Biochar-Based Nanocomposite And Nano Biochar Advances, Application And Future Prospects For Sustainable Agriculture Environmental Remediation

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By

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DECALARATION

I Maneesh Kumar 24/IBT/03 hereby certify that the work which is being presented in the thesis entitled "Biochar-Based Nanocomposite And Nano Biochar Advances, Application And Future Prospects For Sustainable Agriculture Environmental Remediation" in partial fulfillment of the requirements for the award of the Degree of Master of Technology, submitted in the Department of Biotechnology, Delhi Technological University is an authentic record of my own work carried out during the period from 2024 to 2026 under the guidance of Dr. Navneeta Bharadvaja.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that Maneesh Kumar (24/IBT/03) has completed her research work entitled "Biochar-based Nanocomposites & Nano-biochar: Advancements, Applications & Future Aspects for Sustainable Agriculture & Environmental Remediation" for the award of Master of Technology from the Department of Biotechnology, Delhi Technological University, Delhi, under my guidance. The thesis contains the findings of original research work done by the student and no part of the work contained herein shall form the basis of another degree awarded to this or any other person from this or any other institution.

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Abbresion 's list

FTIR	Fourier Transform Infrared Spectro Scopy
BET	Brunauer Emmett Teller
XRD	X-ray diffraction
UV-VIS	Uv-visible spectroscopy
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
TGA	Thermogravimetric Analysis
ZnO	Zinc Oxide

ABSTRACT

Sustainable and environmentally related remediation technologies are desolately needed due to the sharp rise in environmental pollution brought on by urbanization, industrialization, and concerted agricultural practices. Green-synthesised biochar nanocomposites derived from plants have become a rising class of advanced functional materials for useful in environmental applications. Biochar has a biggest surface area, a porous structure, and a potent adsorption capacity. It is pyrolyzing plant biomass in low oxygen environments. Biochar's physicochemical qualities are improved while maintaining environmental safety and biocompatibility when it is combined with green-based nanoparticles that use plant extracts as reducing and stabilisingagents.The green synthesis, characterization, and environmental uses of biochar nanocomposites basedfrom plants are the main topics of this work. To known the formation of nanoparticles, surface functionalization, and structural stability, characterization processes like FTIR, XRD, SEM, BET, and UV–Vis spectroscopy are come in. Heavy metals, dyes, pesticides, and organic pollutants are all effectively cut from water and soil by the synthesized nanocomposites. The study suggests the potential of these environmentally friendly nanocomposites as long-term substitutes for chemically synthesized materials in the areas of soil remediation, water purification, pollution control, and climate change mitigation.

Keywords - Pollution, Green Synthesis, Environment, Bio-remediation, Plant Derived, Biochar etc.

CHAPTER 1

INTRODUCTION

Environmental pollution is more challenging that faced by mankind in modern century [1]. Environmental pollution is due to rapid industrialization, urbanization, growth in population, and agricultural activities which may lead to the release of many types of pollutants in the environment[1]. Industrial waste which contains many toxins like dye, heavy metals, pharmaceuticals, pesticides, and other organic pollutants finds its way rapidly into the water sources creating various health and environmental threats. The conventional methods used for water treatment like chemical precipitation[3], coagulation, membrane filtration, and adsorption using activated carbon are costly and energy intensive, besides also causing secondary pollution[2].

As such, there has been a great need for the development of materials that can be disposed environmentally friendly and can be used to clean pollutants. In this times, green nanotechnology has originated as a fascinating area for the development of environmentally friendly materials with enhanced physical and chemical properties[3]. It involves the use of small amounts of toxic materials, energy-efficient and biological materials in the production process. Several sustainable materials such as biochar nanocomposites have been proposed for the cleanup of the environment. Biochar is defined as the porous carbonaceous material that is produced from biomass via thermal conversion, which takes place in the absence of o2. Different kinds of biomass as agricultural residues have been used under oxygen-limiting conditions[7].

But biochar can also demonstrate low adsorption efficiency and selective affinity to particular pollutants[5]. In order to overcome such challenges, the scientists have been paying considerable attention to biochar modification through the incorporation of nanoparticles and metal oxides into biochar to develop nano-biochar composites[5]. The incorporation improves the surface activity, absorption capacity, catalytic activity, and ability to remove contaminants from water and soil. Therefore, this approach could prove to be effective in overcoming these challenges[2].

