Sci Tech
العلوم والتكنولوجيا
Science Today
ISSN: 3078-994X

Biochar: a sustainable material for wastewater treatment

Muddassar Alam

Department of Biological Sciences and Chemistry, University of Nizwa, Oman.

Abstract

The creation of sustainable materials for practical environmental applications is the main emphasis of the scientific community. A stable carbon-rich substance, biochar has great promise for treating water and wastewater pollutants because of its accessibility, ease of synthesis, and improved physico-chemical characteristics. The surface area, distribution of pore sizes, surface functional groups, and molecular size of biochar all affect how effective it is. Among the many benefits of biochar are its good surface and structural qualities as well as its ease of production. It is used as a catalyst for the breakdown of pollutants and dyes, as well as an additive and filter media in the treatment of water and wastewater. Various biochar manufacturing techniques and contemporary wastewater treatment applications are covered in the current review. It is essential to evaluate created technologies in order to find technical gaps and encourage commercialization. In addition to addressing environmental concerns, this study covers new developments, and biochar modification methods. It draws attention to the environmental issues of biochar and makes recommendations for future research to improve its usefulness in the treatment of water and wastewater.

Keywords: Biochar, wastewater treatments

Full length article **Corresponding Author*, e-mail: e-mail: mudasaralam@yahoo.com, doi# 10.71111/Science today/3-25-2-2-st-3

1. Introduction

Water resources around world are being degraded by the release of organic and inorganic pollutants into bodies of water, raising worries about the harm they may cause to ecosystems. Reverse osmosis, chemical precipitation, ion-exchange, coagulation-flocculation, adsorption, membrane filtration, electrochemical treatment, solvent extraction, and flotation are examples of conventional technologies for the removal of wastewater pollutants [1]. Nevertheless, these technologies have drawbacks such inefficiency, high chemical and energy consumption, complicated processes, and expensive operation and maintenance [2]. Because of its effectiveness in eliminating pollutants, biochar—an inexpensive and environmentally benign substance made from organic waste—has drawn attention. The physico-chemical properties of biochar determine its adsorption capability and are influenced by feedstock and manufacturing techniques [3]. The removal efficiency can be increased by altering the characteristics of biochar. However, as biochar could include heavy metals and other pollutants, its possible harmful effects should be examined [4].

The stability of biochar and its relationship to the experimental circumstances utilized during manufacture require further research. The potential uses of biochar, a thermally decomposed result of oxygen-free biomass, in soil amendments, agricultural yield enhancement, and soil carbon sequestration have drawn interest. Recent developments in the manufacturing of biochar have enhanced its functionality and broadened its use in a variety of interdisciplinary domains. With its effectiveness and applicability in eliminating certain impurities depending on pyrolysis temperatures and feedstock types, water and wastewater treatment is one of the newer subgroups of biochar application [5]. This study examines current developments in the use of biochar, covering environmental problems, modification techniques, and mechanisms for eliminating particular organic and inorganic pollutants. The review also addresses how different emphases have changed the characteristics and removal efficiency of biochar through modification techniques. The report also emphasizes ongoing environmental issues. Along with highlighting ongoing environmental issues and potential study avenues, the article also offers potential remedies [6].

2. Pyrolysis for the synthesis of BC

A thermochemical process called slow pyrolysis turns biomass into non-condensable gases, bio-oil, and biomass fuel (BC). Charcoal has been made using this method for thousands of years, and the BC has a high lignin and ash content. The reactor configuration and pyrolysis conditions are the main determinants of the relative proportion of the pyrolysis products (BC, bio-oil, and syngas). Both slow (traditional) and quick pyrolysis can be carried out; slow pyrolysis often yields a comparatively high

BC yield. The source of the biomass and the conditions under which it is pyrolyzed determine the content of the bio-oil that is produced in this process. In contrast, fast pyrolysis provides comparatively less BC than slow pyrolysis, but it produces substantial quantities of bio-oil and non-condensable gasses. The pyrolysis process can also change the characteristics of BC due to inherent metallic compounds [7].

Plant tissues typically contain cations like potassium, sodium, calcium, magnesium, iron, and aluminum as well as inorganics like sulfur, phosphorus, and chlorine. By raising the pyrolysis temperature to 700°C, heteroatoms are eliminated, and charred reactions may lead to formation of a graphene layer and biochar's aromaticity. The char content releases sulfur due to protein breakdown at temperatures lower than 500 ◦C. Another thermochemical process that produces hydrogen gas (H_2), carbon dioxide (CO_2), carbon monoxide (CO), and trace amounts of hydrocarbons like methane (CH_4) is gasification. The process parameters and oxygen introduction medium in reaction system determine gas's composition. Influence of feedstock on BC's mechanical characteristics, carbon fraction, surface complexation, and polycyclic aromatic hydrocarbon concentration has emphasized in recent research. Constituent makeup of prepared BC is determined by temperature, which is second factor influencing BC attributes [8].

3. W&W treatment in BC: Sustainability factors

Use of biochar as a valuable material for industrial effluents and water pollution has increased recently due to interest in pyrolysis-based biomass valorization. A promising method for cleaning up water and wastewater contaminated by both established and new pollutants is biomass valorization. This section addresses current developments, sustainability considerations, and knowledge gaps in the use of biomass to treat wastewater and dirty water [9].

3.1. Technical aspects

Efficiency, process stability, scalability, compatibility with other methods, ease of application, and health and safety considerations are all important aspects of BC's technological viability for treating contaminated waste and water.

