, or chelation • Ligand concentration: 1wt%–20wt% • TR: 50°C–200°C • RT: Few hours to several days	• Enhanced adsorption of pollutants and biomolecules • Improved catalytic properties • Selective binding • Better chemical stability	• Ligand leaching • Structural degradation of biochar • Expensive ligands • Environmental concern in waste disposal	• Pollutants removal from wastewater • Catalysis • Biomedicine • Energy storage • CO_2 adsorption	• Optimize ligand concentration • Conduct thorough washing and stabilization to prevent ligand leaching • Development of alternative functionalization methods for sustainability	[74, 75]
Salt Activation	• Type of salt: KCl, NaCl, $ZnCl_2$, $CaCl_2$ • Activation method: Molten salt impregnation, salt-assisted pyrolysis, or salt leaching • TR: 400°C–900°C • RT: few hours to several days	• Superior adsorption of pollutants • Improved catalysis • Enhanced stability • Electrochemical applications	• Generation of salt residue • Structural damage • High cost of salt and equipment • Disposal of salt-functionalized biochar	• Electrochemical applications • Agriculture • Wastewater treatment • Energy storage • Carbon capture	• More studies on environmental safety and sustainability • Develop alternative salt activation methods • Explore cost reduction strategies	[76, 77]
Biological functionalization techniques						
Microbial inoculation treatment	• Microbial strains: nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi • Inoculation method: Soaking, spraying, or mixing • RT: few hours to several days	• Improved soil fertility • Promotes soil aeration and moisture retention • Degrade organic contaminants • Improved nutrient cycling	• Microbial survival • Challenges in maintaining microbial viability • Require specialized equipment • Possible microbial imbalances	• Enhances soil fertility and plant growth • Bioremediation • Waste management • Wastewater treatment	• Optimize microbial selection based on soil and crop requirements. • Ensure proper incubation and stabilization for long-term effectiveness. • Explore low-cost inoculation methods • Conduct DNA sequencing, microbial activity assays to assess modifications	[78, 79]

(Continues)

TABLE 3 | (Continued)

Biochar functionalization technique	Operating conditions	Benefits	Limitations	Areas of application	Remarks	References
Enzymatic treatment	• Type of enzyme: laccase, peroxidase, cellulase, and protease • Immobilization method: Physical adsorption, covalent bonding, entrapment, or cross-linking • Enzyme concentration: 0.1wt%–5wt% • TR: 25°C–60°C • RT: few hours to several days	• Enhanced biodegradation • Boosts efficiency in oxidation and hydrolysis reactions • Selective binding • Better chemical stability	• Enzyme leaching • Excessive functionalization may degrade biochar structure • High cost of some enzymes and equipment • Disposal of enzyme-functionalized biochar	• Wastewater treatment. • Drug delivery and biosensing • Used in biofuel production and enzymatic reactors • Agriculture	• Optimize enzyme concentration • Explore alternative immobilization methods • Perform detailed characterization • Further R&D to improve process efficiency	[80, 81]
Advanced and Hybrid Functionalization techniques						
Heteroatom doping	• Type of heteroatom: N, S, P, and B • Doping method: Pre-decoration doping or post-decoration doping • TR: 400°C–900°C • RT: few hours to several days	• Enhanced adsorption • Improved catalytic properties • Increased surface area and porosity • Better Electrochemical Performance	• Complex synthesis techniques • Excessive doping may degrade biochar structure • High cost of some heteroatoms • Disposal of doped biochar	• CO_2 adsorption • Removal of heavy metals and organic pollutants • Supercapacitors and batteries production	• Optimization of heteroatom concentration • Develop cost reduction strategies • Conduct thorough research to prevent heteroatom leaching • Explore alternative doping methods	[82, 83]
Plasma treatment	• Type of plasma: Non-thermal plasma, dielectric barrier discharge, radio-frequency (RF) plasma • Gas composition: O_2, N_2, Ar, Cl_2 • RT: a few seconds to several minutes. • TR: below 200°C	• Enhanced adsorption • Improved catalytic properties • Increased surface area and porosity • Better electrochemical performance	• Requires specialized plasma generators • Excessive plasma exposure may degrade biochar structure • Expensive treatment systems • Environmental concerns	• Wastewater treatment • Organic synthesis reaction • Energy storage application • Agriculture • Carbon capture	• Optimize plasma exposure time • Conduct thorough characterization • Explore alternative plasma sources • Ensure proper disposal and environmental safety measures	[84, 85]
Electrospraying	• Voltage: 5 kV to 30 kV • Flow rate: 0.1 mL/h to 5 mL/h • Solvent: Ethanol, acetone, and water-based	• Enhanced adsorption • Improved catalytic properties • Uniform surface modification • Better electrochemical performance	• Requires specialized electrospraying systems • Structural damage • High cost of electrospraying equipment • Disposal of electrosprayed biochar	• Electrochemical application • Wastewater treatment • Energy storage for supercapacitors and batteries • CO_2 adsorption	• Optimization of electrospraying parameters • Conduct thorough characterization • Ensure proper disposal of spent biochar	[86, 87]

Abbreviations: R&D, research and development; RE, renewable energy; RT, reaction time; TR, temperature range.

additional thermal processing to remove impurities and enhance its adsorption capacity [61]. Biochar functionalized by thermal treatment shows increased specific surface area, improved adsorption capacity, better graphitization, and more resistance to degradation, and is applied for energy storage, soil amendment, carbon sequestration, pollutants adsorption, and environmental remediation [62].

The microwave irradiation functionalization technique involves exposing biochar to microwave energy, causing dipole rotation and ionic conduction, which induces efficient, rapid, and uniform heating and structural changes, improving its surface morphology, porosity, functional groups, and creating more active sites. The process occurs typically between 400°C and 900°C, 500–2000 W, for 5–30 min, and in an inert gas (nitrogen or argon) environment [92, 93]. In a recent study, Zhang et al. [63] employed microwave irradiation to increase the micropore structure and absorptive characteristics of raw biochar for various applications. They reported that the functionalized biochar demonstrated excellent reusability, improved pollutant absorption, CO_2 capture, catalysis, and wastewater treatment. Improved Adsorption: Enhances biochar's ability to remove heavy metals and organic pollutants. Application of the microwave irradiation functionalization technique is cost-effective, consumes low energy, ensures environmental sustainability, and improves the utilization of biochar. The limitations of the technique include high cost of specialized equipment, challenges in industrial-scale implementation, and feedstock sensitivity [64]. With appropriate R&D in process parameters optimization, implementation of hybrid modification methods, and industrial scale development, microwave irradiation biochar functionalization can become a more useful and effective biochar modification technique.

Ultrasonic treatment biochar functionalization is a technique that enhances biochar properties using ultrasound waves. The process involves exposing biochar to ultrasonic energy, which induces cavitation, exfoliation, and structural modifications, improving its surface area, porosity, and functional groups. During the process, ultrasonic waves at 20 kHz to 40 kHz and 100 W to 1000 W are applied to break down raw biochar particles, thereby enhancing their dispersion in solutions during applications [94]. Ultrasonic treatment of biochar is energy efficient, sustainable, and guarantees fast and uniform modification of biochar. Ultrasonically functionalized biochar demonstrates improved porosity and adsorption capacity, sustainability, and better bioremediation, notwithstanding the high cost of specialized ultrasonic reactors, limited scalability, and other technical challenges. In their separate studies, Wang et al. [65] and Shafawi et al. [66] ultrasonically modified raw biochar to trigger the sonocatalytic performance and promote the adsorption ability of raw biochar for the removal of heavy metals in water, the adsorption of carbon dioxide, and soil remediation. They recommended further study on optimization of ultrasonic parameters and further research to address the scalability issue and promote industrial-scale development.

