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Sources, production methods, and applications of biochar

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Abstract. With the rapid depletion of resources like oil and coal, the world is actively seeking sustainable, efficient, and eco-friendly energy alternatives. Biochar, a versatile material, can be produced from diverse sources including agricultural residues, forestry waste, and urban organic matter. Moreover, biochar preparation methods such as pyrolysis, hydrothermal carbonization, and microwave-assisted techniques offer flexible production options. Concurrently, physical, chemical, and microbial modifications can enhance biochar's properties, enabling it to address energy challenges, restore the environment, and promote agricultural development effectively.

Keywords: Biochar; Preparation method; Modification method; Agricultural applications; Environmental remediation.

1. Introduction

Biochar, as a carbon-rich solid material generated by the thermochemical conversion of biomass under anaerobic or limited oxygen conditions, has attracted significant global interest in recent years. Domestically and internationally, its diverse functions are being explored to provide more efficient and innovative solutions to challenges in agriculture, environmental protection, energy, and related fields. In agriculture, biochar can enhance soil structure, boost soil fertility, and reduce carbon dioxide emissions. In environmental applications, it can effectively purify contaminated water and soil. However, there are still challenges hindering its large-scale application, such as relatively high production costs and unstable performance.

2. The source of biochar

The feedstocks used for biochar production are diverse, covering agricultural residues, forestry by-products, urban organic waste, and other biomass resources. Different raw materials vary in chemical composition and physical structure, resulting in biochar with different properties and effects.

2.1. Agricultural waste

China, as a major agricultural country, generates a substantial amount of agricultural waste every year, with crop straw being the most widely used raw material for producing biochar. According to statistics, the global annual production of straw is about 3 billion tons, of which China contributes over 900 million tons. The chemical composition of common discarded straw such as corn, rapeseed, and rice primarily includes cellulose (30%–50%), hemicellulose (20%–35%), and lignin (15%–30%), along with minor amounts of protein, ash, and minerals. Straw-derived biochar is characterized by abundant microporous and mesoporous structures, with a specific surface area generally ranging from 10 to 200 m^2/g, providing excellent sites for pollutant adsorption and microbial colonization. Huang Baoyuan et al. [1] used biochar produced from rice straw and corn straw to study its ammonia nitrogen adsorption capacity and analyzed its adsorption mechanism through isotherm models, kinetics, and thermodynamic parameters, aiming to develop an efficient method for removing ammonia nitrogen from water. He Mengfan et al. [2] carried out detailed studies on removing heavy metals from water using straw biochar. Dong Yanqiao et al. [3] prepared geopolymer biochar composites using slag and corn stover biochar activated with sodium hydroxide, and investigated how biochar can enhance the adsorption capacity of single adsorbents to effectively treat lead pollution.

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2.2. Forestry waste

Forestry residues such as sawdust, bark, and tree branches are also valuable raw materials for producing biochar. These materials are typically rich in lignin, which gives the resulting biochar high structural stability and a high degree of aromatization after pyrolysis. The resulting biochar generally features a well-developed pore structure, with a specific surface area that can reach 200–500 m^2/g, making it highly suitable for applications requiring strong adsorption performance, such as the removal of organic pollutants from water. Liu Qinghong et al. [4] demonstrated that biochar produced from boxwood sawdust could effectively enhance the anaerobic digestion efficiency of sludge and stabilize heavy metals. Shang Jie et al. [5] investigated the effects of applying different amounts of biochar made from fruit tree trunks and branches on soil microbial biomass carbon (SMBC), microbial biomass nitrogen (SMBN), and enzyme activity, providing a scientific basis for using biochar to improve soil quality. Lv Zhiwei and colleagues [6] also produced biochar using discarded tree branches collected from gardens.

