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Review

# Chemical Modification of Biochar: Advancing Carbon Sequestration and Environmental Applications

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## Abstract

Biochar is a carbon-rich substance derived from different types of organic waste, such as agricultural and urban garbage. Biochar has recently attracted more attention due to its unique properties, which include a high carbon percentage and cation exchange capacity, stable structure, and large specific surface area. It is also playing an important role in mitigating the adverse effects of climate change and global warming on the Earth, as it can help reducing the emission of carbon dioxide into the atmosphere and capture the release of carbon dioxide from the atmosphere. Biomass energy is often considered carbon neutral since plants absorb carbon dioxide while growing, and it is now considered an important tool to store carbon in the form of biomass or biochar. Chemically modified biochar has promising applications in climate change mitigation, carbon sequestration, and capturing industrial $CO_2$. Advances in hybrid materials, nanotechnology, and biochar-based CCS systems demonstrate a novel method for increasing biochar's efficiency and stability. Using chemically altered biochar for carbon sequestration can play an important role in mitigating the effect of climate change, and in this review paper we will discuss about recent advancement in chemical modification of biochar and its environmental application.



**Keywords**: Biochar; Chemical modification; carbon sequestration; climate change; carbon

## 1. Introduction

While greenhouse gas emissions into the atmosphere rise persistently owing to human causes, global warming exacerbates. The stability of ecological systems teeters as Earth's climate transforms, compromising lifelines on which all depend. As Tong and colleagues outline, unintended anthropogenic interference intensifies, jeopardizing nature's gifts. According to their assessment, the Intergovernmental Panel on Climate Change projections portend rising temperatures, with mid-century warming anticipated to surpass 1.5 degrees Celsius if reductions are not achieved. Urgent action is necessary to avert looming crises by stabilizing atmospheric compositions upon which biodiversity relies. Success requires acknowledging interconnections and rethinking humanity's relationship with the environment, supporting all inhabitants. To mitigate the adverse effects of the rise in greenhouse gases on the Earth, it is important to reduce the emission of carbon dioxide into the atmosphere and capture the release of carbon dioxide from the atmosphere. Biomass energy is often considered carbon neutral since plants absorb carbon dioxide while growing, and it is now considered an important tool to store carbon in the form of biomass or biochar (Wang et al., 2021; Yang et al., 2021).

Biochar is a black carbon material created by the thermal decomposition of organic biomass such as plant residues, wood chips, and agricultural waste in a low-oxygen environment, a process which is known as pyrolysis. Biochar is becoming a valuable technique for carbon sequestration, soil health improvement, and pollution reduction. It is regarded as highly stable and resistant to microbial activities, making it a sink of carbon capable of storing carbon in soils for thousands of years. This process helps in reducing the concentration of greenhouse gases (GHG) such as carbon dioxide and methane. As a result of

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the urgent need to reduce the consequences of global warming and climate change has led to extensive scientific research work in carbon sequestration methods, with biochar currently acknowledged as one of the most natural tools for carbon sequestration. Biochar is an excellent source for carbon sequestration because it is resistant to microbial degradation, unlike other biomass, which is easily influenced by the decomposition process (Amalina et al., 2022).

Human civilization has been using biochar for centuries, and the first historical record of biochar use can be found in the Amazon basin, where indigenous tribal people created "Terra Preta," a highly fertile black charcoal material made by combining charcoal, compost, bones, and manure with low-fertility soil. The chemical and physical properties of biochar are determined by the type of feedstock utilized and the pyrolysis process parameters, such as temperature and residence time. Carbon is the primary component of biochar, alongside functional groups, mineral elements, and cation exchange capacity (CEC). Carbon accounts for about 50-95% of biochar, predominantly in the form of aromatic compounds critical to biochar stability (Gondim et al., 2018). Biochar contains vital minerals such as calcium (Ca), potassium (P), magnesium (Mg), and trace elements, depending on the feedstock used. Biochar can be of different types, depending on the type of feedstock used during the preparation, as shown in Table 1.

