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An Evaluation of Biochar Derived from Agro-Industrial Waste as an Alternative Material for the Elimination of Pathogenic Load from Water

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Abstract: The contamination of water bodies is becoming more frequent due to uncontrolled discharges into them, including those of domestic or industrial wastewater (WW) characterized by the presence of heavy metals, a high pathogenic load, pesticides, and pharmaceuticals, among other pollutants, which represent a risk to both humans and the health of the ecosystem. Consequently, conventional water treatment processes have been implemented. However, they are not efficient enough. In this regard, exploring and analyzing new alternatives and sustainable systems that efficiently degrade the different pollutants found in WW are required, and biochar can be considered as an attractive treatment option, since it is an adsorbent carbonaceous material that allows for the removal of several pollutants. The generation and use of biochar contribute to the promotion of the circular bioeconomy and the achievement of sustainable development goals by enhancing the reuse and recycling of agricultural and agro-industrial waste as raw material for its production. The objective of this work is to evaluate the utilization of biochar as an alternative material for the elimination of the pathogenic load in water.

Keywords: wastewater; pathogenic load; alternative treatment; circular bioeconomy; biochar; agro-industrial waste

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1. Introduction

Water pollution results from different human activities taking place daily, which generate wastewater (WW) that is not properly disposed of, leading to the quality deterioration of receiving water bodies [1]. The levels of polluting substances in water increase every day due to the direct discharge of WW containing both organic and inorganic contaminants, such as pathogens, heavy metals, nutrients, dyes, pesticides, surfactants, pharmaceuticals, and personal care products, among others [2].

In WW, various types of microorganisms contribute to the pathogenic load. These include bacteria such as total and fecal coliforms, *Escherichia* sp., *Pseudomonas* sp., and *Aeromonas* sp., as well as protozoa and helminths [3,4]. Viruses like enteroviruses, caliciviruses, rotaviruses, and hepatitis viruses are also included within the pathogenic load that can be found in WW [3,4]. Additionally, some bacteria may be present in drinking water due to their high resistance to chlorine, a primary disinfectant. Among these resistant microorganisms, *Pseudomonas* spp. are included, which can impact human health by causing various diseases, including nosocomial infections caused by *P. aeruginosa* [3,5]. Furthermore, consuming water contaminated with viruses, protozoa, and helminths can result in clinical diseases such as paralysis, aseptic meningitis, and encephalitis, which are associated with polioviruses and coxsackieviruses [5]. Moreover, symptoms including diarrhea, nausea, and vomiting are linked to parasites like *Giardia* sp., *Cryptosporidium* sp., and *Trichuris trichiura* [5].

The presence of these pathogenic microorganisms in water compromises its quality and availability, reducing the biodiversity. This highlights the critical importance of wastewater treatment plants (WWTPs), which are equipped with diverse operation units to eliminate these pollutants [6]. Nevertheless, conventional treatment processes are often ineffective at removing certain contaminants. They also consume significant amounts of energy and produce substantial unwanted waste [7]. As a matter of fact, traditional disinfection techniques using oxidizing agents like chlorine can generate disinfection byproducts, such as total trihalomethanes and haloacetic acids [8,9].

This underscores the need for new, sustainable, and effective alternative treatment systems that do not produce carcinogenic, mutagenic, or teratogenic byproducts, while also contributing to the achievement of sustainable development goals (SDGs). In this regard, biochar has emerged as a prominent material, gaining significant attention from the scientific community for its wide range of applications in soil and air remediation, as well as water treatment [10].

Biochar is a carbon-rich material produced through the thermochemical transformation of biomass, which is subjected to high temperatures using torrefaction, pyrolysis, gasification, and hydrothermal carbonization techniques. Among these, pyrolysis, gasification, and hydrothermal carbonization are the most commonly used methods for converting organic waste into carbon-rich products [11]. Notably, agricultural waste is often used as feedstock for biochar production by using materials such as waste from oil palm, cocoa, corn, and nut crops [12]. The effective management of this type of waste can maximize its utility through its use in biochar production as an alternative material for water treatment [13]. Research has demonstrated that biochar is highly efficient in treating water contaminated with organic load due to its strong adsorption capacity [14]. However, from the authors' knowledge, few studies have been conducted aiming at compiling the use of biochar derived from agricultural and agro-industrial waste in the removal of pathogens from water. Additionally, the application of biochar in water treatment for disinfection purposes avoids the formation of toxic reaction intermediates, such as disinfection byproducts, which are usually formed when chlorine or ozone (conventional disinfectant agents) are used. Furthermore, biochar could be effective in the removal of pathogenic load resistant to these traditional disinfection methods.

The production and use of biochar are aligned with the principles of circular bioeconomy and sustainable development, since biochar production can involve the reuse and conversion of renewable biological resources, such as organic waste, into this carbonaceous material. This promotes recycling, recovery, and reuse, and contributes to achieving sustainable development goals (SDGs), particularly those related to clean water access, job creation in the agro-industry, and the efficient use of resources [15].

Under this scenario, this study is focused on evaluating the effectiveness of biochar generated from the thermochemical conversion of agricultural and agro-industrial waste in removing pathogenic loads from water, addressing the challenges associated with water pollution and exploring the potential of biochar as an alternative solution for water treatment.

2. Pathogenic Load

2.1. Concept and Types of Microorganisms in Water

Surface water (SW) bodies, including rivers, lakes, lagoons, and wetlands, are often polluted by untreated wastewater (WW) discharges [16]. WW, which contains fecal matter, harbors pathogenic microorganisms such as bacteria, viruses, protozoa, and helminths that can cause diseases of varying severity.

Some of these microorganisms are used as water quality indicators by quantifying their concentration and reaction to water pH, temperature, and other environmental factors [4], as detailed in [3,4,17,18].

2.1.1. Bacteria

Commonly found in water, some enteric bacteria—also known as fecal bacteria—exhibit limited survival and reproduction in aquatic environments due to physiological stress. This makes them challenging to use as water quality indicators because of identification and quantification limitations. Their presence is linked to fecal matter and specific conditions such as pH, temperature, and humidity that support their reproduction and survival.

Due to the difficulty of detecting these bacteria directly in the laboratory, coliform bacteria, which include *Enterobacteriaceae*, are used as indicators. Coliforms are more easily detected, remain in water longer, and exhibit similar behaviors to those of pathogenic bacteria during disinfection processes. The group of total coliforms includes *Escherichia* sp., *Enterobacter* sp., *Klebsiella* sp., *Serratia* sp., *Edwarsiella* sp., and *Citrobacter* sp. [3,4,17].

Fecal coliforms are thermotolerant, meaning they can persist at higher temperatures. They are of particular interest due to their potential to cause respiratory tract infections, skin infections, and acute diarrheal diseases, among other diseases. *Enterococcus* spp. (fecal streptococci) are found in human and warm-blooded animal feces and exhibit high persistence in contaminated soil and water. This group includes *E. faecalis*, *E. faecium*, *E. gallinarum*, and *E. avium*, which can thrive in environments with high sodium chloride concentrations, pH levels between 6 and 9, and temperatures ranging from 10 °C to 45 °C. Thus, they can remain in the environment for extended periods and are considered indicators of long-term fecal contamination [3,4,17].

