BILINGUAL PUBLISHING GROUP

Journal of Building Material Science
https://journals.bilpubgroup.com/index.php/jbms

REVIEW

Innovative Approaches to Pretreatment and Modification of Sewage Sludge-Derived Biochar for Resource Recovery: A Short Review

Vijendra Singh Tanwar [1], *Santosh Kumar Singh* [2], *Jitendra Kumar Sharma* [1], *Ritesh Patidar* [3*]

[1] *Department of Civil Engineering, Rajasthan Technical University, Kota 324010, India*
[2] *Department of Civil Engineering, Delhi Technological University, Delhi 110042, India*
[3] *Department of Petroleum Engineering, Rajasthan Technical University, Kota 324010, India*

ABSTRACT

The uptake of biochar from sewage sludge has developed into a critical avenue for resource reclamation whilst solving waste disposal concerns. However, despite the latter side in environmental palliative, the use of this biochar for remediation, recovery of nutrients, or adsorption of pollutants is often suboptimal due to poor surface area, high percentage of ash and functional group scarcity. Sewage sludge-derived biochar (SSB) has emerged as a promising material for resource recovery, environmental remediation, and sustainable waste management.This review paper scopes out the recent developments in the field of sludge derived biochar and focuses on the advances in hydrothermal carbonization biochar and its modified forms. Pretreatment methods such as hydrothermal carbonization, enzymatic treatment, ultrasonic, and acid/base wash are looked into in order to improve the purity and the characteristics of the feedstock. Post the structural adjustments some of the molecular modification methods are implemented using KOH, $ZnCl_2$ and H_3PO_4 for chemical activation, doping with Fe/Mn or Mg, and thermal and microwave processes which are aimed at increasing porosity, adsorption and catalytic activity. The review also evaluates the combination of various methods to fabricate multifunctional biochar for applications such as phosphate recycling, heavy metals and carbon absorption and utilization, as well as the application of biochar as catalysts in advanced oxidation processes.

Keywords: Geotechnical Properties; Municipal Sewage Sludge; Particle size Distribution; Treatment Process

*CORRESPONDING AUTHOR:
Ritesh Patidar, Department of Petroleum Engineering, Rajasthan Technical University, Kota 324010, India; Email: rpatidar@rtu.ac.in

ARTICLE INFO
Received: 19 March 2025 | Revised: 15 April 2025 | Accepted: 18 April 2025 | Published Online: 23 September 2025
DOI: https://doi.org/10.30564/jbms.v7i3.9157

CITATION
Tanwar, V.S., Singh, S.K., Sharma, J.K., et al., 2025. Innovative Approaches to Pretreatment and Modification of Sewage Sludge-Derived Biochar for Resource Recovery: A Short Review. Journal of Building Material Science. 7(3): 206–219. DOI: https://doi.org/10.30564/jbms.v7i3.9157

1. Introduction

One of the increasing problems in the society is the management of municipal sewage sludge. Its increasing generation coupled with the stringent regulations surrounding it make it an economic challenge and an environmental deficit. Sewage sludge is termed as the 'separated biosolid' and is generated from the treatments of wastewater and is rich in organic matter as well as nutrients. It also contains hazardous materials such as heavy metals, pathogens and persistent organic matter which restrict its use and disposal [1–5]. Some of the common means of disposal, including landfilling, incineration and land application spew substantial amounts of greenhouse gasses have soil, water and public health repercussions [5–7].

However, this scenario can now be changed, as a result of the thermal and chemical biomass transformation processes—especially pyrolysis—that organic waste or sewage appears to be 'organic black gold' in the shape of biochar. Additionally, biochar increases the surface area of pollutants alongside decreasing the amount of sludge within the mixture. Consequently, biochar can be utilized for three major purposes: improvement of soil, adsorption of pollutants, and recovery of nutrients [8–10]. Raw biochar that is created from sewage sludge, comes at a cost as it comprises of several hurdles which affect its performance in the advanced segments, such as low porosity, limited surface area and high ash content. Pathways and Treatment Processes for Biochar Derived from Various Wastewater Sources shows in **Figure 1**.

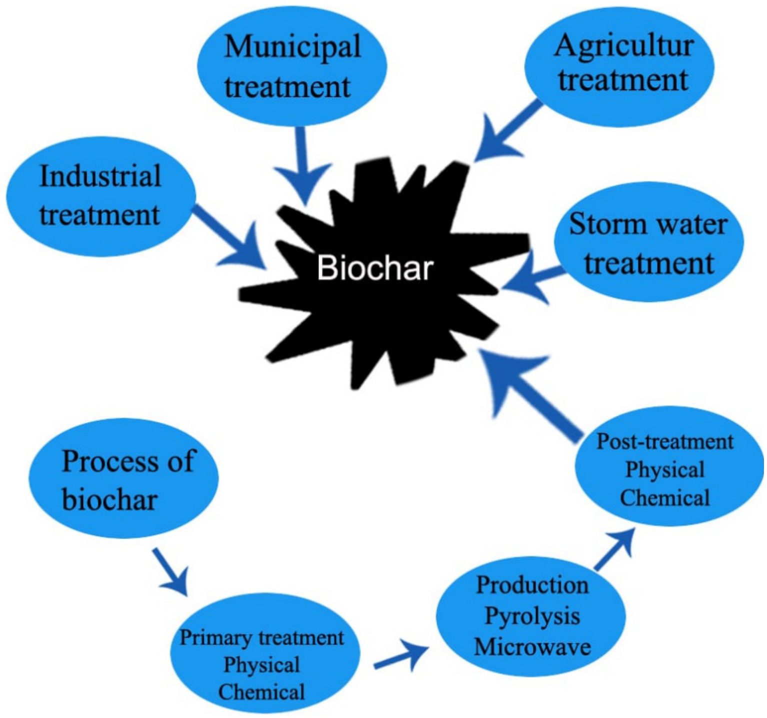

Figure 1. Pathways and Treatment Processes for Biochar Derived from Various Wastewater Sources.