Biochar-based nanocomposites have demonstrated superior characteristics in treating wastewater, dye degradation, heavy metal adsorption, soil conditioning, and environmental detoxification processes[6]. Nanocomposites created from plant extracts through green chemistry methods have some advantages compared to those fabricated through chemical synthesis approaches[4]. This is because green chemistry approaches do not involve reducing agents and harmful solvents that might harm the environment[1]. The biomolecules present in the plant extracts include phenols, flavonoids, alkaloids, proteins, and carbohydrates. These biomolecules play a vital role in reducing, stabilization, and capping processes in the fabrication of nanoparticles[1]. Thus, the preparation process for these nanocomposites through biomolecules is eco-friendly and retains their biological function. Environmental pollution entails introducing toxic chemicals into the environment.

Water pollution, air pollution, and soil pollution are just a few of the most important environmental problems that affect both developed countries and developing countries[3]. Industrial effluents are one of the sources of water pollution. Textile industries, leather

industries, drug companies, paper industries, mining industries, electroplating industries, and chemical industries discharge vast amounts of poisonous substances into water sources[1]. These pollutants include artificial dyes, heavy metals, oil, detergents, pesticides, phenols, and pharmaceutical drugs. Most of these pollutants are non-degradable, persistent, and highly dangerous even in small concentrations[8].

These pollutants include lead, cadmium, chromium, mercury, arsenic, and nickel among others. These are highly dangerous because of their high toxicity, biomagnifications, and resistance to biodegradation[6]. Consumption of these heavy metals may lead to mental illness, kidney malfunction, lung diseases, cancer, and many other illnessesIn addition, dyes used in textile industries and dye industries reduce light penetration and hence inhibit photosynthesis in water systems and form toxic degradation products[4]. Wastewater treatments are often expensive, ineffective, lead to production of sludge, secondary pollution, and failure to eliminate contaminants from water systems[7]. Thus, discovery of more effective and environmentally friendly adsorption materials has become vital.

All aspects of the green chemistry and nanotechnology principles to develop nanomaterials that are environmentally sustainable are included in green nanotechnology.[2] Green nanotechnology focuses on minimizing any negative impact caused by nanoparticle production using traditional methods, apart from improving the effectiveness of producing nanoparticles.[6] Conventional production of nanoparticles uses hazardous organic solvents, toxic reducing agents, high temperatures, and expensive production techniques. These processes may even generate toxic substances and cause environmental degradation[8]. In contrast, green production methods use biological resources like extracts of plant origins, microorganism, enzymes, and biopolymers to produce nanoparticles. Among the various production methods, plant-based nanoparticle synthesis method has proved to be very effective since plants have abundant phytochemicals that can help in the reduction of metal ions and formation of nanoparticles.[7] Some of the advantages of using plants include easy handling, economic efficiency, rapid processing, practicality, and environmental sustainability. Furthermore, green nanotechnology supports sustainable development through renewable resources and minimized chemical wastes.[10]

Green Synthesis Method for Biochar Nanocomposites for environmental engineering is very important[9]. The term Biochar is a form of stable carbon product created by the use of pyrolysis or some other similar method where biomass is converted into biochar through processes like thermal degradation of biomass in oxygen limited conditions[1]. Biomass Precursor Pyrolysis Temperature Heating Rate Residence Time Surface Functionalization Techniques Biochar has some specific properties, namely, Mesopores, Micropores developed on the surface[2]. Large Surface Area Surface Functional Groups Thermal Stability Chemical Stability High Adsorption Ability and other Biochar properties have enormous potential in reducing pollutants due to mechanisms like Surface Adsorption, Ion Exchange, Electrostatic Attraction, Complexation, Precipitation, and π-π Interactions[4]. Plant based biochar has several benefits because the biomass of plants is highly available, biodegradable, renewable, and cost-effective[5]. Rice husk, sugarcane bagasse, coconut shells, banana peels, saw dust, leaf, crop residue can be used to create biochar or remove contaminants, Carbon Capture, Soil Enhancement, Waste Disposal, Reducing Green House Gases, and sustainable farming. Nanocomposites refer to substances

produced by mixing or reacting two or more distinct substances at the nano level to achieve enhanced physical or chemical properties.[11]

However, along with the progress and advancement, industrialization has posed a number of environmental problems that threaten the ecosystem.[1] Contamination of water, land pollution due to accumulation of toxic and poisonous wastes poses a serious threat.[1] Textile industry, leather processing, electroplating, mining, pesticide production, and dyeing industries discharge a large number of chemicals and pollutants in the environment.[3] These include;

1- Heavy metals

2- Synthetic dyes

3- Toxic organic compounds

4- Industrial chemicals

5- Pharmaceutical wastes

These toxicants are extremely persistent, non-biodegradable and toxic. They tend to cause ecological imbalance in aquatic ecosystems.[2] Moreover, the presence of these pollutants leads to the phenomenon of bioaccumulation and biomagnification which may prove fatal to the ecosystem and also human health. The heavy metals have been identified as a major problem as they are not decomposed easily in natural conditions and remain persistent in the environment for long duration. Heavy metals include chromium, lead, cadmium, arsenic, and mercury[18]. They cause health hazards such as;