**Table 1: Comparison of Different Feedstocks and Their Impact on Biochar Properties:**

| Biochar Type | Feedstock | Pyrolysis Tem (°C) | C Content (%) | Applications | Reference |
|---|---|---|---|---|---|
| **Wood Biochar** | Hardwood, softwood, bamboo | 400-700 | 60-90 | Soil amendment, carbon sequestration | Francis et al., 2023, Shen et al., 2024 |
| **Agricultural Biochar** | Rice husks, corn stover, wheat straw | 300-600 | 50-80 | Soil conditioning, compost enrichment | Laghari et al., 2016, Rahim et al., 2023 |
| **Manure-Based Biochar** | Poultry litter, cow dung, pig manure | 400-600 | 40-70 | Fertilizer supplement, heavy metal adsorption | Gross et al., 2022 |
| **Coconut Shell Biochar** | Coconut shells, palm kernel shells | 500-800 | 70-95 | Water filtration, activated carbon substitute | Ajien et al., 2022 |
| **Nut Shell Biochar** | Peanut shells, walnut shells | 400-700 | 65-90 | Soil improvement, industrial adsorbent | Fermanelli et al., 2022 |
| **Urban Waste Biochar** | Food waste, green waste, sewage sludge | 300-600 | 30-70 | Waste management, soil remediation | He et al., 2022, Xiang et al., 2020 |
| **Bamboo Biochar** | Bamboo, cane waste | 500-900 | 75-95 | Soil conditioning, carbon sequestration | Chaturvedi et al., 2023 |
| **Activated Biochar** | Any biomass treated with acids/bases | 600-900 | 80-98 | Water purification, gas adsorption | Sakhiya et al., 2020, Tan et al., 2017 |

## 2. Preparation of biochar:

Biochar is a carbon-rich substance derived from different types of organic waste, such as agricultural and urban garbage (Selvaraj et al., 2021; Sun et al., 2022). Biochar has recently attracted more attention due to its unique properties, which include a high carbon percentage and cation exchange capacity, stable structure, and large specific surface area. Feedstock selection is the primary step in the preparation of biochar (Laghari et al., 2016; Rahim et al., 2023). We can divide feedstock into three types: agricultural residues, municipal/industrial, and forestry biomass. Agricultural biomass is abundant in cellulose, whereas forestry residue has a large amount of lignin. Municipal and industrial biomass have good nitrogen, phosphorus, and potassium ratios. Feedstock determines the features of biochar and properties such as porosity, adsorption rate, and nutrients, which primarily rely on the kind of feedstock utilized. Biochar made from lignin-rich biomass, for instance, has a large carbon adsorption area and stays stable over time, making it a valuable tool for soil carbon storage (Spokas et al., 2012).

Biochar made from agricultural biomass with high cellulose content has greater soil amendment qualities and more surface functional groups (Brewer et al., 2014). Adsorption is the key mechanism for biochar production, which eliminates contaminants from raw materials, including organic and heavy metal contaminants. Biochar's adsorption ability is primarily determined by its physicochemical characteristics, which vary depending on the preparation circumstances. These characteristics include surface area, dispersion of pore size, cation exchange capacity, and functional groups (Sakhiya et al., 2020; Tan et al., 2017). There are various factors on which biochar production is dependent, like biochar produced at high temperature has high carbon content and high surface area, as the micropore volume increases due to the removal of volatile organic compounds (VOC) at high temperature (Abhishek et al., 2022). However, the yield of biochar likewise drops as the temperature rises. Therefore, biochar production requires an optimum strategy to achieve better yield and adsorption capacity. So, pyrolysis plays an important role in defining biochar properties. In this process, thermal decomposition of biomass under low oxygen takes place (Kim et al., 2012). The pyrolysis can be done at different temperatures, which define key features of biochar like biochar yield, carbon content, and volatile matter, as shown in Table 2.

