International Journal of Science, Strategic Management and Technology
Volume **02** Issue **06** June-**2026** | ISSN: **3108-1762 (Online)** | Impact Factor: 3.8
An International, Peer-Reviewed, Open Access Scholarly Journal Indexed in recognized academic databases

Biochar from Sugarcane Bagasse for Environmental Pollution Remediation

Usha Sah [1st] **and Jayanand**[2nd]
[1st, 2nd]School of biotechnology and Life sciences
[1st, 2nd]Shobhit Institute of Engineering and Technology, Modipuram, Meerut, UP, India
[1st]Email**: *ushasah152@gmail.com*** [1st]ORCID **: https://orcid.org/0009-0002-2660-2424**

[2nd]Email : jayanand@shobhituniversity.ac.in [2nd]ORCID : https://orcid.org/0000-0002-2274-3150

https://doi.org/10.55041/ijsmt.v2i6.047

Cite this Article: Sah, U. & Jayanand, (2026). Biochar from Sugarcane Bagasse for Environmental Pollution Remediation. International Journal of Science, Strategic Management and Technology, *02*(6). https://doi.org/10.55041/ijsmt.v2i6.047

Abstract

Industrialization, urbanization and poor waste management have led to environmental pollution which has emerged as a major global concern requiring the development of sustainable and eco-friendly remediation strategies. In this sense, biochar from agricultural residues has been shown to be a promising material for environmental management. The pyrolysis of sugarcane bagasse, an abundant by-product of the sugar industry, provides a promising opportunity for the production of inexpensive and renewable biochar feedstock. This review highlights the production, physicochemical properties and environmental applications of sugarcane bagasse biochar for pollution mitigation and sustainability enhancement. Biochar has high porosity, large surface area, functional groups, mineral content and aromatic carbon structure that are important structural and surface properties making it very efficient for different environmental applications . Its role in carbon sequestration is particularly important, with the stable carbon matrix of biochar helping to store carbon for the long-term and reduce greenhouse gases. Also, the sugarcane bagasse biochar is capable of improving soil fertility by increasing the retention of nutrients, water holding capacity, microbial activity and balancing the soil pH which contributes to sustainable agriculture. The review also discusses the adsorption capacity of sugarcane bagasse biochar in removing organic and inorganic pollutants such as dyes, heavy metals and toxic compounds from water and air. The factors influencing the adsorption performance such as pyrolysis temperature, surface modification, pH and contact time are also discussed. Recent advances of engineered and modified biochars for improved removal of pollutants are also reviewed. Sugarcane bagasse biochar is, in general, an environmentally sustainable, economically viable and multifunctional material with great potential for pollution control, waste valorization and climate change mitigation. Further research is needed to optimize the production processes and expand its large scale environmental applications.

Index terms : Agricultural Waste, Biochar, Environmental Pollution, Pyrolysis, Soil Amendment, Sugarcane Bagasse

I. Introduction

According to annual report released on November 2024 of USDA United States Department of Agriculture Foreign Agriculture Service production of Sugarcane has been increased to 183.8 million tons. As a result the sugar industry has generated a significant amount of agricultural waste. This waste primarily takes the form of bagasse after crushing sugarcane to extract juice. Bagasse is the most important by product and one of the most abundant agricultural waste in the world(Candido *et al*., 2017). The annual global production of sugarcane bagasse is estimated to be around 700 million tonnes. India is the second largest producer of sugarcane in the world after Brazil(Ministry of agriculture, Government of India).Sugarcane is a most important cash crop of India. With rising income consumption of sugar is anticipated to rise in India. Sugarcane provides raw material for the second largest agro based industry after textile. It is estimated that there are around 716 installed sugar factories with sufficient capacity to produce around 330 lakh MT of sugar (NFSM). Sugarcane mills extract sugarcane juice leaving behind lignocellulosic biomass known as Bagasse comprises almost 12.3% wt basis of clean sugarcane mass. (Varshney *et al*., 2019) India generates around 90 million tons of sugarcane bagasse as a residue annually from sugar mills (Konde *et al*., 2021). Sugarcane bagasse are choosen as raw material for the preparation of biochar since it is abundant and inexpensive(Qureshi *et al*., 2023). In the absence of adequate sustainable practice around 90 MT of crop residue are burned every year causing excessive particulate matter emission and air pollution. Crop residue burning in the city of Delhi and other northern India has been observed in recent yerars. Converting Bagasse into Biochar is an effective sustainable technique(Bhuwaneshwari *et al*., 2019)

Biochar is porous carbonaceous material obtained during the low oxygen pyrolysis of biomass derived from different feedstock. Biochar has high specific surface area, porous, different functional groups on the surface, ion exchange capacity and these qualities are effectively utilised for removal of pollutants from the environment (Yaashikaa *et al*., 2020). Biochar production is lowest when synthesised from fast pyrolysis and through fast pyrolysis biochar yield is highest. Biochar is mainly composed of Carbon ranging from 65%-90%, and Oxygen and aromatic compound which contribute to protection against biological degradation. Biochar from sugarcane bagasse is high quality Biochar since its carbon content is 82% . Biochar from bagasse also has high Nitrogen content. Since bagasse biochar has high oxygen and high Nitrogen content significantly increase the soil quality by providing nutrients and enhance crop yield. In bagasse volatile matter content is 85% while biochar has 57% volatile content. Bagasse Biochar has high Carbon content so it has high heat value which suggesting its burning potential. Bagasse Biochar surface functional group significantly impact on removal of pollutant through adsorption. The surface acidity or basicity of Biochar primarily decided by the presence of Oxygen and Nitrogen. Presence of Oxygen mainly shows acidic groups such as carboxylic acid, lactones, phenols and lactols while Pyrones is oxygen containing basic group. As the temperature rises from 100-700°C oxygen containing acidic functional group break down yield CO2 and CO. As the temperature rises above 600°C basic functional group decomposes. When Bagasse biochar is subjected to high temperature leads to elimination of acidic functional group which make the Biochar more receptive to adsorption of acidic compounds. Nitrogen containing functional group such as amino group gives a basic characteristic. Biochar prepared through pyrolysis above 400°C doesnot contain amino group instead nitrogen is incorporated into aromatic ring such as pyridine.(Zafeer *et al.,* 2023).
Biochar is produces by thermochemical conversion of biomass under inert or low stoichiometric oxygen atmosphere at temperature range between 400-1200 °C (. Pyrolysis technology is differenciated based on temperature of pyrolysis and carbonization process or the residence time of the pyrolysis. In slow Pyrolysis process the heating rate is around 5-10°C/min and long residence time. In the slow pyrolysis heating temperature range is 400-500°C and the time duration is 5-30 min. In the fast Pyrolysis heating temperature range is 800-1200°C for a short period of time varying between