2.3. Urban organic waste

Urban sludge is a solid or semi-solid waste produced during sewage treatment, and its output continues to grow each year with ongoing urbanization and improvements in wastewater treatment rates. It is estimated that China’s annual urban sludge production has surpassed 60 million tons (with a moisture content of 80%). The chemical composition of urban sludge is complex, consisting mainly of organic matter (30%–60%), inorganic matter (40%–70%), and water. The organic fraction primarily includes proteins, carbohydrates, and lipids, while the inorganic portion contains substantial amounts of oxides such as silicon, aluminum, iron, and calcium, along with heavy metals (e.g., Cd, Pb, Zn, Cu, etc.). Yang Jiangfeng et al. [7] modified raw sludge biochar (SBC) with a NaOH solution to obtain modified sludge biochar (NSBC) for the removal of Cd (II) from acidic my wastewater. Zhang Xin [8] produced biochar from municipal sludge using pyrolysis technology. The resulting biochar features a high specific surface area, a well-developed pore structure, and is rich in plant nutrients, making it a potential soil amendment to improve soil structure and fertility. However, applying urban sludge-derived biochar also poses challenges due to its high heavy metal content. If not properly treated, it may cause secondary release of heavy metals during use, potentially leading to environmental contamination.

2.4. Other waste materials

Other organic wastes like animal manure, kitchen waste, and tea industry residues can also be used to make biochar. Animal manure-derived biochar is rich in nitrogen, phosphorus, and potassium, which can be slowly released to enhance soil fertility. Xiaoqian Wei et al. [9] combined wood, herbs, sludge, and livestock manure to produce biochar for CO_2 conversion into solar fuel.