Templating biochar functionalization is a technique used to modify biochar properties by introducing a structured template during synthesis. This method enhances the surface area, porosity, and functional groups of biochar, making it more effective for applications such as adsorption, catalysis, and energy storage. During templating, raw biochar is heated to between 400°C and 900°C for several hours in the presence of templates such as silica, zeolites, and metal oxides, and in the process, creates well-organized porous structures in the biochar. The templating technique can be categorized either as soft templates or hard templates. Soft templates use surfactants, block copolymers, and ionic micelles to control porous structures in raw biochar [95]. On the other hand, hard templates involve the use of zeolites, silica, metal oxides, clay materials, and other inorganic porous solids for raw biochar functionalization [96]. Previous studies by Zheng et al. [97] and Hu et al. [98] employed templating technique for the functionalization of raw biochar to enhance its absorbability and ensure higher removal efficiency of tetracycline and other pollutants from wastewater. The technique produced structured biochar with physicochemical properties for the specific applications, with adsorption capacity of 238.7 mg/g. Templating is energy efficient, modifies the pore structure, and ensures improved porosity and adsorption capacity of raw biochar. However, the high cost of specialized templating materials, prohibitive setup expenses, and the need for additional template removal setup are some of the challenges of the process [67, 68]. Figure 7 illustrates the process of physical functionalization techniques.

3.2 | Chemical Biochar Functionalization Techniques

Chemical biochar functionalization involves modifying biochar properties using chemical treatments to enhance its surface chemistry, adsorption capacity, catalytic activity, and environmental applications. This process typically includes acid/base treatments, oxidation, metal impregnation, and polymer grafting to introduce functional groups that improve biochar's reactivity.

Acid/base biochar functionalization involves treating biochar with acidic/alkaline solutions to enhance its surface properties. This process introduces functional groups such as carboxyl, hydroxyl, and sulfonic groups, improving its adsorption capacity, catalytic activity, and chemical reactivity. The process entails using common acids such as H_2SO_4, HNO_3, H_3PO_4, or alkaline solutions like NaOH, KOH, $Ca(OH)_2$, and so forth, at concentrations 0.1–2 M, and temperatures between 50°C and 150°C to introduce functional groups, enhance surface charge, porosity, and adsorption capacity [99]. The pH control ensures the adjustment of the acidity to achieve optimal functionalization and prevents excessive degradation. Yameen et al. [68] and Varkolu et al. [69] in their separate studies modified raw biochar from various biomass sources by acid functionalization for various applications. The acid-functionalized biochar demonstrated enhanced efficiency in the removal of arsenic and lead from contaminated water and better CO_2 adsorption capacity in industrial settings. Acid-functionalized biochar was effective in the removal of dye and other organic pollutants, better porosity and surface configuration, and improved chemical stability. However high cost of acid and environmental concerns arising from handling and disposal of spent acids are some of the limitations of the process. Optimization of acid concentration, use of alternative acids, and further studies of details characterization to assess modification are the recommended areas of improvement [100].

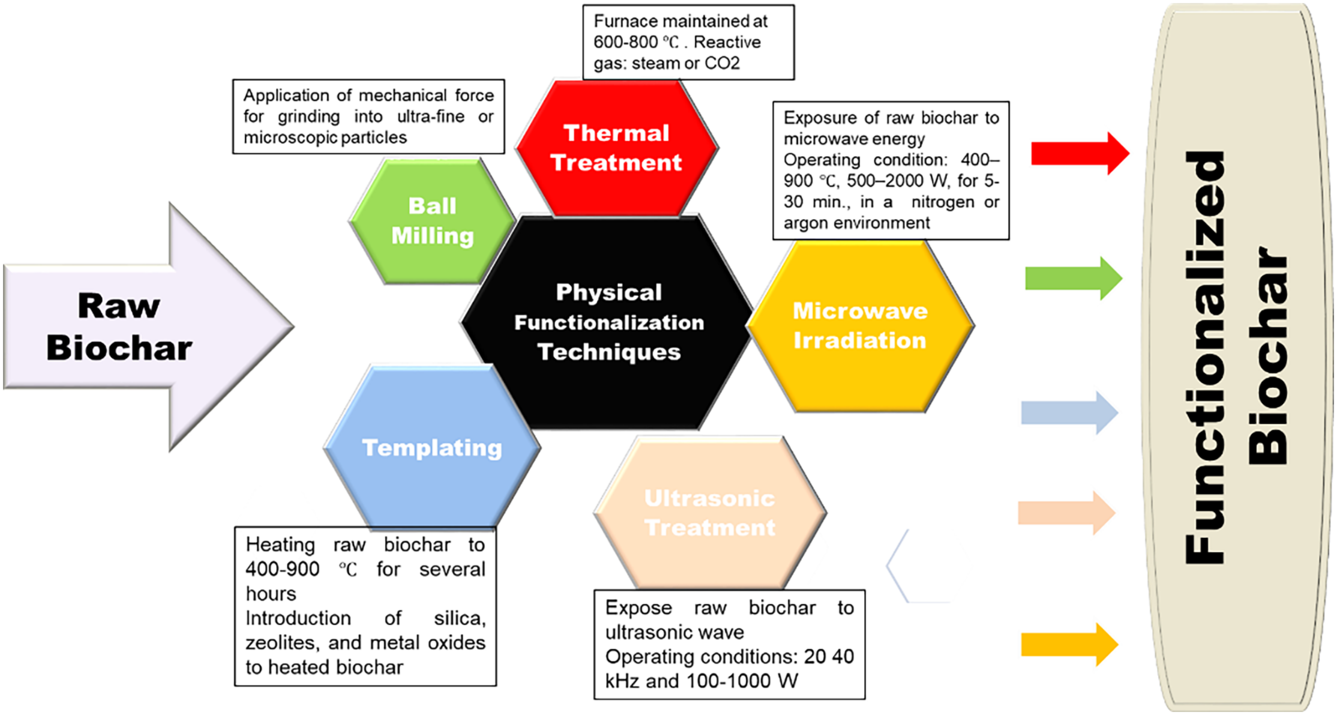


FIGURE 7 | Figurative illustration of biochar physical functionalization techniques.

Oxidation functionalization involves treating biochar with oxidizing agents such as nitric acid, hydrogen peroxide, or ozone to introduce functional groups like carboxyl, hydroxyl, and carbonyl. This process enhances biochar's adsorption capacity, catalytic activity, hydrophilicity, and chemical reactivity. Raw biochar reacts with propriate oxidizing agent such as nitric acid, hydrogen peroxide, ozone, or piranha solution at 50°C–150°C to facilitate functional group attachment [101]. Di Vincenzo et al. [70] reported that oxidized biochar has been successfully used to remove heavy metals from contaminated water and for CO_2 adsorption in industrial applications. The oxidized biochar was effective in pollutants removal, and demonstrated improved catalysis, and greater resistant to environmental degradation. Researchers have recommended the use of alternative oxidation methods, thorough washing to remove excess oxidizing agents, and optimization of oxidizing agent concentration to balance functionalization and structural integrity as areas of further study [71].

Metal/metal oxide functionalization method involves impregnating biochar with metal or metal oxide nanoparticles (e.g., Fe, Cu, Zn, TiO_2, MnO_2) to improve its reactivity, stability, adsorption capacity, and electrochemical properties. The process enhances biochar's ability to act as a catalyst, adsorbent, or electrode material. The common impregnation techniques, wet impregnation, sol–gel synthesis, precipitation, or hydrothermal treatment, are carried out at 50°C–300°C for several hours to facilitate metal/metal oxide attachment [102]. Dey and Ahmaruzzaman [72] and Ramos et al. [73] demonstrated the impregnation of raw biochar with nano metal, nano metal oxides, and nano nonmetal to improve its physical adsorptive and electrochemical properties for sustainable biorefinery, electrocatalysis, and energy storage applications. Metal/metal oxide impregnation functionalization is effective in enhancing the adsorptive, structural stability, and catalysis capabilities of raw biochar, making the product suitable for batteries, supercapacitors, and fuel cells. However, the high cost of metal/metal oxide nanoparticles, handling of residues, and environmental concerns regarding the disposal of metal-functionalized biochar are potent limitations that must be addressed through more R&D [103].

