# Innovative Biochar Applications for Sustainable Water Purification

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## Abstract

The modern world's increasingly developed industries have significantly polluted the planet on which we live. The water resources, on which human existence depends, are being gravely compromised and degraded due to pollution. Currently, it is imperative that we address the issue of water pollution. In the process of treating water, new materials are constantly being used in an effort to achieve sustainable development. Biochar material is one of them. During the thermochemical method, biofuel generates a by-product known as coke or biochar through the breakdown of the biofuel source. With its affordability and expansive specific surface area this substance offers numerous advantages and uses in catalysis, fuel cell technology, adsorption, enhancing soil quality, along with a significant potential for widespread application. As a result, biochar has emerged as a method for increasing thermochemical processes' efficiency and monetary benefits in water treatment. This summary initially covers the techniques utilized in producing novel biomass materials. It then organizes and evaluates various approaches to modifying them before delving into the possible utilization of biochar substances in addressing wastewater concerns.

**Keywords:** Water treatment, bio-char, adsorption, sustainable development, biomass.

## Introduction

The world we live in today is exposed to huge amounts of pollutants which are released from many industries. Water bodies have been seriously affected by pollution. Poisonous water that cannot be drunk or used for important purposes such as agriculture and also causes diseases such as diarrhea, cholera, dysentery etc. The main water pollutants are bacteria, viruses, parasites, fertilizers, pesticides, drugs, nitrates, phosphates, plastics and even radioactive substances. The world is focusing on sustainable development and proposing many suggestions for the sustainable treatment of water in order to reduce carbon dioxide emissions, secondary pollution and consumption. In this scenario, biochar material is introduced. It is obtained from plant and animal biomass which is low pollution and economic material.

Biomass consists mainly of cellulose, hemicellulose and lignin. Most of the hemicellulose and some of the cellulose are broken down during torrefaction up to about 300 °C. Biochar can be used in many applications, from heat and power generation to soil remediation (Xiang W et al (2020)). The properties of bio-char depend on the raw material and process conditions. Choosing suitable conditions for the production of biochar with the desired properties therefore requires proficiency on dependencies and influencing factors, both quantitatively and qualitatively. Biochar is a solid product of biomass pyrolysis. The amount of product obtained from the pyrolysis of a given biomass depends on process conditions such as temperature and residence time. (Weber K et al (2018)).

Physical pretreatment technology usually involves drying, crushing, screening and washing of biomass. The lignocellulosic raw material/plant is usually dried to a standard weight at 105°C or other temperature, ground with a hammer mill into smaller particles and then cut into different pieces. Physical pretreatment method of biomass the raw material refers to its own properties. Chemical pretreatment technology often relies on chemical reactions for conversion characteristics or composition of the raw material. One of the most commonly used chemicals pretreatment technology is the treatment of biomass raw materials with chemicals or functional substances materials for loading chemical precursors or functional substances into raw materials.

Thermal processes to convert biomass into biochar mainly include pyrolysis, hydrothermal carbonization, gasification and microwave pyrolysis. Pyrolysis is a thermochemical process for breaking down biomass under anoxic or hypoxic conditions to the environment. Pyrolysis processes depend on the operating temperature, heating velocity and residence time used, which can affect compositions and physicochemical properties of products (Xiang W et al (2020)).

## Mechanism of Preparation of Biochar Materials for Water Treatment

An organic material such as wood, agricultural waste, or animal dung is heated without oxygen to create biochar, a type of charcoal. A highly porous substance with a substantial surface area and the ability to absorb contaminants from water, biochar is a promising candidate for environmentally friendly water treatment (Selvarajoo et al (2020)).The following steps are necessary to prepare biochar materials for sustainable water treatment:

Raw material selection: Picking out the raw materials is the first step in making biochar materials for water treatment(Al-Wabel et al (2013). The features of the biochar, such as its porosity, surface area, and adsorption capacity, can be impacted by the choice of source material. Rice husks, sawdust, wood chips, and coconut shells are typical raw materials used in the manufacturing of biochar.