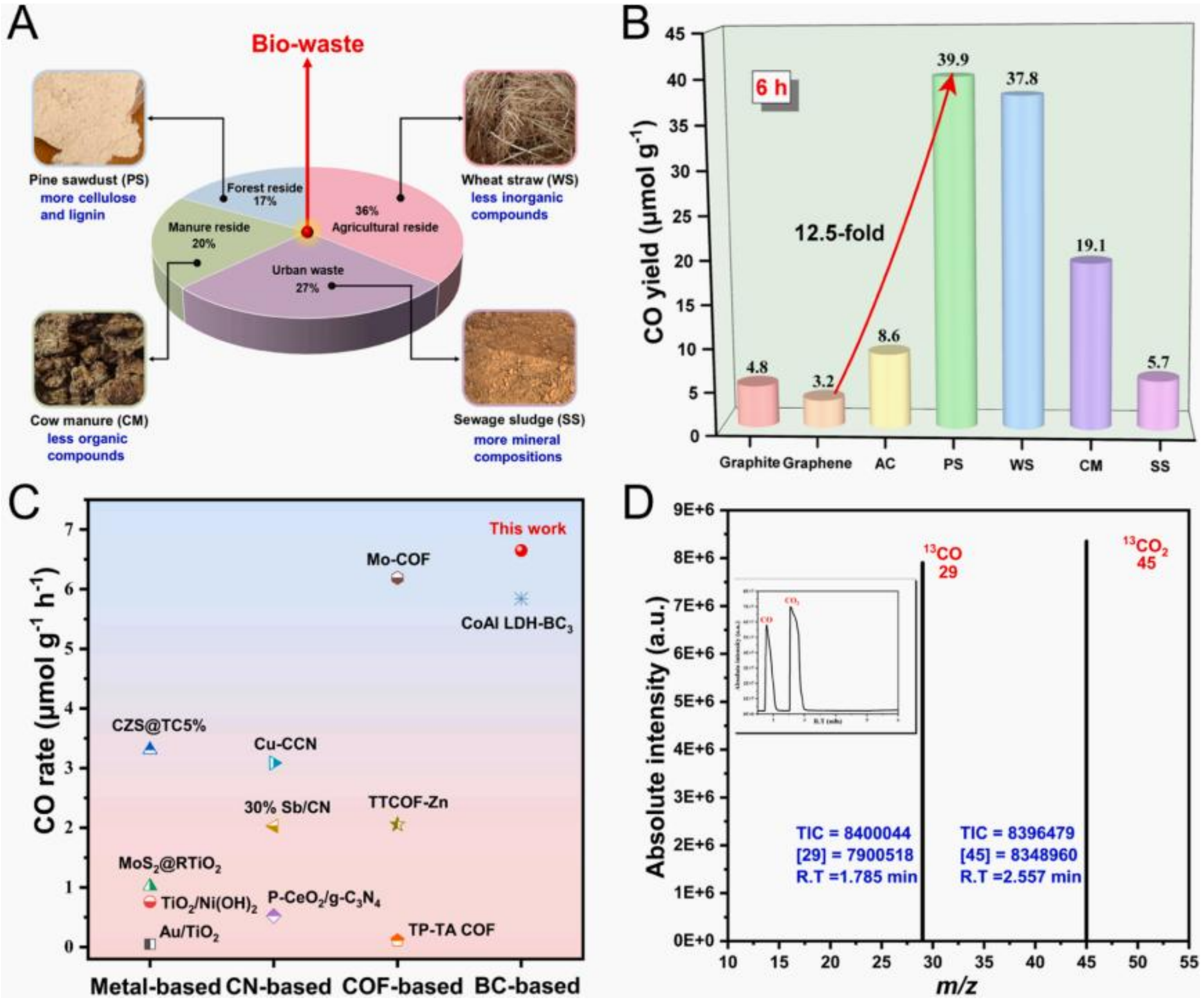

Figure 1. (A) Composition of four bio-waste resources. (B) Production of CO from CO2 photoreduction by graphite, graphene, AC, and various waste-derived biochar under light illumination. (C) Comparison of CO evolution rate in solar conversion of CO2 by PS350 (this work) to that of advanced metal or carbon based photocatalysts in previous studies. (D) GC-MS spectrum of the products of photocatalytic 13CO reduction over PS350.

Kitchen waste-derived biochar, due to its high carbohydrate content, tends to form unique functional groups during pyrolysis, which endow it with good adsorption capabilities for certain specific pollutants. Liu Liang et al. [10] provided valuable guidance for treating composite heavy metal pollution in water using biochar produced from kitchen waste. Tea, as one of the most widely consumed beverages globally, also generates a significant amount of waste each year. As a major tea producer and consumer, China produces large quantities of tea industry by-products annually, including tea residues, stems, pruned branches, and leaves. These wastes contain abundant biomass resources and represent high-quality feedstock for biochar production. Nadi et al. [11] employed potassium hydroxide pyrolysis to modify tea waste and successfully prepared tea waste biochar capable of effectively adsorbing crystal violet from textile dyeing wastewater. Madi [12] investigated the structural features and adsorption behavior of biochar modified with malic acid, using Tie Guan Yin tea stems as the raw material, and provided deeper insight into its adsorption mechanisms, offering a feasible solution for removing residual atrazine from water environments.

