



Biochar Characterization Techniques for Environmental Applications

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Biochar has emerged as an effective and sustainable material for environmental remediation due to its high adsorption capacity, carbon stability, and soil enhancement potential. The environmental performance of biochar is highly dependent of its physicochemical properties, which are, in turn, a function of feedstock type and pyrolysis conditions. There is a growing interest in customizing biochars for specific applications. Therefore, biochar characterization using sophisticated analytical methods is important for assessing its quality for environmental applications. This article reviews major biochar characterization techniques including BET surface area, FTIR, SEM, XRD, TGA, Raman and elemental analysis. These techniques give insights into surface morphology, pore structure, mineral composition, thermal stability, and functional groups which adsorb pollutants. It also goes into wastewater treatment, soil remediation, carbon sequestration, and aquaculture waste. Its characterization is key to developing effective and eco-friendly biochar-based technologies.

Keywords: Biochar characterization, Environmental remediation, Analytical techniques, Wastewater treatment, Carbon sequestration.

Introduction

Biochar is a biomass-derived carbon sequester that results from thermochemical conversion of biomass under oxygen-limited conditions. In recent years, biochar has garnered worldwide attention due to its multifunctional role in environmental remediation, carbon sequestration, soil enhancement, wastewater treatment, and sustainable waste management. Biochar's environmental performance is intimately related to its physicochemical properties including surface area, porosity, elemental composition, mineral content, and surface functional groups. So, adequate characterization of biochar by high-end analytical techniques is important before its use in environmental systems.

Biochars derived from different feedstocks, including agricultural residues, sewage sludge, aquatic plants, shells, forest waste, and manure, vary in their structural and chemical properties. Likewise, pyrolysis temperature, heating rate, and residence time have a major impact on biochar's final characteristics (Tomczyk et al., 2020). State-of-the-art techniques such as FTIR, SEM, XRD, BET, TGA, Raman and NMR have become commonplace characterizations of biochar for applications in the environment. Characterization is not only useful in identifying the adsorption potential of biochar, but also in predicting its environmental behavior, stability, toxicity and remediation efficiency. The growing concern of engineered biochar and modified biochar has also broadened the significance of analytical techniques in environmental studies (Panahi et al., 2020).

Feedstock and Production Factors Influencing Biochar Properties

Biochar's properties are heavily dependent on the feedstock and pyrolysis conditions. Biomass such as rice straw, wood chips, coconut shell, sewage sludge, algae, and shellfish waste vary significantly in lignin, cellulose, hemicellulose, ash and mineral contents. These variations translate directly into differences in the physical and chemical characteristics of the biochar produced (Ippolito et al., 2020).

Pyrolysis temperature is thought to be the most important parameter influencing biochar properties. Low-temperature biochar (300–400°C) typically has more oxygen-containing functional groups, lower aromaticity and higher volatile matter content. In comparison, high-temperature biochar (600–800°C) tends to have more surface area, porosity, carbon stability, and aromatic carbon structures (Tomczyk et al., 2020).

Heating rate and residence time also impact the formation of pores, ash content, and carbonization efficiency. Slow pyrolysis is preferred for biochar production since it results in higher solid carbon fractions. Feedstock mineralogy also provides a source of nutrients and adsorbents of pollutants. Calcium, magnesium, potassium, and phosphorus mineral rich biochars have been shown to be very well suited for soil amendment and nutrient recovery (Vijayaraghavan, 2021).

Because of this variability, some analytical characterization is needed to assess biochar's suitability for certain environmental applications like wastewater treatment, heavy metal adsorption, and soil remediation.

Physical Characterization Techniques

➤ BET Surface Area Analysis

One of the most commonly used techniques for assessing the specific surface area of biochar is the Brunauer–Emmett–Teller (BET) method. The method quantifies nitrogen gas adsorption and desorption to the biochar surface. Surface area is an important factor as it directly influences adsorption rate and pollutant removal capacity (Yaashikaa et al., 2020). Biochars with a higher BET surface area typically perform better at removing heavy metals, dyes, pharmaceuticals and organic pollutants from water. High-temperature pyrolysis generally boosts pore development and surface area because of the expulsion of volatile matter during carbonization.

➤ Pore Size and Porosity Analysis

Pore structure analysis will aid in understanding the micropore, mesopore, and macropore distribution of biochar. Mesoporous biochar is particularly convenient for wastewater treatment because it enables effective diffusion of contaminants and their subsequent adsorption. Porosity additionally promotes microbial colonization and nutrient retention in soils. Gas adsorption and mercury intrusion porosimetry are frequently used to assess pore characteristics. Being more porous also allows better water holding capacity and better contact between pollutants and adsorption sites.

➤ Bulk Density and Particle Size

Bulk density and particle size influence hydraulic behavior, transport, soil mixing and sedimentation. Also, finer biochar particles typically offer superior adsorptive capacity due to more surface area exposure. But excess fine particles can cause handling and filtration problems in environmental applications.

Chemical Characterization Techniques

➤ Proximate and Ultimate Analysis

Proximate analysis determines moisture content, ash content, volatile matter, and fixed carbon in biochar. High fixed carbon indicates greater stability and long-term carbon sequestration potential. Ash content reflects the presence of mineral components, which impacts nutrient availability and alkalinity. Ultimate analysis measures elemental composition such as carbon (C), hydrogen (H), nitrogen (N), sulfur (S) and oxygen (O). These atomic ratios assist in assessing aromaticity, hydrophobicity, and environmental

stability. Lower H/C and O/C ratios typically suggest increased aromatic carbon production and enhanced biochar stability (Ippolito et al., 2020).