1 to 10 s (Yaashikaa *et al* 2020). The biochar yield during the pyrolysis process is a determinant of the nature of biomass used, the type of reactor, and process conditions heating rate, residence time , pressure, temperature (Dehaghi *et al.,* 2020). In pyrolysis technique wide range of products formed depending on the temperature, feedstock used and residence time. Products such as liquid (bio-oil), solid (biochar), gas (bio syngas), these producs are formed in significant amount via via chemical reactions processes like depolymerisation, fragmentation and cross linking (Braghiroli *et al*., 2018). Product yield depends upon defferent parameter generally low temperature and high residence time favour the biochar production. Slow pyrolysis favour the formation of char but liquid and gaseous products is often accompanied. It is observed by the reasearcher that biochar which are derived from sugarcane bagasse at varying temperature , the average pore diameter of biochar decreases with increasing pyrolysis temperature and the adsorption behavior of the biochar increased with rising pyrolysis temperature. (Dehhaghi *et al* 2020).

This review summarizes the most recent and comprehensive knowledge on the production of biochar from sugarcane bagasse as a green strategy for the control of environmental pollution. Unlike earlier studies examining either biochar synthesis or individual environmental applications, this review introduces an integrated framework for the valorization of sugarcane bagasse, covering feedstock characteristics, conversion technologies, physicochemical properties, and multifunctional environmental applications. This review is novel in its focused discussion on sugarcane bagasse derived biochar as a sustainable circular-economy material for simultaneous waste management, carbon sequestration, soil fertility improvement and pollutant remediation. Moreover, the review critically compares the recent thermochemical conversion methods such as pyrolysis, hydrothermal carbonization, gasification, and torrefaction with respect to their influence on biochar properties and biochar adsorption performance. Recent advances in engineered and modified bagasse biochar for the removal of heavy metals, dyes, pesticides and emerging contaminants from water and soil systems are also given particular attention. This review provides a compilation of recent findings and identification of current research gaps that give valuable insights for the development of cost-effective, scalable and sustainable biochar technologies for environmental remediation and climate change mitigation.

2. Production methods

2.1 Pyrolysis

Pyrolysis is the thermochemical conversion of biomass under inert or low stoichiometric oxygen atmosphere at temperature range between 400-1200 °C. Pyrolysis technology is differenciated based on temperature of pyrolysis and carbonization process or the residence time of the pyrolysis. In slow Pyrolysis process the heating rate is around 5-10°C/min and long residence time. In the slow pyrolysis heating temperature range is 400-500°C and the time duration is 5-30 min. In the fast Pyrolysis heating temperature range is 800-1200°C for a short period of time varying between 1 to 10 s. The biochar yield during the pyrolysis process is a determinant of the nature of biomass used, the type of reactor, and process conditions heating rate, residence time , pressure, temperature. In pyrolysis technique wide range of products formed depending on the temperature, feedstock used and residence time. Products such as liquid (bio-oil), solid (biochar), gas (bio syngas), these producs are formed in significant amount via via chemical reactions processes like depolymerisation, fragmentation and cross linking. Product yield depends upon defferent parameter generally low temperature and high residence time favour the biochar production. Slow pyrolysis favour the formation of char but liquid and gaseous products is often accompanied. It is observed by the reasearcher that biochar which are derived from sugarcane bagasse at varying temperature , the average pore diameter of biochar decreases with increasing pyrolysis temperature and the adsorption behavior of the biochar increased with rising pyrolysis temperature. (Zafeer *et al*., 2023)

2.2 Hydrothermal Carbonization

Hydrothermal Carbonization is a thermochemical decomposition of biomass which produce a carbon rich material that is hydrochar and the liquid fraction is also produced which is also known as process water. One major challenge of this process is process water reuse or disposal. The process HTC (Hydrothermal Carbonization) is done at medium temperature usually between 180°C and 350°C and the autogenous vapour condition is 10-80 bars. A series of Hydrolysis condensation, decarboxylation and dehydration reaction occur during the HTC reaction. This method of preparing biochar is cost effective since it can be prepared at low temperature and exclude the drying operation. Hydrochar was prepared in a stainless steel closed chamber coated with Teflon, in each experiment sugarcane bagasse and vinasse was mixed in 1:20 ratio . Vinasse was used as hydrothermal medium and chemical additive sulphuric acid and phosphoric acid was used. Mixture was heated at 230°C ± 10°C under self generated pressure for 13 hr. Hydrochar was separated from process water.(dos Santos *et al.,* 2021). Hydrochar which is obtained from HTC has low surface area and low porosity.(Zhou *et al.*, 2022). Biochar production from Sugarcane bagasse through HTC was done by Prasannamedha et al (Prasannamedha *et al.,* 2020) followed by NaoH activation for removal of sulfamethoxazole (SMX) from water. The result showed that HTC derived biochar had great adsorption affinity for SMX removal and can serve as an effective sorbent for removal of contaminants. HTC is also known as wet pyrolysis because it requires wet feedstock and so the raw digestate can be directly used. Moisture content may be 54-98%. This process doesnot require prior drying therefore saving substantial energy.(Michela Langone and Daniele Basso 2020). As compared to Pyrolysis process the HTC method requires low temperature and does not require drying.(Sharma *et al.,* 2019)

2.3 Gasification :

Gasification is the thermochemical method of decomposing sugarcane bagasse biomass or other organic matter into gaseous products (Syngas) containing H2, CO, CO2, CH4, thaces of hydrocarbons, a solid char(biochar) and liquid product (tar) at high temperature typically between 700-1000°C. The process of Gasification is divided into four discrete sub process they are pyrolysis, combustion, cracking and reduction. In gasification process the main product is syngas while char and tar are undesirable byproduct. During gasification process higher temperature and different gaseous condition was used and the result was in lower biochar yield , total surface area of biochar was high , high pH and high ash content. While in the slow pyrolysis process the biochar has small surface area and higher PAH than the gasification biochar. (Lydia Fryda and Rianne Visser 2015)