Escherichia spp. include both pathogenic and non-pathogenic strains, with the latter making up about 80% of the normal intestinal microflora, where they are generally harmless. Pathogenic *Escherichia coli* strains can cause acute diarrhea, and their resistance to disinfection processes is similar to that of non-pathogenic strains, making E. coli a common water quality indicator in many countries [3,18].

Spores of sulfite-reducing clostridia and *Clostridium perfringens* are frequently found in contaminated water and soil. These bacteria can withstand high temperatures, desiccation, and extreme pH conditions. Their presence in drinking water suggests inefficiencies in the purification process and disinfection failures. While these microorganisms are indicators of fecal contamination due to their high environmental resistance and longevity in water, *Escherichia coli* and total coliforms are more commonly used as indicators due to their higher quantities in feces [3,4,17].

Pseudomonas sp. is a non-spore-forming, large, and Gram-negative bacilli encased in a dense layer of polysaccharides that protects it from the effects of residual chlorine. These species are commonly found in both water and soil, produce a fluorescent pigment, use glucose in an oxidized manner without forming gases, and exhibit high resistance to environmental factors. Their ability to survive and proliferate has been confirmed by their presence in drinking water distribution systems. Additionally, *Pseudomonas* sp. can inhibit coliforms, leading to interference from other microorganisms like *Sarcina* sp., *Micrococcus* sp., *Flavobacterium* sp., *Proteus* sp., *Bacillus* sp., and *Actinomyces* sp. in the detection of coliforms [3,4].

Aeromonas spp. are small, Gram-negative bacilli that typically inhabit water sources, where they can be found in significant quantities, regardless of the presence of fecal contamination. They also thrive in environments with low nutrient levels. Other notable genera of Gram-negative bacteria include *Neisseria*, *Moraxella*, and *Acinetobacter* [3].

Lastly, emerging microorganisms including cyanobacteria, which are oxygen producers, and *Campylobacter* sp., are often found in natural water bodies that are potential sources of drinking water. These microorganisms are relatively fragile and sensitive to various environmental factors [3,5].

2.1.2. Viruses

Viruses are the primary cause of mortality and morbidity caused by waterborne diseases. While they are not present in human feces, they are found in the gastrointestinal tract of infected individuals. Enteric pathogenic viruses can be transmitted to humans through the consumption of contaminated water. The main viruses include the following [3,17,18]:

- Enteroviruses are composed of polioviruses, coxsackieviruses, and echoviruses. Poliovirus is an RNA virus that causes poliomyelitis, while coxsackievirus has more than 30 serotypes that cause febrile pharyngitis, epidemic pleurodynia, myocarditis, herpangina, and some cases of aseptic meningitis. On the other hand, echovirus causes asymptomatic infections, rashes, and pericarditis [3,17,18].
- Hepatitis virus is the cause of viral hepatitis. There are different types of hepatitis viruses, A, B, C, D, E, F, and G, with types A and E being the most commonly transmitted through water contaminated with feces from infected people [3,17,18].
- Rotavirus is represented by seven groups, of which groups A, B, and C are the most notable. These are stable in the environment and spread easily due to their low infective dose [3,17,18].
- Calciviruses, belonging to the *Caliciviridae* family, are non-enveloped viruses that are highly resistant to various environmental factors and disinfection processes. Phages belonging to the calciviruses, specifically somatic coliphages and F-specific coliphages, were identified as indicators of water quality since they are easily detected, are abundantly found in WW, their population is greater than that of enteroviruses, they can be isolated and quantified using simple methods, and they are as resistant as enteroviruses to disinfection processes [3,4,17].

2.1.3. Protozoa and Helminths

Other groups highlighted for their ability to cause infectious diseases in water are protozoa and helminths [3,4]. Protozoa have a life cycle that includes a vegetative form (trophozoite) and a resistant form (cyst). Most protozoa are retained during filtration processes; however, cysts are resistant to water disinfection processes. Some of the best-known protozoa found in contaminated waters include *Giardia intestinalis*, *Entamoeba histolytica*, *Balantidium coli*, *Toxoplasma gondii*, *Blastocystis* sp., *Enterocytozoon bieneusi*, *Encephalitozoon intestinalis*, *Cryptosporidium* sp., *Cystoisospora belli*, and *Cyclospora cayetanensis*. Notably, *Cryptosporidium* spp. can survive in water for up to 140 days and are highly resistant to disinfection processes. This group, along with *Giardia* spp., serves as a key indicator of water quality [3,4,17,18].

In turn, helminths are highly persistent in the environment, capable of withstanding various changes in humidity (greater than 70%), temperature (25–40 °C), and pH (4–9). The eggs of these parasites can remain viable in the environment for extended periods. Studies have identified the need to use *Ascaris lumbricoides* as an indicator to analyze the behavior of helminth eggs in the laboratory, given their persistence in the environment, ease of identification, well-known parasitism index globally, and high transmission risk. Other pathogenic helminths found in water include *Trichuris trichiura*, *Paragonimus* sp., *Schistosoma* sp., *Necator americanus*, and *Ancylostoma duodenale* [3,4,18].

2.2. Risks to Human and Ecosystem Health

Waterborne diseases are caused by the ingestion of water polluted with pathogenic microorganisms. Therefore, water acts as a passive carrier of these pathogens, such as bacteria, viruses, and parasites. Most of these diseases affect the human gastrointestinal system, diarrhea, fever, vomiting, nausea, abdominal pain, and other conditions classified as clinical diseases being the most common symptoms [5,19,20].

Bacteria like *Salmonella typhi* are associated with typhoid fever, while *Escherichia coli* can cause diarrhea, vomiting, cramps, fever, and dehydration, depending on the strain. *Shigella* species are often found in water used for recreational activities such as swimming pools, and the symptoms related to their presence include abdominal pain, vomiting, diarrhea, and cramps, as well as bacillary dysentery. Infection with *Campylobacter jejuni* can cause fever, diarrhea, nausea, abdominal pain, headaches, muscle pain, and can lead to conditions such as reactive arthritis and meningitis. In turn, *Pseudomonas aeruginosa* is known for causing nosocomial infections and can lead to severe progressive lung infections. *Aeromonas* sp. can cause diarrhea and a variety of infections, including septicemia [5,20,21].

Viruses are associated with various clinical diseases. Polioviruses can cause paralysis, aseptic meningitis, and febrile illness. Different types of coxsackieviruses, which belong to the enteroviruses, can also lead to paralysis and aseptic meningitis, as well as encephalitis, myocarditis, and respiratory diseases. Echoviruses are known to cause diarrhea. The characteristic symptoms of hepatitis A virus include fever, nausea, malaise, anorexia, and abdominal pain. These symptoms can also occur with hepatitis E virus, along with jaundice and arthralgia. Diseases associated with rotavirus group A include acute nonbacterial infectious gastroenteritis, acute viral gastroenteritis, and childhood diarrhea; rotavirus group B is associated with severe diarrhea epidemics in adults, and rotavirus group C is linked to sporadic cases of diarrhea in children [5,18,20].

Protozoan parasites, such as *Giardia lamblia* and *Cryptosporidium parvum*, are known to cause chronic diarrhea accompanied by abdominal cramps, fatigue, and nausea. Other parasitic microorganisms, like *Entamoeba histolytica*, can lead to invasive amoebic dysentery by invading the liver, bloodstream, and intestinal wall [5,18,20].