2. Sewage Sludge as A Feedstock for Biochar Production

In the process of treating municipal effluent, sewage sludge is produced, currently it is increasingly viewed as a useful biochar feedstock. The reason for this is its concentration of organic matter which is rich in certain nutrients, For example, in general, sewage sludge contains significant concentrations of nitrogen (N) phosphorus (P) and potassium (K) and other trace elements which when added to biochar can improve productivity of degraded soils [11–15]. Besides, the large quantity of carbon available from sludge could also be used for carbon sequestration and hence lessen greenhouse effects. However, the use of sewage sludge has drawbacks due to the fact that it may contain heavy metals, antibiotics, and pathogens, and this fact can limit its usage [15–20]. To get over these problems, pre-treatment methods, including solar drying, dewatering and chemical stabilization in most cases have to be resorted to. Moreover, the high ash content found in sludge may modify the structural attributes of the produced biochar which may lead to decreased adsorption ability and porosity of the biochar.The biochar obtained depends on the sewage sludge, its origin and treatment received. Summary of Sewage Sludge as a Feedstock for Biochar Production shows in **Table 1**. Applications of Biochar in Agriculture and Soil Enhancement shows in **Figure 2**.

Table 1. Summary of Sewage Sludge as a Feedstock for Biochar Production.

Aspect	Details	References
Composition	Rich in organic matter, nitrogen (N), phosphorus (P), and potassium (K).	Zhao et al., 2017
Carbon Sequestration	Stabilizes organic carbon, contributing to climate change mitigation.	Lehmann et al., 2021
Challenges	Contains heavy metals, pathogens, and organic pollutants requiring pretreatment.	Ahmad et al., 2014
Feedstock Variability	Varies based on wastewater source and treatment process, influencing biochar properties.	Qambrani et al., 2017
Pyrolysis Conditions	Temperature and heating rate affect nutrient retention, surface area, and contaminant immobilization.	Qambrani et al., 2017
Applications	- Soil amendment: Improves fertility and structure. - Water treatment: Removes pollutants. - Environmental remediation: Immobilizes contaminants.	Beesley et al., 2011

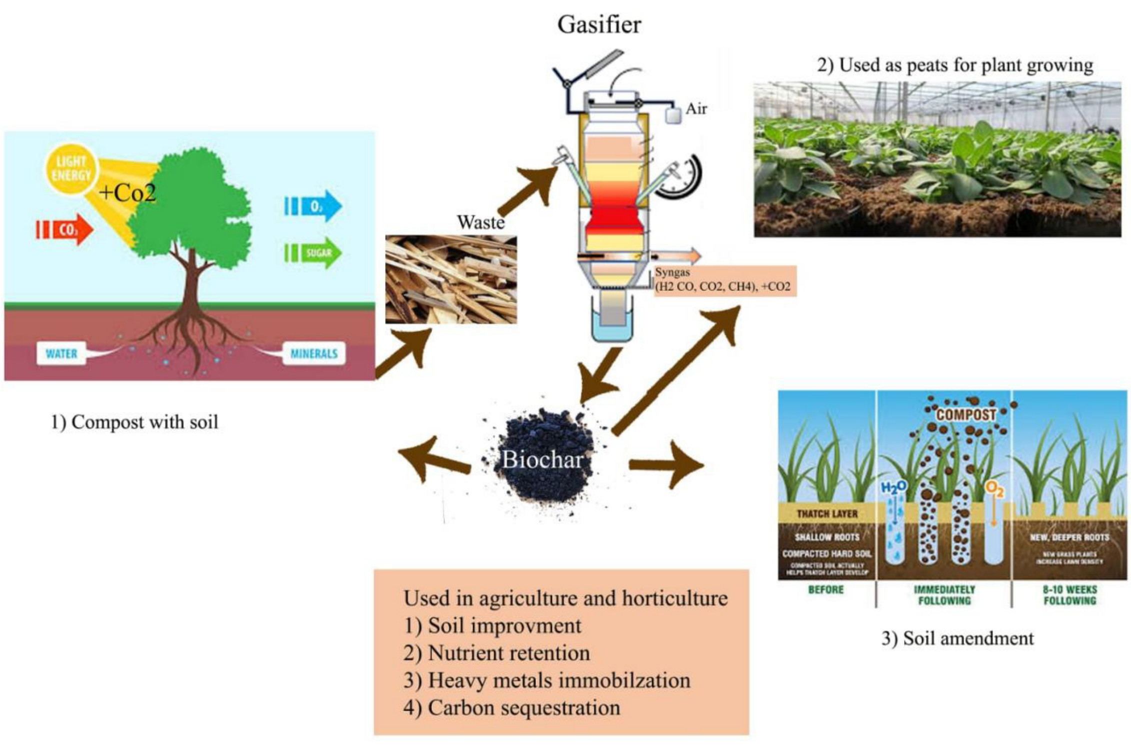

Figure 2. Applications of Biochar in Agriculture and Soil Enhancement.

2.1. Composition and Characteristics of Sewage Sludge

Sewage sludge is known to be an end product of wastewater treatment dominated by water, organic matter, inorganic substances as well as contaminants. Some of the organic elements are proteins, carbohydrates, lipids and other complex carbon compounds which account for a large portion of the biochar carbon content that is derived from sewage sludge [4,20–24]. There is a potential high value in the calorific of biochar due to the energy materials provided by these organic materials. There is also a non-negligible quantity of sewage sludge which contains such nutrients as nitrogen (N), phosphorus (P) and potassium (K) necessary for plant's development and can be reused through biochar thus increasing its efficiency as soil modifier [24–29]. Severally being a contributor to organic matter, sewage sludge has a profile of diverse organic nutrients within it some of which comprise of major and trace metals such as iron, copper, zinc, cadmium, lead, manganese, magnesium, potassium, sodium as well as heavy metals. Trace metals and persistent organic pollutants (POPs) in the sewage sludge-derived biochar are unable to suit environmentally friendly application since leaching of these pollutants to the environment graph, soil and plants is an eventuality [30–32]. Typical Composition of Sewage Sludge shows in **Table 2**.

Table 2. Typical Composition of Sewage Sludge.