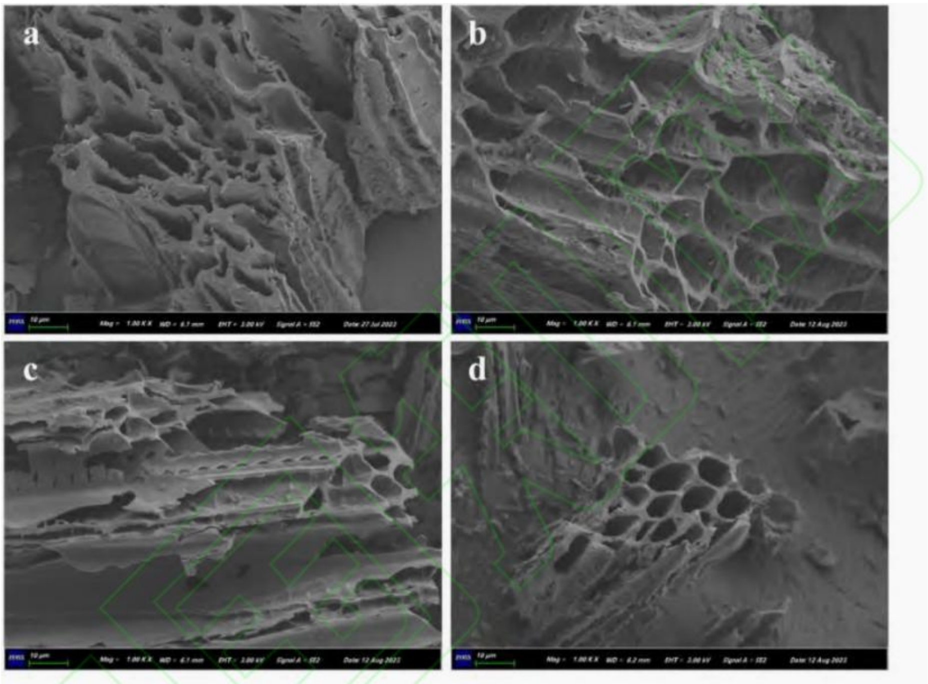

Figure 2. Madi et al. prepared four types of tea stem biochars, namely TBC-400, TBC-500, TBC-600, and TBC-700, at 400°C, 500°C, 600°C, and 700°C, respectively, and obtained their scanning electron micrographs.

3. Method for producing biochar

Common methods for producing biochar include pyrolysis, hydrothermal carbonization, and microwave pyrolysis.

3.1. Thermal decomposition method

Pyrolysis is the most widely used method for producing biochar, involving the thermal decomposition of biomass under anaerobic or oxygen-limited conditions to generate biochar, bio-oil, and combustible gases. Slow pyrolysis is typically conducted at a low heating rate (<10°C/min), with a pyrolysis temperature generally ranging from 300 to 700°C and a longer residence time (from several hours to several days). This approach favors higher biochar yields, achieving a mass fraction of 30%–50%, while producing biochar with good structural stability and a well-developed pore network. In contrast, rapid pyrolysis operates at a higher heating rate (100–1000°C/s), with temperatures between 400–650°C and a very short residence time (<2 s). This method mainly targets bio-oil production, resulting in a lower biochar yield of about 10%–20%, but the obtained biochar features a large specific surface area and high reactivity. Flash pyrolysis uses an even faster heating rate (>1000°C/s) and typically higher temperatures above 700°C, mainly producing small molecule gases and bio-oil, with minimal biochar output. Lv Zhiwei [6] investigated the effects of pyrolysis temperature and duration by setting five reaction times (12, 24, 36, 48, and 60 minutes) at conventional pyrolysis temperatures of 450 and 650°C, aiming to clarify how these factors affect the physicochemical properties and adsorption performance of biochar. Yao Jinzhou et al. [13] explored the slow pyrolysis of biochar under limited or complete oxygen-deficient conditions.

3.2. Hydrothermal carbonization method

Hydrothermal carbonization is a biomass conversion process that takes place in a high-temperature, high-pressure aqueous environment. The typical reaction temperature ranges from 180–250°C, with a pressure of 2–5 MPa, and the reaction duration generally lasts between 0.5 to 12 hours. Under hydrothermal conditions, carbohydrates, proteins, lignin, and other biomass components undergo hydrolysis, dehydration, condensation, and aromatization reactions, gradually forming biochar.

Compared with pyrolysis, hydrothermal carbonization offers several advantages: first, it can directly handle biomass with high moisture content without requiring prior drying, thus reducing energy consumption; second, the reaction conditions are relatively mild and the equipment requirements are less demanding; third, the resulting biochar has a surface rich in oxygen-containing functional groups such as hydroxyl and carboxyl groups, which provides good hydrophilicity and ion exchange capacity.