2.4 Torrefaction:

Torrefaction is a mild thermochemical pretreatment (200–300°C) in inert or oxygen-deficient atmosphere to improve the fuel and carbonization properties of biomass such as sugarcane bagasse. Torrefaction removes moisture and volatile organic compounds increasing the carbon content, hydrophobicity, grindability and energy density of biomass. Torrefied bagasse is a better precursor for the production of biochar due to its better thermal stability and the fact that it can produce biochar with enhanced porosity and adsorption capacity. The process also leads to a decrease in O/C and H/C ratios, which enhance the chemical stability of the material for environmental applications such as pollutant adsorption and soil remediation. Several studies have reported that pretreatment of torrefaction can improve the physicochemical characteristics and yield quality of bagasse-derived biochar especially for application in wastewater treatment and carbon sequestration.(Kalifa *et al.*, 2025)

Table 1: Comparative table of different thermochemical process their advantage and disadvantage

Process	**Typical Temperature & Conditions**	**Main Products**	**Advantages**	**Disadvantages**	**Recent Reference**
Slow Pyrolysis	300–700 °C, slow heating rate, long residence time, absence of oxygen	Biochar, bio-oil, syngas	High biochar yield; simple technology; suitable for carbon sequestration and soil amendment; can process diverse biomass	Long processing time; lower liquid fuel yield; lower throughput; energy-intensive heating	Rasaq et al., 2024
Fast Pyrolysis	400–650 °C, rapid heating, short vapor residence time, no oxygen	Bio-oil (major), syngas, char	High liquid bio-oil yield; rapid conversion; suitable for renewable fuel production; scalable technology	Bio-oil instability and high oxygen content; requires dry feedstock; complex reactor design	Tsoutsa et al., 2024
Hydrothermal Carbonization (HTC)	180–280 °C, high pressure, wet biomass in water medium	Hydrochar, process water, gases	No need for biomass drying; suitable for wet waste; energy efficient; produces carbon-rich hydrochar	High-pressure reactor required; wastewater generation; corrosion and maintenance issues	Teoh et al., 2024
Gasification	700–1200 °C, limited oxygen/steam environment	Syngas (CO, H_2, CH_4), ash	High energy conversion efficiency; syngas usable for electricity and fuels; lower solid waste	High operating cost; tar formation; complex gas cleanup; catalyst deactivation	H. N. Nguyen et al., 2022; Saleh et al., 2025
Torrefaction	200–320 °C, mild thermal treatment under inert or low-oxygen atmosphere, slow heating rate	Torrefied biomass, gases, condensable vapors	Improves biomass energy density and hydrophobicity; enhances grindability; reduces moisture content; suitable as a	Lower solid mass yield; energy loss during devolatilization; requires controlled atmosphere; limited large-scale commercialization	Kalifa et al., 2025

			pretreatmentfor pyrolysis and gasification		

III. Cause of Environmental Pollution

Increasing population leads to increase in demands of goods and services and to fulfil the demands industries are increasing. Industrialization has been contributing to the economic development of countries all over the globe but it is also causing deterioration of environment as well as human health (Yaashika *et al*., 2020). Urbanization and Industrilization also leads to increase in pollution. Pollution is defined as the introduction into the environment of substances that is pollutant and which are harmful to human and other living organisms. Pollutants are harmful solids, liquid, gases produced in higher than usual concentrations that reduce the quality of our environment. Human activities have adverse effect environment by polluting the water we drink, the air we breathe, the soil in which plant grow. Air and water pollution in industrial areas has emerged as an hasten issue in recent years due to its aggravated effect on health and well being. The atmosphere has hundreds of air pollutants from natural or from anthropogenic sources. The important pollutants are sulphur dioxide, carbon monoxides, oxides of nitrogen, hydrocarbons, radioactive substances hydrogen sulphide (David, 2022). The water resources are being deteriorated due to continuous discharge of organic and inorganic contaminants such as dyes, heavy metals, surfactant pharmaceuticals, pesticides and personal care products from industries and municipalities into water bodies. Most of the pollutants are highly persistent in nature and are otherwise converted into recalcitrant form. These pollutants causes serious negative impact on ecosystem (Hou *et al.,* 2023).

3.1Existing treatment for Removal of pollution and its disadvantages

Conventional methods for removing the pollutants based on biological, physical, and thermal properties include biodegradation, oxidation, ion exchange, precipitation, adsorption, coagulation, flocculation, filtration, irradiation, electrodialysis, reverse osmosis, membrane process, ozonation, distillation and solvent extraction.(Saravanan *et al*., 2021) Most of these techniques have disadvantages such as high cost, less flexibility, low efficiency and possibility of second pollutant production(Gwenzi *et al.,* 2020). Use of Biochar as adsorbent which is low cost does not produce secondary pollutant and production process is easy(Yaashika *et al* 2020).

IV. Characteristics of Sugarcane Bagasse Biochar responsible for pollution remediation

Surface area **-** Surface area is an important property influencing the adsorption capacity of biochar. Sugarcane bagasse is considered a suitable raw material for biochar production due to its high carbon content and porous structure. Biochar produced from sugarcane bagasse typically exhibits a high surface area of around 500 $m^2\ g^{-1}$**,** which makes it an effective bio-adsorbent for environmental applications. The surface area of biochar is commonly determined using theBrunauer–Emmett–Teller (BET) method**,** which measures nitrogen adsorption–desorption to estimate the specific surface area (Manyuchi *et al*., 2020). Studies have reported that digested bagasse biochar possesses a higher surface area compared to untreated bagasse biochar, which enhances its potential for soilremediation and wastewater treatment (Inyang *et al*., 2010). Furthermore, modification of sugarcane bagasse biochar with ZnO nanoparticles has been shown to significantly increase the BET surface area, nearly doubling it, which improves the adsorption efficiency for dyes such as Reactive Red 24 (RR24**)** from wastewater (Van ., *et al* 2020). Similarly, when sugarcane bagasse biochar was chemically activated using NaOH, the treated biochar exhibited a higher BET surface area (SBET) compared to untreated biochar. This increase in surface area enhanced its adsorption performance for dyes such as methylene blue and crystal violet, demonstrating that treated biochar (T-BC) can serve as a more efficient adsorbent (Moharm ., *et al* 2022).