Parameter	Range	Description	References
Moisture Content (%)	60–85	Reduces efficiency during pyrolysis.	Xiao et al., 2022
Volatile Solids (% dry)	50–70	Represents organic matter contributing to biochar.	Zhang et al., 2023
Ash Content (% dry)	20–40	Determines mineral content and stability.	Gopinath et al., 2021
pH	6.0–8.5	Affects microbial activity and pretreatment processes.	Fan et al., 2023
Nitrogen (%)	2–5	Influences biochar's nutrient recovery potential.	Giwa et al., 2023
Phosphorus (%)	1–3	Significant for resource recovery applications.	Wang et al., 2022
Heavy Metals (mg/kg)	Varies (Zn, Cu, Pb, Cd)	Requires mitigation to meet safety standards.	Chen et al., 2021

2.2. Challenges in Direct Utilization of Sewage Sludge

When it comes to direct usage of sewage sludge there are so many problems, which are associated with the use of sludge, as its nonspecific nature, and presence of pathogens. Toxic and recalcitrant heavy metals such as arsenic (As), chromium (Cr), and nickel (Ni) are present in sludge and are traceable in the wetlands. Long term exposure to these elements can result in soil and water pollution, which in turn can affect the food chain Compounding the problem, the moisture retention of sewage sludge is another mountain to climb, and it may take anywhere from 70- 85%. Raw sludge which is wet can prove to be economical expensive to transport and reduces the efficiency of the end process, in this case, transformation into useful products through pyrolysis, incineration or even composting. Dewatering is one of the reliable methods for volume reduction and making preconditioning and mounting easier. Intestinal pathogenic bacteria such as E.coli , viruses such as helminths and other microorganisms make it more difficult to apply sludge directly for agricultural and crop purposes. The application of untreated sludge especially without proper stabilization and or disinfection treatments might result into endemics and specific forms of disease or infection through mass consumption of contaminated plants or contact with polluted underground water. Challenges in Direct Utilization of Sewage Sludge shows in **Table 3**.

Table 3. Challenges in Direct Utilization of Sewage Sludge.

Challenge	Description	Impact	References
Heavy Metal Contamination	Presence of metals like Cd, Pb, Hg, Cr, and Ni, which are toxic and persistent.	Soil and water pollution; bioaccumulation.	Ahmad et al., 2014
High Moisture Content	Moisture levels often exceed 70–85%, increasing handling and processing costs.	Reduces efficiency of treatment processes.	Qambrani et al., 2017
Pathogenic Microorganisms	Contains bacteria, viruses, and parasites that spread diseases.	Public health risks in agricultural reuse.	Smith et al., 2019
Emerging Contaminants	Includes pharmaceuticals, microplastics, and endocrine disruptors.	Environmental persistence; soil degradation.	Chen et al., 2017
Odor Emissions	Emission of gases like NH_3, H_2S, and VOCs causing unpleasant smells.	Affects air quality; operational challenges.	Wang et al., 2021
Variability in Composition	Composition changes due to wastewater sources and treatment processes.	Inconsistent quality; limits reuse potential.	Lehmann et al., 2011
Energy Costs	High energy demand for dewatering, drying, and advanced treatments.	Increases operational and economic burden.	Beesley et al., 2011
Regulatory Constraints	Stringent standards for heavy metals, pathogens, and contaminants in sludge reuse.	Limits direct application in various sectors.	Ahmad et al., 2014

2.3. Advantages of Biochar Derived from Sewage Sludge

The biochar that is produced from sewage sludge has some characteristics that are beneficial to the environment and economy which makes it possible to be used for waste treatment and resource recovery. Its primary advantage is that it can be used as a soil conditioner. Because of its porous structure and high ratio of carbon, biochar can enhance soil fertility, water retention ability, and microbial activity which are important for agricultural development .Moreover, the presence of elements such as phosphorus (P), potassium (K), and nitrogen (N) in the sludge biochar increases its benefit as a slow release fertilizer and helps to cut synthetic inputs .

Another non-negligible benefit is its ability to remove pollutants. Both lead and zinc biochar which is produced from sludge, has good low-cost heavy metal adsorption, organics and emerging contaminants, such as pharmaceuticals and dyes in wastewater, such biochar possesses attributes such as high surface area, a range of functional groups and cation exchanger capacity. This means biochar can be used effectively in the treatment of wastewater and in restoration of the environment. Advantages of Biochar Derived from Sewage Sludge shows in **Table 4**.

Table 4. Advantages of Biochar Derived from Sewage Sludge.

Advantage	Description	Impact	References
Soil Fertility Improvement	Biochar enhances soil nutrient retention, water-holding capacity, and microbial activity.	Improves crop yields and soil health.	Beesley et al., 2011
Slow-Release Fertilizer	Rich in nutrients like nitrogen (N), phosphorus (P), and potassium (K).	Reduces dependence on synthetic fertilizers.	Laird et al., 2010
Pollutant Removal	Adsorbs heavy metals, organic pollutants, and emerging contaminants like pharmaceuticals.	Enhances water and soil quality.	Qambrani et al., 2017

Table 4. *Cont.*

Advantage	Description	Impact	References
Carbon Sequestration	Converts organic carbon in sludge to stable biochar, reducing CO_2 emissions.	Contributes to climate change mitigation.	Shen et al., 2021
Energy Generation	Pyrolysis of sewage sludge produces syngas and bio-oil for renewable energy.	Increases energy efficiency and sustainability.	Hossain et al., 2011
Waste Volume Reduction	Reduces the volume and toxicity of sewage sludge, lowering disposal costs.	Minimizes landfill use and environmental risks.	Beesley et al., 2011
Pathogen Elimination	Thermal conversion of sewage sludge eliminates pathogens.	Makes biochar safer for use in agriculture.	Liu et al., 2019
Environmental Remediation	Adsorptive capacity of biochar helps in cleaning contaminated sites.	Supports environmental restoration efforts.	Chen et al., 2020

3. Pretreatment Techniques for Sewage Sludge

Sewage sludge first has to be converted into biochar, and in order to make this process efficient, proper treatment techniques need to be employed. These methods can alter some of the chemical, physical and structural properties of the sludge and make it easier for the pyrolysis to happen while increasing the effectiveness of the biochar produced. Here we introduce and present some more advanced and conventional pretreatment techniques backed by literature.