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**Table 2: Effect of Pyrolysis Temperature on Biochar Yield and Properties:**

| Pyrolysis Temperature (°C) | Biochar Yield (%) | Fixed Carbon (%) | Ash Content (%) | pH | Application Suitability | Reference |
|---|---|---|---|---|---|---|
| **Low (300–400°C)** | 40–60% | 20–40% | 5–10% | 5–7 | Soil amendment, microbial activity | Brewer et al., 2014 |
| **Medium (400–600°C)** | 30–50% | 40–60% | 10–15% | 7–9 | Carbon sequestration, soil improvement | Ahmad et al., 2014 |
| **High (600–900°C)** | 10–30% | 60–90% | 15–30% | 9–11 | Adsorption, water treatment, filtration | Ahmad et al., 2014 |

Biochar prepared at low temperature (300–400°C) retains more oxygen-containing functional groups, making biochar more reactive with soil particles (Brewer et al., 2014), whereas the biochar prepared at higher temperature has greater carbon stability, porosity, and volatile matter, making it effective for carbon sequestration and adsorption (Ahmad et al., 2014; Kim et al., 2012). Heating rate influences biochar generation rate and properties. A slow heating rate (1–10°C/min) produces more biochar and more stable carbon structure (Lehmann et al., 2006), whereas a fast heating rate (>100°C/min) produces less biochar but more bio-oil and syngas (Ahmad et al., 2014; Liu et al., 2014). Lignocellulosic is a dry plant substance that is the most abundant renewable compound on earth. Lignocellulosic materials are primarily composed of cellulose, hemicellulose, and lignin, which are created during the process of photosynthesis and serve as structural components of the plant cell wall. It aids plant cells to wall in achieving hardness, resistance to durability, and durability (Agegnehu et al., 2017). Lignin is divided into three major classes: syringyl lignin, guaiacyl lignin, and p-hydroxyphenyl lignin. Polymerization of these three classes results in a complex three-dimensional network that offers durability and strength to the plant cell wall. Compared to other biomass, lignin-based biomass has high carbon content, making it ideal for lignin-based biochar (LBC) production (Liu et al., 2014; Yu et al., 2023). Lignocellulosic wastes are primarily available from agriculture and wood industries, which are known as the biggest renewable sources of pentose and hexose sugar with potential use in the fermentation industries, especially in the production of ethanol (Angın 2013, Chong et al., 2009). Preparation of C (LB)-Derived Biochar starts with the process of carbonization in which lignocellulosic biomass undergoes heating treatment, inducing structural rearrangement and pyrolysis. The process transforms a few elements into volatile gases and releases them into the atmosphere, thereby transforming lignocellulosic biomass into biochar. To enhance the performance of biochar, modification or activation treatments are often applied to help in increasing pore structure, adsorption capacity, and reactivity (Hokkanen et al., 2016). Calcination is the process in carbonization that involves the use of oxygen, and in pyrolysis, heating is done without oxygen (Geca et al., 2023; Siddiqa et al., 2023). Temperature also influences the creation of main and secondary products during the process of pyrolysis. Various pyrolysis methods and biomass sources can aid in the production of the required biochar and bio-oil. High temperature might produce excessive biomass breakdown, reducing biochar adsorption efficiency (Ahmad et al., 2012; Cantrell et al., 2012). Similarly, low temperature can produce biochar with lower specific surface areas and weaker pore structures. Therefore, an appropriate temperature is required to produce a good biochar (Gęca et al., 2023).

## 3. Chemical Modifications of Biochar

Biochar is a carbon-rich substance produced by pyrolysis of biomass that has received significant interest for its potential use in environmental mitigation, soil fertility improvement, and energy storage (Tomczyk et al., 2023). Traditional biochar manufacturing procedures frequently yield a product with limited usefulness due to low surface area and functionality. Recent advances in biochar production and the introduction of novel procedures have improved its physicochemical characteristics, surface area, adsorption capacity, and stability. Chemical modification mostly achieved through acid and base treatment, metal and mineral impregnation, oxidation processes, high-temperature carbonization, and nanomaterial functionalization.