1- Kidney damage

2- Nervous disorders

3- Respiration related illnesses

4- Skin irritation

5- Cancer and mutagens

Furthermore, some types of dyes released into water due to textile industries as well as other industrial sources hinder photosynthesis and reduce oxygen levels in water. Dye industry causes cancer in aquatic life. With the increasing environmental pollution, there is now an urgent need to develop efficient treatment techniques. Techniques such as 1- Chemicals precipitation 2- Coagulation flocculation 3- Membrane separation 4- Ion exchange 5- Reverse osmosis 6- Activated carbon adsorption Are commonly applied to remove pollutants. But these methods have certain limitations due to the fact that chemicals harm the environment if applied beyond the limit[2].

1- High operational cost

2- Sludge formation in water bodies

3- Generation of secondary pollutant

4- Complex maintenance

5- High energy consumption for installation

6- Low efficiency for trace pollutants

There has been a recent increase in the use of biochar as a possible adsorbent material[4]. Biochar is produced by subjecting organic biomass to a process of thermal carbonization known as pyrolysis [1].

Different types of biomass materials can be used in biochar production,

- Agro-industrial wastes
- Crop residues
- Plant leaves
- Fruit peels
- Wood wastes
- Timber residue
- Food processing residues

Biochar has many physiological characteristics that are advantageous,

- High carbon content
- Porous nature
- Large surface area
- Surface functional groups
- Thermal stability
- High adsorptive capacity

All these make biochar ideal for use as an adsorbent material in pollution control[1]. Porous nature of biochar enhances the surfaces available for interactions and provides many active sites[7]. Surface functional groups such as hydroxyl, carboxyl, carbonyl, and phenolic groups make it ideal for adsorption through different mechanisms like,

- Electrostatic interactions
- Hydrogen bonds

- Ion exchange
- Surface complexation
- Chemical adsorption

One of the most efficient methods of enhancing biochar qualities includes use of nanoparticles which form nanocomposites material within the biochar matrix[20]. Nanocomposites consist of properties of nanoscale particles in conjunction with supporting material to yield advanced functional material which enhances adsorption efficiency[1].

Nanoparticles have special properties attributed to their very small particle size and high surface area to volume ratio.

- Elevated chemical reactivity of functional groups
- Increased catalytic activity of functional groups
- Enhanced adsorption performance of surfaces
- Large surface energy due to presence of different functional groups
- Better pollutants interaction with surfaces

The combination of nanoparticles on biochar surfaces results in synergy which enhances the following features;

- Surface functionalities of biochar
- Adsorption capacity of adsorbate
- Selectivity of pollutants by pollutants
- Activity of surfaces as catalyst
- Toughness in environmental conditions

Biochar nanocomposites are increasingly being studied in applications including but not limited to;

- Removal of heavy metals
- Removal of dyes
- Waste water treatment
- Soil remediation
- Photo-degradation
- Environmental clean-ups

The preparation of nanoparticles requires chemical and physical processes that include toxic and carcinogenic reducing agents, toxic solvents, and environment-harming substances[23]. Such processes may result in the emission of toxic wastes. Thus, there has been an increased interest in developing environmentally friendly synthesis approaches in nanotechnology research.

There are environmentally benign methods in nanomaterials that make it possible to sustainably synthesize nanoparticles[21]. The green approach relies on using natural biological products including plants extract, microorganisms, animals, and natural compounds[6].

The plant-mediated synthesis method is highly recommended due to the natural components found in plant extracts that include;

1. Flavonoids
2. Alkanoids
3. Tannins
4. Polyphenols
5. Proteins
6. Terpenoids

Green synthesis has many benefits including;

- Eco-friendly and low toxicities
- Cost-effective
- Simplicity
- Energy efficient

The quick rise in industrialization, agriculture, and urbanization has resulted in an increased amount of toxic waste in soil and water, including heavy metals, pesticides, pharmaceuticals, and synthetic dyes [2]. The traditional approaches like advanced oxidation, filtration, and chemical precipitation tend to face issues like high costs, production of second pollutants, or low effectiveness, requiring alternative solutions to be found [4]. Biochar, which is a form of carbonaceous solid formed as a result of pyrolysis of biomass with limited access to oxygen, has become more popular due to the versatility in its applications for environmental, soil improvement, and climate control purposes [2]. One of the modern developments is the application of nanotechnology techniques that have allowed decreasing the size of biochar particles or combining them with other nanoparticles [4].