3.1. Thermal Pretreatment

In the case of so-called physical pretreatment, the focus is on changing the structure and moisture content of the sludge in order to enhance the efficiency of pyrolysis. Drying and Dewatering: Reduction of the moisture content leads to lower energy requirements in pyrolysis. Mechanical dewatering and thermal drying are commonly practiced .Grinding and Milling: Reduced particle size will lead to an enlarged surface area and therefore enhanced heat exchange during pyrolysis .Ultrasound Pretreatment: Ultrasound treatment breaks down sludge flocs and walls of cells, this makes organic matter further available for the process of pyrolysis (Xue et al., 2019).

3.2. Chemical Pretreatment

The composition of sludge can be altered with the use of chemical methods which also increases the nutrients embedded in resulting biochar.Acid and Alkali Treatments: The pH of the sludge is modified during acid (for e.g. HCl, H_2SO_4) and alkali (NaOH) application thereby increasing the nutrient content in the resulting biochar and the biochar adsorption capacity .Oxidative Pretreatment: The use of peroxide and ozone treatment oxidizes polysaccharides resolving complex organic molecules and optimizing the performance of pyrolysis as well as changing the characteristics of the biochar.Metal Ion Addition: The use of metal salts such as Fe^{3+} or Mg^{2+} are useful in increasing the amount of phosphorus in biochar during the recovery process.

3.3. Biological Pretreatment

Biological approaches use microorganisms for the purpose of organic degradation and the development of sludge quality.Anaerobic Digestion: Anaerobic digestion as a pre-treatment of sludge minimizes the organic substance and increases the pyrolysis performance.Enzymatic Hydrolysis: Certain enzymes can degrade proteins and lipids, thus increasing the synovial bioavailability of organic materials.

3.4. Combined Pretreatment Approaches

Before the pyrolyses, sludge overcomes thermal pretreatment. This means it needs to be heated in order to achieve the wanted change in its structure and composition.Hydrothermal Carbonization (HTC): During the HTC process, the sludge is treated at a temperature below its critical point in water, which increases the carbon content of sludge, and decreases the hazardous contents.Microwave Heating: By pre-treating with microwaves, organic compounds are first decomposed, resulting in a more porous and adsorptive biochar.

4. Modification Techniques for Biochar

Changing sewage sludge based biochar is a quite essential segment of study as it is aimed on improving the biochars structural, chemical or functional characteristics for resource recovery. Several approaches, namely, physical, chemical, and biological modifications are made to enhance the particular properties of biochar. More detail is provided in the review section with citations below. Multifunctional Benefits of Biochar for Environmental Sustainability shows in **Figure 3** and Modification Techniques for Sewage Sludge-Derived Biochar shows in **Table 5**.

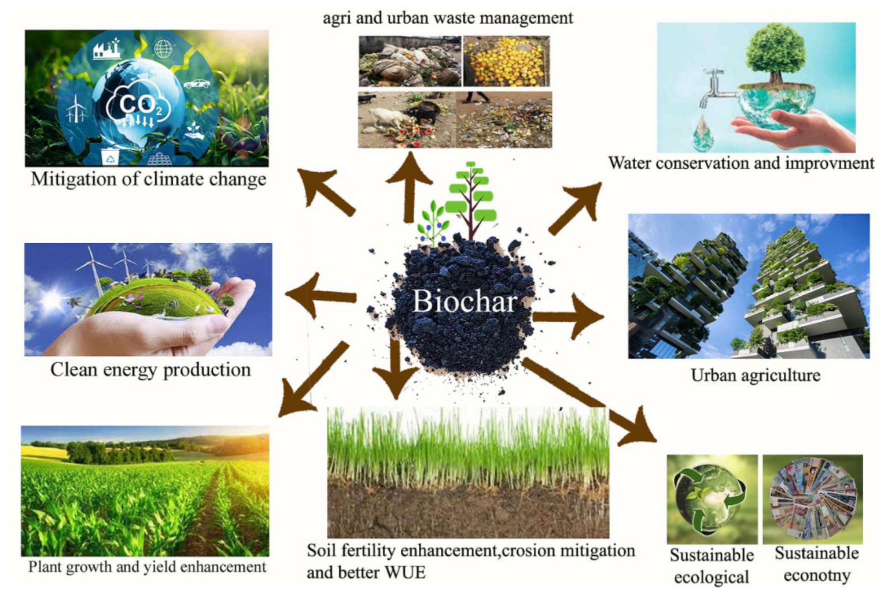

Figure 3. Multifunctional Benefits of Biochar for Environmental Sustainability.

Table 5. Modification Techniques for Sewage Sludge-Derived Biochar.

Modification Technique	Description	Advantages	References
Thermal Activation	Heating biochar in controlled atmospheres.	Expands pore structure and increases specific surface area.	Zhu et al., 2018
Ball Milling	Mechanical reduction of particle size.	Exposes active sites and improves dispersion.	Kim et al., 2023
Chemical Modification	Introduces or modifies functional groups.	Enhances adsorption, reactivity, and selectivity.	Zhao et al., 2019
Acid Treatment	Treatment with HNO_3, H_2SO_4, etc.	Introduces oxygen-containing groups for heavy metal and organic pollutant adsorption.	Inyang et al., 2012
Alkali Treatment	Treatment with NaOH, KOH, etc.	Increases porosity and adds negative functional groups, improving phosphate recovery.	Zhao et al., 2019
Oxidation Treatments	Use of H_2O_2 or O_3.	Enhances hydrophilicity and reactivity.	Wu et al., 2012
Metal Doping	Incorporation of Fe, Zn, Mg, etc.	Improves magnetic, catalytic, and adsorption properties.	Xu et al., 2020
Biochar-Nanoparticle Composites	Incorporating nanoparticles like nZVI.	Enhances adsorption and catalytic performance.	Chen et al., 2019

4.1. Physical Modification

Physical methods involve surface coating the biochar and change its pores structure thereby making its sorption and reactivity characteristics better. Thermal Activation: Treating biochar at elevated temperatures increases specific surface area and the pore volume at controlled atmosphere leading to improved adsorption performance. Microwave Irradiation: Microwave treatment rapid and uniform heating inducing improvement on pore and surface functional devises Ball Milling: Mechanical milling reduces particle size which improves dispersion and active sites; thereby enhancing its potential in catalysis and adsorption.