Pore size - Pore size distribution is an important characteristic that influences the adsorption efficiency of biochar. The pore size of biochar is commonly determined using the nitrogen (N_2) adsorption–desorption method based on the Brunauer–Emmett–Teller (BET) technique (Wang *et al*., 2023; Ge *et al*., 2024). Studies have reported that sugarcane bagasse biochar contains two main types of pores: micropores with pore sizes less than 2 nm and mesopores with pore sizes ranging from 2 to 50 nm. This pore size distribution provides a large number of adsorption sites, which enhances the ability of biochar to adsorb metal ions and other contaminants from aqueous solutions (Chang *et al*., 2022). The average pore size of sugarcane bagasse biochar pyrolysed at 750°C was reported to be approximately 1.76 nm, while KOH-activated biochar showed a slightly larger average pore size of about 1.94 nm. The activation process using KOH is mainly associated with internal reactions that release gases and create additional pore structures within the biochar matrix. Pore size and pore distribution are typically calculated using the Brunauer–Emmett–Teller (BET) and Barrett–Joyner–Halenda (BJH) models. The presence of micropores provides a large number of accessible adsorption sites, which significantly enhances the adsorption of contaminants such as norfloxacin (Zhou *et al*., 2023).

Particle size distribution: Transmission electron microscopy (TEM) is commonly used to determine the particle size distribution of biochar, while scanning electron microscopy (SEM) is used to examine the surface morphology and structural characteristics. SEM images of sugarcane bagasse biochar have revealed a tubular and porous structure, indicating the presence of well-developed pore networks that enhance adsorption properties (Hou *et al*., 2023). In one study, TEM analysis showed that the particles exhibited a monodispersed polygonal shape with an average size of approximately 400 ± 32 nm. Smaller particle sizes provide a larger surface area and create additional active sites, which enhance the adsorption capacity of the biochar (Chang *et al*., 2023).

pH: The pH of sugarcane bagasse biochar in water is reported to be slightly acidic, around 6.56, whereas many other biochars are typically slightly alkaline, with pH values ranging from 7.5 to 9.4. The relatively higher surface acidity of sugarcane bagasse biochar indicates the presence of acidic functional groups such as carboxylic and phenolic groups, which can be confirmed using Fourier transform infrared (FTIR) spectroscopy (Carrier *et al*., 2012). The pH of the solution plays an important role in the adsorption of pollutants from aqueous environments. For example, during the removal of Ni(II) ions, experiments conducted in the pH range of 2–7 at constant temperature showed that Ni(II) uptake increased from 0.577 to 2.57 mg g^{-1} as the pH increased from 2 to 6. However, when the pH increased beyond 6, the uptake of Ni(II) decreased due to the precipitation of nickel hydroxide. At low pH values, hydrogen ions compete with Ni(II) ions for the binding sites on the biosorbent surface, resulting in reduced metal uptake. As the pH increases, the biosorbent surface becomes negatively charged, which enhances the adsorption of positively charged metal ions. At higher pH levels, more negatively charged ligands such as phosphate, amino, and carboxyl groups become exposed and attract metal ions (Kulkarni *et al*., 2022). Similarly, solution pH significantly affects the adsorption of dyes. In a study evaluating the adsorption of reactive red 24 (RR24) by biochar within a pH range of 3–10, the adsorption capacity slightly decreased as the pH increased. At lower pH levels, the surface of biochar becomes positively charged, while RR24 molecules in aqueous solution are negatively charged due to the presence of sulfate groups. Therefore, higher adsorption capacity at lower pH values is attributed to electrostatic attraction between positively charged functional groups on the biochar surface and negatively charged dye ions (Van *et al*., 2021). Sugarcane bagasse biochar has also been reported to show the highest lead removal efficiency at pH 5 (Praipipat *et al*., 2023).

Surface functional groups: Surface functional groups play a significant role in determining the effectiveness of biochar in applications such as catalysis, adsorption, and electrode materials (Murtaza *et al*., 2023). Fourier transform infrared (FTIR) spectroscopy is a vibrational spectroscopic technique widely used to identify the functional groups present on the surface of biochar. Studies have reported the presence of hydroxyl groups as the dominant functional groups, along with other groups such as amines, aldehydes, alkenes, and aromatic compounds (Mansee *et al.*, 2023). FTIR analysis is also useful for examining how pyrolysis temperature influences the functional groups present in biochar. According to Sahoo et al. (2021), changes in pyrolysis temperature significantly affect the formation and transformation of surface functional groups. In a study conducted by Adekanye et al. (2022), it was observed that an increase in temperature resulted in the expansion of the O–H group absorption band within the range of 3383–3402 cm^{-1}.

Electrical conductivity: Biochar is effective in remediating cationic pollutants such as heavy metals because of its generally negative surface charge. The electrical conductivity of biochar can increase with higher pyrolysis temperatures due to the formation of more ordered carbon structures. In an experiment conducted by Ahmed et al. (2021), it was found that biochar produced at higher pyrolysis temperatures significantly improved electrical conductivity. A conductivity value of 7.67×10^{-2} S was observed when 12 wt% biochar produced at 1000°C was added, indicating improved electron transfer properties.

Cation exchange capacity: The cation exchange capacity of biochar is closely related to the presence of surface functional groups identified through FTIR analysis. The FTIR spectrum of biochar shows several absorption peaks corresponding to different functional groups. Peaks within the range of 3436–3433 cm^{-1} are mainly associated with hydroxyl (O–H) and C–H groups. Other peaks in the region of 2386–2286 cm^{-1} correspond to C–H and O=C=O groups, while peaks in the range of 1702–1589 cm^{-1} indicate the presence of amines, alkenes, and aromatic functional groups. The presence of these polar functional groups on the biochar surface contributes significantly to its cation exchange capacity, thereby enhancing its ability to adsorb positively charged contaminants (Mansee *et al.*, 2023).