The performance of these nanocomposites in terms of physicochemical properties, including surface area, porosity, stability, and functional groups, exceeds that of macro-biochar, thereby facilitating effective adsorption, catalysis, and nutrient control [5]. In addition, modifications with metals and metal oxides like iron, nickel, silver, cobalt, and zinc oxide can significantly boost the effectiveness of pollutant adsorption, catalysis, and antimicrobial activity [6]. With respect to agriculture, nanobiochar holds more advantages apart from its efficacy in wastewater purification by being able to improve the soil, retain nutrients, reduce pathogens, and serve as fillers for biocomposites [1]. Nevertheless, although lab experiments have proved to be encouraging, there are some difficulties associated with nanocomposites. Environmental safety issues, inconsistency in feedstocks and biochar fabrication techniques, and limited scalability of

green syntheses are some of the problems that exist within the realm [1]. This article will present recent findings related to biochar-nanocomposites with regard to the advancement in the synthesis and modifications of these compounds, their application to environmental and agricultural uses, contradiction and limitation in the current studies, and future considerations in order to ensure safely and sustainable utilization of nanocomposites [9].

CHAPTER 2

REVIEW OF LITERATURE

The greatest increment in environmental pollution from industrialization, urbanization, agriculture, and anthropogenic actions has led to various environmental and human health hazards at a worldwide level. Pollution of water sources with heavy metals, dyes, pesticides, pharmaceutical waste, and toxic organic compounds is regarded as one of the toughest challenges of our times [10]. Traditional treatment processes usually involve several issues like expensive cost, inefficiency, use of energy, and creation of second pollutants. As a result, the emergence of an alternative and environment-friendly material to deal with these issues has drawn considerable scientific interest. Recent years have witnessed an increasing trend of using biochar based nanocomposites for environmental applications because of their superior adsorption properties, high surface area, porous structure, and eco-friendliness [15].

Moreover, biochar produced from the plant biomass is cost-effective and sustainable carbonaceous substance which serves as an ideal nanocomposite. Introduction of the nanoparticles to the biochar enhances its physicochemical properties for effective removal of contaminants[19]. In view of this, the necessity of decreasing the use of chemicals and creation of sustainable materials becomes crucial since green synthesis of nanocomposites based on biochar gains popularity [17]. The plants, which are used for generation of the biomass, serve as the source of phytochemicals, which facilitate the synthesis and stabilization of nanoparticles[21]. Pollution can be described as the negative alteration of any physical, chemical, or biological property of the environment due to the presence of contaminated components.Pollution may manifest itself differently, but water pollution can be regarded as one of the worst types. Textile industry, leather processing, mining, chemicals, electroplating, paints, pesticides, fertilizers, and papermaking industries contaminate water supplies with harmful contaminants[19].

Toxic substances include:

- Heavy metals
- Synthetic dyes
- Phenols
- Organic solvents
- Pesticides
- Medicines
- Radioactive materials

The major pollutants produced by industries are of non-biodegradable nature and thus able to survive in the environment for an indefinite period of time[21]. These pollutants accumulate in

the water bodies which result in adverse effects on the aquatic organisms and eventually end up in human food chain through the phenomenon of bioaccumulation[3].

Limitations associated with wastewater treatment technologies include;

- High operating costs
- Formation of sludge
- Secondary pollution
- High energy usage
- Low removal efficiency

Thus, scientists have developed various technologies for sustainable and environmentally friendly remediation that are low cost and sustainable [22]. Biochar and biochar nanocomposites are among the emerging eco friendly technologies for pollution control and environmental remediation applications [23].

Biochar is a porous carbon based material obtained by the thermochemical process of pyrolysis under limited oxygen availability conditions. Because of;

- The high surface area,
- The porous morphology,
- The functional surface groups,
- The carbon-rich structure,
- The adsorption properties,

Biochar gained much interest from researchers for waste water treatment, soil remediation, carbon sequestration and environmental sustainability application [23]. Biosources such as plants, algae, bacteria, fungi, biopolymers were widely used for nanomaterial synthesis in an eco friendly way. Plant mediated synthesis of nanoparticles was more advantageous as it introduced phytochemicals like flavonoids, phenolics, alkaloids, terpenoids, proteins, carbohydrates into nanomaterials. These phytochemicals acted as reducing agents, stabilizing agents and capping agents in the synthesis of nanoparticles [2]. The green synthesis methods had many advantages which included eco friendliness, reduced toxicity, economicness, simplicity, high yield and large scale production[1].

Physicochemical Properties of Biochar

Biochar possesses various physicochemical properties that make it a great adsorbent. The physicochemical properties include high porosity, high surface area, surface functional groups, aromatic carbon structure, ion exchange capacity, and thermal stability[4]. The surface functional groups common to biochar are OH groups, COOH groups, carbonyl groups, and phenolic

groups. Surface functional groups play a significant role in the adsorption of pollutants through chemical reactions[5]. Although biochar can serve as an excellent adsorbent, its effectiveness can be limited when trying to remove certain pollutants. This calls for various methods used to modify biochar in order to increase its effectiveness.