3.1.1. Effectiveness

❖ ***Elimination of Nutrients***

As an adsorbent for the adsorption-based removal of nutrients, BC (Byproduct) has been thoroughly investigated. The surface chemistry, specific surface area, porosity, and shape of BC all have a significant impact on its adsorption capacity. The impact of functional groups on the BC surface on nutrient adsorption has been investigated; the properties of BC are influenced by feedstock type, temperature, reaction medium parameters, operating pH, and aluminum chloride ($AlCl_3$) treatment. One successful method for increasing BC's propensity to absorb anions is structural functionalization (STF). According to reports, one efficient method for creating BC with the required qualities is to impregnate it with metal oxides or metal salts. The removal of nutrients like phosphate has been accomplished using a variety of metallic compounds, including BC coated with magnesium [10]. Impregnation with magnetic particles has enhanced the BC capabilities of Magnetic BC (M BC). The effectiveness of magnetically impregnated BC has also been compared to that of impregnated BC with other elements. The only treatment method that has been utilized to achieve the required treatment efficiency is biochar, which has the ability to remove many contaminants at once. The effectiveness of BC products for the simultaneous removal of several nutrients from contaminated effluents has been investigated in recent studies; phosphate, ammonium, and humate have the best adsorption capabilities. Additionally, electrodes based on biochar have been created to adsorb inorganic substances from aqueous systems [11].

❖ ***Heavy Metals***

The poisonous nature of heavy metals (HMs) and their effects on human health and the environment have drawn a lot of attention to the removal of HMs from polluted water and wastewater (W&W) streams. Because of the low effectiveness of conventional treatment methods, biochar (BC) has emerged as a more practical and cost-effective alternative to activated carbon, particularly for chromium and zinc. The capacity of several BC types to eliminate HMs has been investigated; however, results differ based on the BC's origin, changes, and experimental setup. BC's ability to adsorb HMs is determined by the pyrolysis temperature. According to studies, BC made at 700°C is more efficient than those made at 300°C, especially when it comes to removing As (III) as opposed to As (V). The most effective methods for increasing adsorption capacity for environmental pollutants have been determined to be alkali-treatment and nanomaterial impregnation. Although structural changes to BC may have a negative impact on its characteristics, they may also increase its potential for the intended uses. For the removal of both organic and inorganic contaminants, magnetic BC composites have demonstrated greater efficiency than non-magnetic BC. Prior to pyrolysis, adding magnetic compartments to rice straw can enhance adsorption of heavy metals and cadmium. Effluents from industrial activities are typically laden with various environmental contaminants, making simultaneous removal of HMs a key parameter determining the overall efficiency of any treatment technology. Since industrial wastewaters are frequently loaded with several environmental pollutants, simultaneous removal of heavy metals (HMs) is a crucial factor in determining overall effectiveness of any treatment system.

❖ ***Organic Compounds***

The effectiveness of biochar (BC) in handling organic chemicals such as dyes, phenolics, halogenated hydrocarbons, insecticides, aromatics, and antibiotics has been investigated in studies [12]. The most common method for removing organic molecules from water and wastewater is adsorption. SSA, porosity, ash content, and functional groups are among of the factors that affect BC's adsorption ability. Micro-porosity and SSA expand at high pyrolysis temperatures, which is advantageous for immobilizing organic pollutants. It has been shown that activating BC is an effective way to increase its effectiveness. Through manipulation of pyrolysis conditions, such as conducting pyrolysis in an environment of carbon dioxide, attempts have been made to increase specific surface area of BCs. However, in order to advocate for more, economic and environmental evaluations of these technically viable approaches are required. By creating π-electron-rich sites on the BC surface and increasing adsorption capacity, nitrogen doping of biochar can aid in the adsorption of pollutants. It has been discovered that using biochar (BC) to remove different kinds of organic chemicals from a variety of materials works well.

In order to create nanostructured materials in the biochar structure for further catalytic reactions to break down adsorbed organic molecules, porogens like $MgCl_2$ can be applied to BC to improve its porosity and specific surface area [13]. BCs have effectively eliminated dye chemicals, halocarbons, phenolics, insecticides, medications, and personal care items. It has been discovered that different kinds of BCs are effective at eliminating different kinds of medications, pesticides, and personal hygiene items. Physical, chemical, and biological changes can improve BC's effectiveness against pesticides. Furthermore, BCs have been successful in eliminating pharmaceutical and personal care products (PPCPs). Persulfate can be effectively activated by modified BCs to facilitate effective breakdown of contaminants. Magnetic BCs coated with humic acid can improve BC's effectiveness in degrading antibiotics. With a maximal sorption capacity of 37.7 mg/g at pH 3, the sorption process of BCs is strongly influenced by pH. By increasing BC's porosity and producing nanostructured materials for further catalytic processes to break down adsorbed the organic molecules, this technique might be regarded as a sustainable one [14].

❖ ***Pesticides***

Agriculture and the economy benefit from the use of pesticides, but overuse can be harmful and detrimental to human health and the environment. Biochar is a novel remediation technique for treating pesticide pollution. Research has demonstrated that sorption takes place through $\pi-\pi$ contact, hydrophobic interaction, and pore-filling. Biochar made from pyrolyzed swine dung, almond shell, and triazine insecticides is an efficient way to get rid of pollutants. Surface sorption mechanisms explain atrazine and simazine's sorption ability on biochar. Since biochar made at 700 ◦C has more surface area, micropores, and aromaticity, it can effectively remove pollutants [15].

❖ ***Antibiotics***

Pharmaceutical wastewater containing antibiotics, especially tetracyclines and sulfonamides (SAs), which are often used antibiotics in intensive agriculture, can be hazardous to the environment. After three cycles, elimination rate of TCs was over 89%, demonstrating potential of biochar, more especially $ZnCl_2/FeCl_3$ solution-doped sawdust. Micropore-filling is a frequent process by which high-temperature biochar can sorb SAs molecules, according to studies. Because of its hydrophobic, electrostatic, and EDA interactions as well as the creation of hydrogen bonds, magnetic biochar covered with humic acid can also sorb fluoroquinolones with excellent removal efficiency [16].