V. Factors affectiong Biochar performance

5.1 Temperature

The temperature at which biochar is pyrolysed greatly afect its adsorptive capacity. For example biochar which is pyrolysed at low temperature below 400 C will have more functional group and will have more adsorptive capacity for pollutants(Sun et al., 2022). Biochar which is pyrolysed at high temperature will decrease the functional groups but there will be increase in aromaticity and ts specific area. For example Biochar has porous structure and high specific surface area which help in adsorption of microplastics(Wang *et al*., 2020). As the pyrolysis temperature increases volatile matter content decreases creating more pores, fixed carbon content increases, moisture content decreases and ash content gradually decreases, pH of biochar increases with increase in pyrolysis temperature. Iodine number shows the development of micropore in biochar as the temperature increases Iodine number increases showing the development of more micropore which increases the adsorption of contaminants.(Sun *et al.,* 2017)

5.2 Residence time

Contact time was found to affect adsorption onto biochar, and is an important factor for evaluating removal efficiency and understanding adsorption kinetics. First, the adsorption is quick due to the large number of active sites on the biochar surface and the quick attachment of pollutants through physical and chemical interactions. This phase has a high concentration gradient between the solution and the biochar surface which results in an increase in mass transfer. With increasing contact time, the adsorption rate decreases gradually because the most easily accessible surface sites are occupied and adsorption in the pores of the biochar by intra-particle diffusion begins . Eventually the system reaches a steady state, i.e. the amount of adsorbate attached to the biochar equals the amount desorbing back
(Pieczykolan, 2025)

5.3 Dose or amount of adsorbent

The adsorbent dose (amount of biochar added) is one of the most important factors in batch adsorption systems. The removal efficiency of target pollutants generally increases with increasing the dose of biochar as more mass of adsorbent provides more available surface area and active sites for adsorbate molecules to bind, which increases the probability of collision and uptake from solution. But the relationship is not linearly indefinitely – above an optimum dose biochar may aggregate in particles, adsorption sites may overlap and there is a relative decrease of adsorption capacity per unit mass, which decreases the efficiency of adsorption in relation to the adsorbent used. This behaviour is due to the trade-off between maximizing the active surface area and avoiding excessive sorbent amounts leading to the saturation of the adsorption sites and the inefficient utilization of the material. These trends have been confirmed in recent experimental studies on the adsorption of organic pollutants by biochar: increasing biochar doses increases the uptake of pollutants and the removal efficiency up to a certain point, beyond which the benefit of the addition of biochar diminishes or reverses owing to a limited availability of the adsorbate and a limited use of the effective surface area. (Nguyen *et al.,* 2023)

5.4 Activating Agents

The activating agents have a great impact on the pore structure, surface functionality and adsorption properties of carbon materials. Dehydration, oxidation, gasification and structural rearrangement in biomass can be enhanced by chemical activation with acids, alkalis and salts during thermal treatment. Common activating agents such as, KOH (Potassium hydroxide), Sodium hydroxide or NaOH, Phosphoric acid (H3PO4), Zinc chloride (ZnCl2), Potassium, carbonate (K2CO3),Hydrogen sulphate (H2SO4). Different activating agents lead to different pore structures and surface characteristics like activation with KOH usually yields a highly microporous carbon with a very high surface area, H3PO4 activation increases mesopore formation while also maintaining carbon yield, $ZnCl_2$ catalyzes dehydration and carbon aromatization. Activating agents are important for area, pore volume, functional groups, selectivity in adsorption and stability to heat . Recent studies demonstrated that chemically activated biomass derived carbons have higher adsorption efficiency for heavy metals, dyes, antibiotics and pharmaceutical contaminants compared to non-activated carbon materials. However, overuse of chemical activating agents may lead to increased production cost and generation of secondary chemical waste. In this context, recent research has been focused on environmentally friendly activation methods and hybrid activation approaches. (Bumajdad *et al*., 2023)

5.5 Feedstocks

The type of biomass used as feedstock has a strong influence on the physical and chemical properties of the biochar. Agricultural residues, wood waste, manure and algae have different portions of cellulose, hemicellulose, lignin and minerals, which influence carbon content, pore structure, ash composition and surface functional groups . For example, biochar made from lignin-rich biomass tends to have higher fixed carbon and aromaticity, while biochar from manure tends to have higher mineral and nutrient content. Feedstock composition directly influences adsorption capacity, nutrient retention and environmental remediation efficiency. Recent studies have reported that rice husk and coconut shell-derived biochar showed superior adsorption of heavy metals due to their porous structure and silica-rich composition.(Đukanović *et al*., 2025)

5.6 Surface area and pore size:

The adsorption efficiency is heavily influenced by the surface area and pore size distribution of biochar. Biochars with higher surface area and well-developed microporous structure provide more active sites for the adsorption of pollutants such as dyes, pesticides and heavy metals. High porosity improves water retention and microbial colonization in soil applications. Further pore formation and adsorption performance can be improved by activation processes with steam or chemicals .(Hamaoud *et al.*, 2024)

VI. Mechanism involved in pollution removal

6.1 Adsorption:-

In the adsorption process adsorbate is associated with the adsorbent's surface until equilibrium is achieved. In this process firstly the physical adsorption in which adsorbate settles on the adsorbent surface and next is precipitation and complexation in which the adsorbate deposits on the adsorbent's surface and then pore filling in which the adsorbate is condensed into the pore of the adsorbate. During this process three zones are formed. First is the clean zone in which adsorption takes place , second is mass transfer zone in which adsorption is in progress , last is exhausted zone where equilibrium is achieved(Dong *et al.*, 2023). The temperature at which biochar is pyrolysed greatly afect its adsorptive capacity. For example biochar which is pyrolysed at low temperature below 400 C will have more functional group and will have more adsorptive capacity for pollutants(Sun *et al.*, 2022). Biochar which is pyrolysed at high temperature will decrease the functional groups but there will be increase in aromaticity and ts specific area. For example Biochar has porous structure and high specific surface area which help in adsorption of microplastics(Wang *et al.*, 2020).

6.2 Cation/ion exchange:-

The exchange of protons and ionized cations with dissolved salts on the biochar's surface is the main principle of this mechanism (Ge *et al.*, 2024). Trakal *et al.* (2016) investigated the removal of Cd and Pb using biochar prepared from different feedstocks such as wheat straw, graph stalk, grape husk, plum stone and nutshell. The author showed that biochar modified with iron oxide that is magnetic modification enhances the biochar structure for removal of Pb and Cd.