Modification Process of Biochar

Biochar modification processes include

- Chemical Activation,
- Physical Activation,
- Acidic Modification,
- Basic Modification,
- Magnetic Modification,
- Nano-inclusion

Nanocomposites refer to multi-phase materials with not less than one of these phases occurring at the nanoscale[7]. Biochar nanocomposites refer to a combination of two constituents, namely, biochar and nanomaterials. Nanoparticles added to biochar in the form of nanocomposites include Zinc Oxide Nanoparticles, Iron Oxide Nanoparticles, Titanium Dioxide Nanoparticles, Silver Nanoparticles, and Copper Oxide Nanoparticles, among others[2]. The major advantages of these nanoparticles are that they have a tremendous potential for enhancing Surface Reactivity, Pollutant Interaction, Photocatalytic Activity, Magnetic Separation, and Adsorption Capacity as well [21]. for biochar nanocomposites, biochar serves as an effective Matrix for Stabilization as well as being a Porous Adsorbent while the nanoparticles help in enhancing Active Sites as well as Catalytic Property through Green Synthesis involving the utilization of biological sources such as plant extracts[3].

CHAPTER 3

Methodology and Approaches

The current study is based on a literature review concerning biochar-based nanocomposites and nano-biochars with regard to their applications and future potentials in sustainable agriculture and environmental protection. The aim of the methodology adopted in this study is to systematically compile information from the current scientific literature regarding the properties, characteristics, applications, potentials, drawbacks, and future directions of biochar nanotechnology.

The adopted methodology is purely literature-based, meaning that no experimental activities will be conducted within a laboratory setting. The collection of literature has been done from published journal articles, scientific papers, books, and other academic sources such as conference proceedings. In doing so, key research trends, innovations, environmental, and agricultural applications were noted within the field of biochar nanocomposites.

Research Approach

It was chosen since it allows for a thorough explanation and interpretation of scientific discoveries that are already known without performing experiments in practice[6]. The main focus of the research is the examination of the influence of nano-biochar and biochar nanocomposites on the enhancement of environmental sustainability and agricultural yield[9].

Methodology Highlights

- Literature collection
- Critical comparison of available scientific publications
- Literature interpretation
- Determination of further research perspectives

Literature Search Strategy

Related literature has been found by means of relevant scientific terms and combinations of key phrases pertaining to biochar nanotechnology and environmental usage[7].

Data Organization and Analysis

The collected literature was meticulously classified into major themes, including:

- Biochar production techniques
- Biochar preparation at the nano level

- Biochar characterization techniques
- Agricultural uses of biochar
- Environmental remediation applications
- Technological applications of advanced level biochar
- Limitations of Biochar

Biochar Preparation

The methodology chapter also highlighted common approaches that are used in biochar preparation as described by earlier studies. Majority of researchers prepared biochar using pyrolysis which involves thermal decomposition of biomass under limited oxygen.

Common Biomass Materials

- Rice husk
- Sawdust
- Sugarcane bagasse
- Coconut shell
- Agricultural residues
- Poultry manure
- Sewage sludge

The study evaluated the impacts of pyrolysis temperature and heating rate on:

- Surface area
- Porosity
- Carbon content
- Adsorption capacity

Nano-Biochar and Nanocomposite Synthesis Approaches

Various synthesis techniques reported in literature were descriptively examined.

- Mechanical ball milling
- Ultrasonication
- Chemical activation

- Hydrothermal treatment

Nanocomposite Modification Methods

The use of nanoparticles including:

- Ferric oxide (oxide of ferous)
- Zinc oxide (oxide of zinc)
- Titanium dioxide (di oxide of titanium)
- Magnesium oxide (oxide of mg)

It has been done to enhance functionalities and adsorption capability.

Techniques for Nano-Biochar Characterization

The technique described herein involved review of methods used in characterization of

Techniques	Purpose
SEM	Surface Morphology Analysis
TEM	Nanostructure Observation
FTIR	Functional Group Identification
XRD	Crystalline Struc. Analysis
BET	Surface Area Determination
TGA	Thermal Stsbility Analysis

Characterization approaches assist in finding out the properties that contribute towards better results.

Evaluation of Agricultural Uses

The gathered literature was assessed in order to comprehend the contribution of nano-biochar in sustainable agricultural practices[4].

Important Agricultural Aspects Discussed

- Soil fertility improvement
- Improvement in water retention capacity
- Efficiency of nutrient delivery
- Potential of crop yield
- Tolerance of plants against stresses
- Carbon sequestration

Findings of comparative researches were briefly discussed to explain the benefits of nano-biochar for plant growth and soils[6].