Helminth infections, such as those caused by *Ascaris lumbricoides*, can generate a range of symptoms that often depend on the number of parasites ingested through contaminated water. As these helminths migrate through the lungs on their way to the small intestine, they can cause pneumonitis. In turn, *Trichuris trichiura* can cause symptoms including constipation or diarrhea, anemia, vomiting, insomnia, and appendicitis. *Necator americanus* and *Ancylostoma duodenale* are known to cause anemia and significant blood loss, and they are the leading causes of iron deficiency in tropical regions [5,18,22].

The presence of these pathogenic microorganisms has been demonstrated in groundwater. *Salmonella* sp., *Escherichia coli*, *S. faecalis*, and some enteroviruses have been found in groundwater, where they remain stable because some surface water bodies that recharge aquifers are contaminated with these pathogens, increasing the vulnerability of this resource [18,23,24]. In SW bodies like lakes, reservoirs, and rivers, the presence of these microorganisms is also evident due to untreated wastewater discharges, reducing their suitability as drinking water sources and posing significant health risks, as many diseases originate from them. Additionally, the biodiversity of these ecosystems is compromised [4,25]. The excessive growth of cyanobacteria in these environments can reduce the light that penetrates the water. This phenomenon contributes to eutrophication and causes fish death, reducing aquatic biodiversity [5,19,26].

3. Biochar Derived from Agricultural and Agro-Industrial Waste

3.1. Concept and Production of Biochar

Agricultural waste refers to organic and plant-based materials generated during cultivation, harvesting, and processing activities. This type of waste includes stems, leaves, peels, seeds, straw, husks, and bagasse from various fruit and vegetable crops such as corn, rice, sugarcane, coconut, walnuts, peanuts, pineapple, and oil palm, among others [27,28]. This type of waste can be classified by its biodegradability, state (solid or liquid), toxicity, and source. For example, solid agricultural waste includes leaves, peels, seeds, etc., which are mostly non-toxic and biodegradable. In contrast, liquid waste can include wastewater from crop irrigation, which may contain various pesticides and other toxic chemicals [29,30].

Agro-industrial waste, on the other hand, comes from the processing of agricultural products and includes materials such as husks, seeds, fruit pulp, and their byproducts [31,32]. This category also encompasses waste generated through livestock farming, such as manure or animal fertilizers, as well as waste from slaughterhouses and the meat processing industry [32,33].

Similar to agricultural waste, agro-industrial waste is also classified into biodegradable, recyclable, and hazardous categories. For example, some first-order biodegradable and recyclable wastes include leaves, bagasse, straw, and stems, while second-order wastes, such as skins, peels, shells, and bones from the processing of agricultural products, can also be reused. Nonetheless, non-recyclable and hazardous waste from barn construction, livestock transportation and protection, and crop irrigation, such as plastic or metal containers, metal structures, and containers for chemicals, fertilizers, and herbicides, cannot be sustainably reused for a specific purpose, often resulting in their improper disposal [32].

Worldwide, around 2.01 billion tons of waste are generated, with the agricultural and agro-industrial sectors contributing approximately 998 million tons. This waste can be sustainably reused and utilized for energy generation and the production of carbon-rich biomaterials like biochar [31,34]. Agricultural and agro-industrial waste, also known as biowaste, has significant potential for reuse due to its biodegradable, recyclable, and non-toxic nature, providing added value. The proper and sustainable management of this type of waste, which is generated daily and typically discarded in landfills, allows for its effective use in energy generation and biomaterial production [31,35]. This waste is also commonly referred to and considered to be biomass [27].

Biomass is an abundant renewable resource in the Earth's crust. In recent years, this resource has gained importance due to its potential in the production of biodiesel, bioethanol, and biogas, making it a valuable asset for ecological sustainability due to its low production cost. Furthermore, research highlights that biomass can also be used to produce biochar, a highly porous material that enhances water, contaminant, and nutrient adsorption and retention. Biochar is produced through the thermal decomposition of biomass from various sources under controlled temperature and oxygen (O_2) conditions [2,36–39].

The production of biochar involves several thermochemical processes, with torrefaction, gasification, pyrolysis, and hydrothermal carbonization being the primary techniques [40–43]. Key factors influencing biochar production include the type of biomass (raw material), temperature, residence time, and heating rate. These factors significantly affect the quantity, carbon content, durability, porosity, and other desired characteristics of the resulting biochar [43–45]. The essential aspects of each technique and method are detailed below.

3.1.1. Torrefaction

Torrefaction is a pretreatment technique where biomass is exposed to gradually increasing temperatures over short retention periods, leading to its partial decomposition (Figure 1). During this process, volatile gases are released, resulting in the production of both condensable and non-condensable gases. Biochar is among the products obtained from this process [41,43,45].

The efficiency of torrefaction equipment is influenced by the moisture content of the biomass. Higher moisture levels result in increased energy consumption. Therefore, it is crucial for the biomass moisture content to be between 5% and 8% to minimize greenhouse gas (GHG) emissions [42,45].

As the temperature of the torrefaction equipment rises, the biochar produced exhibits a high carbon content (CC), increased oxygen content (OC), and a low hydrogen content (HC). The high OC makes it suitable for being used as an adsorbent material [40].

Various types of biowaste, including agricultural and agro-industrial residues, have been reused in torrefaction. Examples include sugarcane bagasse, mango seeds (MS), passion fruit peels (PF), bamboo (*Phyllostachys edulis*), and rice husks. These materials are processed at different temperature ranges (T) and residence times (RT) to produce biochar with a high CC and ash content (AC), while decreasing the volatile matter (VM) as the temperature increases [46–49]. Table 1 lists several studies reported in the scientific literature related to the operating conditions used, as well as the type of biomass and the characteristics of the biochar obtained through torrefaction.

Table 1. Biowaste used as raw material for biochar production through torrefaction.

Raw Material	Operating Conditions	Results	Ref.
Cane bagasse	RM: the sample was crushed to 3 mm in size, ground to 250 μm, and subjected to a drying process at 105 °C for 24 h. T: 200, 225, 250, 275, and 300 °C. RT: 15, 30, 45, and 60 min.	A decrease in VM, from 79.01% to 49.61%, and an increase in CC, from 16.09% to 42.79%, as well as AC, from 4.9% to 7.6%, were observed in the resulting biochar, by augmenting the torrefaction T from 200 °C to 300 °C and RT from 15 min to 60 min. The optimized operating conditions were T = 300 °C and RT = 60 min.	[46]
Mango seed (MS) and passion fruit peel (PF)	RM: The samples were cut into small pieces and dried in the sun for several days, then crushed and ground into 0.5 mm mesh and finally stored in a desiccator at 25 °C. RM was dried again in an oven at 100 °C for 10 min. T: 210, 240, 270, and 300 °C, at a fixed heating rate of 30 °C/min. RT: 30 and 60 min. Gas: constant nitrogen (N_2) flow rate of 25 mL/min.	An increase in CC in the MS and PF samples from 2.1% and 6.5% to 4.7% and 13.4%, respectively, was found in the biochar. Concerning AC, a decrease was achieved in both samples from 2.7% and 2.1% to 16.7% and 10.1%, respectively. A decrease in the VM content for the MS and PF samples from 95.8% to 78.6% and from 91.4% to 78.3%, respectively, was observed in the biochar obtained, with the increase in T from 210 °C to 300 °C at a 60 min RT.	[47]
Bamboo (*Phyllostachys edulis*)	RM: Bamboo was ground into powder to have particle sizes between 75 and 106 μm and subsequently dried at 105 °C for 12 h. A total of 5 g of bamboo powder was used. T: 210, 240, 270, and 300 °C at a fixed heating rate of 10 °C/min. RT: 30 min. Gas: N_2 carrier gas flow rate with a high purity (>99.9%) of 300 mL/min.	The solid products obtained gradually decreased from 95.34% to 59.98%; there were reductions in VM content, from 82.96% to 64.8%, and increases in CC and AC, from 15.9% to 33.22% and 1.14% to 1.98%, respectively, when increasing T from 210 °C to 300 °C.	[48]
Rice husks	RM: Rice husks were dried in an oven at 105 °C for 12 h, and a particle size from 0.125 to 0.3 mm was used. A total of 3 g of biochar was used. T: 220, 260, and 300 °C. RT: 30 min. Gas: O_2 at 0, 2, 5, 10, and 15%.	At a concentration of 0% O_2, the VM content decreased from 65.2% to 41.26% and the CC increased from 18.73% to 35.31%, as did the AC from 15.95% to 23.43%, in the solid products obtained. T increased from 220 °C to 300 °C. On the other hand, at 5% and 10% O_2, the CC reached a maximum value of 37.23% and the VM content obtained a minimum value of 35.49% at a T of 300° C.	[49]