6.3 Electrostatic interaction:-

This mechanism involves the electrostatic interaction between charged biochar and metal ions to limit the mobilization of potentially toxic metals. This mechanism also depends on pyrolysis temperature , increasing temperature greater than 400C can enhance carbonization of the biochar and leads to an increase in electrostatic interaction of biochar. (Agrafioti *et al.*, 2014;)

6.4 Electron donar and acceptor interaction:-

The electron donar and acceptor interaction mechanism is mostly applied to the adsorption of aromatic compounds on biochar presenting a grapheme like structure. To have a complete graphatization a temperature greater than 1100°C should be reached during the biochar preparation . However the electron density of biochar to generate deficient or enriched Pi electron depends upon the pyrolysis temperature of the biochar, that if the pyrolysis temperature is below 500°C the system of the biochar pi aromatic acts as electron acceptor, while if the temperature is above 500°C the biochar acts as a donor (Sun *et al.*, 2022)

6.5 Precipitation:-

It is one of the main mechanism that can be used for the removal of inorganic pollutant onto biochar (Ge *et al.*, 2024). It involves the formation of mineral precipitates into the solution or onto the surface of the mineral precipitates into the solution or onto the surface of the sorbing material, especially for biochar which is produced from degradation of cellulose and hemicelluloses material through pyrolysis temperature greater than 300C and having alkaline property(Puga *et al.* 2016)

6.6 Complexation:-

This mechanism of metal complexation includes the arrangement of multi atom formation through the interactionof specific metal ligands to form complex (Wang *et al.*, 2023). The biochar produced at low temperature can bind with heavy metals due to the functional group which contains oxygen in their structure such as phenolic , lactonic and carboxyl. This oxygen content can increase surface oxidation of the biochar leading to enhance the metal complexation. It has been showed that biochar prepared from vegetal biomass has high efficiency in the binding of potentially metals such as Cu, Cd, Ni and Pb to form metal complex with carboxylic phenolic functional groups when compared with biochar prepared from animal such as dairy manure and poultry litter(Zhang *et al*. 2018, Ge *et al*., 2024).

6.7 Hydrophobic interaction:-

This mechanism can be used for the adsorption of Hydropphobic and neutral organic compounds through partitioning and hydrophobic interaction process. This mechanisms requires less energy. Chen *et al*., (2023) showed that adsorption of imidacloprid through iron modified biochar from sugarcane bagasse showed hydrophobic interaction mechanism. Liang *et al*.,(2021) showed that hydrophobic interaction is the main mechanism involved in the adsorption of ionizable organic pollutants such as benzoic acid , o-chloro benzene acid and p-chlorobenzene acid . Chen et al.,(2011) investigated the perfluro octane sulfonate sorption on biochar produced from maize straw. The removal took place via the hydrophobic interaction due to high hydrophobic nature of the organic pollutant.

VII. Applications of Sugarcane Bagasse Biochar in water, air and soil treatment :

7.1 Wastewater treatment:-

7.1.1 Effect of water pollution :

Water is essential source for human survival. The global use of freshwater has increased six fold in the past 100 years.With increase in water consumption, water quality is facing severe challenge.Water pollution occurs when unwanted materials enter into water and changes quality which is harmful for human health and environment. Water pollution is mainly concentrated in industrialization, agricultural activities, natural factors and insufficient water supply and sewage treatment facilities. Firsly Different industrial effluents that are drained into the river are major cause of water pollution. Industries like paper and pulp, textiles, sugar, electroplating, distillery, tannery, iron and steel, food, nuclear etc are polluting the water. Various toxic chemicals, organic and inorganic substances, toxic solvents, volatile organic compounds are released in aquatic ecosystem without proper treatment which leads to water pollution. Arsenic, Cadmium Chromium Lead and other heavy metals are vital pollutants discharged in waste water from industries. Pesticides, nitrogen fertilizers, phosphorus, organic farm wastes from agriculture are also significant cause of water pollution. Agriculre will contaminate water with pesticides, nitrates, phosphorus, salts, sediment soil, pathogens. Increase in pesticide use in recent time causes increase in medical disability index. Pollutants from sewage poses risk to environment and health. Number of people die each year by water born disease. In developing countries nearly 5 % children are died before age of five by using unsafe drinking water.(UNESCO 2021 world water development report). Some of the deadly water borne diseases are Cholera, Typhoid, Paratyphoid, Tuberculosis, Jaundice, Amoebiasis etc. According to Who survey 80% of world's disease and 50% of world's child deaths are related to poor drinking water. It is estimated that more than 50 diseases are caused by poor drinking water.

7.1.2 Treatment of wastewater with Biochar :

Biochar has certain characteristics like porous structure, large specific surface area, mechanical resistance acid and alkaline corrosion resistance, ion exchange capacity, diverse functionality and due to its properties Biochar is used as adsorbent of pollutant. Biochar as adsorbent has certain advantage as production cost is low and it is environmentaly sustainabe. Biochar and its derivative has been used in removal of heavy metals(Cadmium, Zinc, Lead , Copper) from aquous environment. (Komkiene *at el*., 2016). Magnetic Biochar which contain Iron particle has improvised textural properties i.e pore volume and surface area which helps easy adsorption of Cd+ from aquous environment and biochar can be easily regenerated through external magnet. (Saeed *et a*l., 2021). The micriporous structure and polar groups on the carbon surface were favorable for the adsorbtion of pigment methyl blue by the biochars(Sawalha *et al*., 2022).