Evaluation of Environmental Remediation Applications

Another aspect studied in the report was the efficiency of nano-biochar when used for environmental cleanup purposes.

Environmental Parameters

- Adsorption of heavy metals
- Dye removal
- Water treatment
- Soil remediation
- Adsorption of air pollutants

Various adsorption procedure are:

- Ion exchange
- Surface complexation
- Electrostatic attraction

CHAPTER 4

RESULTS AND DISCUSSION

Based on an evaluation of published works, it became evident that biochar-based nanocomposites and nano-biochar had received considerable academic interest owing to their multipurpose nature and applications in sustainable agriculture and environmental clean-up processes. Studies revealed that engineered nano-biochar had been found to be more reactive, have a greater surface area, increased porosity, and high adsorption capacities when compared to regular biochar[8].It was observed that using nanoparticles as fillers within biochar greatly facilitated efficient pollutant removal, fertilizer retention, improvement in soil fertility, and increased catalytic activities[5]. The researchers unanimously agreed upon the fact that nano-biochar could serve as a sustainable and cost-effective solution for resolving a range of environmental problems[28].

Results Concerning Biochar Synthesis and Nanoengineering

Type of biomass material

- Pyrolysis temperature
- Rate of heating
- Duration of stay at high temperatures
- Process of activation

It has been noted that an increment in pyrolysis temperatures from 500°C to 800°C increases:

- Surface area
- Carbon concentration
- Enhanced porosity
- Adsorption properties

Nanoengineering methods like ball milling, ultrasonication, and chemical activation decreased particle size effectively and improved surface chemistry.

3. Results of Characterization Studies

CharacterizationTechniques	Mazor findings
SEM	Highly Porous And Rough Surface Morphology
TEM	Uniform Nanoscale Particle Distribution
FTIR	Presence Of o2 Containing Functional Groups
XRD	Improved Crystalline Struc. In Nanocomposites
BET	Significant Increase In Surface Area

Sustainable Agriculture

The majority of research conducted on agriculture indicated beneficial effects of nano-biochar on soil and crop.

- Advancements in agriculture through nano-biochar
- Soil water retention ability
- Nutrient retention
- Contamination activity improvement
- Better seed germination
- Crop yield increase
- Fertilizer losses reduction

A number of researchers proved high power of using nano-biochar in the fertilizers as it provides controlled and slow release of nutrients[30].

Removal of Toxic Heavy Metals

An ample amount of scientific literature was devoted to examining adsorption capacity of nano-biochar in relation to such toxic metals as:

- Pb
- Cd
- Cr
- As
- Hg

It may have:

- High adsorption capacity
- Fast pollutants removal
- Toxic metal immobilization improvement
- Soil contamination stabilization

Magnetic nano-biochar is easily separable because it is made of Fe_3O_4 nanoparticles.

Applications for Wastewater Treatment

The majority of researches showed that biochar nanocomposites removed effectively:

- Organic dyes
- Pharmaceuticals
- Antibiotics
- Pesticides
- Industrial chemicals

CHAPTER 5

APPLICATIONS

Applications in Environmental Remediation

The utilization of biochar nanocomposites has had greater success in the environment sector for treating waste water as well as microbial remediation. Due to their increased surface area, porosity, and base chemistry that can be controlled, they find applications in the removal of inorganic as well as organic contaminants. In addition, biochar nanocomposites are also photocatalysts and antimicrobials.

1. Adsorption of Heavy Metals

Heavy metals like chromium, cadmium, lead, and nickel are common pollutants in soil and aqueous environments because of their emission from industries or runoff from agriculture activities. While pristine biochar can bind these metals with cation exchange and surface complexation, the process is impeded by inadequate concentration of active sites on the biochar surface[9]. Metal-functionalized biochar composites have, however, been invented. reported that zero-valent nickel nano-biochar, prepared using guava leaf extract, had high affinity towards heavy metals because of combined effect of Ni nanoparticles and porous structure of biochar[18]. Likewise, nZVI-biochar composites made using sugarcane bagasse and microwave plasma pyrolysis process quickly adsorbed arsenic and other hazardous metals. In addition to their adsorption capacity, they could also be recycled by applying magnetic separation. One notable work in this regard comes from who developed a novel material of cobalt oxide-reduced graphene oxide-biochar composite, which reduced hexa valent chromium (Cr[VI]) to relatively less toxic chromium (Cr[III]) using visible light[25]. Hybridization with reduced graphene oxide improved the electron transfer rate and metal oxidation. These works show that iron-, nickel-, and cobalt-based biochars can perform better than pristine biochar for metal removal, although metal nanoparticle leakage remains unresolved[31].

