

Investigation of biochar properties - comprehensive review of instrumental techniques

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The circular economy concept applied to biomass waste highlights its transformation into valuable products, aligning with sustainability principles. Additionally, the circular economy aims to decrease reliance on limited natural resources. It encompasses economic activities related to the invention, development, production, and utilization of products and processes for the production of energy, materials, and chemicals. Biomass waste, which includes agricultural residues, organic industrial waste, and food industry by-products, holds significant potential for conversion into diverse bioproducts. These include biochar, biofuels, bioplastics, and biochemicals, which serve as environmentally friendly alternatives to traditional fossil fuel-based products. This holistic approach not only adds economic value to waste streams but also plays a pivotal role in addressing pressing environmental challenges, such as waste management, resource depletion, and climate change.

The conversion of biomass into these value-added products reduces waste and also mitigates the environmental impacts of conventional industries (Li 2023). For instance, biofuels derived from biomass can decrease greenhouse gas emissions associated with transportation. Bioplastics and biochemicals offer sustainable solutions to the growing concerns of plastic pollution and chemical production's ecological footprint. Biochar characterizes the following key properties, including hydrophobicity, high carbon content, high surface area, non-polarity, the presence of surface functional groups, specific mineral composition, and alkalinity (Novotný 2023, Wu 2024). These properties give biochar a wide range of potential applications, such as: i) mitigating climate change (by sequestering carbon in soil, ii) energy production (contributing to lower carbon and greenhouse gas emissions), iii) environmental remediation (effectively removing organic contaminants such as pesticides, herbicides, polycyclic aromatic hydrocarbons, and antibiotics), iv) adsorption of metals (acting as a carbonaceous material to adsorb metals in soil and water), v) CO₂ adsorption (helping to capture carbon dioxide). These applications highlight the versatility and environmental benefits of biochar. There are a lot of organizations and actions promoting biochar as a “powerfully circular way to fight climate change” e.g. The International Biochar Initiative, UN Climate Change Conference, The European Biochar Certification, UN Food and Agriculture Organization and others.

Taking into account mentioned advantages of biochar, this study presents a comprehensive review of instrumental techniques employed in the investigation of biochar properties, highlighting its applications in the food industry, water treatment, and environmental sustainability initiatives. Biochar, derived from thermochemical processes such as torrefaction, pyrolysis, gasification, and hydrothermal carbonization (Table 1). The choice of methodology relies on the properties of biomass waste and the main product that needs to be obtained and its potential applications.

Table 1. The most common thermochemical conversion of biomass waste into biochar production (Jerzak 2024, Magdziarz 2024, Wądrzyk 2023)

Process	Temperature range	Atmosphere	Products (advantages of biochar)
Torrefaction	200 – 300 °C	Inert/low oxygen content	Biochar (higher carbon content and hydrophobic properties, enhancement energy density, reduced biodegradability)
Pyrolysis	300 – 900 °C	Inert	Biochar (higher carbon content and highly porous structure)
Gasification	800 – 1200 °C	Air, CO ₂ , H ₂ O, or mixture of agents	Bio-oil and syngas Syngas (main product) Biochar (secondary product – solid residue, containing residual minerals and high fixed carbon content)
Hydrothermal Carbonization	150 – 300 °C	Water-rich, high pressure	Biochar (hydrochar -lower carbon content but enhanced energy density) Aqueous phase

This study presents the importance of physicochemical properties, including ultimate and proximate analysis, surface functional groups, mineral composition, and surface alkalinity, in influencing biochar's sorption capacity and performance. Advanced instrumental techniques such as scanning electron microscopy dispersive X-ray spectroscopy (SEM-EDX), mercury porosimetry, Fourier transform infrared (FTIR) spectroscopy, and thermogravimetric analysis (TGA) are explored for their role in understanding the changes in biochar's properties. SEM is used to examine changes in surface morphology, such as pore widening and the formation of new pores. EDX analysis complements this by determining the elemental composition of the biochar surface, giving detailed insights into its inorganic chemical properties (it is crucial when alkali metals are introduced to the biochar to enhance surface basicity). The surface area and porosity of biochar, including micro- and mesopores, are typically evaluated using N₂ gas adsorption techniques. FTIR absorption peaks allow to identify functional groups. TGA is utilized to assess the thermal stability of biochar, a critical factor for its regeneration and industrial applications. Depending on the synthesis conditions and treatment methods used for biochar, researchers often combine these analytical techniques to thoroughly characterize its physicochemical properties.

The investigations conducted by authors demonstrate the potential of biochar produced from various biomass and organic waste sources, including agriculture and woody biomass, food waste biomass like (maize cobs, sunflower hulls, buckwheat hulls, cherry seeds, and chicken bone waste) (Ionescu 2025, Jerzak 2023, Mlonka-Mędrala 2025). Thermal methods, such as pyrolysis and steam gasification, were applied to obtain value-added biochar properties (Table 2). The application and efficiency of biochar in various sectors can be significantly enhanced through specialized treatment methods. These methods include physical (treatment at high temperatures in a steam agent) and chemical activations (using substances like KOH, H₃PO₄, ZnCl₂); doping with metals or metal oxides; and modifying the biochar's surface by introducing specific functional groups, such as carboxyl, hydroxyl, and amine groups.

Table 2. Biochar physical and chemical properties

Biomass waste	Process	Biochar properties
Rape cake, 45 wt. % C	Pyrolysis, 600 °C, N ₂	62 wt. % C, R ₅₀ = 56%
Walnut shells, 48 wt. % C	Pyrolysis, 600 °C, N ₂	87 wt. % C, 174 m ² /g surface area
Turkey bone, 20 wt. % C	Gasification, 800 °C, H ₂ O	100 m ² /g surface area, 15 cm ³ /g micropore vol.
Chicken bone 20 wt. % C	Pyrolysis, 500 °C, N ₂	14 wt. % C, 113 m ² /g surface area, 26 cm ³ /g micropore vol.

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