3.3. Microwave pyrolysis method

Microwave pyrolysis is a technique that exploits the dielectric heating properties of microwaves to rapidly heat biomass, facilitating pyrolysis reactions within a short timeframe. Compared to conventional pyrolysis methods, microwave pyrolysis offers advantages such as faster heating rates, more uniform heat distribution, and shorter reaction times, thereby significantly enhancing both the production efficiency and quality of biochar. During this process, polar molecules in biomass—including water, cellulose, and hemicellulose—undergo rapid vibration and rotation under microwave electromagnetic fields, generating internal frictional heat that leads to self-heating. This distinctive heating mechanism enables simultaneous internal and external biomass heating, effectively eliminating the temperature gradients common in traditional methods, reducing heat transfer resistance, and accelerating the pyrolysis reaction rate. Yan Xiang et al. [14] applied a microwave–H_2O_2–ultrasound coupling method to prepare modified soybean straw biochar, investigating its adsorption behavior toward Pb (II) ions in wastewater.

4. Biochar modification method

4.1. Physical Modification

Physical modification enhances biochar properties by adjusting its physical structure, such as increasing surface area and pore size distribution. Common physical methods include high-temperature treatment and mechanical milling. Duan Xiaotong et al. [15] used co-ball milling to load Fe_3O_4 onto biochar to prepare magnetic biochar, which catalyzed the degradation of Rhodamine B in water with peroxymonosulfate.

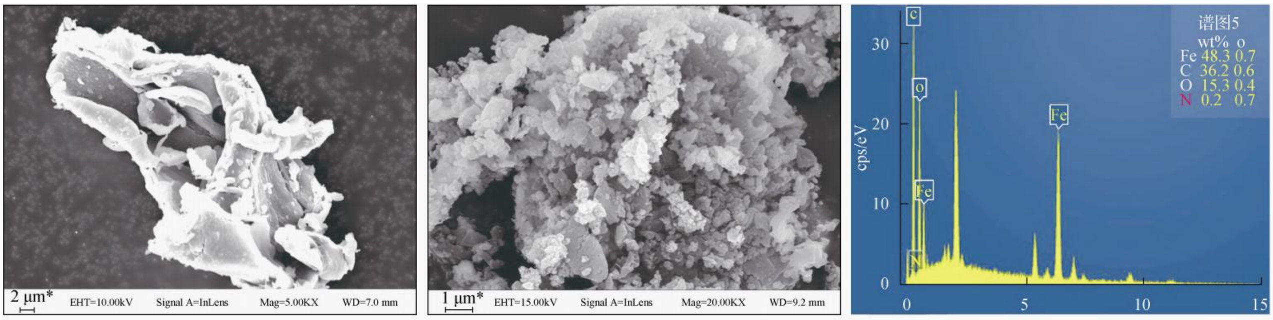

Figure 3. The SEM image of WB500, the SEM image of MWB900, and the EDS point scan image of MWB900 by Duan Xiaotong et al.

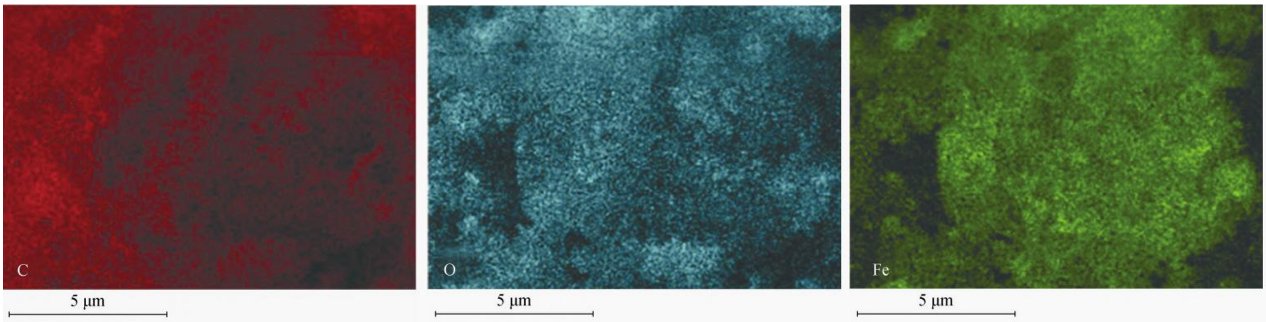

Figure 4. The SEM image of WB500, the SEM image of MWB900, and the EDS point scan image of MWB900 by Duan Xiaotong et al.