❖ ***Indicator Organisms and Pathogens***

Urban storm water runoff can contaminate vegetables with microorganisms, thus biochar is used to remediate it. The possibilities and limitations of biochar filters have been investigated. According to studies, biochar filters are more successful at removing bigger pathogens and negatively charged bacteria than rice husk and regular sand filters. The effectiveness of microbial eradication is significantly influenced by the size of the biochar's particles. Additionally, studies have demonstrated that sand biofilters altered with biochar can improve the removal capacity of pathogens by retaining more Escherichia coli and preventing their mobility during continuous, intermittent flows [17].

❖ ***Inorganic Ions***

Biochars are widely used to remove inorganic ions, especially the nutritional components F^- in drinking water and N and P from wastewater. A maximum of 6.4 mM g^{-1} has been shown to be the sorption capacity of biochars for NH^{4+}. Surface complexation, pH, electrostatic attraction, and ion exchange between NH^{4+} and negatively charged functional groups all have an impact on the sorption process. Ionic bonds with exchangeable cations and electrostatic attraction control the sorption mechanisms for NO^{3-}. By co-pyrolyzing sewage sludge and walnut shell, biochar was created for PO^{4-}sorption from eutrophic water. Due to a combination of surface precipitation, complexation, and electrostatic attraction, magnetic biochars have twice the sorption capacity of unmodified biochars. The greatest removal capacity of Al-modified spruce wood biochar for F^- is 13.6 mg g−1, and best model for F^- sorption is the Langmuir isotherm model [5].

❖ ***Multi-contaminants***

The effectiveness of BC (carbon) in practical applications, including stormwater discharge, where a variety of contaminants might be present, has been investigated. Pollutants as metals, nitrate, and trace organic components have been effectively removed from urban storm runoffs using BC-amended woodchips. But Zn cannot be eliminated by BC. Nutrients and HM can be eliminated at the same time as organic pollutants. In water desalination operations, BC-based electrodes have been utilized to adsorb multiple ions; hierarchical porous carbon (SSA) electrodes made from rice husk biochar have a high electrosorption capacity. This research can provide a sustainable method of desalinating water, particularly in desert areas where access to resources for drinking water is scarce [18].

3.1.2. Process Stability

The majority of biological treatment techniques, including activated sludge and anaerobic digestion, are not very stable when applied to toxic and non-biodegradable effluents, such those from pulp and paper mills [19]. The microbial community is adversely affected by the existence of resistant and possibly hazardous components, which causes treatment procedures to fail. Complex and hazardous compounds have shown a significant degree of resistance to physicochemical treatment approaches. Properties like specific surface area and pore volume are closely related to adsorption capability of biochar-based materials employed in the removal of contaminants. As contaminants occupy available surface area, BC gradually loses its effectiveness. Key to avoiding failure or any decline in system performance is having a thorough understanding of the properties of BC-based materials. It is crucial to evaluate BC's performance on actual contaminated wastewater and wastewater treatment (W&W) streams since laboratory-scale studies using a single pollutant typically cannot yield sufficient data on BC's true performance. Process's stability and dependability may also be impacted by how simple it is to implement and whether complex facilities and equipment are required [20].

3.1.3. Scale-up Capacity

The initial steps for scaling up technologies developed in lab-scales involve proving their efficiency in dealing with complex conditions, such as the presence of multiple pollutants in real effluents. Optimization methodologies like the Taguchi experimental approach can be adopted to identify optimum conditions and maximize treatment system performance. Biomass (BC) can be considered an attractive candidate for large-scale adsorption of nutrients due to its higher efficiency and lower costs compared to conventional adsorbents. However, there are limited reports on pilot-scale applications of some BCs, such as BC-nZVI for stormwater treatment. Full-scale production and applications have also been reported to deal with real effluents, but efforts for full-scale application of BC for polluted W&W are limited. Scaling up can be made easier by the potential to combine BC with other technologies, particularly during cold seasons when effluents contain high amounts of nutrients [21].

3.1.4. Hazards to Health and Safety

Full-scale wastewater and wastewater treatment facilities based in Biochar are anticipated to be built in other nations soon [22]. Although dust produced during BC manufacture and applications is the main route of human exposure to BC, the routes of human exposure to BC have not been thoroughly investigated. As of now, little is known about the harmful consequences of BC on exposed organs. A BC's overall toxicity is typically determined by the presence of poisonous components in its structure. Such hazardous components can be changed in quantity and presence by regulating the conditions in which BC is produced. Studies have indicated that the pyrolysis temperature plays a crucial role in stabilizing potentially harmful elements in the BC structure, and that BCs made at higher temperatures include fewer dangerous and nontoxic elements [23]. The existence of harmful effects may also be influenced by BC's place of origin. According to experimental research, BC can have certain harmful effects on living things. To reduce the chance of exposure, practitioners should wear respiratory protection equipment when making BC. Although magnetic BC is currently receiving attention for treating contaminated wastewater, nothing is known about its hazardous activity. Before employing BCs for actual applications, more study is required to discover any potentially harmful compounds in the composition of BCs made from different feedstock materials and to create strategies for getting rid of them [24].