4.2. Chemical Modification

An approach involving contact with a chemical agent that is designed to bring about specific pollutants or nutrients in the biochar chemical alteration.Acid Treatment: For biochar, acid treatment using HNO_3 and H_2SO_4 not less results in improvement by introducing oxygen containing groups which are necessary for adsorption of heavy organic and metal pollutants.Alkali Treatment: Applying NaOH or KOH to Biochar improves its microporosity as well as giving it negative charged functional groups that are useful for phosphate and ammonium recovery.Oxidation Treatments: Oxidation of Biochar using H_2O_2 or O_3 increases surface reactivity and wettability of biochar to pollutants. Metal Doping: Enhanced magnetism and catalytic activities of biochar through incorporation of Fe, Mg and Zn are relevant in applications of resource recovery.

4.3. Biological Modification

Approaches targeting specific application of charcoal using biological modes such as microbes or enzymes as catalysts are called biological approaches.Biofilm Coating: Growth of microbial biofilms onto biochar particles is said to enhance bioreactors and wastewater treatment systems. Enzyme Treatment: Biochar application is made easier by modifying the surface of the carbonaceous substrate selectively with bioactive enzymes in a bid to enhance nutrient recovery.

4.4. Composite Formation

When biochar is mixed with other materials, it has increased functional properties due to synergistic effects. Biochar-Clay Composites: Such composites allow for improved agricultural implements with a greater capacity for nutrient retention with slow-release properties. Biochar-Nanoparticle Composites: Such composites generally contain nanoscale zero-valent iron (nZVI) which significantly enhances the adsorption and catalytic efficiency.

4.5. Hybrid Techniques

Biochars having multiple functional properties are developed by using hybrid techniques which combine a number of modification methods. For example, it was shown that the use of metal doping in conjunction with oxidation treatments improves the catalytic activity and adsorption ability.

5. Resource Recovery Applications

Because of the synthetic characteristics obtained after modifying these bio chars, they have been increasing spotlight particularly in resource recovery applications. These resources include nutrients, metals, and energy and aim to be environmentally sustainable in the process. Resource Recovery Applications of Sewage Sludge-Derived Biochar show in **Table 6**.

Table 6. Resource Recovery Applications of Sewage Sludge-Derived Biochar.

Application	Description	Key Benefits	References
Nutrient Recovery	Recovery of essential nutrients like nitrogen and phosphorus.	Enhances agricultural productivity; reduces reliance on chemical fertilizers.	Zhao et al., 2019
Ammonium Recovery	Using alkali-treated biochar for ammonium adsorption.	Provides a sustainable nitrogen source for fertilizers.	Zhao et al., 2019
Heavy Metal Recovery	Adsorption and recovery of heavy metals from wastewater.	Reduces environmental contamination; recovers valuable metals.	Xu et al., 2020
Carbon Sequestration	Stabilizing carbon in biochar for long-term storage.	Reduces greenhouse gas emissions.	Lehmann et al., 2021

Table 5. *Cont.*

Application	Description	Key Benefits	References
Water Purification	Adsorption of organic pollutants and nutrients from wastewater.	Improves water quality; enables pollutant recovery.	Chen et al., 2019
Soil Amendment	Application of biochar to improve soil properties.	Enhances soil fertility, structure, and water retention.	He et al., 2020
Slow-Release Fertilizers	Use of biochar as a carrier for slow-release nutrients.	Reduces nutrient leaching; improves fertilizer efficiency.	Gao et al., 2021

5.1. Nutrient Recovery

Biochar has been found to recover some nutrients such as nitrogen (N), Phosphorus (P) that are useful in agriculture.Phosphorus Recovery: Biochar can effectively adsorb and recover phosphorus, which is a non-renewable resource and crucial nutrient, particularly when it is modified with metal ions, such as magnesium or calcium, which contain a significant amount of ion strength. Such a process is favorable for the treatment of wastewater.Ammonium Recovery: Biochar treated with alkalis high ammonium affinity and thus its ammonium ions can be recovered and applied in agriculture as fertilizer.

5.2. Heavy Metal Recovery

Due to a good surface area and gold surface groups, biochar has the ability to fix and extract heavy metals in effluents and polluted waters.Metal Adsorption and Recovery: It's possible to reclaim copper, lead, zinc, and cadmium from aqueous solutions by using metal oxide or functional group doped biochar.Catalytic Applications: The doped biochars metal is a catalyst for any advanced oxidation processes and the purpose is to enable the retrieval of precious metals from obsolete industrial wastes.

5.3. Carbon Recovery

The biochar is a carbon sink and it is also a way to capture and recycle carbon in different ways.Carbon Sequestration: Carbon storing which has long duration is what biochar contributes in as it is stable in form and aids in the recovery of carbon while also minimizing the emission of greenhouse gases. Energy Recovery: Biochar can then become a renewable fuel, be it in solid form or for production of biogas via gasification or pyrolysis.

5.4. Energy Generation and Resource Recovery

Biochar derived from sewage sludge can be used as a feedstock in energy generation and resource recovery activities.Gasification and Pyrolysis: Gasification is also known as Aqueous Phase Reforming which is a thermal process that transforms biochar into syngas, considered to be a renewable energy expression, pyrolysis oil and biochar are also produced with a potential of further extraction. Hydrothermal Liquefaction (HTL): The Hydrothermal liquefaction – of Biochar of biochar leads to the production of liquid biofuels which also opens the opportunity of resource recovery as well as solving energy issues (**Figure 4**).