4.2. Chemical Modification

Chemical modification introduces or adjusts surface functional groups through reactions, improving biochar's chemical properties and adsorption capacity.

4.2.1. Acid base modification.

Acid–alkali treatment involves reacting biochar with acidic or alkaline solutions to alter the types and quantities of surface functional groups. Treating biochar with hydrochloric acid can remove ash and metal impurities from its surface, while simultaneously increasing the content of acidic functional groups—such as carboxyl and phenolic hydroxyl groups—thereby enhancing the hydrophilicity of the biochar surface and improving its cation exchange and adsorption capacity. Conversely, treatment with sodium hydroxide solution can introduce more alkaline functional groups onto the biochar surface, which is advantageous for adsorbing acidic gases or anionic pollutants. Eze F. Ahuekwe [16] conducted a chemical modification study utilizing KOH treatment to effectively remove heavy metals during wastewater treatment.

4.2.2. Metal Modification.

Metal loading refers to the process of introducing metals or metal oxides onto the surface of biochar via impregnation, co-precipitation, or other techniques, thereby imparting new functionalities to the biochar. For instance, loading iron oxides onto biochar produces magnetic biochar that retains the adsorption capabilities of the original material while gaining magnetic properties, which facilitates easy separation and recovery using an external magnetic field in applications such as wastewater treatment. Kou Han [17] prepared a carbon-based microbial agent (FBCS) by loading Bacillus subtilis (BS) onto iron-modified biochar (FBC), and investigated the synergistic effects of FBC and BS on organic nitrogen biomineralization and abiotic mineralization. Zhou Yuanming [18] studied how the preparation method of Fe (II) and H_2O_2 synergistically modified biochar influences its adsorption performance toward Cr (VI).

4.2.3. Microbial Modification.

Microbial modification is a technique that leverages the metabolic activity or functional traits of microorganisms to alter the surface structure, chemical composition, or functional groups of biochar. Through microbial adsorption, secretion, and metabolism, this approach imparts new properties to biochar, such as enhanced adsorption capacity, accelerated pollutant degradation, and improved soil ecology. Sheng Yikun et al. [19] studied the effects of biochar and biochar loaded with Bacillus subtilis on rapeseed growth under tetracycline stress, concluding that biochar treatment significantly promoted chlorophyll synthesis, thereby expanding the light intensity range and improving photosynthetic parameters including apparent quantum efficiency, maximum net photosynthetic rate, and PSII maximum photochemical efficiency. Yiping Jin et al. [20] employed microorganisms combined with organic acid solvents (ρ-toluene sulfonic acid, ρ-TsOH) to remove lignin from straw, then prepared biochar from the extracted lignin via carbonization activation, achieving efficient antibiotic removal using the resulting straw lignin-derived biochar in aqueous environments.