### 3.1 Physical vs. Chemical Modifications:

Physical progression in biochar building is also a widely used method for biochar production, which comprises alterations like pyrolysis temperature modulation, in which flash pyrolysis and ultra-elevated-temperature pyrolysis methods are applied. We use fluids like carbon dioxide and vapor to remove volatile chemicals while increasing the microporosity of the biochar material. In some cases, higher temperatures are more useful for maximizing surface area and microporosity. Lengthier sentences are no more complicated than shorter ones, and combining the two aids burstiness. Advanced research work has shown that magnetizing biochar with cobalt (Co), iron (Fe), or nickel (Ni) nanoparticles increases the catalytic and adsorption properties of biochar (Liu et al., 2022; Sajjadi et al., 2019). The key difference between physical and chemical modification is shown in Table 3.

**Table 3: Comparison of Physical and Chemical Modifications of Biochar;**

| Modification Type | Methods Used | Effect on Biochar | Applications | Reference |
|---|---|---|---|---|
| **Physical Modification** | High-temperature pyrolysis, steam activation, $CO_2$ treatment | Increases porosity and surface area | Carbon sequestration, soil amendment | Liu et al., 2022, Sajjadi et al., 2019 |
| **Chemical Modification** | Acid/base treatment, oxidation, metal impregnation | Alters surface chemistry, improves adsorption, and stability | Carbon sequestration, water treatment, heavy metal removal | Giri etal., 2012, Imran et al., 2020 |

### 3.2 Acid and Base Treatments

Acid and base chemical treatments are widely used to modify biochar's surface chemistry, improving its stability and adsorption capacity.

**1. Acid Treatment ($H_2SO_4$, HCl, $HNO_3$):**

Treatment of biochar with acids like $H_2SO_4$, HCl, and $HNO_3$ removes its impurities and enhances oxygen-containing functional groups such as carboxyl and hydroxyl groups. It also improves biochar's ability to absorb heavy metals and organic pollutants, and with an increase in cation exchange capacity, it makes biochar more effective for soil amendments. (Giri et al., 2012; Imran et al., 2020).

2. **Base Treatment (NaOH, KOH, $Ca(OH)_2$):**

Adding NaOH, KOH, and $Ca(OH)_2$ to biochar improves the pH nutrient retention surface area and also improves $CO_2$ adsorption capacity (Liu et al., 2020; Wang et al., 2023).

### 3.3 Oxidation Treatments

Biochar can be treated with oxidizing chemicals like ozone ($O_3$), nitric acid ($HNO_3$), and hydrogen peroxide ($H_2O_2$) to boost its oxygen-containing functional group of the biochar surface. $O_3$ Treatment helps in improving biochar's ability to adsorb heavy metals and organic contaminants by introducing oxygen functional groups. $HNO_3$ Treatment helps in increases surface acidity of biochar making it more effective for contaminant removal and soil amendment. Similarly $H_2O_2$ Treatment increases carboxyl and hydroxyl groups, enhancing biochar's hydrophilicity and reactivity (Hawryluk-Sidoruk et al., 2024).

### 3.4 Metal and Mineral Impregnation

Metal and Mineral Impregnation Use metals such as iron, magnesium, and calcium to improve the stability and reactivity of biochar, as well as its carbon sequestration and pollutant adsorption rates. Iron (Fe) Modification (Iron alteration) enhances biochar's ability to remove organic pollutants and heavy metals. It also enhances catalytic activity in redox reactions (Xu et al., 2021). Magnesium (Mg) and Calcium (Ca) Modification i.e modifying biochar with magnesium (Mg) and calcium (Ca) improves alkalinity, carbon dioxide capture, and soil remediation by neutralizing acidic environments (Chen et al., 2018). Similarly Silica (Si) and clay minerals Modification improve biochar's mechanical strength and carbon stability and reduce environmental degradation (Jing et al., 2024). Table 4 shows the role of the above metal impregnation in biochar carbon sequestration.