Pyrolysis: To create biochar, the basic ingredients are pyrolyzed in the second stage. The raw materials are heated at temperatures between 400°C and 800°C during the pyrolysis process without the presence of oxygen(Xu et al(2016)). A very porous solid material is left behind after the heating process causes the organic ingredients to disintegrate and release gases.

Activation: The biochar is activated in the third step to increase its capacity for adsorption. In order to build more holes and enhance the biochar's surface area, activation entails subjecting the material to an oxidizing agent like steam, air, or chemicals like potassium hydroxide.

Application: Using the biochar material to treat water is the final stage. In filtering systems, biochar can be used alone or in conjunction with other materials like sand or gravel as an adsorbent material(Selvarajoo et al (2020)). Many variables, including the biochar's characteristics, the kind and quantity of contaminants present in the water, the flow rate and length of time the water is in contact with the biochar material, affect how well biochar treats water.

Overall, there are various phases involved in creating biochar materials for sustainable water treatment, including the choice of raw materials, pyrolysis, activation, characterisation, and application.The use of biochar materials for water treatment has the potential to be a sustainable and cost-effective solution for the removal of pollutants from water.

Due to its high porosity and adsorption capacity, biochar is a promising material for sustainable water treatment. But, by using modification methods, the performance of biochar can be further improved. Many strategies are involved in the alteration of biochar materials for sustainable water treatment:

Chemical modification - entails subjecting the biochar material to chemical agents, such as acids, bases, and oxidising agents, in order to change its surface chemistry and improve its ability to adsorb particular pollutants (Wang et al(2011)). For instance, it has been demonstrated that biochar may be modified with citric acid to increase its capacity to adsorb heavy metals, and that it can be modified with hydrochloric acid to increase its capacity to adsorb organic contaminants.

Physical modification: To improve the surface area and pore size distribution of the biochar material, physical modification entails changing the structure of the biochar substance(Salleh et al(2019)). Steam activation, microwave treatment, and ball milling are examples of physical alteration procedures. With the use of these methods, the biochar's surface area and number of pores can be increased, which improves the biochar's ability to absorb contaminants.

Biological modification: Biological modification entails modifying the biochar material using microorganisms like bacteria or fungi. These bacteria can attach to the charcoal surface and release extracellular enzymes that alter the surface chemistry of the biochar and increase its ability to adsorb particular pollutants(Padzil et al(2020)).

Activated carbon, zeolites, or clay minerals are some examples of additional elements that can be combined with biochar to generate a composite material with improved adsorption capacity for contaminants. Adding biochar to other materials can have synergistic effects that increase its ability to adsorb pollutants and increase its selectivity for particular contaminants.

Surface functionalization includes adding functional groups, such as carboxyl, hydroxyl, or amino groups, to the surface of the biochar material in order to increase its ability to adsorb particular pollutants. Either biological or chemical alteration can be used to implement this strategy(Basri et al(2015)).

Overall, the adsorption capability, selectivity, and durability of biochar materials for sustainable water treatment can be improved. Depending on the specific application and the kind of contaminants that need to be removed from water, a modification strategy is chosen.

One of the most popular techniques for surface modification of biochar materials for environmentally friendly water treatment is chemical modification. It entails chemically modifying the biochar material to add functional groups to its surface, increasing its potential for adsorption and selectivity towards particular contaminants (Selvarajoo et al (2020)).

**Chemical alteration techniques**

Acid treatment: To produce carboxylic and phenolic functional groups on the surface of the biochar material, powerful acids such as sulfuric acid or hydrochloric acid are used to treat the biochar material. This modification method raises the surface charge and enhances the ability of contaminants, such as heavy metals, which are positively charged, to be absorbed.

Base treatment: To produce hydroxyl and amino functional groups on the surface of the biochar material, the biochar material is treated with strong bases like sodium hydroxide or potassium hydroxide(Al-Wabel et al(2013)). This modification method raises the surface charge and enhances the ability of negatively charged contaminants, such as organic molecules, to be adsorbent.