Ligand functionalization involves chemically modifying raw biochar by attaching ligands such as amine ($—NH_2$), thiol ($—SH$), carboxyl ($—COOH$), and phosphate ($—PO_4$). These ligands enhance biochar's ability to interact with metal ions, organic pollutants, and biomolecules, making it more effective in adsorption, catalysis, and environmental remediation. Reactions between raw biochar and ligand through covalent bonding, electrostatic interactions, or chelation at specified conditions facilitate the attachment of ligand to the surface of the biochar, thereby modifying the structure for effective operation [74]. Raw biochar modified with lignands shows enhanced adsorption, improved catalytic properties, and better chemical stability. Huang et al. [75] reported that raw biochar manufactured from wheat straw and modified with phosphate was effective in the removal of 99.98% phosphorus, arsenic, and lead from contaminated water. Modified with ligands demonstrates better adsorption, improved chemical stability, and enhanced catalytic properties. Ligand leaching, high cost of ligands, and environmental concerns about the disposal of modified biochar are some of the limitations of the process. Ligand-functionalized biochar is useful in wastewater treatment, as a catalyst for chemical reactions, energy storage, and applied in drug delivery and biosensing [104].

Salt activation functionalization of biochar is a technique used to enhance its surface properties by introducing molten salts or salt solutions such as KCl, NaCl, and $ZnCl_2$ that modify its porosity, adsorption capacity, and catalytic activity. The process improves biochar's structural and chemical properties and enhances biochar's ability to adsorb pollutants, catalyze reactions, and store energy [76]. The raw biochar are activated with the appropriate salts through molten salt impregnation, salt-assisted pyrolysis, or salt leaching at 400˚C–900˚C, depending on the salt and biochar source. Egun et al. [77] investigated the production, usefulness, and applications of molten salts activated raw biochar. The activated biochar showed improved specific surface area and effective in energy storage, catalysis, and pollutants adsorption. Salt activation of raw biochar ensures superior adsorption of pollutants from water and air, improves environmental remediation and chemical synthesis, and excellent resistant to degradation in harsh environments [105]. Some of the drawbacks of the process include structural damage, high cost of salts and equipment, and environmental concerns arising from disposal of salt-functionalized biochar. Figure 8 illustrates the process of chemical functionalization techniques.

3.3 | Biological Biochar Functionalization Techniques

Microbial inoculation treatment of biochar is a technique used to enhance its biological activity by introducing beneficial microorganisms. The process involves integrating raw biochar with beneficial microbes such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi. This process improves biochar's ability to support soil health, nutrient cycling, and pollutant removal. The inoculation is done by soaking, spraying, or mixing biochar with microbial cultures for a specified duration [106]. Gryta et al. [78] and Sharma et al. [79] modified raw biochar with microorganisms to alter the composition and physicochemical properties of biochar for diverse applications. The microbial-inoculated biochar was used for bioremediation, to improve soil fertility, and to promote soil aeration and moisture retention. The challenges of microbial survival, maintaining microbial viability, and the high cost of specialized equipment are some of the limitations of the process. Further studies are required to optimize microbial selection based on

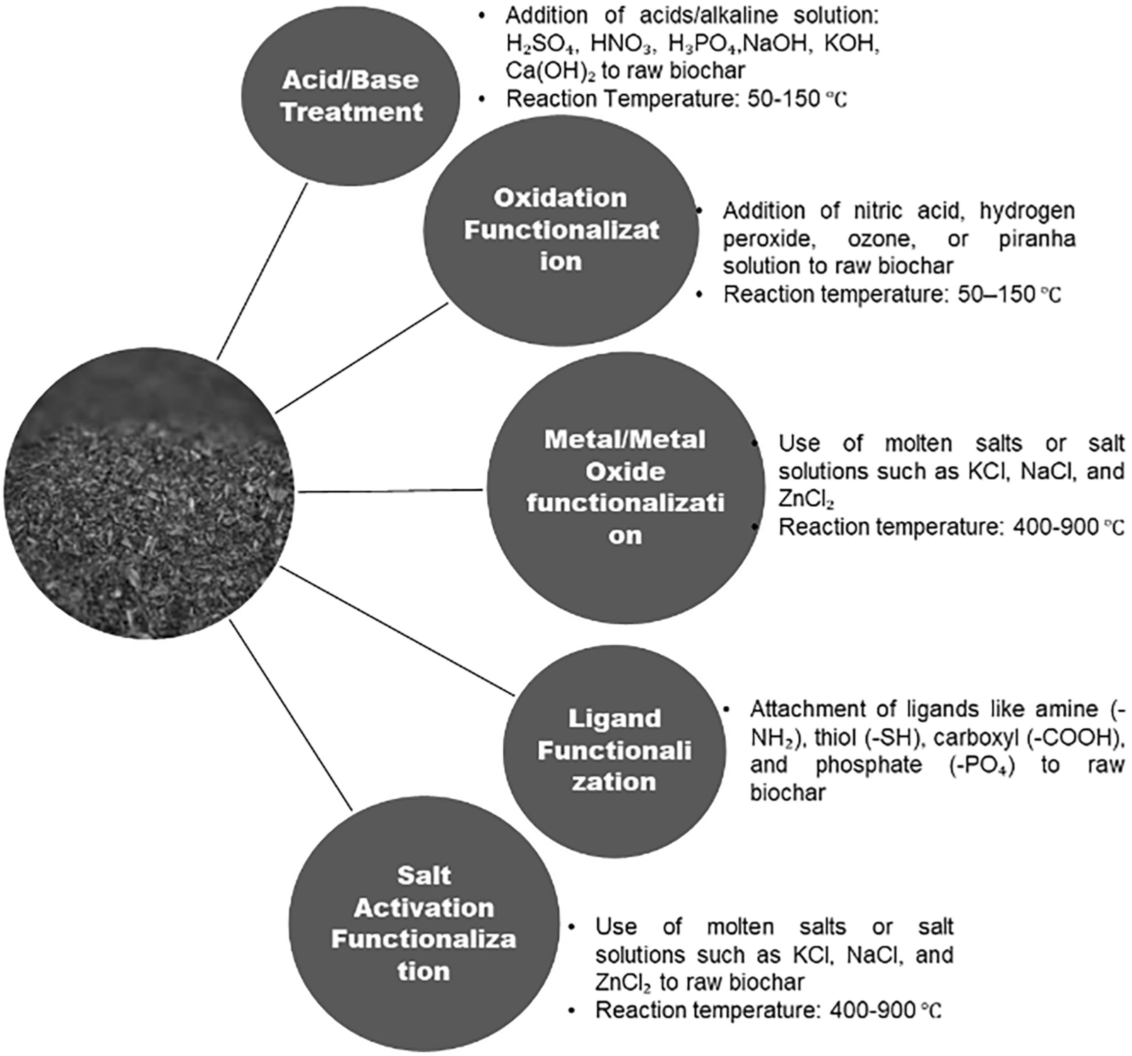


FIGURE 8 | Figurative illustration of chemical biochar functionalization techniques.

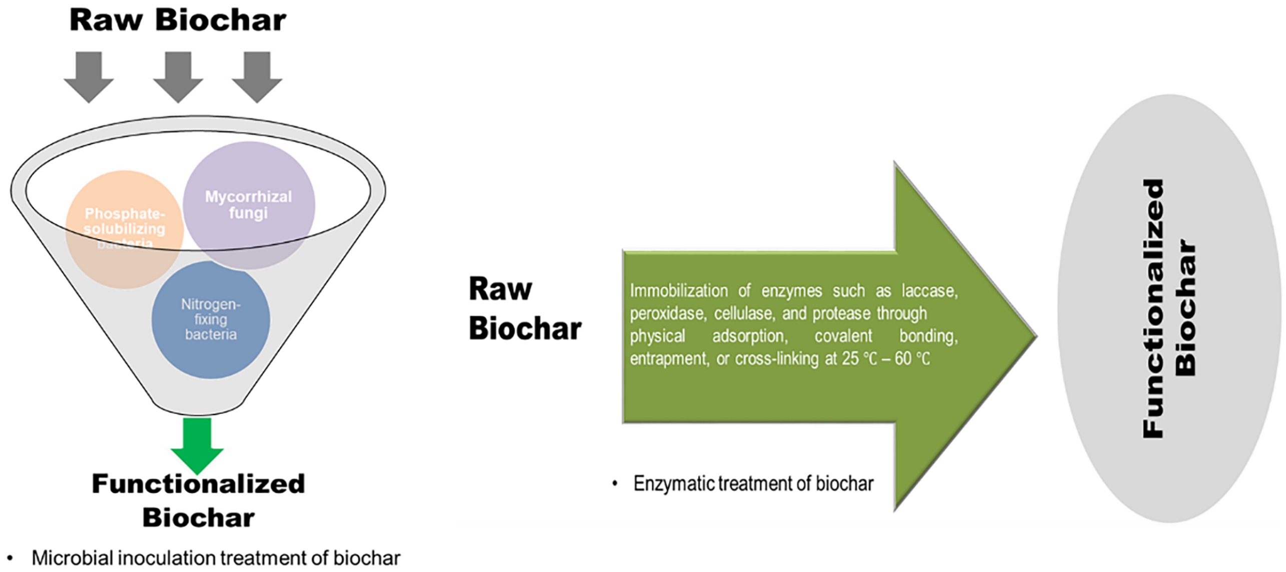


FIGURE 9 | Figurative illustration of biological biochar functionalization techniques.

soil and crop requirements, as well as to conduct DNA sequencing and microbial activity assays to assess the effects of the modifications [107].