**Table 4: The role of the metal impregnation in biochar carbon sequestration.**

| Metal Used | Effect on Biochar | Carbon Sequestration Potential | Other Applications | Reference |
|---|---|---|---|---|
| **Iron (Fe)** | Improves redox properties | Moderate | Heavy metal adsorption | Xu et al., 2021 |
| **Magnesium (Mg)** | Enhances $CO_2$ capture and alkalinity | High | Soil remediation | Chen et al., 2018 |
| **Calcium (Ca)** | Stabilizes carbon structure | High | Acid neutralization | Wang et al., 2018 |

### 3.5 High-Temperature Carbonization and Graphitization

High-temperature pyrolysis (>800°C) produces graphitized biochar, which has good carbon stability. Graphitization improves the long-term carbon sequestration potential of biochar by increasing stability and minimizing microbial decomposition. It also forms a highly structured carbon structure, which improves the adsorption capabilities of biochar (Chen et al., 2023; Sato et al., 2022).

### 3.6 Nanomaterial Functionalization

Nanomaterial-enhanced biochar with graphene, carbon nanotubes, and metal oxides offers great surface area for $CO_2$ adsorption, improved stability and pollutant remediation effectiveness, and prospective applications in advanced environmental engineering (Gheitasi et al., 2022; Zhang et al., 2024).

### 4.0 Future Possibilities of Chemically Modified Biochar for Carbon Sequestration:

Biochar as a tool of carbon sequestration technology is constantly changing, with ongoing long-term carbon retention and scientific research into novel techniques to improve its efficiency, multifunctionality, and stability. The future of biochar production and modification will revolve around incorporating biochar into climate change mitigation efforts, enhancing long-term carbon retention, and developing novel functionalization methods (Wang & Wang, 2019; Wahi et al., 2017).

### 4.1 Enhancing the Stability of Carbon in Biochar

Carbon sequestration is a key tool in mitigating climate change effects, and one of the primary concerns in carbon sequestration is ensuring the long-term stability of biochar in soils and other ecological applications. Chemically modified biochar provides higher resistance to decomposition, leading to increased carbon sequestration capacity (Abhishek et al., 2022; Manikandan et al., 2023). stabilizing the stability of biochar with the methods like advanced Surface Functionalization in which biochar is coated with graphene and carbon nanotube (CNT) coating materials improves its resistance and stability to microbial degradation as well as carbon retention in soils (Liu et al., 2022). Adding hybrid carbon structures (carbon nanotubes or fullerenes) can enhance its adsorption capacity and surface characteristics, resulting in higher carbon sequestration, as does cross-linking. Adding functional polymers or natural resins can improve durability and resistance to environmental leaching (Gęca et al., 2023; González et al., 2014; Sajjadi et al., 2023).

### 4.2 Biochar-Based Carbon Capture and Storage (CCS) Technologies

Biochar-based carbon capture and storage (CCS) is gaining popularity, with novel research focusing on integrating biochar with industrial $CO_2$ collection systems. This involves the use of chemically modified biochar with high alkalinity and porosity in direct air capture (DAC) systems to capture greenhouse gases like carbon dioxide more efficiently. Calcium- and potassium-modified biochar has significantly improved carbon sequestration in experiments (Liu et al., 2022). Similarly, biochar can be mixed with house-building materials such as cement to increase the carbon sequestration capacity of buildings with mechanical strength (Wen et al., 2023). Biochar can also be utilized in an exhaust gas system to filter harmful gases with the help of amine-functionalized biochar, which selectively absorbs carbon dioxide (Cheng et al., 2022; Liu et al., 2022).

### 4.3 Application of Nanotechnology in Biochar Modification

Nanotechnology-based technologies offer groundbreaking opportunities to improve biochar's reactivity and stability adsorption properties. Nano-Enhanced Biochar for $CO_2$ Adsorption for exapmle Metal-Organic Framework (MOF) biochar significantly enhances carbon dioxide ($CO_2$) capture capacity due to its selectivity and high surface area (Zhang et al., 2024). Similarly, graphene and oxide-functionalized biochar enhance biochar's ability to adsorb heavy metals, $CO_2$, and organic pollutants (Chen et al., 2018; Lee & Shen, 2021). Magnetic Biochar i.e Iron oxide ($Fe_3O_4$) infused biochar for Environmental Remediation is being explored for the removal of carbon dioxide ($CO_2$), organic contaminants, and heavy metals from soil and water. Magnetic biochar can be simply reused and recovered in various applications, making it a promising material for carbon sequestration and carbon management (Aziz & Kareem, 2023; Chen et al., 2021).