2. Adsorption of Organic Pollutants

Organic pollutants including dyes, pharmaceuticals, and endocrine disrupting chemicals are other important pollutants causing problems for aquatic life apart from heavy metal pollutants.Coconut husk biochar combined with iron oxide nanoparticles is used to remove crystal violet dye successfully. Another team has proven that methylene blue was effectively degraded by Ag@Biochar composites, resulting in an efficiency rate of above 88%, which can be repeated for up to six rounds.Pharmaceuticals include manganese ferrite biochar composite materials to remove ketoprofen (non-steroidal anti-inflammatory drug) and benzophenone (sunscreen agent)[25].Their experiments found that physiosorption played an overwhelming role in the removal process of ketoprofen; both Langmuir and Freundlich models were appropriate for the adsorption equilibrium. Emerging contaminants have also been pointed out as the reason why nano-biochar would work well due to its unique surface functionality for low concentration, hard to deal with contaminants like antibiotics and pesticides[25].

3. Photocatalysis and Catalytic Applications

Apart from adsorption, there have been considerable breakthroughs in the use of biochar nanocomposites as catalysts and photocatalysts in the degradation of organic pollutants. Catalysts with silver: Ag@biochar catalysts not only assist in dye degradation, but they also act as antimicrobial agents towards bacterial cells such as E. coli and Pseudomonas aeruginosa[26]. The multifunctionality makes these catalysts ideal candidates for wastewater treatment processes. Magnetic catalysts, biochar/Fe_3O_4 and SiO_2–Ag nanocomposite acted as a catalyst in organic chemical synthesis, which is sustainable over at least five cycles[41]. Photocatalyst with synergy showed that composite made up of cobalt oxide, graphene, and biochar generates oxygen radicals (OH, O_2^-), hence the mineralization of various dyes, in addition to reduction of hexavalent chromium [6]. This explains the significance of biochar as a stabilizer for photocatalytic nanoparticles[34].

4. Antimicrobial and Pathogen Control

There have been recent applications of nano-biochar in microbial remediation. The study showed that silver- and cobalt-loaded materials were highly effective at inhibiting bacteria while eliminating chemical contaminants [41]. The two applications make the technology useful for dealing with both chemicals and microbes in agricultural waste water.

Agricultural Applications of Nanocomposites

Although there are many studies in environmental remediation involving nanocomposites made from biochar, there are other areas where the same technology can be applied in agriculture. Due to the porous nature of nanocomposites and their ability to sequester carbon, the technology can help enhance soil fertility, manage nutrients, inhibit pathogens, and alleviate climate change[40].

1. Soil Fertility and Nutrient Retention

It has always been known that biochar can improve soil fertility through the increase of cation exchange capacity, moisture retention capability, and availability of nutrients. The conversion of biochar to nano-biochar is even more beneficial owing to greater specific surface area and reactive sites[17]. They noted that biochar-metal nanocomposites provide better nutrient immobilization and controlled nutrient release characteristics. For example, ZnO/biochar nanocomposites act as pollutant scavengers as well as micronutrient supply sources for plant uptake. Moreover, MgO/biochar nanocomposites have proven to enhance phosphorus availability without causing nutrient leaching[10].

The special nature of surface chemistry makes the use of nano-biochar efficient in adsorbing excess amounts of nitrogen and phosphorus from runoff water and their subsequent release into the soil.

2. Plant Growth and Productivity

Most scientific literature mentions the potential benefits of using biochar nanocomposites to promote plant growth and productivity. The application of nano-biochar is effective in controlling the transport and intake of macronutrients and micronutrients and hence supporting healthy plant growth. Further, the increased porous structure of this nanomaterial supports proper aeration and the presence of microbes[23]. Some other benefits that could be achieved through ag-, or ferro-nano-biochar include pathogen suppression in the soil, with demonstrating strong antimicrobial effects in Ag@biochar. In the same way, the complexes of iron enhance both nutrient recycling and microorganism suppression owing to their reductive and catalytic effects. However, several scientists have found contradictory evidence in relation to biochar dosage since low amounts support healthy plant growth while high concentrations of metal-based biochars promote nanotoxicity[24].

3. Soil Health and Microbial Activity

Porous nature of biochar nanocomposites is a breeding ground for soil microbes that increases rhizosphere activity. This has immediate benefits for soil nutrient cycling, humus stabilization, and biological antagonism. At the same time, biochar can bind agrochemicals, thus decreasing their adverse effect on the soil microbes[21]. On the other hand, introduction of nanomaterials raises doubts because while silver/cobalt nanoparticles ensure antimicrobial safety, they can have negative effects on soil microorganisms. Such ecological contradictions require further research and are one of the most important areas of study.