Enzymatic treatment of biochar is an innovative technique that enhances its surface properties by integrating enzymes onto biochar to enhance its ability to degrade pollutants, catalyze biochemical reactions, and improve nutrient cycling. The process leverages biochar's porous structure to provide a stable environment for enzyme activity. Enzymes such as laccase, peroxidase, cellulase, and protease are immobilized through physical adsorption, covalent bonding, entrapment, or cross-linking at 25°C–60°C to ensure enzyme stability [108]. Mota et al. [80] reported that enzymatic immobilization of raw biochar modified the physicochemical, chemical structure, and stability of the biochar for various applications. Enzyme-coated biochar demonstrated enhanced drug delivery capabilities, improved oxidation reaction, and better biodegradation of organic pollutants in wastewater. Though the process is sustainable and occurs at low temperatures, the high cost of some enzymes and equipment, possible structural damage of the biochar, and enzyme leaching limit the application of the process [81]. Figure 9 illustrates the process of biological biochar functionalization techniques.

3.4 | Advanced Biochar Functionalization Techniques

Heteroatom doping involves introducing non-carbon elements into the biochar matrix through chemical or physical methods. These heteroatoms alter the electronic structure, surface functional groups, and porosity of biochar. The process entails doping heteroatoms such as nitrogen, sulfur, phosphorus, and boron into raw biochar at 400°C–900°C for a few hours. The doping can occur before pyrolysis (pre-decoration doping) or after pyrolysis (post-decoration doping) [109]. Sun et al. [82] and Yang et al. [83] in their separate studies on the fabrication, characterization, doping methods, and functions of heteroatom-doped biochar, reported that the modified biochar demonstrated increased surface area, porosity, adsorption, and better electrochemical performance. The heteroatom-doped biochar was effective for CO_2 adsorption, energy storage, contaminant removal, and other environmental remediation purposes. However, there is a need for more research to devise cost reduction measures, explore alternative doping methods, and optimize heteroatom concentration to balance functionalization and structural integrity [110].

Plasma treatment involves exposing biochar to ionized gases (plasma) to introduce functional groups, increase porosity, and improve surface reactivity. Different types of plasma, non-thermal plasma, dielectric barrier discharge, and radio-frequency plasma, have been used to expose gases such as oxygen (O_2), nitrogen (N_2), argon (Ar), and chlorine (Cl_2) at temperatures less than 200°C [111]. Zhou et al. [84] carried out non-thermal plasma surface functionalization to introduce more oxygen-containing functional groups and promote follow-up applications. The plasma-treated biochar demonstrated improved metal-adsorption rate and higher adsorption capacity of heavy metals and other pollutants. Though plasma treatment enhances the electrochemical performance of the biochar, the process requires complex and expensive equipment and excessive plasma exposure may result in structural damage of the biochar. There is a need to optimize plasma exposure time, conduct thorough characterization, and explore alternative plasma sources to ensure cost reduction and sustainability [85].

Electrospraying is an advanced technique used to modify biochar by dispersing fine droplets of functionalizing agents onto its surface. It involves applying a high-voltage electric field to a liquid suspension containing biochar and functionalizing agents. Voltage ranging from 5 to 30 kV are applied to the fine droplets of solvents such as ethanol, acetone, and other water-based solutions, to be deposited at a controlled flow rate between 0.1 and 5 mL/h for precise deposition [86]. This process generates fine droplets that deposit onto biochar, leading to uniform coating

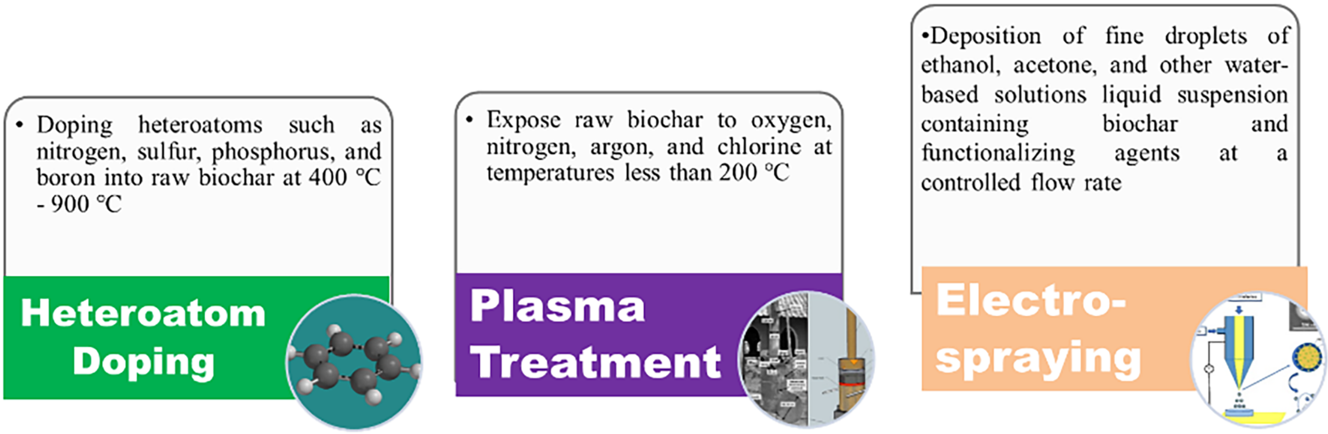


FIGURE 10 | Figurative illustration of advanced biochar functionalization techniques.

and improved surface characteristics. Li et al. [87] carried out simultaneous electrospinning and electrospraying to modify the raw biochar to enhance the electrochemical, adsorption properties of the biochar, and uniform surface modification. The process requires expensive and specialized electrospraying systems, and the inappropriate disposal of spent electrosprayed biochar may trigger environmental issues. Figure 10 illustrates the process of advanced biochar functionalization techniques.

4 | Biochar as Adsorbents for Sulfur-Containing Gaseous Pollutants

Sulfur-containing pollutants originate from industrial activities, fossil fuel combustion, and natural sources and contribute to acid rain formation, air pollution, and respiratory health issues, making their mitigation a key environmental priority. Generally, functionalized biochar exhibits enhanced adsorption capabilities for sulfur-containing pollutants, such as H_2S, SO_2, and COS, through a combination of physisorption, chemisorption, and surface-mediated redox interactions. Surface modifications techniques are deployed to introduce reactive functional groups (e.g., −OH, −COOH, −SH) and catalytic sites that facilitate pollutant binding [112]. For example, H_2S, a corrosive gas from anthropogenic sources, typically undergoes dissociative chemisorption, forming metal sulfides on biochar impregnated with transition metals like Fe or Zn while SO_2 can be physically adsorbed within micropores or chemically oxidized to sulfite/sulfate species on redox-active surfaces. COS, being less reactive, interacts via nucleophilic substitution at electron-rich sites, particularly those introduced by nitrogen doping [112, 113]. The pore architecture and surface area of biochar further influence mass transfer and adsorption kinetics, while environmental factors such as temperature and humidity modulate the efficiency and mechanism of capture. These processes form the basis of adsorption mechanism and underscore the importance of tailored functionalization in optimizing biochar for selective and efficient sulfur pollutant remediation. Biochar-based adsorption has gained attention as a potential sustainable solution for capturing these pollutants due to its high surface area, tunable porosity, and cost-effectiveness [114, 115]. Figure 11 shows the major sulfur-containing pollutants.