3.1.5. Environmental Destiny

Carbon sequestration and the treatment of wastewater and contaminated water are two potential uses for biochar (BC). Concerns have been expressed, meanwhile, regarding the effects of BC production on the environment as well as the fate and behavior of the generated BC after it is released into the environment. Air pollutants like CO_2, NOx, and particulate matter may be released into the atmosphere as a result of the pyrolysis process. The amount of environmental effects from the manufacturing of biochar is also influenced by the feedstock materials. Iron in the feedstock may fix nitrogen, preventing its emission to the atmosphere, according to methods established to minimize NOx emissions from the pyrolysis of ferric sludge. The conditions of BC production also affect emissions into the atmosphere; higher temperatures during the pyrolysis of rice husks increase the generation of bio-oil and PM_{10} and $PM_{2.5}$ emissions [25]. A portion of the generated BC can be utilized to eliminate air contaminants in order to reduce atmospheric emissions. Contaminants such carbon nanoparticles, heavy metal particles, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) are produced during the manufacturing of BC and may persist in the product. Following BC application, these substances may leak out and endanger the environment. The movement of BC is influenced by environmental factors, including infiltration, runoff, and decomposition. Since most standard approaches take into account the effects of BC on plants and soil invertebrates, the ecotoxicological effects of BC are not well understood. More research is required to determine BC's fate and how it affects environmental factors. One potential solution to stop BC from leaking into the environment is magnetic BC development [26].

3.1.6. Economic Factors

Commercializing laboratory-scale biochar-based (BC) wastewater treatment methods requires careful consideration of economic factors. One of the main obstacles to BC's quick commercialization for practical uses is thought to be its high production costs. Since production prices have decreased due to recent advancements in BC production technology, these technologies are appealing options for use in the treatment of wastewater that has been contaminated. Burning and soil covering (B-SC) procedures are two examples of more cost-effective BC production methods that have been tried. The price of energy affects BC production costs as well; electricity costs are higher in North America than in Europe. New technologies, like solar energy, have been created and used to lower production costs. Using a concentrated solar thermal energy facility, Giwa et al. pyrolyzed date palm trash, proving that the method was economically feasible with a payback period of four years and 132 days [27]. According to recent research, virgin BC need surface functionalization alterations since they are insufficiently effective at handling environmental pollutants. It has been established that adding metallic compounds to BC improves its abilities for the elimination of environmental contaminants. In-depth research highlighting the economic viability of BC-based technologies for treating contaminated wastewater offers precise cost estimates, enabling decision-makers to evaluate and select the most environmentally friendly BC-based technologies [28].

3.1.7. Social Aspects

Social acceptability is crucial for the wider application of Biochar-based materials for treating polluted water and wastewater. Factors such as odor and noise impacts, as well as the potential for job creation, influence the social image of a new technology. Biochar-based technologies can eliminate odor problems and create negligible noise. Large-scale applications may attract experts and engage local, regional, national, or international markets for trading services, equipment, materials, and products. However, technology attributes, dimensions, and required supplementary technologies can determine the number of job opportunities [29].

4. Indirect Water and Wastewater Treatment

Wastewater treatment has made extensive use of wastewater wetlands (CWs) to eliminate organic, phosphorus, and nitrogen pollutants. However, limited oxygen supply, transport capacity, and substrate sorption capacity limit their effectiveness. Biochar has been investigated by researchers as a substrate to improve the performance of CWs with high concentrations of pollutants. In order to increase removal efficiency with low C/N ratio influent strengths, Zhou et al. (2018) employed biochar as a substrate in vertical flow built wetlands (VFCWs) [30]. According to Bolton et al. (2019), enriched biochar worked well as a substrate for the removal of PO_4-P. Although more research is required, waste biochar has the potential to regenerate as soil fertilizer [10]. According to Deng et al. (2019), biochar increased the removal rates of NH_4-N and TN in SFCWs. By altering microbial communities and boosting the number of dominant species, biochar also facilitates the removal of nitrogen. In addition to improving the physical characteristics of the soil and reducing surface runoff and soil erosion, biochar additives can also increase runoff time by absorbing rainfall [31].

5. Current application of biochar in wastewater treatment facilities

Wastewater treatment plants have employed biochar, a heterogeneous substance, to eliminate impurities such as mineral and phosphorus pollutants. In contrast to more established technologies, there aren't many initiatives to create facilities based on biochar. Even though studies have been published, they are based on lab tests and do not include the settings and operating parameters of actual facilities. The performance of wastewater treatment has improved using biochar-based filters, and scalability of biochar-engineered applications demonstrated in 2015 with the construction and patenting of a pilot-scale system named N-E-W Tech [32].

6. Biochar Modification

The limited removal efficacy of biochar for specific contaminants or water conditions limits its use in water solutions. Surface area and functionality were shown to be related to sorption capacity; higher sorption sites were indicated by larger micro pores and mesopores. Increasing surface area, porosity, surface characteristics, and embedding materials are some of the modifications made for advantageous composites [33].

6.1. Raising Porosity and Surface Area

The sorption capacity of biochar is enhanced by its greater surface area, which contains more sorption sites. To accomplish this attribute, a number of alteration techniques have been suggested. Physical treatment removes incomplete combustion components and improves porosity by treating biochar at temperatures above 700 ◦C using gases like CO_2 and steam. Longer action periods and greater flow rates have been found to enhance Zn, Cu, and Cd sorption on the surface of biochar. Surface area is also increased by acidic or alkaline treatment; research indicates that pyrolysis of biochar-KOH mixtures improves surface area and cadmium sorption [34]. Certain biochar-based composites have a greater surface area because they impregnate biochar with particular substances, including montmorillonite, during the pyrolysis of bamboo powder. Using a scanning electron microscope (SEM), the layered surface of clay-modified biochar can be seen to resemble the morphology of a typical clay structure [33].