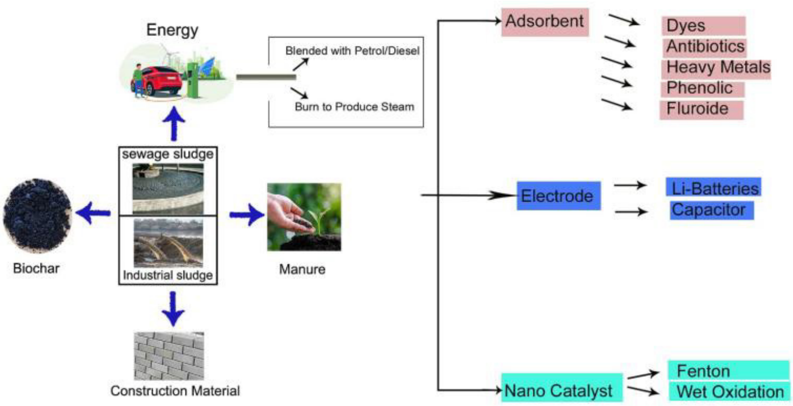

Figure 4. Utilization of Sewage and Industrial Sludge: Biochar Applications for Energy,Environmental Remediation, and Construction.

5.5. Removal of Dyes and Other Pollutants from Wastewater Using Biochar

Biochar is a promising adsorbent for use wastewater troubled with organic compounds such as dyes, pharmaceuticals among others.Adsorption of Organic Pollutants: Functionalized biochar performs better in removing particle-attached organic pollutants and has much better potential in pollutant harvesting from and water treatment. Nutrient Recycling in Agriculture: The nutrients removed from wastewater can also be reutilised on land to improve its nutritional status and reduce the use of chemical fertilizers.

5.6. Recovery of Fertilizers and Amendment of Soils

Sewage Sludge Biochar can be utilized directly on soils or as a carrier of fertilizers.Enhancement of Soil Fertility: Biochar improves the structure of the soil, water retention and nutrient availability for sustainable agricultural development.Slow-Release Fertilizers: Nutrients bound onto surfaces of biochar function as slow release fertilizers and effectively improve nutrient use efficiency and minimize leaching loss [33].

6. Comparative Analysis of Pretreatment and Modification Techniques

Environmental Friendly Technologies One of the Small and Micro-scale Technologies for Resources Recovery and Reutilization Pretreatment and modification methods are vital for improving the physicochemical properties of biochar obtained from sewage sludge so that it can meet different environmental as well as industrial needs. Bol grinding, thermal activation, microwave irradiation, mechanical activation and ball milling to name a few augment porosity, surface area, active sites and other properties of biochar. Thermal activation is particularly known for improving the adsorption capacity of biochar but it is highly energy dependent .In sharp contrast, Even though microwave has advantages saelling thermal-activated, it is/ microwave-synthesized materials, resulting in pore formation. It helps to improve the reaction by expanding the active site; nevertheless, amalgamating may lead to loss of micro integrity . Supertites are available within the Synthetic Biology Modification Techniques Metals Doping, Acidic treatment, and Alkalis treatment Ou Enlarge Enzyme S Group Adsorption Cheat and Alteration Biochar of Functional Groups. Oxygens functionalisation are capable to increase adsorption capacity of heavy metals – appeared reasonable to use acid treatment but of costly – are highly corrosive to work with In contrast, negative functional groups impair cross linking between biochar particles, which in turn leads to limitations in the recovery of - phosphate adsorption. Alkaline treatment enhances nutrient recovery. Enhancing the Fiber Reinforced Thermoplastics marketNew biological modifications like application of biofilm and enzyme treatment are also aimed at facilitating biochar surface functionalization. On the other hand, biochar coated with biofilm was proven to perform in nutrient recovery and wastewater treatment but could be a challenge especially under extreme conditions. Enzyme treatment improves the functional quality of biochar, hence making it suitable for certain purposes but its expensive nature limit its bulk utilization.

Besides the composite formation and thermal chemical techniques also acts to improve the functionality of biochar. For instance clay-biochar composites have improved retention and slow release of nutrients, and the same can be said of the nanoparticle composites, however concerns still exist over nanoparticle leaching. A concept like hydrothermal carbonization allows the combination of heat and chemicals for the production of biochar with improved topological properties although the energy demands of the process currently warrants improvement before the technology can be widely adopted.

7. Challenges and Limitations

While there are many ways that biochar produced from sewage sludge can be employed so starting with the resource utilization and moving on to various applications, there are notable challenges and shortcomings. In those applications, the biochar properties can become an issue since they are dependent on the slew of sewage sludge that is affected by many factors. Besides, the presence of pollutants such as heavy metals and organic contaminants in sewage sludge creates the concern of secondary pollution during biochar use, thus, they require sufficient pretreatment and quality control.

note that for several modification techniques, like thermal activation, the energy and cost requirements are quite substantial that affects the large-scale application. The use of thermal activation for biochar production is not practical as it raises the adsorptive properties but consumes a lot of energy, which is not suitable for resource challenged environments. Acid-base modification and other chemical means also build safety issues as they require dangerous agents and create chemical wastes that need to be appropriately managed. Another obstacle exists in the area of scalability of the application of more advanced modification techniques such as microwave irradiation, enzyme treatments, and nanoparticle doping. While some of these methods help to enhance biochar functionality, they do require specialized equipment and high accuracy which is not feasible for global operations scale up Also, it is necessary to continue developing answers to questions related to the possible negative ecologic consequences of certain modifications such as the leaching of nanoparticles from composite biochars if these modifications are to be used in a sustainable manner.

Finally, there are also regulatory and marketing issues such as insufficient harmonization of biochar production and its application that inhibit its use. Failure to have well-defined quality specifications discourages user confidence and market development while uncertainties on the outcome on the environment in the long run also serve to make widespread use of it more complicated. In order to tap into the full benefits of biochar made from sewage sludge, technology improvement, cost reduction measures and holistic policies frameworks will be needed to address these issues.

8. Future Perspectives

In terms of sludge-based biochar, we hope that the design and applications are enhanced and the processes are improved in coming years considering the international environmental and resource recovery problems. Also, biochar can be made more functional by combining biomass with a certain combination of biological, chemical, and physical methods during the pretreatment and modification step. However, working with biochar and nanomaterials for catalytic applications, water treatment and energy storage will be promising directions, while the issue of potential environmental hazards associated with emission of nanoparticles should be addressed too . Another important aspect is scaling up jakaba production while ensuring cost and charge containment and bio-sustainability. Should processes such as hydrothermal carbonization (HTC) and microwave-assisted pyrolysis be perfected, they have the potential to become effective and energy-efficient methods of biochar production. In addition, embedding biochar in circular economy principles, such as employing nutrient-rich biochar as slow release fertilizers or participating in carbon credit systems, could improve its commercial prospects and take off.