FIGURE 11 | Schematic representation of sulfur-containing pollutants.

4.1 | H_2S

H_2S is a highly toxic, volatile, colorless, and corrosive gas generated by various natural, anthropogenic, and human activity sources. The natural sources of H_2S include volcanic eruptions, hot springs and geothermal vents, anaerobic bacterial decomposition, and oceans and sediments. H_2S is also generated from anthropogenic sources such as industrial processes, coal and natural gas extraction, waste treatment facilities, and manure storage and decomposition. Human activities such as the burning of fossil fuels, decomposition of organic waste, poorly managed drainage systems, and fish processing and fermentation industries also contribute to H_2S emissions. H_2S is one of the impurities generated during the anaerobic digestion of waste for biogas production [116]. Even at very low concentrations, H_2S has several health, environmental, and safety impacts. Inhalation of H_2S can cause breathing difficulties, throat irritation, and lung damage, while prolonged exposure triggers eye and skin irritation, headaches, dizziness, memory loss, and rapid unconsciousness. Environmental impacts of atmospheric H_2S include acid rain, water contamination, and air quality degradation. H_2S is highly flammable, corrosive, and poses occupational risks for oil refineries, mining workers, and biogas producers. The total global emission of H_2S is estimated to be 70−80 Gg-S-yr-1 or 70−80 million metric tons of sulfur per year, which makes its containment and proper management of great interest [117]. When recovered, H_2S

can be converted to hydrogen, syngas, carbon disulfide, ammonium thiosulfate, ethylene, and other value-added products, contributing to the circular economy and sustainability.

However, the various H_2S recovery technologies have been plagued with technical, economic, environmental, safety, operational, and infrastructural limitations. Biochar, a versatile, low-cost, environmentally benign, and renewable material, is an effective technique for H_2S removal from the atmosphere and possible conversion into non-toxic sulfur compounds. Functionalization of raw biochar has increased its porosity, adsorption capacity, structural integrity, and chemical reactivity, enhancing its capability to adsorb H_2S [118, 119]. Researchers have utilized different functionalization techniques to modify raw biochar to improve its adsorptive capability for H_2S removal. In a study, Wang et al. [120] modified biochar generated from pomelo peel with copper for the removal of H_2S in a polluted atmosphere. The desulfurization process was more effective with the use of modified biochar than unmodified biochar, due to the improved adsorptive capacity of the functionalized biochar. Raw biochar constructed from corn stover and maple wood was modified with iron in a metal impregnation functionalization process. The novel iron-impregnated biochar demonstrated improved physicochemical properties, composition, porosity, and surface area and was more effective in H_2S removal from raw biogas generated from the AD system than unmodified biochar [121, 122]. The deployment of doping as a novel functionalization technique to modify biochar manufactured from sewage sludge, pine chips, and rice hull for the purification of raw biogas showed improved adsorption, which was attributed to lower pyridinic-N content, improved microporous structure, and better micropore utilization, which ultimately leads to better H_2S removal [123, 124]. Zhu et al. [125] experimented with the application of microwave-modified sludge-derived biochar using red mud for H_2S removal. The results of their study on the performance of the modified biochar showed that the adsorption capacity of the biochar increased from 1.47 mg/g to 22.83 mg/g. The improved adsorption capacity was due to a higher number of oxygen-containing functional groups of the activated biochar and the oxidation of H_2S to form FeS, and later to SO_4^{2-}. Functionalized biochar enhances H_2S removal by improving adsorption capacity and microporous structure, ensuring a cost-effective and environmentally friendly desulfurization process. Summary of the outcomes of the desulfurization process using functionalized biochar is listed in Table 4.

4.2 | SO_2

SO_2 is a colorless gas with a strong, odorous smell. It is usually generated as effluent during the burning of FB fuels, especially coal and oil, for power generation and industrial activities, and the smelting of sulfur-containing mineral ores. SO_2 is a dangerous gas with far-reaching environmental and health impacts. SO_2 gas can damage plant morphology, inhibit plant growth, and pollute sensitive ecosystems and waterways. Prolonged inhalation of SO_2 contributes to respiratory illness and exacerbates heart and lung deformities. When mixed with rainwater, SO_2 forms H_2SO_4, in the form of acid rain during rainfall, contaminating water bodies and impacting aquatic animals [128, 129]. Due to

TABLE 4 | Summary of H_2S adsorption by functionalized biochar.

Bicohar feedstock	Functionalization technique	Functionalization reagents	Adsorption performance		H_2S RE (%)	Remark	References
			BF (mg/g)	AF (mg/g)			
Pomelo peel	Metal impregnation	$Cu(NO_3)_2{\cdot}3H_2O$	12.1	358.3	NR	Functionalization enhances the adsorption capacity and H_2S removal	[120]
Corn stover	Metal impregnation	$FeCl_{30}.6H_2O$	1.7 ± 0.4	3.2 ± 0.4	NR	Metal impregnation enhances H_2S removal	[121]
Maple wood	Metal impregnation	$FeCl_{30}.6H_2O$	3.9 ± 0.2	16.8 ± 0.6	NR	Functionalized biochar was more effective in H_2S removal	[121]
Corn stover	Metal impregnation	$FeSO_4{\cdot}7H_2O$	2.0 ± 0.1	4.6 ± 0.0	91	Fe-impregnated biochar was more effective in H_2S removal from raw biogas	[122]
Maple wood	Metal impregnation	$FeSO_4{\cdot}7H_2O$	2.7 ± 0.1	4.5 ± 0.0	93.3	High H_2S removal efficiency due to metal impregnation	[122]
Sewage sludge and pine chips	Heteroatom doping	Nitrogen doping	35.1–72.9	140.2–365.5	97.2	N-doped biochars demonstrated high H_2S removal capacities	[123]
Rice hull	Nitrogen doping	$NH_3{\cdot}H_2O$	2.54	23	NR	Doping enhanced pyridinic-N content and better micropore utilization	[124]
Raw sludge	Microwave	Red mud	1.47	22.83	NR	Oxidation of H_2S to FeS and later to SO_4^{2-}	[125]
Walnut shell	Plasma treatment	Non-thermal plasma	NR	390	100	Improved pore structure enhanced oxidation of H_2S	[126]
Sawdust	Doping	Urea phosphate	0.24	54.8	NR	Better H_2S removal due to improved microporous structure and increased adsorption site groups on the biochar	[127]

Abbreviations: AF, after functionalization; BF, before functionalization; NR, not reported; RE, removal efficiency.

TABLE 5 | Summary of SO_2 adsorption by functionalized biochar.

			Adsorption performance				
Bicohar feedstock	**Functionalization technique**	**Functionalization reagents**	**BF (mg/g)**	**AF (mg/g)**	**SO_2 RE (%)**	**Remark**	**References**
Rice straw	Metal impregnation	$MgCl^{2-}\cdot 6H_2O$	11.1	194.6	NR	$N-H$ groups promote the oxidation removal of SO_2	[131]
Soybean stalks	Microwave irradiation	Fe_2O_3	96	146	NR	The addition of Fe_2O_3 promotes the oxidation of SO_2	[132]
Soybean straws	Physical activation	$NH_3\cdot H_2O$	92.8	175.9	NR	Enhanced adsorption of SO_2	[133]
Soybean straws	Nitrogen doping	$NH_3\cdot H_2O$	98.6	201.9	90	Addition of NH_3 promote SO_2 to form sulfate	[134]
Oil palm fiber	Thermal treatment	Heat 753°C for 73 min	18.62	33.09	80	Thermal activation aided adsorption capacity of biochar	[135]
Soybeanstraws	Ultrasonic	CO_2	NR	100.18	NR	CO_2 activation promotes the formation of micropores	[31]
Walnut shell	Metal oxide impregnation	MnO_2	NR	157.8	27.5% higher	Low cost activation of biochar	[136]
Walnut shell	Metal oxide impregnation	Fe_2O_3	NR	140.6	13.6% higher	Improved SO_2 removal by modified biochar	[137]
Coir organisms	Microwave heating	NA	10.9	16.9	NR	Increased adsorption of SO_2 on the biochar surface.	[137]
Corncob	Acid impregnation	Methyldiethanolamine	57.8	156.2	NR	Amine impregnation increased biochar adsorption capacity	[138]
Walnut shell	Metal impregnation	TiO_2	70	228.62	NR	Metal oxide promote catalytic oxidation of SO_2	[139]
Walnut shell	Metal impregnation	Fe_2O_3	NR	125	NR	Improve pore structure enhance desulfurization performance of biochar	[139]