6.2. Rising Positive Surface Charge

Biochar is a poor sorbent for oxyanions such as NO^{3-}, PO^{4-}, and AsO^{4-}, but it is a great sorbent for metal cations due to its negative surface charge and higher pH value. Metal oxides can precipitate and increase their surface area and surface charge by using biochar as a porous carbon substrate to create biochar-metal oxide composites. Frequently, biochar is soaked in solutions of metal chloride or nitrate, which subsequently transform into metal oxides. Sorption of metal cations and oxyanions in aqueous solutions can be enhanced by embedding magnesium, aluminum, or manganese oxides onto the surface of biochar. The sorption of metal cations takes place through co-precipitation or chemical sorption on oxygen-containing functional groups on the unmodified portion of biochar, whereas the sorption of oxyanions by biochar-metal oxide composites happens through electrostatic attraction or chemical sorption with positively charged metal oxides in biochar matrix [35].

6.3. Increasing the Number of Functional Groups with Oxygen on Surface

Functional elements like carboxyl, hydroxyl, and phenolic groups found in biochar, a form of wood, have the ability to chemically bond with impurities and extract them from aqueous solutions. The possibility of binding with positively charged pollutants by selective sorption is increased by acidic treatment. By altering biochar with acidic solutions, scientists have increased the number of surface carboxylic groups that serve as metal cation sorption sites. Strong acids, however, are expensive and harmful to the environment. Alternatives with higher oxygen levels and cation exchangeability, such as $KMnO_4$ and H_2O, have been created to modify biochar. Increasing the number of oxygen-containing functional groups on the surface of biochar is another effect of alkaline solutions [36]. After adding the graphene structure, the biochar-graphene oxide composite material—which is made by impregnating the raw material in graphene oxide solution and pyrolyzing it—displays more functional groups that include oxygen. The more graphene oxide there is in the composite, faster Hg^{2+} is removed [37].

6.4. Including Surface Amino Functional Groups

The sorption ability of biochar is improved by amino functional groups on its surfaces, which complex pollutants with amino sites. Chemical reactions or combining biochar with amino-rich polymers like chitosan and polyethyleneimine (PEI) can accomplish this. According to studies, the sorption capacity for Cu^{2+} is increased by five times when amino groups chemically bond with functional groups on the surface of biochar. For the remediation of heavy metals in aquatic environments, chitosan-modified biochars have been created from a variety of sources. By improving the elimination of Cd^{2+}, Cu^{2+}, and Pb^{2+} from aqueous solutions, these biochars lessen \toxicity of lead [38].