Note. T: temperature, RT: residence time, RM: raw material, VM: volatile matter, CC: carbon content, AC: ash content.

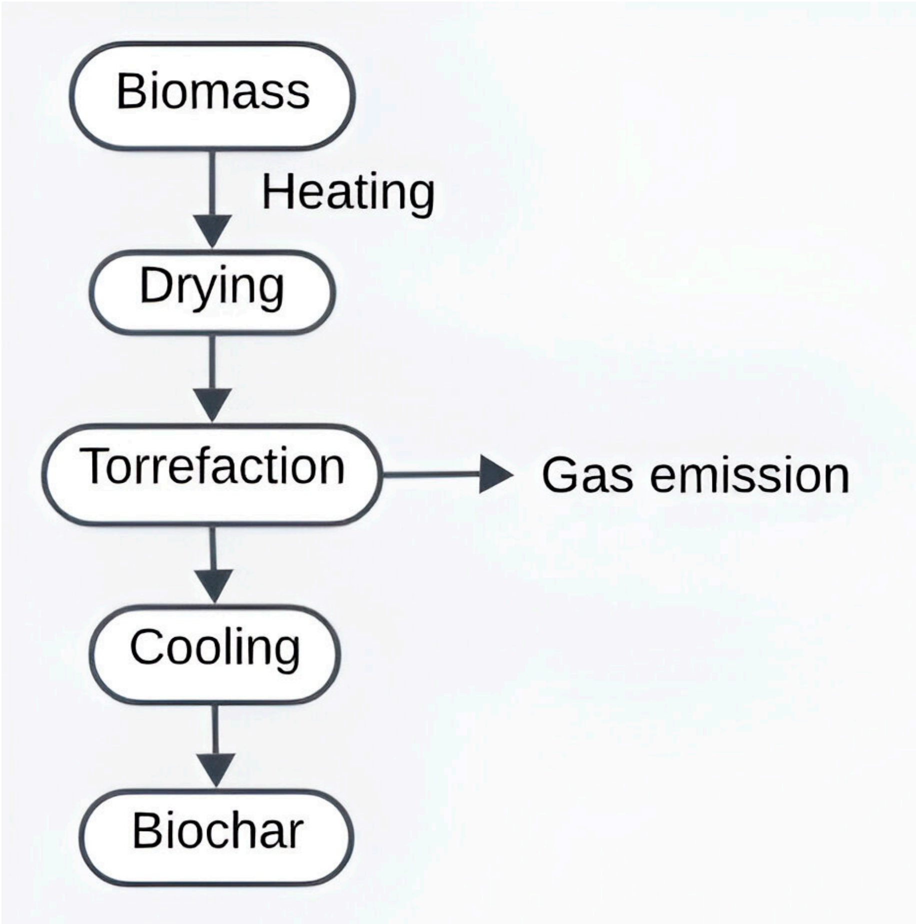

Figure 1. Diagram of the torrefaction process. Source: adapted from Ong et al. [50].

3.1.2. Pyrolysis

Pyrolysis is a thermal process used to obtain synthesis gas, bio-oil, and biochar (Figure 2). As in torrefaction, biomass decomposes in an inert atmosphere due to the use of nitrogen (N_2) when exposed to high temperatures, which has an important role in the production of biochar (with or without the presence of O_2), since the physicochemical properties of the biochar depend on it. Other factors such as the residence time, heating rate, and the type of raw material used to produce biochar influence its properties [2,40–43].

Temperature, being a relevant factor in this process, should be carefully measured, as it can help the biochar to obtain a high CC and stability, but it can also cause it to lose its properties and produce a dried biochar, and it can range from 300 to 900 °C without the presence of O_2 [2,40,42]. Some studies have shown that the pyrolysis process is environmentally friendly, energy efficient, and economically profitable [45].

The biomass obtained from the valorization of biowaste, such as sugarcane bagasse, rice straw, coconut shell, and pecan nut shell, were used in the conventional and fast pyrolysis process with operating conditions such as T (from 400 to 800 °C); heating rate (HR) (from 100 to 500 °C/min and 10 °C/min); and RT (from 1 to 8 min and 60 min), where a slight decrease in biochar production was observed when increasing T within the aforementioned range through fast pyrolysis. On the other hand, 30% of the biochar yield had a high CC and AC, low VM, and a large surface area [51,52]. Table 2 lists several studies reported in the scientific literature related to the operating conditions used, as well as the type of biomass and the characteristics of the biochar obtained through pyrolysis.

Table 2. Biowaste used as raw material for biochar production through pyrolysis.

Raw Material	Operating Conditions	Results	Ref.
Cane bagasse (CB)	RM: the sample (10 g) was dried in the sun and then ground into particle diameter fractions < 0.50 mm. T: from 400 °C to 800 °C. HR: from 100 °C to 500 °C/min. RT: from 1 to 8 min.	When T increased from 400 °C to 800 °C, the produced biochar from CB biomass decreased from 65 to 33%; meanwhile, when T increased from 500 °C to 800 °C, the biochar yield decreased from 33 to 21%.	[51]
Rice straw (RS)		Similarly, for RS biomass under the same pyrolysis conditions, the biochar yield decreased from 74% to 38% when T increased from 400 °C to 800 °C. Within the T range of 500 °C to 800 °C, this decrease was not so evident, resulting in values of 38 and 21%, respectively.	
Coconut shell (CS)		Concerning CS biomass, similar results were obtained, since BC production decreased from 75 to 38% when T increased from 400 °C to 800 °C. The biochar decreased when T increased from 500 °C to 800 °C, resulting in values from 38 to 25%.	
Pecan shell	RM: The sample (50 g) was washed with deionized water and then dried in an oven at 60 °C for 8 h. Fractions with particle diameters < 710 µm were obtained. T: up to 800 °C. HR: 10 °C/min. RT: 60 min. Gas: cooling with flow of N_2 up to room T.	The biochar obtained was treated with sulfuric acid (H_2SO_4) to eliminate traces of ash and it was dried at 105 °C. The biochar generated resulted in a carbonaceous material with a large surface area.	[52]

Note. T: temperature, HR: heating rate, RT: residence time, RM: raw material, VM: volatile matter, CC: carbon content, AC: ash content, C: carbon.