Abbreviations: AF, after functionalization; BF, before functionalization; NA, not applicable; NR, not reported; RE, removal efficiency.

continuous dependence on FB energy sources and enhanced industrial activities, the mission of SO_2 has increased significantly in recent years. The global SO_2 emission, which was 69.15 million tons in 2020, rose to 73.17 million tons in 2022 [130]. Environmentalists, government, and other stakeholders have instituted and implemented measures, policies, and regulations to prevent, reduce, and control SO_2 emissions. The use of sodium sulfite solution, flue gas desulfurization, transition to low-sulfur fuels, RE adoption, and implementation of stricter regulations of SO_2 emissions have been expensive and require sophisticated infrastructure, necessitating the development of low-cost, eco-friendly, and sustainable strategies. Biochar has shown promising potential as an adsorbent for SO_2 due to its porous structure and surface chemistry. Studies indicate that modified biochar, especially when activated with steam or chemical treatments, enhances SO_2 adsorption capacity.

In a study, Chen et al. [131] investigated the desulfurization performance of raw biochar manufactured from rice straw for SO_2 removal. The MgO-impregnated raw biochar demonstrated a better adsorption capacity of 194.6 mg/g compared with unmodified biochar with 11.1 mg/g, showing the effectiveness of the functionalization process [131]. A microwave irradiation technique was applied to modify raw biochar manufactured from soybean stalks for the desulphurization of polluted air. The addition of iron oxide to the raw biochar enhanced its adsorption capacity and promoted SO_2 removal [132]. Physical activation and nitrogen doping techniques were also effective in enhancing the physical and chemical properties and adsorptive performance of raw biochar generated from soybean straws, leading to improved adsorption of SO_2. The modified biochar performed better than the unmodified biochar in desulphurization, and the nitrogen functional groups promote the SO_2 adsorption [133, 134]. Application of thermal treatment to oil palm fiber-derived biochar resulted in high adsorption capacity of SO_2 by the modified biochar. The adsorption capacity of biochar increased from 11.62 to 33.09 mg/g, while high SO_2 removal efficiency was recorded [135]. Chen et al. [31] deployed optimization technique to optimize activation parameters in the preparation of the desulfurized biochar. The application of ultraviolet CO_2 activation on the raw biochar engenders larger specific surface area, richer pores, and better adsorption performance of SO_2 from the polluted air. The application of metal oxide components (MnO_2 and Fe_2O_3) for the modification of walnut shell-derived biochar in a desulfurization experiment for the removal of SO_2. The outcome of the study showed that the modified biochar resulted in the adsorption capacity of 157.8 mg/g for MnO_2 and 140.6 mg/g for Fe_2O_3, representing about 13.6%–27.5% improved pollutant removal efficiency [136]. Outcomes of demonstration of modified biochar for the desulphurization performance of SO_2 removal are summarized in Table 5.

4.3 | Cos

Carbon oxysulfide (COS), also known as carbonyl sulfide, is a colorless, toxic, and flammable gas and a precursor to H_2S and other sulfur compounds in the atmosphere. It is emitted from both natural and anthropogenic sources, including oceans, soils, volcanic activity, biomass burning, and industrial processes, and plays a role in atmospheric chemistry and the global sulfur cycle. The global emission of COS is estimated to be around 3 million tons per year, mainly from natural sources. In terrestrial ecosystems, COS emissions are influenced by factors such as soil properties, microbial activity, and plant uptake. COS can be converted to CO_2 by plants and microbes and contributes to the formation of SO_2 and sulfate particles, which can impact the ozone layer. Persistent exposure to COS exacerbates nervous system breakdown, respiratory failure, and other health challenges [140, 141]. Though COS has been removed through catalytic hydrolysis, alkaline solvent absorption, and other gas processing techniques, the high operational and maintenance costs and complexity of these techniques have made the search for renewable and sustainable alternatives inevitable. The high porosity, impressive surface reactivity, and ability to capture sulfur compounds make biochar a promising candidate for COS removal in industrial gas treatment. Recent studies have indicated that functionalized biochar, enriched with metal oxides or nitrogen-containing groups, can improve COS adsorption efficiency [34, 85].

Li et al. [142] experimented with KOH for the activation of walnut shell biochar for the removal of COS from yellow phosphorus tail gas. The results showed that KOH activation significantly increased the specific surface area and pore volume of the biochar, raised the alkaline adsorption sites on the biochar, and provided a large number of hydroxyl functional groups, enhancing COS removal. A similar study by Wang et al. [143] deployed KOH impregnation to modify coconut shell biochar for the adsorption of COS. After KOH impregnation, the adsorption capacity of the modified biochar increased from 5.81 to 40.64 mg/g. The enhanced COS adsorption was attributed to the increase in the –OH functional group on the surface of biochar, better surface alkalinity of biochar, improved hydrolysis and catalytic oxidation of COS. The use of $AgNO_3$ and $Cu(NO_3)_2$ as reagents for the functionalization of coconut shell biochar led to an increase in the adsorption capacity of the modified biochar. The results showed that the modified biochar achieved an adsorption capacity of 14.8 mg/g compared with the 7.5 mg/g recorded with unmodified biochar [144]. The use of a metal activator to modify biochar manufactured from gulfweed was tested. It was reported that the modification of raw biochar with metal oxides enhanced the specific surface area and pore volume and promoted the chemisorption of COS. The modified biochar demonstrated excellent removal capacity of COS, and nearly 99.5% of the COS was separated [145]. A study by Ruan [146] on the removal of COS, using biochar derived from tobacco stalks biochar modified with $Cu(NO_3)_2$ as a reagent. The results showed that metal impregnation enhanced the adsorption capacity of the modified biochar, and about 161.93 mg/g COS was removed when the CuO load was 10% while the COS was oxidized to metal sulfate. Similar work by Sun et al. [147] with $Cu(NO_3)_2Fe(NO_3)_3$ reagent showed that metal oxides impregnation enhances surface alkalinity and hydrolysis of COS to produce H_2S and CO_2. The generated H_2S was later oxidized to sulfate. Table 6 summarizes the outcomes of COS adsorption by modified biochar. These analyses show that the removal mechanism of COS by modified biochar was predicated mainly on hydrolysis and catalytic oxidation. During the hydrolysis, the alkaline groups and metal oxides enhance the formation of H_2S and CO_2 as a result of better surface alkalinity. The generated H_2S is subsequently oxidized into elemental sulfur and sulfate by catalytic oxidation and reacts with metal oxides to form metal sulfide. Similarly, the oxygen functional groups can promote the catalytic oxidation of COS to produce SO_2 and CO, and the resulting SO_2 is oxidized to sulfuric acid and sulfate [34, 148].

5 | Artificial Intelligence and Biochar as Sulfur Pollutants Adsorbent

The integration of AI in research is expanding rapidly, revolutionizing various fields, including biochar research. Among other important applications, AI has been deployed to optimize biochar production, model pollutant adsorption mechanisms, enhance biochar modification, and reduce experimental costs and time. The integration of AI into biochar research and applications has opened up exciting possibilities for enhancing its effectiveness as an adsorbent for sulfur-containing gaseous pollutants like H_2S, SO_2, and COS. AI-driven models, particularly machine learning (ML) algorithms, enhance efficiency, improve accuracy, and help

TABLE 6 | Summary of COS adsorption by functionalized biochar.