➤ **pH and Electrical Conductivity**

Biochar pH plays a critical role in nutrient availability, microbial activity and heavy metal immobilization. Most biochars are alkaline because of the concentration of mineral ash during pyrolysis. High temperature biochars tend to exhibit higher pH than others. Electrical conductivity (EC) indicates soluble salt concentration and potential nutrient release. High EC can harm plants, but moderate EC can increase soil fertility.

➤ **Cation Exchange Capacity (CEC)**

CEC represents the ability of biochar to adsorb and exchange cations. High-CEC biochars enhance nutrient retention and mitigate nutrient leaching in soils. Functional groups such as hydroxyl and carboxyl groups contribute significantly to ion exchange processes.

Spectroscopic and Microscopic Characterization Techniques

➤ **Fourier Transform Infrared Spectroscopy (FTIR)**

FTIR is widely used to identify surface functional groups present on biochar. Functional groups such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and aromatic C=C play major roles in pollutant adsorption and ion exchange mechanisms (Yaashikaa et al., 2020). Changes in FTIR spectra help researchers understand structural modifications occurring during pyrolysis and pollutant adsorption. Biochars with abundant oxygen-containing functional groups generally show improved heavy metal adsorption capacity.

➤ **Raman Spectroscopy**

Raman spectroscopy reveals details about carbon structure, graphitization, and aromaticity. There are two significant peaks in general, the D- and G-band. The D-band corresponds to the structural disorder and the G-band represents the graphitic carbon. Raman analysis is particularly useful in evaluating carbon stability and degree of carbonization, which are important for long-term environmental applications and carbon sequestration.

➤ **Scanning Electron Microscopy (SEM)**

SEM also aids in visualizing biochar surface morphology and pore structures. SEM images show that cracks, cavitations and roughness are generated and porous network are formed during pyrolysis. These structural properties influence adsorption capacity and microbial colonization. SEM with Energy Dispersive X-ray Spectroscopy (SEM-EDX) can also discern elemental composition on biochar surfaces as well as adsorbed contaminants following remediation studies.

➤ **Transmission Electron Microscopy (TEM)**

TEM allows for high-resolution imaging of internal nanostructures and mineral distribution in biochar. While costly, TEM is valuable for modified engineered biochar research and nano-biochar analysis.

Mineralogical and Thermal Characterization

➤ **X-Ray Diffraction (XRD)**

XRD is used to identify crystalline minerals and inorganic phases associated with biochar. Minerals like quartz, calcite, silica compounds, and metal oxides affect nutrient release and adsorption capabilities (Vijayaraghavan, 2021). Mineral-enriched biochars exhibit enhanced abilities for phosphate adsorption and heavy metal immobilization. Thus XRD analysis is important in assessing biochar suitability for wastewater treatment and soil remediation.

➤ **Thermogravimetric Analysis (TGA)**

TGA analyzes weight loss as it heats, measuring the thermal decomposition behavior and stability of the biochar. Stable biochars typically exhibit less mass loss at higher temperatures due to their highly aromatic carbon structures. TGA also aids volatile, decomposition, and combustion analysis. Thermally stable biochar is what you want for carbon sequestration and long term soil applications.

➤ Nuclear Magnetic Resonance (NMR)

NMR spectroscopy provides detailed information about aromatic and aliphatic carbon structures in biochar. It aids in assessing molecular changes during pyrolysis. While highly accurate, NMR demands advanced equipment and expertise.

Environmental Applications of Characterized Biochar

Characterized biochar has numerous environmental applications due to its adsorption capability, stability, and nutrient-holding capacity. In wastewater treatment, biochar is widely used for removing heavy metals, dyes, pharmaceuticals, pesticides, and emerging contaminants. Surface area, pore structure, and functional groups determine pollutant removal efficiency (Cui et al., 2020). In soil remediation, biochar enhances soil fertility, water retention, microbial activity, and nutrient availability. It also stabilizes heavy metals and decreases pollutant bioavailability. Biochar builds sustainable agriculture and decreases fertilizer run-off. Biochar is additionally being used in aquaculture systems for ammonia removal, sediment enhancement, and nutrient recycling. Engineered biochar and modified biochar with enhanced surface functionalities are emerging for advanced environmental remediation function. And just as importantly, biochar's stable aromatic carbon ties directly into its value toward carbon sequestration and climate change mitigation. Biochar offers a long-term carbon sink and thus has the potential to contribute to efforts against climate change.

Conclusion

Biochar characterization is crucial for environmental efficiency and biochar potential. Techniques such as BET, FTIR, SEM, XRD, TGA, Raman spectroscopy, and elemental analysis can also provide valuable information about surface properties, structural composition, thermal stability, and adsorption mechanisms. Feedstock type and pyrolysis conditions strongly impact biochar properties, necessitating this characterization for environmental applications. Developments in engineered biochar, nanostructured biochar, and modified biochar have continued to extend the analytical role of biochar in environmental studies. Characterized biochar has shown promise for use in wastewater, soil, nutrient recovery, carbon sequestration, and aquaculture waste. Future research focusing on standardized characterization as well as more advanced analytical approaches will better enable the sustainable use of biochar in environmental process.

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