Oxidation - Treatment using oxidising chemicals, such as hydrogen peroxide or potassium permanganate, to produce carboxylic and carbonyl functional groups on the surface of the charcoal material is known as oxidation. This modification method boosts the surface charge and enhances the ability of contaminants like phenols and dyes to be absorbed by the material.

Silane treatment: Silane treatment entails adding organosilane functional groups to the surface of the biochar material by treating it with organosilanes like trimethylchlorosilane or tetraethoxysilane. During this modification process, a hydrophobic surface is produced, improving the adsorption capability for non-polar contaminants like hydrophobic organic molecules(Xu et al(2016)).

Chelation treatment entails treating the charcoal material with chelating substances like citric acid or ethylenediaminetetraacetic acid (EDTA) to produce chelating functional groups on the surface. By creating compounds with metal ions, this modification method boosts the capacity for heavy metal adsorption.

In general, the sort of chemical modification technique chosen relies on the application in question as well as the kind of pollutants that need to be eliminated from the water. The selectivity and adsorption capability of biochar materials for environmentally friendly water treatment applications can be greatly increased through chemical modification(Salleh et al(2019)).

Another typical technique for surface modification of biochar materials for environmentally friendly water treatment is physical modification. In order to boost the biochar material's adsorption capacity and selectivity towards particular contaminants, it must be treated physically to create new pores, increase surface area, and improve accessibility of adsorption sites. Several different kinds of physical modification procedures are available, such as:

**Physical Modification Techniques**

pyrolysis therapy - Pyrolysis is a process that includes heating up biochar material at a high temperature in an oxygen-free environment. This process enhances the biochar's surface area and develops new pores(Padzil et al(2020)). The adsorption capacity for several contaminants, including organic compounds, heavy metals, and nutrients, is increased thanks to this modification process, which also increases the accessibility of adsorption sites.

Treatment for activation: The biochar material is subjected to an activation procedure that involves heating it to a high temperature and adding activators, such as steam or carbon dioxide, to expand the biochar's surface area and produce new pores. Using this modification process, adsorption sites are made more accessible and numerous contaminants, including heavy metals, organic compounds, and nutrients, are able to bind to them more effectively.

Using a microwave to irradiate the biochar material results in the formation of new pores and an increase in the biochar's surface area(Salleh et al (2019)). Using this modification process, adsorption sites are made more accessible and numerous contaminants, including heavy metals, organic compounds, and nutrients, are able to bind to them more effectively.

Ultrasound treatment: Ultrasonic waves are used to treat the biochar material, causing it to develop new pores and increase its surface area. This modification method raises the accessibility of adsorption sites and increases the ability of numerous contaminants, including heavy metals, organic molecules, and nutrients, to adsorb.

Mechanochemical treatment: Mechanochemical treatment involves applying mechanical pressure to the biochar material, such as milling or grinding, to increase the surface area and generate new pores(Basri et al(2015)). This modification method raises the accessibility of adsorption sites and increases the ability of numerous contaminants, including heavy metals, organic molecules, and nutrients, to adsorb.

In general, the physical modification technique selected relies on the particular application and the kind of pollutants that need to be eliminated from the water. The selectivity and adsorption capability of biochar materials for environmentally friendly water treatment applications can be greatly improved through physical modification.

For surface modification of biochar materials for environmentally friendly water treatment, biological modification is a less popular technique. It entails treating the biochar material with microbes or enzymes to add new functional groups to its surface or change the current functional groups, which improves the material's ability to adsorb pollutants and increase its selectivity for particular pollutants(Wang et al(2011)).

**Biological modification techniques**

Treatment for microbes - The term "microbial treatment" refers to the process of modifying the surface chemistry of biochar by adding microorganisms, such as bacteria or fungi, to the biochar material. In order to increase the adsorption capacity and selectivity for particular pollutants, this modification process can either introduce new functional groups, like carboxylic and phenolic groups, or change the current functional groups.