Crosstraining collaborating teams in material sciences, environmental engineering and policy design will be critical in helping solve the regulatory and market challenges. Establishing comprehensive protocols covering the entire spectrum of biochar among other things its production and use and life cycle assessments as well may simplify the processes and bolster faith in stakeholders. In addition, addressing such issues as biochar's potential use in promoting carbon capture and soil revitalization within a climate change strategy, may greatly broaden biochar applications. Looking forward, the enhancement of re reusing biochar from sewage sludge into advanced environmental management systems, complemented by effective monitoring and predictive modelling, facilitate sustainable resource use and improved decision-making.

9. Conclusions

Biochar produced from sewage sludge is a novel approach for enhancing circular economy activist practices which have promising benefits towards solving some of the most pertinent challenges of ecosystem and resource management. Biochar is instrumental in transforming waste into useful products with several applications, which in turn leads to reduction in environmental pollution and greenhouse gases, and enhancement of carbon capture. The conversion of sewage sludge into biochar not only provides a solution to the challenges associated with disposal of waste but also provides a green alternative to the conventional ways of resource consumption and procurement which ultimately eases the transitioning towards more efficient and sustainable systems in agriculture, waste water handling, and energy sources.

Notwithstanding the wide range of potential uses of biochar as in agriculture, construction and waste management, several issues remain especially of a technological and logistical nature. Biochar's properties vary significantly because of differences in the composition of the sewage sludges and their pre-treatment processes, thus making large scale deployment of biochar more challenging. In particular, the high energy costs and the financial sense of carbonization methods such as pyrolysis and hydrothermal carbonization while targeting enhancements in efficacy remain to be reduced. Also, while biochar is capable of sequestering carbon di oxide which combatsIt is of utmost importance for researchers and stakeholders to focus on technological advancements along with development of systems that are integrated and multi functional as they are the key enablers of the future for sewage sludge derived biochar. The research activity of combining chemical, physical and biological modifictaion of the properties of biochar derived from sewage sludge to be used for targeted applications such as energy production biosorption or nutrient analogy however must have a well defined outline. There is also need to improve control standards associated with biochar as well as uniform production guidelines to further ensure the uniformity in biochar grades making broad easy integration into the trade.

In the same vein, the creation of strong site policies and regulations would assist in the economic feasibility of activities outlined in the biochar vision. In this regard, biochar can be adopted as a perfect substitute for carbon and traditional industry policies, where traditional industry recovery would foster resource recovery policies assisted by biochar. Such thinking and logic can solve the two issues of resource scarcity and ameliorate carbon emissions at the same time, whereas previously it was thought to be contradictory.. An international consensus on the measures needed to use biochar would help eliminate the negative perception of biochar that has been ingrained in the minds of the majority.To wrap up, although there are some problems posed by biochar made from sewage sludge, the tremendous advantages it provides for environmental remediation, resource recovery, and climate change outweighs them all. Biochar is expected to have the added advantage of dealing with many agricultural and environmental issues and more importantly it is expected to change the way waste is managed and resources are recovered. Looking at future scenarios of advancement in technology and regulations and inter-disciplinary collaboration, biochar can evolve into one of the fundamental tools to enable sustainability efforts throughout the world and enable a better and more efficient circular economy.

Author Contributions

Conceptualization, V.S.T. and S.K.S.; methodology, S.K.S.; software, V.S.T.; validation, S.K.S., formal analysis, J.K.S.; investigation, R.P.; resources, J.K.S..; data curation, R.P.; writing—original draft preparation, J.K.S..; writing—review and editing, J.K.S..; visualization, R.P.; supervision, S.K.S. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Giwa, A.S., Maurice, N.J., Ai, L.Y., et al., 2023. Advances in sewage sludge application and treatment: Process integration of plasma pyrolysis and anaerobic digestion with the resource recovery. Heliyon. 9(9), e19765. DOI: https://doi.org/10.1016/j.heliyon.2023.e19765

[2] Gopinath, A., Divyapriya, G., Srivastava, V., et al., 2021. Conversion of sewage sludge into biochar: A potential resource in water and wastewater treatment. Environmental Research. 194, 110656. DOI: https://doi.org/10.1016/j.envres.2020.110656

[3] Ahmad, M., Lee, S.S., Dou, X., et al., 2012. Effects of pyrolysis temperature on soybean stover-and peanut shell-derived biochar properties and TCE adsorption in water. Bioresource Technology. 118, 536–544. DOI: https://doi.org/10.1016/j.biortech.2012.05.042

[4] Ahmad, M., Rajapaksha, A.U., Lim, J.E., et al., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere. 99, 19–33. DOI: https://doi.org/10.1016/j.chemosphere.2013.10.071

[5] Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J.L., et al., 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental pollution. 159(12), 3269–3282. DOI: https://doi.org/10.1016/j.envpol.2011.07.023

[6] Behrouz, M.S., Sample, D.J., Yazdi, M.N., 2023. Robustness of storm water management model parameter sets for dry and wet hydroclimatic conditions. Journal of Cleaner Production. 411, 137328. DOI: https://doi.org/10.1016/j.jclepro.2023.137328

[7] Chen, J., Hu, Y., Zhang, L., et al., 2017. Bacterial community shift and improved performance induced by in situ preparing dual graphene modified bioelectrode in microbial fuel cell. Bioresource technology. 238, 273–280. DOI: https://doi.org/10.1016/j.biortech.2017.04.044

[8] Cheng, Y., Yao, X., 2021. Carbon intensity reduction assessment of renewable energy technology innovation in China: A panel data model with cross-section dependence and slope heterogeneity. Renewable and Sustainable Energy Reviews. 135, 110157. DOI: https://doi.org/10.1016/j.rser.2020.110157

[9] Laird, D., Fleming, P., Wang, B., et al., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma. 158(3–4), 436–442. DOI: https://doi.org/10.1016/j.geoderma.2010.05.012