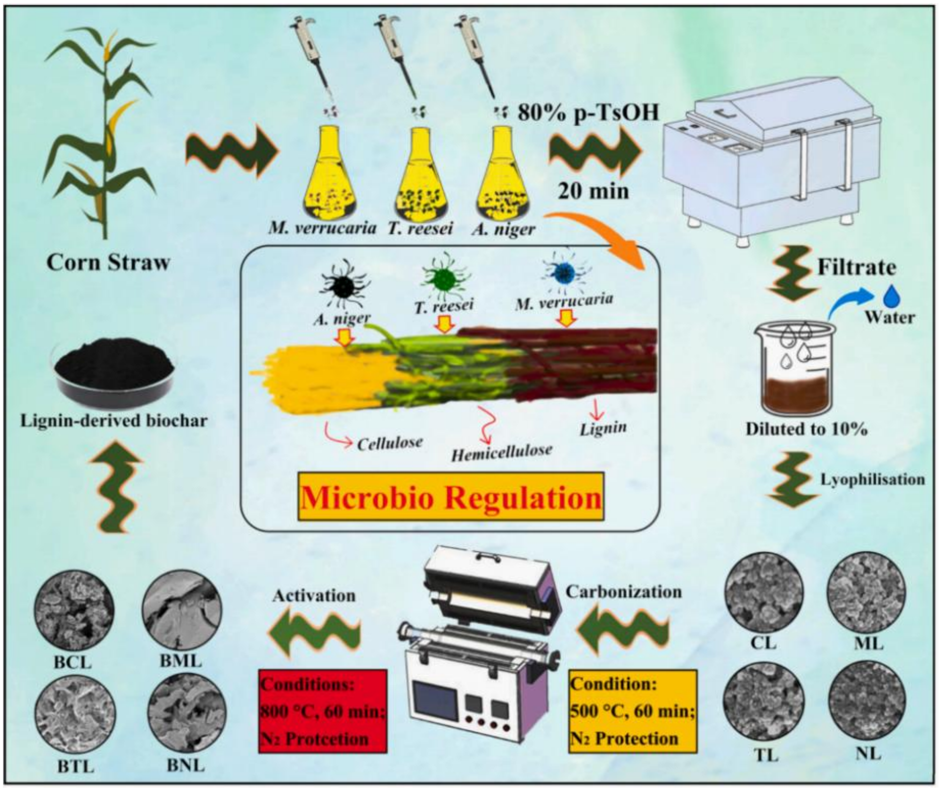

Figure 5. Preparation process of corn straw biochar

5. Application of Biochar

5.1. Agricultural field

When applied to soil, biochar improves porosity, aeration, and water retention. Its porous structure creates habitats for microbes, boosting biological activity. Its high cation exchange capacity helps retain nutrients and reduce losses. For acidic soils, it can neutralize pH, creating a better environment for crops and increasing yields. Biochar can also act as a fertilizer carrier, adsorbing and slowly releasing nutrients, increasing fertilizer use efficiency, and reducing environmental risks. Combined with organic and microbial fertilizers, it promotes fertilizer transformation and improves agricultural product quality.

5.2. Environmental field

Biochar possesses strong adsorption capabilities for heavy metals and organic pollutants, which can effectively reduce their bioavailability and mobility, making it suitable for remediating contaminated soil and water bodies. Its porous structure and abundant surface functional groups enable the adsorption of heavy metal ions and also allow catalysts to be loaded for the degradation of organic contaminants. In aquatic systems, biochar can remove heavy metals, organic dyes, and other pollutants, thereby achieving water purification. Tao Kara [21] developed an efficient approach for removing tetracycline antibiotics from water environments.