4. Climate Change Mitigation

The application of biochar has also been encouraged as a technology for carbon sequestration owing to its stable nature and ability to store atmospheric carbon in the soil. In addition, if used as nanocomposites, biochar may become even more stable and reduce degradation by microorganisms[18]. Nano-biochar can also act as an agent that reduces the emission of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) by sequestering nitrogen species and enhancing the aeration of soils. However, data on using nano-biochar as a means of carbon sequestration in soils is still limited[1].

CONCLUSION AND LIMITATIONS

Biochar-derived nanocomposites and nano-biochar constitute novel material systems that bridge agriculture, environmental cleanup, and nanotechnology applications. Leveraging the sustainability and porosity of biochar as well as the high reactivity of nanometals, nanoparticles, and nanocarbon, the materials provide improved adsorption, catalytic properties, antimicrobial activity, and soil fertilizing effects[3]. All ten selected publications demonstrate the potential of the materials to effectively remove dyes, pharmaceuticals, heavy metals, increase soil nutrients retention, and act as eco-friendly fillers for polymers. However, there is a set of issues associated with the use of such innovative solutions. Namely, the heterogeneity of biomaterial and production processes leads to non-reproducibility and scaling problems. Metal and oxide functionalization improves performance but creates additional environmental risks, including leaching, toxicity, and ecotoxicity. Moreover, most of the research focuses on small-scale studies, while practical validation is needed[27].

Moreover, a lack of technological and economic analyses and the lack of regulations prevent wide use. In order to unlock the potential of the material, it is necessary to use safe-by-design techniques, establish standards for its production and focus on field experiments. Collaboration between experts from diverse fields, including materials science, environmental engineering, agronomy, and policy-making will help achieve these goals[44]. In addition to being used for water and soil remediation, the nanomaterials have the potential to be used in circular economy systems, advanced energy materials, and precision agriculture in the future. Finally, biochar nanocomposites are currently in transition, but they present an exciting prospect of being sustainable multi-functional materials, which could solve numerous problems in agriculture and environmental protection[57].

In addition, the lack of techno-economic analysis and regulation prevent large-scale commercialization of biochar nanocomposites. It is expected that the future of such technology lies in incorporating safety-by-design practices, creating standardized processes for their production, and testing on field leve[39]l. A combination of expertise in materials science, environmental engineering, and agronomy, together with policies and regulation, will be essential for maximizing the advantages of using biochar nanocomposites. Not only do biochar nanocomposites currently find applications in agriculture and environment, but they might also prove beneficial in energy materials, the circular economy, and smart agriculture in the near future. Conclusion To sum up, despite the fact that biochar nanocomposites cannot currently live up to their full potential, they possess great prospects for becoming a breakthrough innovation in agriculture and environment[45].

FUTURE SCOPE

Future prospect of biochar nanocomposites derived from plants appears very bright owing to an increasing need for sustainable environmental technologies[46]. Future directions for the research might be: The methods may be optimized for large-scale synthesis to facilitate industrial-scale production of biochar nanocomposites Treatment of wastewaters containing metal ions, Bioactive materials based on biochar nanocomposites, Metal nanoparticle-loaded biochar nanocomposites, Magnetic biochar nanocomposites, Functionalized polymers with biochar nanocomposites, These enhancements might enhance the performance of biochar nanocomposites even more[3].

Techniques for adsorbent regeneration

- Efficiency of recycling process
- Long-term stability
- Multiple cycles of adsorption and desorption Regeneration efficiency might help enhance economic viability.

Biochar-based nanocomposites could be considered for;

- Enhancement of soil fertility
- Immobilization of heavy metals

Controlled release of nutrientsThe versatility of applications made possible by the multifunctionality of biochar nanocomposites makes possible a wide range of technological applications. It was found out that biochar nanocomposites made from plant material via green approaches are efficient, sustainable, and environmentally friendly materials that can be used to remove pollutants [6]. This makes an attractive approach towards developing low-cost technologies for environmental treatment, because of using renewable resources and the incorporation of nanotechnology into environmental applications. It should also be noted that the environmentally friendly nature of the production process makes this approach very attractive for sustainable development of science and technology[46].

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LIST OF CONFERENCES

1-International conference on biomanufacturing, bio-innovation, and environment sustainability (ICBBES 2026) organized by Chandigarh university, Mohali

- Oral presentation on Green micropropagation of medicinal plants using organic growth additives: A sustainable approach supporting UN sustainable development goals.

Date of conference - 10-11 April 2026

Acceptance of abstract – 28 March 2026

2-International conference on Sustainable biotechnology and bio-innovation (SSB-2026) organized by Amity university, Noida

- Poster presentation on Green synthesis and characterization of plant derived biochar nanocomposites for environmental and agricultural applications.

Date of conference - 25 – 27 feb 2026

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