[10] Deepthi, M.P., Kathireswari, P., Rini, J., et al., 2021. Vermitransformation of monogastric Elephas maximus and ruminant Bos taurus excrements into vermicompost using Eudrilus eugeniae. Bioresource Technology. 320, 124302. DOI: https://doi.org/10.1016/j.biortech.2020.124302

[11] Dong, L., Zeng, W., Wang, A., et al., 2020. Response of soil respiration and its components to warming and dominant species removal along an elevation gradient in alpine meadow of the Qinghai–Tibetan plateau. Environmental Science & Technology. 54(17), 10472–10482. DOI: https://doi.org/10.1021/acs.est.0c01545

[12] Ho, C., Trinh, T., Nguyen, A., et al., 2019. Reconstruction and evaluation of changes in hydrologic conditions over a transboundary region by a regional climate model coupled with a physically-based hydrology model: Application to Thao river watershed. Science of the total environment. 668, 768–779. DOI: https://doi.org/10.1016/j.scitotenv.2019.02.368

[13] Hossain, M.K., Strezov, V., Chan, K.Y., et al., 2011. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. Journal of environmental management. 92(1), 223–228. DOI: https://doi.org/10.1016/j.jenvman.2010.09.008

[14] Iorhemen, O.T., Hamza, R.A., Zaghloul, M.S., et al., 2019. Aerobic granular sludge membrane bioreactor (AGMBR): Extracellular polymeric substances (EPS) analysis. Water research. 156, 305–314. DOI: https://doi.org/10.1016/j.watres.2019.03.020.

[15] Lehmann, J., Rillig, M.C., Thies, J., et al., 2011. Biochar effects on soil biota–a review. Soil Biology and Biochemistry. 43(9), 1812–1836. DOI: https://doi.org/10.1016/j.soilbio.2011.04.022

[16] Zhao, L., Sun, Z.F., Pan, X.W., et al., 2023. Sewage sludge derived biochar for environmental improvement: Advances, challenges, and solutions. Water Research X. 18, 100167. DOI: https://doi.org/10.1016/j.wroa.2023.100167

[17] Joseph, S., 2012. Biochar for environmental management: science and technology. Routledge: Oxford, UK.

[18] Chen, L., Zhou, M., Wu, H., et al., 2021. Modification of sewage sludge-derived biochar for enhanced adsorption and immobilization of heavy metals in contaminated soil. Environmental Pollution. 268, 115948.

[19] Lehmann, J., Pereira da Silva, J., Steiner, C., et al., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and soil. 249(2), 343–357. DOI: https://doi.org/10.1023/A:1022833116184#citeas

[20] Liang, B., Lehmann, J., Solomon, D., et al., 2006.

Black carbon increases cation exchange capacity in soils. Soil science society of America journal. 70(5), 1719–1730. DOI: https://doi.org/10.2136/sssaj2005.0383

[21] Miao, F., Liu, Y., Gao, M., et al., 2020. Degradation of polyvinyl chloride microplastics via an electro-Fenton-like system with a TiO2/graphite cathode. Journal of Hazardous Materials. 399, 123023. DOI: https://doi.org/10.1016/j.jhazmat.2020.123023

[22] Qambrani, N.A., Rahman, M.M., Won, S., et al., 2017. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. Renewable and Sustainable Energy Reviews. 79, 255–273. DOI: https://doi.org/10.1016/j.rser.2017.05.057

[23] Pagano, G., Thomas, P.J., Di Nunzio, A., et al., 2019. Human exposures to rare earth elements: Present knowledge and research prospects. Environmental Research. 171, 493–500. DOI: https://doi.org/10.1016/j.envres.2019.02.004

[24] Smith, S.R., Taylor, C.M., 2019. The effectiveness of sewage sludge treatment processes to control health risks from pathogens: A review. Environmental International. 133, 105167.

[25] Sankar, M.S., Dash, P., Lu, Y., et al., 2023. Seasonal changes of trace elements, nutrients, dissolved organic matter, and coastal acidification over the largest oyster reef in the Western Mississippi Sound, USA. Environmental Monitoring and Assessment. 195(1), 175. DOI: https://doi.org/10.1007/s10661-022-10719-z

[26] Scanlon, B.R., Reedy, R.C., Faunt, C.C., et al., 2016. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. Environmental Research Letters. 11(3), 035013. DOI: https://doi.org/10.1088/1748-9326/11/3/035013

[27] Schneider, L., Haverinen, J., Jaakkola, M., et al., 2017. Effective saccharification of lignocellulosic barley straw by mechanocatalytical pretreatment using potassium pyrosulfate as a catalyst. Bioresource Technology. 234, 1–7. DOI: https://doi.org/10.1016/j.biortech.2017.03.020

[28] State, R.N., Volceanov, A., Muley, P., et al., 2019. A review of catalysts used in microwave assisted pyrolysis and gasification. Bioresource technology. 277, 179–194. DOI: https://doi.org/10.1016/j.biortech.2019.01.036

[29] van Walsem, J., Roegiers, J., Modde, B., et al., 2018. Determination of intrinsic kinetic parameters in photocatalytic multi-tube reactors by combining the NTUm-method with radiation field modelling. Chemical Engineering Journal. 354, 1042–1049. DOI: https://doi.org/10.1016/j.cej.2018.08.010

[30] Tan, X., Liu, Y., Zeng, G., et al., 2015. Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere. 125, 70–85. DOI: https://doi.org/10.1016/j.chemosphere.2014.12.058

[31] Xiao, Y., Chen, Y., Zeng, W., et al., 2022. Pretreatment, modification and applications of sewage sludge-derived biochar for resource recovery—A review. Chemosphere. 287, 131969. DOI: https://doi.org/10.1016/j.chemosphere.2021.131969

[32] Fan, Z., Li, M., Wang, Y., et al., 2023. Co-pyrolysis technology for enhancing the functionality of sewage sludge biochar and immobilizing heavy metals. Chemosphere. 317, 137929. DOI: https://doi.org/10.1016/j.chemosphere.2023.137929

[33] Zhao, S.X., Ta, N., Wang, X.D., 2017. Effect of temperature on the structural and physicochemical properties of biochar with apple tree branches as feedstock material. Energies. 10(9), 1293. DOI: https://doi.org/10.3390/en10091293