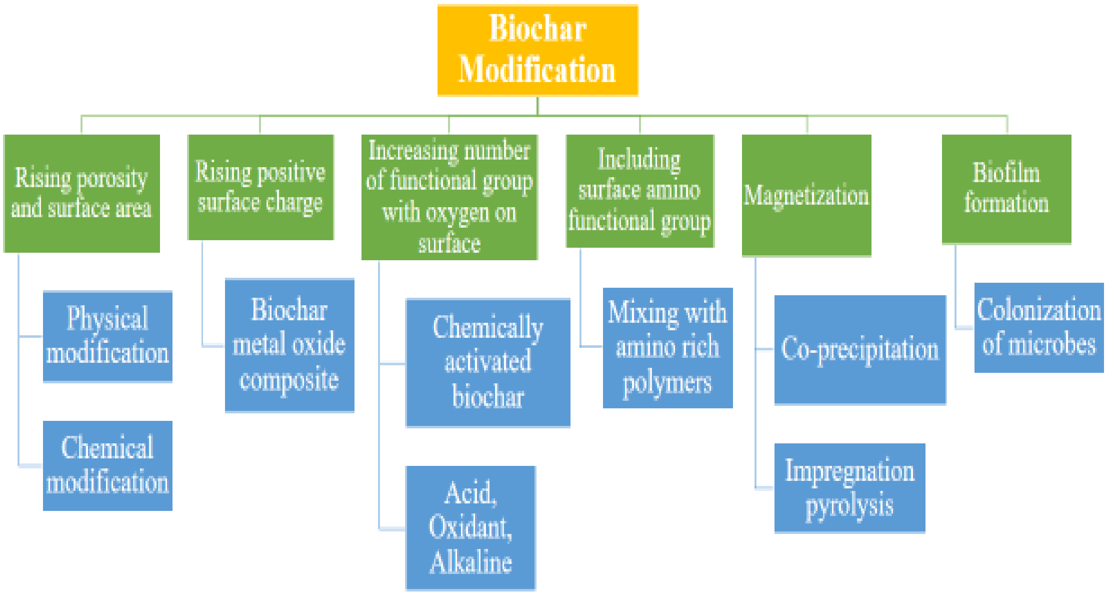

Figure 1: Biochar Modification

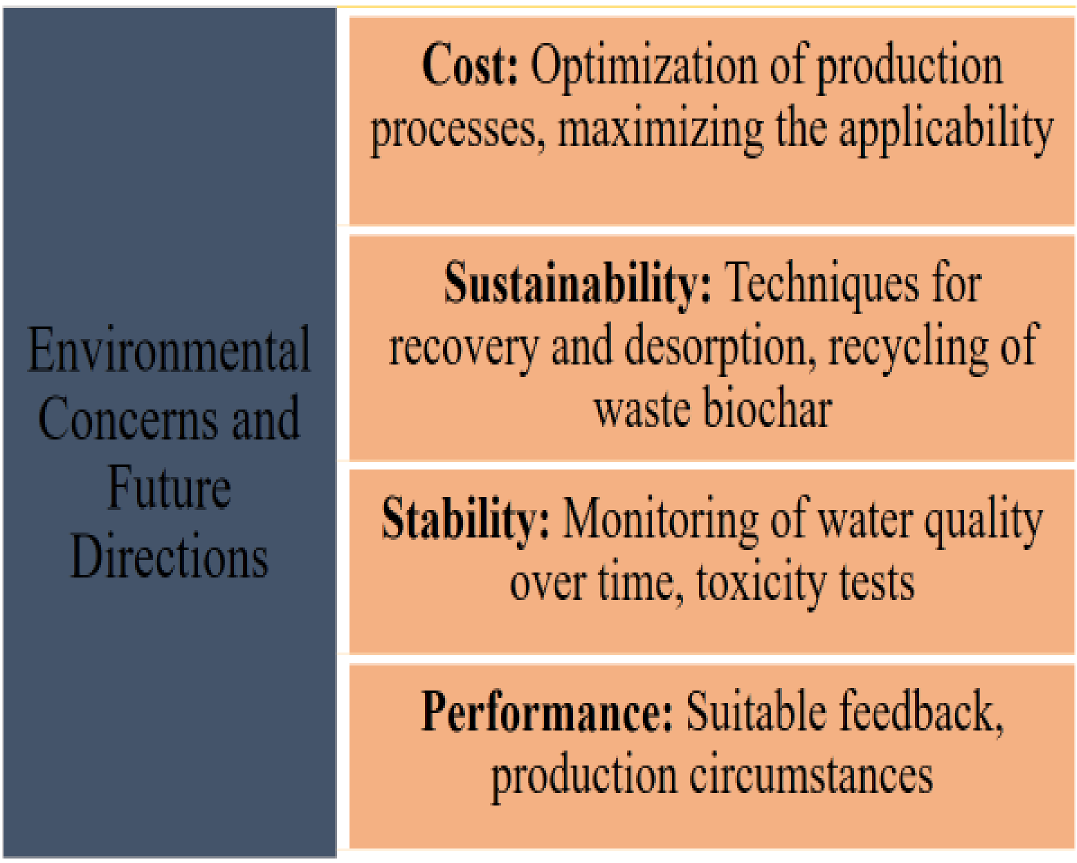

Figure 2: Environmental Concerns and Future Directions

Table 1: Highlights of the most current research that the BC has done on the elimination of different kinds of chemical contaminants.

Organic Compounds	BC Types	Findings
Dyes	AMBC, NaCl activated BC	According to the study, activated carbon nanotubes (BCs) demonstrated dye removal efficiencies ranging from 2 to 104 mg/g. Produced BC shown improved monolayer adsorption because of both –COOH and $–NH_2$ protonated groups.
Aromatics	Municipal solid waste BC	For toluene and m-xylene, high efficiencies of 850 and 550 mu g/g were noted.
Halocarbons	Commercial BCs made from rice husks and BCs made in a lab using maize stalks	High hydrophobicity of COCs, low polarity of BCs, and high aromaticity of BCs can all improve COCs adsorption by BCs.
Phenolics	Magnetic BC immobilized by laccase	Adsorption and enzymatic breakdown processes allowed the magnetic BC to efficiently remove BPA, and even after seven cycles, its efficacy remained above 85%.
Pesticides	Numerous kinds of BCs	Magnetic (BCs) have been shown to remove pesticides with an efficiency ranging from 0.02 to 23 mg/g. Physical, chemical, and biological changes can all improve BC efficiency.

6.5. Magnetization

A novel modification technique that addresses the challenge of removing biochar from aqueous solutions is magnetic biochar. The most popular techniques for making magnetic biochar are impregnation-pyrolysis and co-precipitation, which together make up roughly 69.6% of all preparation techniques [39]. Impregnation-pyrolysis is the process of impregnating a suspension of biochar with a transition metal salt solution, then pyrolyzing the residue. Higher sorption ability for Pb^{2+} and Cd^{2+} removal from solutions is demonstrated by magnetic biochar.

Magnetic biochar is widely synthesized by microwave heating, and biochars have a very high and almost equal sorption capacity for hydroquinone. Moreover, magnetic elements like Fe_2O_3, Fe_3O_4, FeO, and Fe0 are crucial for enhancing sorption capacity. The shape of magnetic components influenced by synthetic circumstances, such as temperature during pyrolysis. The removal efficiency is further improved by novel synthetic techniques that incorporate other metals such as Cu, Zn, and Mn [40].

6.6. Biofilm Formation

Biochar, because to its high surface area, porosity, and inert characteristic, can be employed as a scaffold for colonization and growth of biofilms. Microbes increase their viability by adhering to the surface of the biochar and forming an extracellular biofilm. Microbes' metabolism encourages the breakdown of refractory substances, while biochar's porous structure and surface functional groups aid in the sorption of pollutants. Biochar and biofilm are primarily used to encourage biodegradation of organic pollutants. Research has indicated that removal of pollutants from pharmaceutical wastewater can be accomplished using biochar filters with biofilm instead of traditional sand filters. Sorption and concurrent biodegradation work together to facilitate removal. Target contaminant's properties & removal process should guide the modification approaches chosen [41].

7. Environmental Concerns and Future Directions

Biochar is not yet widely used and is still in the testing stage, particularly in underdeveloped nations with weak industrial chains. Expanding the use of biochar requires addressing the environmental concerns and possible environmental issues. Biochar can be produced from a wide variety of readily available feedstock, however pyrolysis and preparation procedures are necessary. Future studies should strike a balance between boosting the use of biochar and streamlining the production process in order to save expenses. When using biochar and biochar-based composites in practical applications, stability should be taken into account. Particularly those made from sewage sludge, biochars may contain high levels of heavy metals that could leak out during application, leading to further contamination [42]. It is necessary to do research on how carbonization circumstances affect the amount and structure of carbon. Although studies have concentrated on the sorption of individual pollutants in aqueous solutions, the presence of several contaminants can produce both antagonistic and synergistic sorption effects. There is a dearth of empirical data on sorption of co-contaminants, and research on the sorption of biochar should provide enough details regarding the sorbent's characteristics and conditions under which it occurs [43]. Compared to activated carbon, biochar is inexpensive, renewable, and sustainable; nonetheless, sustainability requires recovery and desorption of utilized biochar. Contaminant-loaded biochar can be separated from water by magnetization, however desorption could be costly. As a resource, waste biochar can potentially be utilized as micro-nutrient fertilizer or as a slow-release fertilizer in agriculture. More research is need to determine whether adding waste biochar to soil is safe [44].