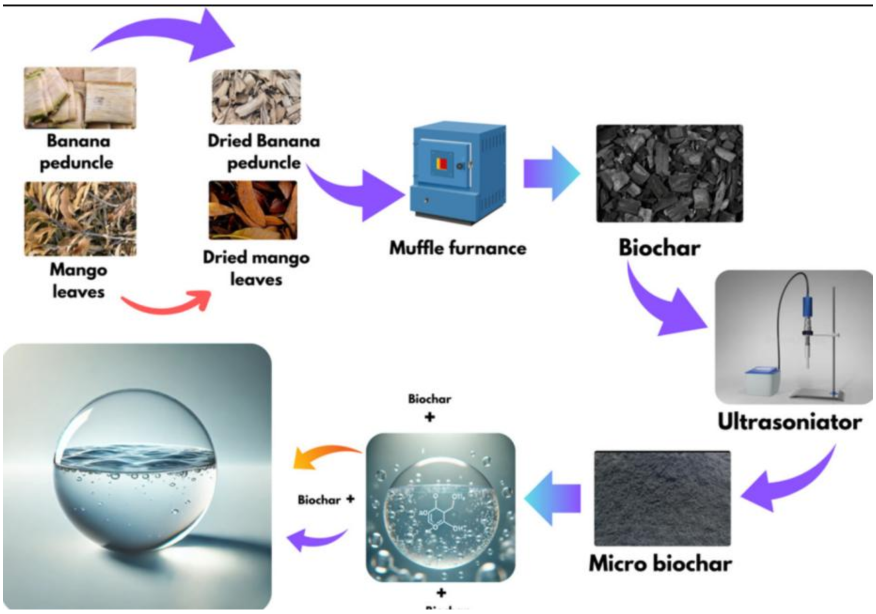

Figure 6. Process of making biochar using banana peduncles, banana peels, green coconut shells and mango leaves

Yiping Jin [20] demonstrated that biochar derived from straw lignin can effectively adsorb antibiotics from water. Moreover, his research examined the impact of different microbial treatments on lignin separation and the properties of lignin-derived biochar, offering new ideas for the further development and utilization of lignocellulosic biomass resources.

Biochar also exhibits high stability and can be applied to soils or natural ecosystems for long-term carbon sequestration, helping to lower atmospheric CO_2 concentrations. In addition, its use in soil can suppress N_2O emissions and, in anaerobic conditions such as paddy fields, reduce CH_4 emissions, thereby contributing to the mitigation of the greenhouse effect. For example, biochar application during the co-composting of pig manure and rice bran can reduce greenhouse gas emissions [22]. Yu Pan [23] and colleagues developed efficient and eco-friendly CO_2 absorbents using textile dyeing sludge (TDS) and corn cobs.

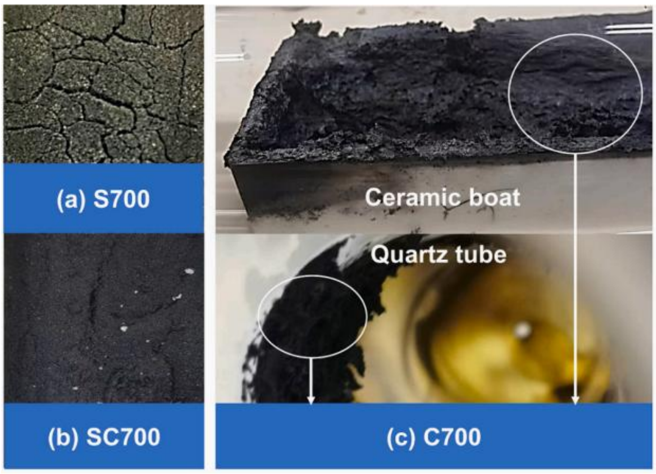

Figure 7. Actual pictures of (a) S700, (b) SC700, (c) C700.

5.3. Energy Utilization Field

Biochar's multifunctional properties offer potential for energy applications. Chu Shuping [24] used low-temperature pyrolysis with KOH activation to convert sludge into biochar with a surface area of 1200 m^2/g. This biochar acts as a catalyst carrier, increasing syngas yield and serving as a clean fuel (18 MJ/kg). Xiaoqian Wei et al. [9] used corn stover biochar with cerium–iron oxides for CO_2 photothermal conversion to syngas, with nitrogen doping further boosting efficiency.

6. Conclusion

In conclusion, biochar can be produced from a variety of raw materials—agricultural residues, forestry waste, urban organic waste, animal manure, and kitchen waste—and optimized using different production (pyrolysis, hydrothermal carbonization, microwave pyrolysis) and modification (physical, chemical, microbial) methods. Biochar plays an important role in agriculture, environmental remediation, and energy utilization, addressing global environmental and energy challenges while supporting China’s “dual carbon” strategy. However, wider application still faces barriers such as high production cost and performance stability, which should be priorities for future research and industrial scale-up.

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