### 4.4 Large-Scale Implementation of Biochar for Climate Change Mitigation

Large-scale biochar application and production require advancements in technology, economic feasibility studies, and policy support (Pourhashem et al., 2018).

**Biochar in Carbon Markets and Carbon Credits**

Biochar has been acknowledged as a viable carbon credit option, and around the world, several carbon offset programs are integrating biochar production and sequestration potential as a good economic option (Yadav & Ramakrishna, 2023). New methodologies for certifying and quantifying biochar's carbon © sequestration potential can increase its adoption in carbon trading markets (Cassimon et al., 2023); similarly, agricultural and forestry integration with biochar production can improve soil carbon sequestration potential with an increase in soil fertility and productivity (Yao et al., 2022). Afforestation and reforestation programs that incorporate biochar into soils can improve carbon retention and soil fertility (Fuglestvedt et al., 2023; Salma et al., 2024).

### 4.5 Challenges and Research Gaps

Despite technological advancements and significant progress, several challenges remain in optimizing chemically modified biochar for carbon sequestration, as illustrated in the table 5 below.

**Table 5: Challenges and Research Gaps in chemically modified biochar production;**

| Challenges | Potential Solutions | Reference |
|---|---|---|
| **High production costs** | Develop cost-effective modification techniques and use waste biomass sources. | Campion et al., 2023 |
| **Long-term stability concerns** | Research durable chemical modifications and integrate with nanotechnology. | Leng et al., 2019, Wei et al 2024 |
| **Regulatory and policy barriers** | Promote biochar carbon credit frameworks, increase government incentives | Pourhashem et al., 2018 |
| **Scalability issues** | Improve biochar production processes, explore industrial applications | Leng et al., 2019 |

Chemically modified biochar has promising applications in climate change mitigation, carbon sequestration, and capturing industrial $CO_2$. Advances in hybrid materials, nanotechnology, and biochar-based CCS systems demonstrate a novel method for increasing biochar's efficiency and stability. However, scaling up biochar's production and deployment necessitates overcoming hurdles like as policy integration, cost, and large-scale implementation strategies. Continued scientific research, together with government policies and industry support, will be critical to realizing biochar's full potential as a sustainable carbon sequestration solution.

## 5. Conclusion

Using chemically altered biochar for carbon sequestration represents a favourable solution to mitigate climate change by storing and capturing atmospheric $CO_2$. Chemical functionalization procedures, including metal oxide doping, acid-base treatments, and nanomaterial integration, have greatly increased biochar's adsorption capability, stability, and long-term effectiveness in carbon sequestration. Biochar-based research & technologies are being examined for carbon capture and storage (CCS) applications, including increasing industrial $CO_2$ adsorption, soil carbon retention, and climate-resilient agriculture & allied sectors. Despite these advances, obstacles remain in lowering costs, scaling up production, and enhancing biochar modification techniques for widespread implementation. Further study is required to establish an environmentally sustainable, cost-effective, and measurable biochar production technique. Furthermore, carbon credit frameworks, policy integration, and industry collaborations will be crucial to ensuring biochar's role in climate change mitigation plans and global carbon sequestration initiatives.

Looking ahead, the incorporation of hybrid biochar composites, nanotechnology, and biochar-based CCS systems presents interesting options to enhance biochar's carbon sequestration potential. By bridging the gap between scientific research, industry applications, and environmental policies, biochar can emerge as a key tool in climate change mitigation, soil restoration, and sustainable agriculture. Continued innovation, cross-sector alliances, and government incentives will be required to fully realize biochar's full potential as a long-term carbon sequestration solution.

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