Bicohar feedstock	Functionalization technique	Functionalization reagents	Adsorption performance BF (mg/g)	Adsorption performance AF (mg/g)	COS RE (%)	Remark	References
Walnut shell	Base functionalization	KOH	45.25	52.67	NR	KOH activation enhances COS removal	[142]
Coconut shell	Base impregnation	KOH	5.81	40.64	NR	KOH impregnation promotes the hydrolysis and catalytic oxidation of COS	[143]
Coconut shell	Metal impregnation	$AgNO_3$ and $Cu(NO_3)_2$	7.5	14.8	NR	$AgNO_3$ and $Cu(NO_3)_2$ increase in the adsorption capacity of the modified biochar	[144]
Gulfweed	Metal impregnation	CaO. MgO	NR	NR	99.5	Efficient removal of COS from syngas	[145]
Tobacco pole	Metal impregnation	$Cu(NO_3)_2$	NR	161.93	NR	Metal oxides and–OH groups promote the hydrolysis of COS	[146]
Tobacco stem	Metal impregnation	$Cu(NO_3)_2Fe(NO_3)_3$	NR	231.28	NR	Metal oxides facilitate the hydrolysis of COS	[147]

Abbreviations: AF, after functionalization; BF, before functionalization; NR, not reported; RE, removal efficiency.

predict and enhance biochar synthesis, adsorption efficiency, and modification techniques [148, 149]. Specifically, the integration of AI into the adsorption of sulfur-containing pollutants by modified biochar can be discussed under the following subheadings.

AI-driven optimization significantly enhances biochar's potential for sulfur pollutant adsorption by pinpointing the most effective functionalization techniques for biochar by analyzing large datasets of experimental results. This accelerates the development of biochar tailored for specific pollutants. The use of ML algorithms helps in analyzing large-scale experimental datasets to determine the ideal functionalization techniques and surface modifications that maximize pollutant capture [150]. AI can predict optimal pyrolysis conditions to enhance biochar porosity, identify the best metal oxide or nitrogen doping techniques for sulfur adsorption, model adsorption kinetics to refine biochar's interaction with pollutants like H_2S, SO_2, and COS, and accelerate material design by reducing experimental trial-and-error. Table 6 shows case studies on AI-generated models for biochar functionalization and its applications.

AI is increasingly being used to model pollutant adsorption with biochar, enhancing efficiency and accuracy in environmental research. Machine learning techniques help predict adsorption efficiency, optimize process parameters, and reveal adsorption mechanisms. AI-driven predictive modeling is revolutionizing the study of the adsorption of sulfur-containing gaseous pollutants using modified biochar. Researchers are leveraging ML algorithms to optimize biochar synthesis, predict adsorption efficiency, and refine modification techniques [151]. Major key advancements include ML for adsorption modeling, optimization of biochar functionalization, and predictive models for biochar surface chemistry. AI integration into predicting adsorption efficiency for H_2S, SO_2, and COS using modified biochar is transforming environmental remediation and gas purification processes. Researchers are leveraging ML algorithms to analyze adsorption behavior, optimize biochar functionalization, and enhance pollutant removal efficiency. AI models assess biochar's surface properties, porosity, and chemical composition to predict its adsorption capacity and refine modification techniques. AI-driven frameworks forecast biochar yield and pollutant removal rates, ensuring efficient adsorption performance. AI predicts adsorption kinetics in fixed-bed adsorption columns, optimizing biochar's pollutant removal efficiency. AI identifies key parameters influencing biochar's adsorption performance, such as surface pH and feedstock composition [152].

By leveraging ML models, researchers can refine biochar modification techniques to maximize pollutant removal. AI analyzes large datasets to determine the most effective chemical activation methods, such as metal oxide doping, nitrogen functionalization, or acid/base treatment, for sulfur pollutant adsorption. AI models predict the ideal functional groups (carboxyl, hydroxyl, amine) that improve biochar's affinity for H_2S, SO_2, and COS. AI-driven simulations help to optimize porosity, surface area, and biochar pore structure, ensuring maximum adsorption capacity. AI models predict reaction rates and pollutant binding mechanisms, allowing researchers to fine-tune biochar properties for enhanced sulfur capture [34, 85]. AI plays a crucial role in environmental monitoring, particularly in sulfur pollutant adsorption using modified biochar. By integrating AI-driven models, researchers can optimize biochar modification techniques, predict adsorption efficiency, and enhance real-time monitoring of sulfur pollutants. AI models estimate how effectively modified biochar removes sulfur pollutants like H_2S, SO_2, and COS from air, water, and soil. To ensure sustainable modification of raw biochar, AI helps refine activation methods such as acid/alkali treatment, metal oxide doping, and microwave activation to enhance adsorption capacity. AI-powered sensors track sulfur pollution levels and suggest biochar applications for remediation, ensuring real-time environmental monitoring [34]. Table 7 shows some of the case studies of AI integration into the use of biochar for the adsorption of H_2S, SO_2, and COS, while Figure 12 illustrates the application of AI in biochar adsorption of pollutants.

The application of AI in the design and deployment of functionalized biochar-based adsorbents for sulfur-containing pollutant remediation introduces a transformative, novel, data-driven paradigm in environmental remediation science and engineering. Novel ML algorithms, like Random Forest, Support Vector Regression, and Deep Neural Networks, are being deployed for predictive modeling of biochar properties based on pyrolysis parameters, feedstock composition, and functionalization strategies. This allows researchers to bypass exhaustive empirical testing and instead simulate optimal configurations for sulfur adsorption. Moreover, AI facilitates mechanistic interpretation of adsorption kinetics and thermodynamics, revealing complex nonlinear interactions between sulfur species and active sites that traditional models often overlook [166]. AI facilitates mechanistic insights through multivariate analysis of adsorption kinetics and thermodynamics, revealing nonlinear interactions between pollutant molecules and active sites that are often obscured in conventional models. In practical applications, AI-enhanced biochar systems have been deployed in industrial flue gas treatment and agricultural odor control, where real-time sensor feedback is used to dynamically adjust adsorption conditions, maximizing pollutant removal while minimizing operational costs. This intelligent integration not only improves environmental outcomes but also supports scalable, adaptive deployment in diverse contexts, positioning AI-functionalized biochar as a next-generation solution for sulfur pollution mitigation [167].

6 | Challenges and Future Research Directions

Functionalized biochar has shown promise in adsorbing sulfur-containing gaseous pollutants like H_2S, SO_2, and COS, but its application presents both challenges and exciting future research directions. Biochar often lacks sufficient functional groups for effective sulfur adsorption, requiring advanced modification techniques. This limitation has hampered the application of biochar for pollutant removal. Some functionalization techniques require many processing parameters that must be managed to ensure an effective modification process. Finding the best techniques and selecting optimal parameters remains complex and poses a great challenge. Large-scale production of highly functionalized biochar is costly and requires specialized infrastructure and efficient synthesis methods, prohibiting scalability and industrial-scale applications. Biochar's

TABLE 7 | Case studies of AI for biochar adsorption of H_2S, SO_2, and COS.