Enzymatic treatment -  entails exposing the biochar material to enzymes, such as peroxidases or laccases, that can oxidise or decrease the surface functional groups of the biochar material. The adsorption capacity and selectivity for particular contaminants are increased by using this modification process, which can add new functional groups or change the current functional groups(Selvarajoo et al (2020)).

Treatment by bioaugmentation - To increase the adsorption capacity and selectivity for particular pollutants, bioaugmentation includes adding microorganisms or enzymes to the polluted water or soil together with the charcoal material. This method of modification can enhance the biodegradation and adsorption of contaminants, such as organic substances, heavy metals, and nutrients(Ahmad et.al (2020))..

Biological modification can, in general, offer a sustainable and environmentally beneficial way for surface modification of biochar materials for sustainable water treatment. However, the application of biological modification approaches necessitates careful evaluation of the microbial or enzymatic activity, compatibility with the biochar material, and potential interactions with the pollutants and environment(Gomez et.al (2017)).

Another technique for surface modification of biochar materials for environmentally friendly water treatment is composite modification. The biochar material is combined with other substances, such as polymers or nanoparticles, to form a composite substance with improved adsorption and selectivity towards particular contaminants(Xu et al (2016)). There are several different kinds of composite alteration methods that can be applied, including:
Combination of polymers: In order to generate a composite material with improved adsorption capacity and selectivity for particular contaminants, including heavy metals, dyes, or organic compounds, polymer composite modification entails mixing charcoal material with a polymer, like chitosan or polyvinyl alcohol. Additional functional groups from the polymer, like amino or hydroxyl groups, can increase the biochar material's potential for adsorption and selectivity.

**Surface Modification Techniques**

Nanoparticle composite: The modification of nanoparticle composites involves combining the biochar material with nanoparticles, such as iron oxide or silver nanoparticles, to produce a composite material that has improved adsorption capacity and selectivity for particular pollutants, such as heavy metals or organic compounds(Gomez et.al (2017)). The nanoparticles may offer more active sites or catalytic qualities that raise the biochar material's ability for adsorption and selectivity.

Carbon composite: In order to modify a carbon composite, the biochar material must be combined with carbon-based substances like graphene or carbon nanotubes. This creates a composite material with improved adsorption capacity and selectivity for particular pollutants, like organic compounds or dyes(Ahmad et.al (2020)). The carbon-based compounds might offer more active sites or catalytic qualities that would improve the biochar material's capacity for adsorption and selectivity.

Metal oxide composite: To modify a metal oxide composite, combine biochar with metal oxide particles, such titanium dioxide or zinc oxide, to produce a composite material with improved adsorption capacity and selectivity for particular contaminants, including organic chemicals or colours(Uchimiya et.al (2011)). The additional active sites or catalytic qualities that the metal oxide particles can offer can improve the biochar material's selectivity and adsorption capability(Fdez et.al (2020)).

The overall adsorption capacity and selectivity of biochar materials for sustainable water treatment applications can be greatly increased through composite modification. The kind of contaminants to be removed from the water and the specific application determine the composite material to be used(Gabhane et.al (2020)). Moreover, composite modification can improve the stability and reusability of the biochar material, among other advantages.

## Factors affecting the yield of biochar

The types of feedstocks used, whether pyrolysis was carried out at a high or low temperature, and the heating rate all affect the biochar yields (Enders et.al (2012)). Due to its advantages over other biomass in terms of economy and food security, biomass residue has been utilised extensively in the biochar sector. Waste biomass such as animal excrement, plant residues, forestry waste, food waste, municipal waste solids, and wastewater are frequently utilised to produce biochar (Cantrell et.al (2012)). Particularly, biomass waste pyrolyzation (especially sewage loops and animal manure) eliminates any bacteria present and reduces adverse environmental effects (Lehmann et.al (2009)). Feedstocks are divided into two categories: (i) biomass used primarily as a source for charcoal and energy, and (ii) waste biomass byproducts. Animal and solid waste can yield more biochar than plant matter or biomass for the majority of feedstock types (Cantrell et.al (2012)).