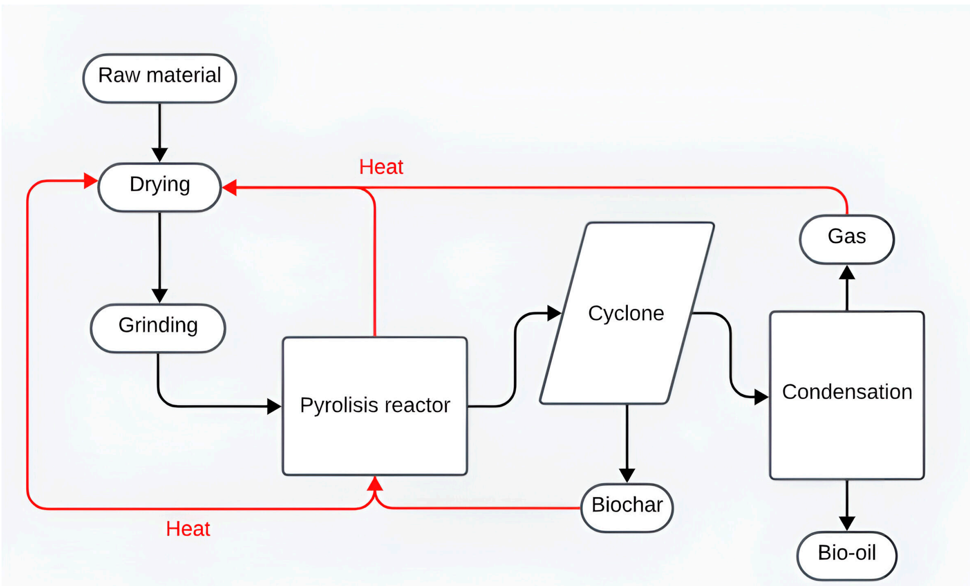

Figure 2. Scheme of the pyrolysis process. Source: adapted from Khitab et al. [53].

3.1.3. Gasification

Gasification is a thermodynamic process that converts the energy contained in carbon-based materials into pitch, synthesis gas, and biochar (Figure 3). This process occurs at high temperatures under certain limited O_2 supply conditions. It usually consists of four stages such as drying, pyrolysis, partial oxidation, and reduction [2,41,43].

There are several types of technologies that are used for the gasification process. The selection of the gasification technology depends on the type of raw material selected and the properties of the biochar that are desired to be obtained. From this process, a smaller amount of biochar is obtained compared to that from the pyrolysis process, since, in addition to biochar, carbon monoxide (CO) is generated due to the partial oxidation conditions. On the other hand, gasification has generally been used to obtain synthesis gas [2,40–42,45].

When the generation of biochar in large amounts and a high porosity is required, high levels of total polycyclic aromatic hydrocarbons (PAHs) can be released in the gasification process, which suggests that biochar can influence the formation and accumulation of PAHs.

In the gasification process, the factors that have an impact on the physical characteristics of biochar, such as the temperature and the heating rate, are determining factors in the amount of biochar obtained and its porosity. Consequently, under high temperatures (>700 °C), low heating rates (10–30 °C), and long residence periods (60–90 min), a large amount of biochar (from 280 to 552 m^2/g) with a high pore volume (<540 cm^3/g) is obtained [2,40–43].

The biochar resulting from this process using biowaste such as horse manure, rice hulls (RH), chicken manure (CM), switchgrass (*Panicum virgatum*), forage sorghum (*Sorghum* spp.), and red cedar (*Juniperus virginiana*) had a high CC and AC, and a low VM content when high temperatures and residence times were used. As the equivalence ratio (RE) was increased, the biochar produced had a high surface area and pore volume, an increase in the VM content, and a decrease in the CC and AC [54–56]. Table 3 lists several studies reported in the scientific literature related to the operating conditions used, as well as the type of biomass and the characteristics of the biochar obtained through gasification.

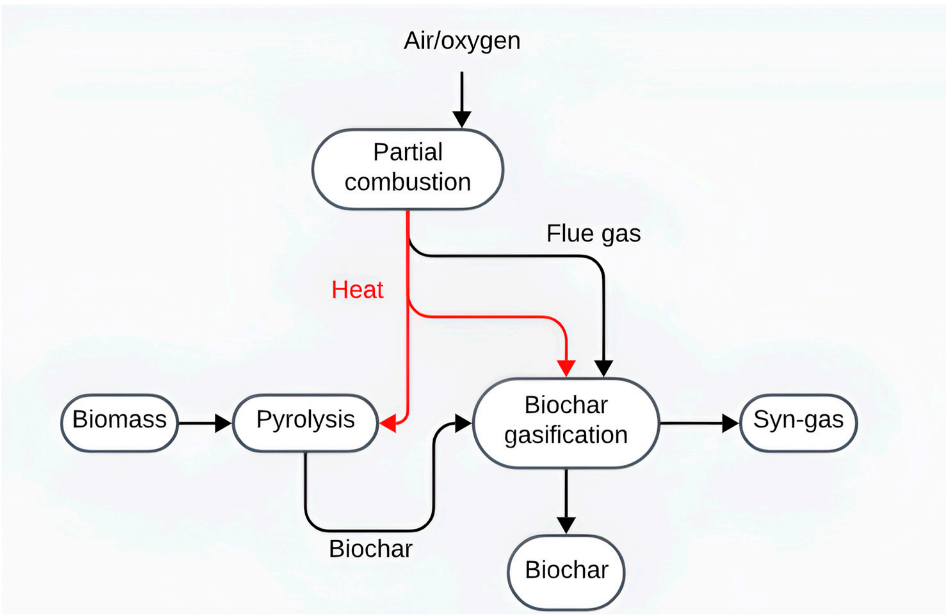

Figure 3. Scheme of the gasification process. Source: adapted from Yan-Ping [57].

Table 3. Biowaste used as raw material for biochar production through gasification.

Raw Material	Operating Conditions	Results	Ref.
Horse manure (HM)	RM: the sample was dried in the sun for a week and then was pulverized and sifted through a 0.5 mm sieve. T: 400, 500, and 600 °C. RT: 15, 30, and 45 min. Gas: N_2 was used to assure an inert atmosphere and pressurize the reactor (from 10 to 15 MPa, depending on the T).	An increase in CC of ~68% was found for T = 600 °C and RT = 45 min compared to 17%, corresponding to T = 400 °C and RT = 45 min. The VM content was decreased from 61% (T = 600 °C and RT = 45 min) to 39% (T = 400 °C and RT = 45 min). As the gasification T increased, the humidity and VM content decreased while the CC and AC increased. A stable value of fixed C was achieved at high temperatures as the VM was eliminated.	[54]
Rice husk (RH) and chicken manure (CM)	RM: Each sample was dried at 105 °C in an oven for 12 h. Subsequently, they were crushed and sieved until an average particle diameter was obtained. T: 273 K. RT: 15 min.	The biochar obtained when three parts of RH and one part of CM were used showed a surface area of 6 m^2/g and a pore volume of 0.03 cm^3/g. These results indicated the existence of mesopores on its surface with a predominant diameter ranging from 2 to 5 nm, and an average pore diameter of 6.8 nm.	[55]
Switchgrass (S), forage sorghum (FS), and red cedar (RC)	RM: large bales of the three biomasses used were cut with a crusher until a sieve size of 1.25 cm was obtained. T: 700, 780, and 800 °C. RE: 0.20, 0.25, and 0.28. RT: 5 and 7 s. TA: 3.9 to 4.2 kg/h.	The VM contents corresponding to S and FS increased as the RE rose from 0.2 to 0.25. The AC of S and RC increased from 51.61 to 64.07% and from 40.41 to 47.52%, respectively, by increasing RE from 0.2 to 0.28. The CC of S, FS, and RC decreased from 34.99 to 21.98%, from 33.76 to 32.67%, and from 40.49 to 35.66%, respectively, as the RE increased from 0.20 to 0.28. This can be ascribed to the RE increase, since the biomass content is oxidized to produce gas, reducing the C that has not been converted in the solid phase.	[56]

Note. T: temperature, RE: equivalence ratio, RT: residence time, RM: raw material, TA: biomass feed rate.