7.1.3 Removal of heavy metals and metals**:-** Metals and heavy metals such as copper, nickel, cadmium, zinc, Chromium, Lead, Mercury are released from industries and municipal waste into water. These are harmful for the environment as well as human health. Particularly heavy metals are carcinogenic in nature. In a comparative study involving sugarcane bagasse biochar and orange peel biochar , the efficiency of biochar in removing Pb (II) from aqueous solution were examined. SC-BC was more effective in removing Pb(II) than OP-BC , with the removal capacity of 89.96% mg/g, much higher than that of OP-BC (27.86%). The higher sorption capacity of SC-BC was attributed to the high surface area compared to that of OP-BC.(Abdelhafez *et al.,* 2016). In one study removal of Cr(VI) ion was investigated using magnetic biochar prepared from sugarcane bagasse and steel pickling waste liquor at various concentrations. The presence of Fe(II) in the magnetic biochar was found to play a crucial role in the removal of Cr(VI), particularly when 1,10-phenanthroline was used as a reagent. Different iron oxides such as FeO, Fe_2O_3, and Fe_3O_4 were employed to remove Cr(VI). Among these oxides FeO in the magnetic biochar was the key active component for thr removal and reduction of Cr(VI). The maximum adsorption capacity of Cr(VI) by magnetic biochar was upto 71.06 mg/g and the adsorption of Cr(VI) was positively correlated with iron content (Yi *et al*., 2020). In another study by Liang *et al* (2020) a novel bagasse magnetic biochar (BMBC) consisting of bagasse biochar and magnetic iron oxide was utilized for the removal of Cr(VI) from aqueous solutions. The batch adsorption experiments were conducted to characterize BMBC before and after Cr(VI) adsorption and to investigate the removal behaviors and mechanisms of Cr(VI) by BMBC. Different parameters such as ionic strength, BMBC dosage, pH, adsorption duration, initial Cr ion concentration, co-existing ions were modified. BMBC were primarily composed of Fe2O3 and Fe3O4 on bagasse biochar with an amorphous structure. The maximum percentage of Cr(VI) removal was achieved with a dosage of 0.20g of BMBC in 50ml of solution at pH 2. BMBC posses maximum adsorption capacity of Cr(VI) in aqueous solution. As compared to conventional biochar sorbents, BMBC showed a maximum Cr(VI) adsorption capacity of 29.08% mg/g at 25C. The desorption of Cr(VI) using a 0.02% mol/L NaOH solution resulted in capacity of 8.21mg/g.The removal efficiency of Cr(VI) remained above 80.36% even after three reuse cycles. The suggested approach offered advantage such as low cost and excellent reproducibility of BMBC application . In a study nanocomposites were developed using sugarcane bagasse based biochar and nano magnetite for the removal of metal ions such as Fe and Zn from aqueous solution. The novel adsorbent was prepared using sugarcane bagasse based biochar and nano magnetite was called SCB-BC/Fe3O4. The experimental result showed that the synthesized nanocomposites exhibited high removal efficiency of 90% for Fe and 96% for Zn, effectively eliminating these metal ions from water (Almawgood *et al.,* 2021). Fe coated sugarcane bagasse biochar effectively remove As(III) from water (Montero *et al*., 2018). Sugarcane bagasse powder doped iron(III)oxide-hydroxide beads are effective material for rwmoving lead ion for inductrial purpose (Praipipat *et al*., 2023).

7.1.4 Removal of dyes**:-** Sugarcane Bagasse Biochar was prepared and biochar was surface activated using 1% NaOH . As compared to bagasse biochar the treated biochar has more adsorption capabilities of dyes methylene blue (MB) and crystal violet (CV) from synthetically prepared wastewater (Moharm *et al*., 2022). Reactive dyes are widely used in industries and are released in environment. It is non degradable and harmful for health. Sugarcane bagasse biochar was modified with ZnO nanoparticles to generate modified SBB-ZnO which has maximum adsoption capacity for Reactive Red 24 (RR24) dye (Van *et al.,* 2021). In one study the sorption and detoxification of malachite green (MG) dye were investigated using biochar produced by pyrolyzing agricultural and industrial waste at temperature of 800°C, 600°C, and 400°C. The highest sorption capacity of MG dye (3000mg/L) was observed with sugarcane bagasse biochar SCB) produced at 800°C. Response surface methods (RSM) were employed to analyze the relationship between various factors affecting MG dye sorption, including dye concentration, pH and temperature. The RSM model based on Box Behnken design revealed that the optimal conditions for MG dye sorption were a dye concentration of 3000 mglL, contact time of 51.89 min, temperature of 60°C and pH of 7.5.

7.1.5 Removal of insecticides, pestisides**:-**Biocharan ecofriendly and low cost adsorbent was introduced for the removal of p-nitrophenol (PNP). PNP one of the most important chemical contaminant that recognized as the main metabolite in many pesticides and as intermediate in many industries. Mg- activated biochar was prepared from sugarcane bagasse and Mg activated biochar has greater adsorption capacity of PNP (Mansee *et al*., 2023). Carbofuran is a broad spectrum insecticide which is present in wastewater. Sugarcane bagasse biochar was prepared through slow pyrolysis at 500°C (SB500) which can be effectively used for the sustainable removal and recovery of carbofuran (Vimal *et al*., 2019).

7.1.6 Removal of Fertilizers chemical from waterbodies **:-** The wide use of fertilizers in agriculture is one of the major sources of nitrate pollution in groundwater and surface water. Sugarcane bagasse biochar is an effective adsorbent for the nitrate adsorption from the aqueous solution. Nitrate adsorption was higher under acidic pH. It was due to electrostatic attraction between nitrate ion and modified biochar surface (Hafshejani *et al*., 2016)

7.2 As adsorbent for harmful gases:-

7.2.1 Effect of air pollution-

Air pollution has various health effects. The health of susceptible and sensitive individuals can be impacted even on low air pollution days. Short term exposure to air pollutant is closely related to COPD (Chronic Obstructive Pulmonary Disease), cough, shortness of breath, wheezing, asthma, respiratory disease, and high rate of hospitalization. Long term effects associated with air pollution are chronic asthma, pulmonary insufficiency, cardiovascular disease, and cardio vascular mortality. Air pollution seems to have various malign health effects in early human life such as respiratory, pulmonary, cardio vascular, mental and perinatal disorders leading to infant mortality or chronic disease in adult age (Hao E Ting, 2020). Air pollution mainly affects those living in large urban areas, where road emissions contribute the most to the degradation quality. There is also danger of industrial accidents where the spread of toxic fog can be fatal to the population of surrounding areas. Indoor air quality is critical to human survival since on an average worldwide 80% of lives of people today are spent indoors. This increase the risk of exposure to harmful indoor air contaminants. CO2 is the major constituents or compound found among indoor air pollutants derived from occupants respiration. Ambient and indoor air pollution is estimated to have caused 1.7 million premature deaths in India in 2019.