Depending on the pyrolysis temperature, biochar has various features. The morphology and surface structure of biochar are closely related to the pyrolysis temperature (Liu et.al (2010)). According to earlier studies, temperature has a significant impact on biochar's adsorption capacity (Ahmad et.al (2020)). Pyrolysis, which takes place at temperatures between 200- 900 °C without substantially lower oxygen levels, can create biochar (Demirbas et.al (2002)). Pyrolysis can be divided into two categories: fast and slow pyrolysis (Mohan et.al (2006)). Bio-oil is well recognised for being produced from biomass through fast pyrolysis, which takes place in a matter of seconds or less and yields 75% of the bio-oil ((Mohan et.al (2006))). The majority of biochar is produced using slow pyrolysis techniques, which can take several hours to several days (Brown et.al (2009)).

In a prior investigation, it was discovered that the amount of biochar decreased as the heating rate increases (Karaosmanog˘lu et.al (2000)). The surface area often rises at increasing pyrolysis temperatures (Uchimiya et.al (2011)). The aliphatic alkyl and ester groups are thought to be eliminated during this process, and the exposed aromatic lignin component helps to enhance the surface area. The increase in surface area is mostly caused by the biochar's improved pore size distribution because micropore volume and surface area are directly proportional. Due to its increased surface area and microporosity, biochar generated at higher temperatures is more effective at removing contaminants from soil and water (Ahmad et.al (2020)). Due to deformation, cracking, or micropore blockage, biochar produced at a low heating rate has a reduced surface area (Lian et.al (2011)) . In order to achieve the greatest quality yield feasible, biochar should be manufactured under clearly defined pyrolysis conditions (Ahmad et.al (2020)).

## Production of Biochar

Notably, two of the key factors affecting the economical and effective manufacturing of biochar are the availability of feedstock and its composition. A range of feedstock choices are available for the creation of biochar. These include aquatic and woody biomass, municipal trash, paper waste, and agricultural biomass (Gabhane et.al (2020)). The most widely employed agricultural wastes in the manufacturing of biochar are rice straw, cotton stalk, and coconut shell. The two types of municipal waste that are most frequently utilized as feedstocks for the manufacture of biochar are sewage sludge and papermill sludge. Woody biomass includes materials like pine sawdust and used wood chips, while aquatic biomass like seaweed and Macroalgae sp. is frequently used as a feedstock for the creation of biochar (Roberts et.al (2015)).

The traditional way to make biochar is to pile it up in dirt pits and let it burn slowly with little to no airflow (Barrow et.al (2012)). Another approach involved burning the biomass outdoors and immediately covering the partially burned biomass with soil (Emrich et.al (2013)). Pyrolysis is the name given to this process. Pyrolysis is a method of thermal degradation that excludes oxygen from the process while using heat to break down biomass (Basu et.al (2010)). Traditional approaches use slow and quick pyrolysis as methodologies.

The chosen biomass is fully dried before being ground into biochar. The pulverized materials were then processed to the next-smallest size of 40 mesh (Rambli et.al (2018)). Biomass must be heated at a rate of 5 to 7°C per minute for at least more than 24 hours in order to accomplish slow pyrolysis. A continuous auger/screw pyrolyzer reactor is typically used to carry out the slow pyrolysis process (Verma et.al (2012)). As a result, syngas (20–30%), bio-oil (25–35%), and biochar (35–45%) are all key products produced (Verma et.al (2012)) . The process of fast pyrolysis is carried out in the absence of oxygen at a temperature more than 500°C and a heating rate greater than 300°C per minute (Dai et.al (2017)). Fast pyrolysis is primarily used to produce biochar on a large scale.

## Application of Biochar in wastewater treatment

As our demand on the environment continues to grow, many pollutants with low concentrations but significant environmental harm are gradually gaining attention. Environmentally dispersed industrial sewage has been linked to human carcinogenicity, toxicity, mutagenicity, and teratogenicity (Goltz et.al (2005)). Despite the fact that there are numerous methods for treating wastewater, five in particular are frequently employed: adsorption (Catizzone et.al (2021)), chemical precipitation, membrane separation, built wetlands, and ion exchange. However, some of these technologies have a number of disadvantages, such as the difficulty of the process, high operating and maintenance costs, inefficiency in removing pollutants at low concentrations, inability to transform contaminants into biodegradable or less harmful by-products, and excessive energy and chemical use (Cheng et.al (2016)).