3.1.4. Hydrothermal Carbonization

Hydrothermal carbonization is an exothermic reaction in which the energy released is approximately one-third of the combustion energy found in carbohydrates (Figure 4). This released energy can be used to improve the process efficiency, maintain optimal temperatures, and reduce the overall energy consumption [42,43,45].

During this hydrothermal process, a combination of gaseous products, liquid hydrocarbons, and biochar is produced under specific conditions similar to those previously mentioned. Studies indicate that increasing the temperature necessitates a higher pressure to prevent the water in the biomass from fully evaporating. Additionally, higher temperatures reduce the biochar yield, resulting in a material with a lower surface area and porosity, as well as reduced carbon stability and biodegradability [40,58].

Biochar can be produced from various types of biomasses such as orange peels, deciduous sawdust, and peat through hydrothermal carbonization under different T and RT conditions. This process can yield biochar with a high specific surface area, pore structure, and mesopores, enhancing its adsorption capacity. Furthermore, as the heat capacity increases, there is a more significant transformation of the biomass, leading to higher biochar yields [59,60]. Table 4 lists several studies reported in the scientific literature related to the operating conditions used, as well as the type of biomass and the characteristics of the biochar obtained through hydrothermal carbonization.

Table 4. Biowaste used as raw material for biochar production through hydrothermal carbonization.

Raw Material	Operating Conditions	Results	Ref.
Orange peel (OP)	RM: OP (15 g) was dried in an oven at 105 °C for 24 h. Then, it was sprayed and sieved through a 200 µm sieve. T: 80, 105, 200, and 800 °C. RT: 2 and 12 h. HR: 3 °C/min. AC: activation of biomass with potassium hydroxide (KOH).	The biochar obtained showed high specific surface areas (2651 m^2/g) and a pore structure (1752 m^2/g). The mesopores on its surface account for a value of 899 m^2/g. Therefore, this biochar had a high adsorption capacity.	[59]
Deciduous sawdust (DS) and peat (DP)	RM: the samples (50 g) were not dried before the process. T: from 190 °C to 230 °C. RT: 4 h.	The biochar produced had a decrease in AC in both RMs, and the number of hydrocarbons was high. In the DS biochar, a greater decrease in O_2 was observed compared to that in the DP biochar.	[60]

Note. T: temperature, RT: residence time, RM: raw material.

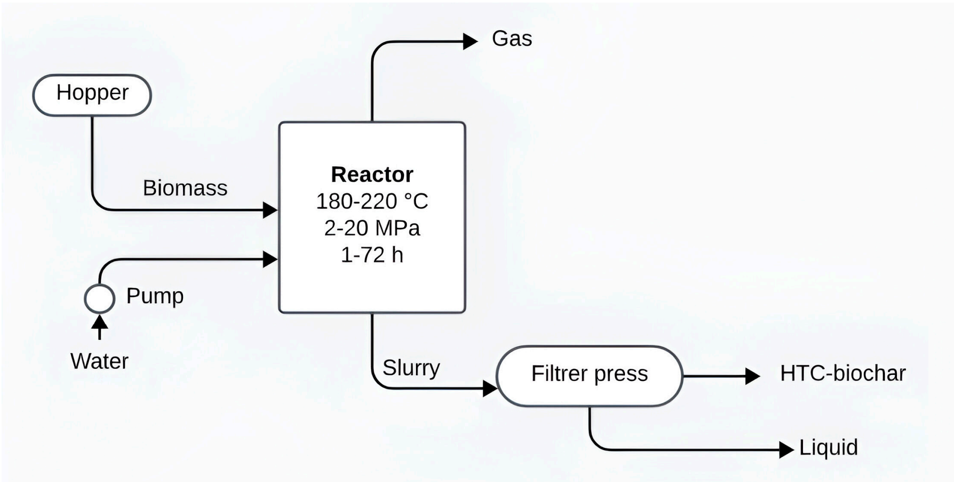

Figure 4. Scheme of the hydrothermal carbonization process. Source: adapted from Lewandoswski et al. [61].

As evidenced, high temperatures (above 650 °C) can negatively affect the biochar yield, quality, porosity, and durability. To enhance the reactivity of biochar, several techniques are employed, such as impregnation—an in situ method—and both physical and chemical activation processes performed after synthesis. These methods are used to alter the physicochemical properties of the biochar for various applications, serving as essential adjustments to complement the thermochemical methods used in its production. This procedure is known as biochar activation [2,40,43].

3.2. Application of Biochar in Water Treatment

In recent years, biochar has gained great interest due to its numerous applications. In agriculture, it is used as a soil amendment and an additive in composting. It also plays an important role in carbon sequestration and reducing greenhouse gas (GHG) emissions [13,45,62]. Additionally, biochar is utilized in water treatment processes for its ability to adsorb and remove contaminants from water, aiding in purification efforts [2,13,14,34,62]. In fact, research has demonstrated that biochar offers an effective and sustainable solution for treating wastewater that contains organic contaminants, nutrients, and heavy metals such as cadmium (Cd^{2+}), lead (Pb^{2+}), and copper (Cu^{2+}). These heavy metals are frequently found in industrial wastewater, where a high adsorption capacity, extensive surface area, and pore structure of biochar are crucial for removing pollutants, thereby reducing risks to human health [2,14,62]

Biochar adsorbs contaminants through several mechanisms, including ion exchange, electrostatic attraction, and surface complexation. Furthermore, as mentioned above, the physicochemical properties of biochar are influenced by the type of biomass used in its production, which allows for the optimization of its adsorption capabilities [2,63]. The mechanisms of adsorption are closely linked to the retention capacity of biochar, focusing on enhancing the efficiency of contaminant removal from water. While research is ongoing to fully understand these mechanisms, certain processes are known to be particularly effective for removing heavy metals and organic pollutants [14,63]. Some of these mechanisms are listed in Table 5.

Table 5. Biochar adsorption mechanisms for the removal of organic contaminants and heavy metals. Source: Adapted from Wang et al. [14].

Adsorption Mechanisms	
Heavy Metals	**Organic Contaminants**
Co-precipitation Complexation Ion exchange Electrostatic attraction	Division in the non-charred area Hydrogen bonds Electrostatic attraction Hydrophobic effects Pore filling

The applications of biochar in the treatment of SW and WW have been widely reported in the scientific literature, including in water contaminated with pesticides, antibiotics, pathogenic microorganisms, and inorganic pollutants [14]. Table 6 shows the applications of biochar in the treatment of SW and WW for the removal of various contaminants.