Application area	Description	Remark	References
Material design	The study explored ML models for the prediction of optimal pyrolysis conditions for biochar production.	ML models accurately predict optimal pyrolysis parameters	[153]
Modeling of pollutant adsorption with biochar	AI models analyze large datasets to predict biochar's adsorption capacity for pollutants like H_2S, SO_2, and COS	Effective modeling of pollutant removal using ML algorithms	[154]
Predictive models for biochar yield and surface area	AI-driven frameworks forecast biochar yield and porosity, ensuring efficient adsorption performance.	ML algorithms accurately predict biochar yield, porosity, and adsorption performance	[155]
Prediction of adsorption efficiency	AI models assess biochar's surface properties, porosity, and chemical composition to predict its adsorption capacity	ML algorithms for accurate prediction of the desulfurization process	[156]
Optimization of biochar functionalization	AI helps refine chemical activation methods and heteroatom doping to improve sulfur pollutant capture	ML algorithms used for prediction and optimization of biochar adsorption capacity of pollutants	[157]
Optimization of experimental conditions	AI-driven simulations forecast biochar yield, surface area, and pollutant removal rates, ensuring optimal adsorption performance	ML algorithms for prediction of adsorption efficiency, optimization of experimental conditions, and revelation of the adsorption mechanism	[154]
Optimization of experimental conditions	AI models, including Multi-Layer Perceptron Neural Networks, predict biochar composition and adsorption behavior under different conditions	ML-assisted prediction of biochar yield and composition	[158]
Environmental monitoring	AI-powered sensors detect SO_2, H_2S, and COS concentrations, providing continuous environmental data	AI technologies for monitoring environmental pollution and management	[159]
Environmental monitoring	AI forecasts pollutant dispersion patterns, helping policymakers implement targeted interventions.	AI-driven models for pollution forecasting, mapping, and mitigation	[160]
Environmental monitoring	AI refines biochar functionalization to enhance pollutant removal efficiency	ML-assisted prediction	[161]
Industrial gas treatment	AI models used to optimize biochar for SO_2 adsorption in flue gas systems	Neural networks predicted optimal dopants (e.g., Fe, Zn) with high accuracy	[145]
Environmental modeling	Predictive modeling of COS adsorption using agricultural waste-derived biochar	Regression models linked pore volume and surface chemistry to performance	[34]
Agricultural air purification	Use in livestock farms to reduce H_2S emissions from manure	Real-time monitoring via AI sensors	[162]
Wastewater treatment	Adsorption of dissolved sulfur compounds from effluents	Optimization of biochar dosage	[163]
Wastewater treatment	Modified biochar applied to remove dissolved H_2S from industrial effluents	AI identified photochemical modification as most effective	[164]
Industrial gas treatment	Removal of SO_2 and H_2S from flue gases in power plants and refineries	Predictive modeling of adsorbent design	[165]

Abbreviation: ML, machine learning.

adsorption efficiency can be affected by humidity, temperature, and pollutant concentration variations, impacting environmental stability. The process of biochar functionalization and biochar utilization generates waste such as acids, bases, metals, water, spent biochar, and so forth. Inappropriate management of these wastes contaminates the atmosphere, impacts air quality, negates environmental sustainability, and can cause secondary pollution. Maintaining biochar's adsorption capacity over multiple cycles without degradation is a key challenge. Regeneration of biochar can be costly, time-consuming, require additional personnel and infrastructure, and may cause secondary pollution.

Going forward, there is a need for the integration of AI-driven optimization using ML models to refine biochar functionalization techniques to ensure improved performance and better sulfur adsorption. Serious attention should be paid to the development of hybrid adsorbents, including the combination of biochar with nanomaterials or catalysts, which could improve adsorption efficiency. While the deployment of novel and hybrid functionalization techniques has been successful, ample opportunities exist in exploring advanced surface modification technologies, such as photochemical, enzymatic, or plasma treatments, to enhance biochar's pollutant capture ability. Technologies for the removal of pollutants should move from

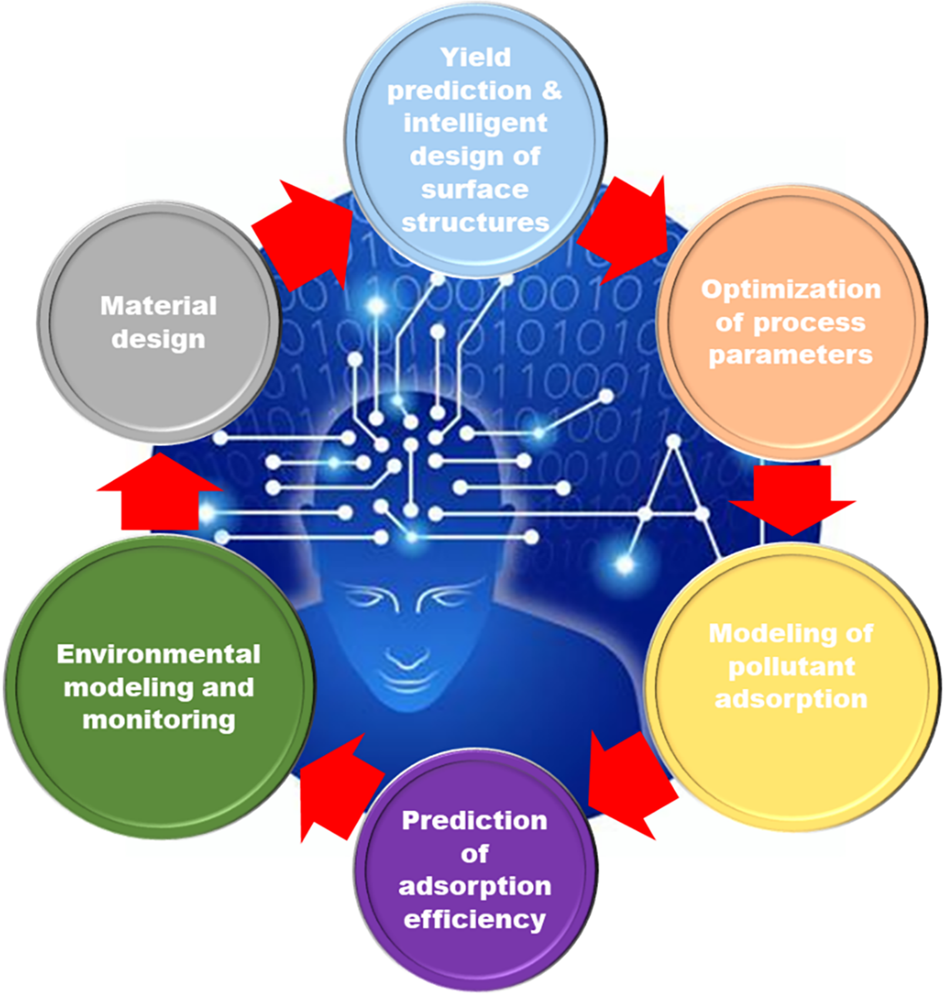


FIGURE 12 | Schematic Illustration of the application of AI in biochar adsorption of pollutants.

the laboratory stage to industrial processes through innovative research into the development of biochar-based filtration systems for real-world applications in gas purification. More innovative and multidisciplinary investigations into biochar's stability, degradation, and secondary pollutant formation are needed. More techno-economic analysis and life cycle assessment are required on biochar development and stability, biochar degradation, modification, and regeneration, pollutant adsorption, secondary pollutant formation, health implications, and the entire value chain of biochar utilization.

7 | Conclusions

Increased consumption of FB fuels and other industrial process has escalated the emission of toxic gases especially of sulfur-containing gaseous pollutants such as H_2S, SO_2, and COS, globally. The limitations of low selectivity, inadequate surface functional groups, and poor pore structure of raw biochar necessitates the need for modification. Adopting appropriate functionalization techniques to modify biochar improve adsorption efficiency by increasing active sites and optimizing pore structures. This study x-rays the various biochar functionalization techniques, pinpointing their benefits, drawbacks, areas of application, and make key recommendations. The benefits and case studies of the integration of AI and other ML models into biochar modification and application in the adsorption of H_2S, SO_2 and COS are highlighted. Despite these advancements, challenges remain, including pore structure limitations, regeneration difficulties, infrastructural inadequacy, environmental and ethical concerns, and cost constraints. The current study does not include the economic analysis and life cycle assessment of the application of biochar for the removal of gaseous pollutants. Multidisciplinary research on the use of novel predictive and modeling technologies, techno-economic analysis, life cycle assessments, and development of legal and institutional frameworks are recommended to promote economically viable and environmentally sustainable biochar production, modification, and utilization methods. Future research should focus on optimizing functionalization techniques, exploring hybrid adsorbents, and integrating biochar into large-scale industrial applications to fully harness its potential in mitigating sulfur-containing emissions. Ultimately, biochar-based technologies represent a sustainable and scalable solution for gas-phase pollutant adsorption, contributing to cleaner air and environmental sustainability. Continued interdisciplinary collaboration, especially between academic and industry players will be crucial in overcoming existing challenges and translating research advancements into practical applications.

Author Contributions

Omojola Awogbemi: conceptualization, writing – original draft, methodology, writing – review and editing, resources, investigation, project administration, formal analysis, software. **Dawood A. Desai:** project administration, supervision, resources, writing – review and editing, funding acquisition, software.

Acknowledgments

The authors appreciate the authorities of the Department of Mechanical and Mechatronics Engineering, Tshwane University of Technology, Pretoria, South Africa, for their support.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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