The primary treatment method is adsorption since it is flexible and efficient. In the study of adsorption, biochar is receiving special interest from researchers because of its enormous specific surface area and functional divisions (Bu et.al (2021)). To increase the effectiveness of adsorption, biochar's surface characteristics can be modified. Another significant aspect of biochar that adds to its attractiveness is its low price. One factor that contributes to biochar's low price is that it is made mostly from agricultural and solid waste. In another study, modified biochar's cost was discovered to be over half that of activated carbon, and its adsorption capacity was demonstrated to be almost identical (Fdez et.al (2020)).

The effectiveness of biochar in removing organic debris, surfactants, and nitrogen (N) from wastewater has been demonstrated in earlier studies. When treating wastewater, biochar can be used effectively as a phosphorus (P) sorbent. The sorbent then produced various products (phosphorus fertilizers) using a recycling technique, which is well known for its capacity to enhance soil quality (Kopecký et.al (2020)). Chemical pollutants known as micropollutants pose a threat to both the environment and human health. Extremely complex chemical molecules known as micropollutants are primarily found in water (Bo et.al (2015)). The most prevalent sources of micropollutants are pharmaceuticals, antibiotics, cosmetics and toiletries, endocrines, organic contaminants with a long half-life cycle, disinfection by-products, and other industrial chemicals (Bo et.al (2015)).These micropollutants are persistent and long-lasting in the environment, and they can be found in a range of settings. The majority of micropollutants are found in water in incredibly small concentrations, but because they can accumulate in creatures at every stage of the food chain, they can still have a negative impact on human health and the environment (Gomez et.al (2017)). Antibiotics like tetracycline, doxycycline, and clindamycin, personal care items like triclosan (Subedi et.al (2014)), analgesics like ibuprofen and carbamazepine (Nieto et.al (2010)), and psychoactive substances like caffeine (Subedi et.al (2014)) are some of the micropollutants that can be discovered in water bodies. Long-term studies have been conducted on the use of modified biochar to remove tetracycline and other micropollutants from water  (Enaemi et.al (2020)).

Recent research has demonstrated the efficiency of biochar in the removal of inorganic contaminants from wastewater, including heavy metals (Enaemi et.al (2020)). Among the contaminants that might be discovered in wastewater are heavy metals. It can build up in creatures, endangering the wellbeing of other members of the food chain, particularly humans.

Dye pollutants in aqueous solutions are the main cause for worry (Enaemi et.al (2020)). Chromium (Cr) removal using biochar made from bio-oil has already been studied (Mohan et.al (2011)). In the industrial, compounds containing hexavalent chromium Cr(VI) are frequently utilized as dye pigments (Li et.al (2010)). It has been demonstrated that the biochar-based adsorbents have a high capacity for adsorbing this substance (Li et.al (2010)). Biochar has been touted as a good way to remove methyl violet from wastewater, which has been anticipated to be a possible adsorbent (Li et.al (2010)).

## Conclusion

The development of new biochar materials has emerged as an exciting area of research in recent years, particularly in the field of wastewater treatment. This has led to significant improvements in efficiency and cost reduction, aligning with the principles of sustainable development. However, it is crucial to evaluate the toxicity of biochar and the environmental impact of chemicals used in its preparation to avoid the risk of secondary pollution. Although immersion in metal solutions is the most common method of biochar modification, exploring new preparation methods, such as microwave activation and hydrothermal carbonization, could add more functionality to biochar materials. Furthermore, it is essential to develop new catalysts that are recyclable, low-cost, and environmentally friendly for environmental pollution control projects. Finally, investigating new uses and functions of biochar materials could lead to further cost and emission reduction in the future.

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