Table 6. Applications of biochar in the treatment of SW and WW. Source: adapted from Wang et al. [14].

Pollutant Group	Specific Pollutant
Heavy metals	Cd^{2+} Pb^{2+} Cu^{2+} Hg (II) Cr (IV) Ni (II)
Pesticides	Thiacloprid Dibromo-chloro-propane Deisopropylatrazine Atrazine and simazine
Antibiotics	Tetracycline Fluoroquinolones
Indicator and pathogenic microorganisms	Fecal bacteria (coliforms) *Saccharomyces cerevisiae* *Escherichia coli*
Inorganic ions	NH_4^+ NO_3^- PO_4^{3-} F^-

Biochar has also been used in artificial wetlands to eliminate macronutrients such as nitrogen (N) and phosphorus (P) species that cause eutrophication in water bodies when contained in high amounts [14]. Zhou et al. [64] reported high removal percentages of ammoniacal nitrogen (N-NH_4^+), Kjeldahl total nitrogen (NTK), and organic contaminants, with values of 39%, 39%, and 85%, respectively, in a vertical flow wetland containing biochar derived from bamboo waste and prepared at 500 °C under anaerobic conditions. This study demonstrated the high adsorption capacity of the resulting biochar.

Similarly, Deng et al. [65] demonstrated the removal efficiency of N-NH_4^+ and NTK in four artificial vertical subsurface flow wetlands to evaluate the response of microbial and metabolite characteristics after biochar addition. The removal values ranged between 49.69 and 63.51% for N-NH_4^+ and 81.83 and 86.36% for NTK. Biochar derived from the cane straw waste was pyrolyzed at 500 °C for 2 h. Improvements were observed in the elimination of N by altering the microbial communities since there is a change in their structure. Additionally, improvements in the metabolism of these compounds were observed due to their ability to convert high-molecular-weight compounds into low-molecular-weight ones.

Recently, biochar has also been applied in WWTPs, where conventional processes such as activated sludge, flocculation, and disinfection are not efficient enough in the elimination of certain contaminants. Sand traps and filters based on biochar and clay enhance the efficiency of contaminant removal [14].

Kaetzl et al. [66] investigated the efficiency of elimination of fecal indicator bacteria (FIB), bacteriophages (BA), COD, and turbidity (TU) in an anaerobic biofilter for the treatment of WW from a large-scale municipal WWTP. Biochar derived from rice hulls through pyrolysis was added to the filtration media. The biochar had a surface area of 143 m^2/g. The removal values of FIB, BA, COD, and TU were 2.27 ± 0.58 $\log_{10}$ units (*E. coli*), 2.38 ± 0.72 $\log_{10}$ units (Enterococci), 1.86 ± 0.36 $\log_{10}$ units (BA), 52% (COD), and 63% (TU), which demonstrates the efficiency of biochar in WW treatment.

Other investigations [67–72] have reported positive results in the elimination of indicator microorganisms such as *Escherichia coli* and enterococci present in SW, WW, and synthetic rainwater (SRW), using biochar derived from biowaste such as wheat straw, willow wood, forest wood, softwood, wood chips, and Bermuda grass after pyrolysis or gasification under different values of T, HR, and TR. It should be noted that some of these adsorbent materials were modified with potassium hydroxide (KOH), sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), sodium hydroxide (NaOH), and iron chloride ($FeCl_3$) to evaluate its efficiency during the removal of microorganisms. In Table 7, the main results of these studies are compiled, as well as the biochar properties, including the specific surface area (m^2/g) (SSA), pore volume (cm3/g) (V), pore size (nm) (PS), content of fixed carbon (%) (CC), volatile matter content (%) (VM), and the ash content (%) (AC).

Additionally, Kamali et al. [67] highlighted several sustainable factors that need to be considered when selecting biochar for water contaminant removal. These factors include technical aspects, such as the removal efficiency, stability, scalability, and potential health risks; economic aspects, including the feasibility of large-scale biochar production; and social aspects, like public acceptance of the biochar production process and its potential to increase new jobs. Additionally, the environmental impact of biochar must also be taken into account. Figure 5 illustrates the key elements associated with each of these considerations.

Currently, conventional disinfection processes and technologies such as chlorine, ozone, and ultraviolet (UV) radiation are used in the treatment of drinking water and WW to eliminate pathogenic microorganisms (enteric bacteria, *Cryptosporidium* sp., *Giardia* sp., virus, etc.), with chlorination being the most common method due to its easy application. However, each of these processes has negative implications or adverse effects when applied [73–76].

Table 7. Removal of microorganisms in surface water (SW), wastewater (WW), and synthetic rainwater (SRW) using biochar derived from biowaste pyrolysis.

Water Type	Raw Material	Operating Conditions	Biochar Characteristics	Type of Microorganism	Removal Results	Ref.
SW	Wheat straw	T: 500–560 °C HR: 9–10 °C/min	SSA: 55.24 m^2/g V: 0.04 cm^3/g PS: 26.11 nm	*Escherichia coli*	0.88 log_{10} units (84%)	[68]
	Willow wood	T: 500–550 °C HR: 85–100 °C/min	SSA: 380.0 m^2/g V: 0.03 cm^3/g PS: 17.60 nm		0.73 log_{10} units (79%)	
SRW	Forest wood	T: 700 °C RT: 3 h	B.C SSA: 137.0 m^2/g V: 0.0622 m^3/g PS: 1.82 nm	*Escherichia coli*	From 96.8% to 98.9%	[69]
			S.B SSA: 230.6 m^2/g V: 0.1052 m^3/g PS: 1.82 nm		From 97.9% to 99.8%	
			P.B SSA: 160.9 m^2/g V: 0.0733 m^3/g PS: 1.82 nm		From 94.1% to 98.2%	
			K.B SSA: 113.8 m^2/g V: 0.0557 m^3/g PS: 1.96 nm		From 92.8% to 99.7%	
WW	Softwood	T: 700 °C	SSA: 485 m^2/g	Enterococci	1.02 ± 0.3 log_{10} MPN/mL	[70]
				Escherichia coli	0.99 ± 0.31 log_{10} MPN/mL	

Table 7. *Cont.*

Water Type	Raw Material	Operating Conditions	Biochar Characteristics	Type of Microorganism	Removal Results	Ref.
SRW	Wood chips	T: 350 °C	SSA: 65.9 ± 1.2 m^2/g VM: 8.73% AC: 15.36%	*Escherichia coli*	3.62 ± 0.27 log_{10} units	[71]
		T: 700 °C	SSA: 64.9 ± 6.5 m^2/g VM: 5.95% AC: 12.74%		3.28 ± 0.52 log_{10} units	
SRW	Bermuda grass	RM: 10 g T: 800 °C RT: 2 h Gas: N_2 of 2 L/min	NaOH-BC SSA: 1991.59 m^2/g CC: 70.96% VM: 19.58% AC: 9.46%	*Escherichia coli*	98.68%	[72]
			Fe-BC SSA: 1013.40 m^2/g CC: 63.19% VM: 22.05% AC: 14.76%		81.16%	

Note. BC: biochar, KB: KOH-modified biochar, PB: H_3PO_4-modified biochar, SB: H_2SO_4-modified biochar, NaOH-BC: NaOH-modified biochar, Fe-BC: $FeCl_3$-modified biochar, RM: raw material.