8. Conclusion

Polluted water and wastewater (W&W) can now be treated with new biological and physicochemical technologies. Although biomass-based (BC) technologies have been evolving quickly, they have mostly been created on a small scale in labs. This study evaluates advancements in the fields of technology, the environment, economics, and society. The most promising for quick commercialization are magnetic granted generations. To choose sustainable alternatives among the current BC-based W&W treatment systems, more research is required. It is necessary to promote the diverse field of BC use for actual W&W applications.

References

[1] F.R. Oliveira, A.K. Patel, D.P. Jaisi, S. Adhikari, H. Lu, S.K. Khanal. (2017). Environmental application of biochar: Current status and perspectives. Bioresource Technology. 246: 110-122.

[2] M. Kamali, K.M. Persson, M.E. Costa, I. Capela. (2019). Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: current status and future outlook. Environment international. 125: 261-276.

[3] S. Meyer, B. Glaser, P. Quicker. (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environmental science & technology. 45(22): 9473-9483.

[4] S. Joseph, C.I. Kammann, J.G. Shepherd, P. Conte, H.-P. Schmidt, N. Hagemann, A.M. Rich, C.E. Marjo, J. Allen, P. Munroe. (2018). Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. Science of The Total Environment. 618: 1210-1223.

[5] M.B. Ahmed, J.L. Zhou, H.H. Ngo, W. Guo, M. Chen. (2016). Progress in the preparation and application of modified biochar for improved contaminant removal from water and wastewater. Bioresource Technology. 214: 836-851.

[6] M. Kamali, L. Appels, E.E. Kwon, T.M. Aminabhavi, R. Dewil. (2021). Biochar in water and wastewater treatment-a sustainability assessment. Chemical Engineering Journal. 420: 129946.

[7] M. Van de Velden, J. Baeyens, A. Brems, B. Janssens, R. Dewil. (2010). Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction. Renewable energy. 35(1): 232-242.

[8] M.H. Duku, S. Gu, E.B. Hagan. (2011). Biochar production potential in Ghana—a review. Renewable and Sustainable Energy Reviews. 15(8): 3539-3551.

[9] M. Kamali. (2020). An Opinion on Multi-Criteria Decision-Making Analysis for Sustainability-Based Spatial Planning Practices. Time to Improve? Journal of Settlements and Spatial Planning. 2020(6): 1-3.

[10] L. Bolton, S. Joseph, M. Greenway, S. Donne, P. Munroe, C.E. Marjo. (2019). Phosphorus adsorption onto an enriched biochar substrate in constructed wetlands treating wastewater. Ecological Engineering. 142: 100005.

[11] Q. Yin, B. Zhang, R. Wang, Z. Zhao. (2017). Biochar as an adsorbent for inorganic nitrogen and phosphorus removal from water: a review. Environmental Science and Pollution Research. 24: 26297-26309.

[12] S. Ortiz-Monsalve, M. Gutterres, P. Valente, J. Plácido, S. Bustamante-López, D. Kelly, S. Kelly. (2020). Degradation of a leather-dye by the combination of depolymerised wood-chip biochar adsorption and solid-state fermentation with Trametes villosa SCS-10. Bioresources and Bioprocessing. 7: 1-18.

[13] S.S. Chen, Y. Cao, D.C. Tsang, J.-P. Tessonnier, J. Shang, D. Hou, Z. Shen, S. Zhang, Y.S. Ok, K.C.-W. Wu. (2020). Effective dispersion of MgO nanostructure on biochar support as a basic catalyst for glucose isomerization. ACS Sustainable Chemistry & Engineering. 8(18): 6990-7001.

[14] B. Wang, Z. Wang, Y. Jiang, G. Tan, N. Xu, Y. Xu. (2017). Enhanced power generation and wastewater treatment in sustainable biochar electrodes based bioelectrochemical system. Bioresource Technology. 241: 841-848.

[15] K.T. Klasson, C.A. Ledbetter, M. Uchimiya, I.M. Lima. (2013). Activated biochar removes 100% dibromochloropropane from field well water. Environmental chemistry letters. 11: 271-275.

[16] J. Zhong, L. Li, Z. Zhong, Q. Yang, J. Zhang, L. Wang. (2018). Advances on the research of the effect of biochar on the environmental behavior of antibiotics. Journal of Safety and Environment. 18(2): 657-663.

[17] W. Gwenzi, N. Chaukura, C. Noubactep, F.N. Mukome. (2017). Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. Journal of Environmental Management. 197: 732-749.

[18] D.V. Cuong, P.-C. Wu, N.-L. Liu, C.-H. Hou. (2020). Hierarchical porous carbon derived from activated biochar as an eco-friendly electrode for the electrosorption of inorganic ions. Separation and Purification Technology. 242: 116813.

[19] M. Kamali, S.A. Alavi-Borazjani, Z. Khodaparast, M. Khalaj, A. Jahanshahi, E. Costa, I. Capela. (2019). Additive and additive-free treatment technologies for pulp and paper mill effluents: Advances, challenges and opportunities. Water Resources and Industry. 21: 100109.

[20] T. Huggins, H. Wang, J. Kearns, P. Jenkins, Z.J. Ren. (2014). Biochar as a sustainable electrode material for electricity production in microbial fuel cells. Bioresource Technology. 157: 114-119.