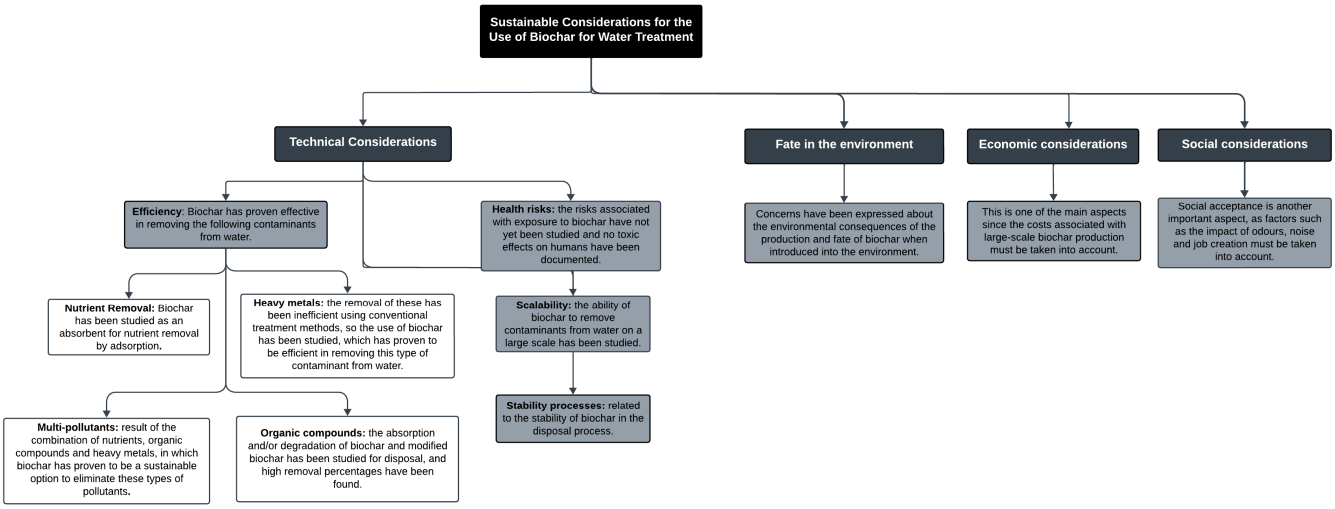

Figure 5. Sustainable considerations to be taken into account for biochar generation and use during the treatment of SW and WW. Source: adapted from Kamali et al. [67].

Chlorination and ozonation can lead to the formation of harmful, carcinogenic, and toxic disinfection byproducts (DBPs) due to the release of residual disinfectants into the environment, affecting the water quality of influents and effluents. On the other hand, UV disinfection is limited by the lack of residual disinfection capacity, unlike chlorination, where the residual chlorine that will continue to act in the distribution networks of drinking water or wastewater (after treatment) is calculated [73,76,77].

Another important aspect to be considered when implementing conventional disinfection processes is that several pathogens cannot be eliminated. Pathogen microorganisms, such as opportunistic pathogens that are resistant to chlorine (*Legionella* sp., *Pseudomonas* sp., *Mycobacterium* sp., and *Acinetobacter* sp.), can create a barrier that protects them from the action of the disinfectant present in the water, managing to survive and reproduce, which is highly dangerous for human health [78,79].

Therefore, the implementation of biochar as an alternative treatment for the elimination of pathogenic loads turns out to be a more efficient option thanks to its high porosity and adsorption properties, in which the microorganisms remain adhered to the surface of the biomaterial and no toxic byproducts are generated during the treatment.

4. Circular Economy, Bioeconomy, and Sustainable Development

Circular economy aims to reduce the environmental impacts caused by the main economic actors during the production processes of materials, inputs, and consumption, through the recovery, reuse, and recycling of the materials used (raw materials). As mentioned previously, the reuse and valorization of biowaste enables its transformation and use in a sustainable manner for the generation of energy and production of carbon-rich materials such as biochar [2,13,15,45,80].

The circular economy also addresses societal challenges, such as population growth, increased consumption, rising demand for resources, and the fluctuating prices of raw materials on the market. This approach encourages improvements in resource acquisition, production processes, and post-consumer waste management [80,81].

Bioeconomy, meanwhile, is closely connected to the circular economy concept, as it focuses on the use and transformation of renewable biological resources or waste, such as those derived from agro-industrial activities, to produce food, bioenergy, and bioproducts like biochar, bio-oil, and syngas, among others. This approach is grounded in sustainable innovation that promotes economic development and, most importantly, reduces the reliance on fossil fuel-based materials [31,34,80,82].

The principles of the circular economy and bioeconomy, collectively known as the circular bioeconomy, align well with achieving several SDGs, such as goals 6–9 and 11–13.

These concepts encourage the efficient and sustainable use of resources to ensure access to clean water, promote growth and innovation in the development of renewable and sustainable energy (such as bioenergy), support job creation in the industrial and agricultural sectors, facilitate the transformation of traditional cities into sustainable ones, and help mitigate climate change through various actions and mechanisms, including policies and national plans [15,80,82].

Even though biochar production is economically viable and has proven to be highly effective as an alternative treatment method for removing various water contaminants, further studies are needed to evaluate its use in large-scale WWTPs from both a technical and an economic perspective. It is essential to determine whether biochar can significantly lower the costs associated with WW treatment compared to traditional techniques [2,40].

As demonstrated, the principles of the circular bioeconomy and sustainable development are applied in biochar production, as it involves the recovery and reuse of agricultural and agro-industrial waste, among other waste, using environmentally friendly techniques and technologies. This approach minimizes environmental pollution during the production process, thereby promoting the circular bioeconomy and supporting the achievement of the SDGs.

5. Conclusions

A wide range of microorganisms can be found in water, including bacteria, viruses, protozoa, and helminths, which are responsible for various diseases and can lead to numerous health issues in humans. Therefore, consuming water contaminated with pathogens poses a significant health risk. Beyond the impact on human health, the presence of these microorganisms also threatens the environment by causing the death of aquatic organisms and compromising the quality and availability of water for different uses.

Reusing and recycling agricultural and agro-industrial waste to produce biochar offers a sustainable solution from both an environmental and economic perspective. This approach incorporates the principles of the circular economy and bioeconomy, creating the concept of circular bioeconomy. In this context, the goal of circular bioeconomy applied to agricultural and agro-industrial waste is to maximize its use to produce carbon-rich materials that can be applied in the remediation of various environmental media, including water contaminated with several pollutants, such as pathogenic microorganisms.

Pyrolysis is the most used thermochemical process for producing biochar due to its effectiveness, cost-efficiency, and higher energy efficiency. This process is environmentally friendly, as it has minimal negative impact on ecosystems. Additionally, biochar has been shown to be effective in removing pathogens from water, particularly in eliminating common water quality indicator microorganisms like coliforms and *Escherichia coli*.

The shortcomings of traditional WW treatment methods, coupled with the push for a circular bioeconomy and the pursuit of SDGs, requires the evaluation of alternative and, importantly, sustainable treatment methods. These methods must be effective in removing contaminants from water to reduce the risks to human health and the environment. Biochar emerges as a promising alternative in this context. However, comprehensive research is required to assess the feasibility of using biochar in large-scale WWTPs, considering both economic and technical aspects. Additionally, it is important to evaluate options for the disposal of biochar after it has absorbed pathogenic microorganisms from WW, as it may contain significant amounts of these pathogens. One viable option could be its use in soil remediation following a thermal treatment process.

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