[21] E.S. Azzi, E. Karltun, C. Sundberg. (2019). Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. Environmental science & technology. 53(14): 8466-8476.

[22] D.D. Sewu, H. Jung, S.S. Kim, D.S. Lee, S.H. Woo. (2019). Decolorization of cationic and anionic dye-laden wastewater by steam-activated biochar produced at an industrial-scale from spent mushroom substrate. Bioresource Technology. 277: 77-86.
[23] G. Enaime, A. Baçaoui, A. Yaacoubi, M. Lübken. (2020). Biochar for wastewater treatment—conversion technologies and applications. Applied Sciences. 10(10): 3492.
[24] S. He, L. Ding, X. Wang, Y. Pan, H. Hu, K. Li, H. Ren. (2018). Biochar carrier application for nitrogen removal of domestic WWTPs in winter: challenges and opportunities. Applied microbiology and biotechnology. 102: 9411-9418.
[25] L. Dunnigan, P.J. Ashman, X. Zhang, C.W. Kwong. (2018). Production of biochar from rice husk: Particulate emissions from the combustion of raw pyrolysis volatiles. Journal of Cleaner Production. 172: 1639-1645.
[26] F. Lian, B. Xing. (2017). Black carbon (biochar) in water/soil environments: molecular structure, sorption, stability, and potential risk. Environmental science & technology. 51(23): 13517-13532.
[27] A. Giwa, A. Yusuf, O. Ajumobi, P. Dzidzienyo. (2019). Pyrolysis of date palm waste to biochar using concentrated solar thermal energy: Economic and sustainability implications. Waste Management. 93: 14-22.
[28] M. Kamali, D. Suhas, M.E. Costa, I. Capela, T.M. Aminabhavi. (2019). Sustainability considerations in membrane-based technologies for industrial effluents treatment. Chemical Engineering Journal. 368: 474-494.
[29] P.P. Otte, J. Vik. (2017). Biochar systems: Developing a socio-technical system framework for biochar production in Norway. Technology in Society. 51: 34-45.
[30] X. Zhou, C. Liang, L. Jia, L. Feng, R. Wang, H. Wu. (2018). An innovative biochar-amended substrate vertical flow constructed wetland for low C/N wastewater treatment: impact of influent strengths. Bioresource Technology. 247: 844-850.
[31] C. Deng, L. Huang, Y. Liang, H. Xiang, J. Jiang, Q. Wang, J. Hou, Y. Chen. (2019). Response of microbes to biochar strengthen nitrogen removal in subsurface flow constructed wetlands: Microbial community structure and metabolite characteristics. Science of The Total Environment. 694: 133687.
[32] L.F. Perez-Mercado, C. Lalander, A. Joel, J. Ottoson, S. Dalahmeh, B. Vinnerås. (2019). Biochar filters as an on-farm treatment to reduce pathogens when irrigating with wastewater-polluted sources. Journal of Environmental Management. 248: 109295.
[33] T. Sizmur, T. Fresno, G. Akgül, H. Frost, E. Moreno-Jiménez. (2017). Biochar modification to enhance sorption of inorganics from water. Bioresource Technology. 246: 34-47.
[34] L. Zhao, W. Zheng, O. Mašek, X. Chen, B. Gu, B.K. Sharma, X. Cao. (2017). Roles of phosphoric acid in biochar formation: synchronously improving carbon retention and sorption capacity. Journal of environmental quality. 46(2): 393-401.
[35] X. Tan, Y. Liu, G. Zeng, X. Wang, X. Hu, Y. Gu, Z. Yang. (2015). Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere. 125: 70-85.
[36] Z. Song, F. Lian, Z. Yu, L. Zhu, B. Xing, W. Qiu. (2014). Synthesis and characterization of a novel MnOx-loaded biochar and its adsorption properties for Cu2+ in aqueous solution. Chemical Engineering Journal. 242: 36-42.
[37] J. Tang, H. Lv, Y. Gong, Y. Huang. (2015). Preparation and characterization of a novel graphene/biochar composite for aqueous phenanthrene and mercury removal. Bioresource Technology. 196: 355-363.
[38] Y. Zhou, B. Gao, A.R. Zimmerman, J. Fang, Y. Sun, X. Cao. (2013). Sorption of heavy metals on chitosan-modified biochars and its biological effects. Chemical Engineering Journal. 231: 512-518.
[39] Y. Yi, Z. Huang, B. Lu, J. Xian, E.P. Tsang, W. Cheng, J. Fang, Z. Fang. (2020). Magnetic biochar for environmental remediation: A review. Bioresource Technology. 298: 122468.
[40] S. Zhang, Y. Ji, J. Dang, J. Zhao, S. Chen. (2019). Magnetic apple pomace biochar: Simple preparation, characterization, and application for enriching Ag (I) in effluents. Science of The Total Environment. 668: 115-123.
[41] X. Duan, H. Sun, S. Wang. (2018). Metal-free carbocatalysis in advanced oxidation reactions. Accounts of Chemical Research. 51(3): 678-687.
[42] X. Wang, Z. Guo, Z. Hu, J. Zhang. (2020). Recent advances in biochar application for water and wastewater treatment: a review. PeerJ. 8: e9164.
[43] Y. Wang, M.B. Villamil, P.C. Davidson, N. Akdeniz. (2019). A quantitative understanding of the role of co-composted biochar in plant growth using meta-analysis. Science of The Total Environment. 685: 741-752.
[44] D. Mohan, R. Sharma, V.K. Singh, P. Steele, C.U. Pittman Jr. (2012). Fluoride removal from water using bio-char, a green waste, low-cost adsorbent: equilibrium uptake and sorption dynamics modeling. Industrial & Engineering Chemistry Research. 51(2): 900-914.