7.2.2 Biochar as removal of harmful gases-

Biochar effectively remove metal vapors particularly elementary Hg, acidic gases(H_2S, SO_2, CO_2), ozone, nitrogen oxide(NOx), and organic contaminants including aromatic compounds, Volatile organic compounds, and adorous substances. The mechanisms for the removal of gaseous contaminants include adsorption, precipitation, size exclusion(Gwenzi *et al* 2020). In a comparative study between sugarcane bagasse biochar and hickory wood biochar it was observed that the highest CO_2 adsorption occurred with BG biochar produced at 600°C, exhibiting a capacity of 73.55 mg/g at 25°C. In the experiment result suggest that surface area play a major role in adsorption of CO2, but although HW600 had a larger surface area than BG600, the CO_2 adsorption curve of HW600 showed slightly steeper trend at 25°C and 75°C adsorption conditions. So along with surface area. Interaction with surface functional groups may also influence the adsorption of CO_2 on biochar. Biochar has porous structure and unique surface properties which enable then to be en efficient CO_2 adsorbent(Creamer *et al*., 2014). In a study a carbonaceous material was prepared from sugarcane bagasse for CO_2 adsorption. Two carbonaceous materials were prepared to quantify the CO_2 capture. First material CA-1 was impregnated into biochar and subsequently pyrolyzed at 350°C, and the second material CA-2 was directly impregnated into dry biomass, resulting into two different carbonaceous materials CA-1 and CA-2. The biochar was chemically activated with KOH, and thermal analysis revealed two primary stages of carbonization – the first occurring occurring around 150°C and the second between 150 and 600°C. Through thermogravimetric testing CO_2 capture was measured. The samples showed similar physic chemical characteristics. However the CA-2 sample showed better adsorption performance with a value of 1.22 mmol/g. (Peres *et al*., 2022). In biogas purification the combination of sugarcane bagasse based biochar with combination of natural zeolites demonstrated effective adsorption capacity of CO_2. The adsorption process was conducted at 5-7 bar pressure range at room temperature. When biochar was utilized as a substitute for zeolite at a 50% volume ratio , a significant reduction in CO_2 content was observed. The mixture of 50% natural zeolites and 50% sugarcane bagasse based biochar showed the highest CO_2 reduction (Wuri *et al*., 2021).

7.3 Soil amendment:-

Biochar shows numerous advantage in increasing soil pH value and organic carbon content, improving soil water holding capacity, reducing the available fraction of heavy metals , increase crop yield and inhibiting the uptake and accumulation of heavy metals.(Cheng *et al*., 2020)**.** Due to mine activities heavy metals such as chromium (Cr) and lead (Pb) enter the soil ecosystem and accumulate in food crop and cause serious health damage to human being and environment as well. In a study on soil remediation the use of popular wood biochar and sugarcane biochar resulted in reduced uptake of chromium(Cr) and lead(Pb) in lettuce, demonstrating their effectiveness in cleaning up contaminated agricultural soil (Khan et al., 2020). In another study it was found that sugarcane bagasse based biochar significantly reduces the availability of Cd and Cr in single or co-contaminated soil. It was found that there was increase in microbial activity and plant growth along with reduction in Cd and Cr uptake by mash bean could possible after biochar addition (Bashir *et al*., 2017). The biochar prepared from dried sugarcane bagasse when applied in salt affected soil, there was a significant increase in organic carbon, and also increase in available P, K, Ca, Mg and decrease in pH and bulk density was observed(Raul et al., 2020).

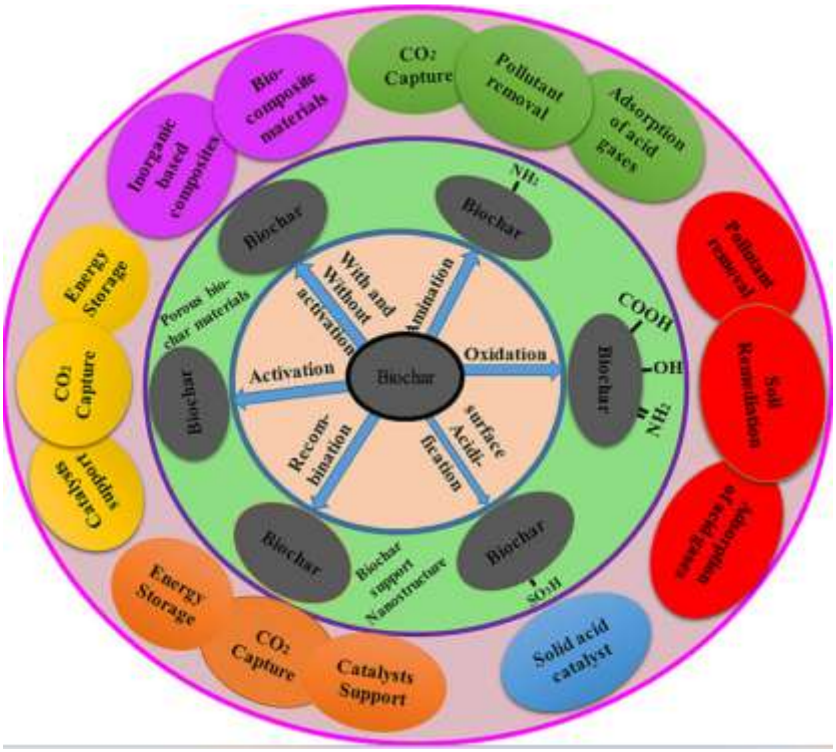

Figure 1 : Environmental Application of Biochar (Mishra & Mohanty, 2023)

VIII. Challenges and future perspective

Despite the great potential of sugarcane bagasse-biochar for environmental remediation, there are still several technical, economic, environmental and commercialization challenges limiting the large-scale industrial application of this material. One of the major challenges is the biochar quality due to the inconsistent feedstock composition and thermochemical conversion conditions. Parameters such as pyrolysis temperature, heating rate, residence time and activation process greatly influence surface area, porosity, functional groups and adsorption efficiency. Variability limits reproducibility and standardization needed for commercial-scale implementation. (Zafeer *et al.*,2024)

Economic viability is another significant limiting factor for large scale commercialization. Abundant and cheap agriculture waste is sugarcane bagasse but the installation of pyrolysis or hydrothermal carbonization systems needs high capital investment, energy input and operation cost . Transportation, drying, storage and pretreatment of bagasse contribute to the cost of production. Financial support, subsidies or carbon credit incentives may be necessary to enable adoption of biochar technologies by small scale industries and farmers. (Hiranobe *et al.*, 2024)

The lack of standard regulations and quality certification systems for biochar products hinders the commercialization. Many countries do not have provisions on biochar production standards, environmental safety, accounting for carbon sequestration and a ceiling on its application in agriculture. Uncertainty in regulation harms investor confidence and retards the growth of the market. Further, the industries and farmers are also not aware of the environmental and economic benefits of biochar and this further restricts the market penetration.(Yameen *et al.*, 2024)

The environmental risk of biochar production and application should also be carefully evaluated. Depending on the quality of the feedstock and production conditions, biochar may contain potentially toxic substances such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds, heavy metals and ash residues . Incorrect use of contaminated biochar may have negative effects on soil microbial activity, ground water quality and plant growth. Furthermore, excessive biochar application can result in changes in soil pH, nutrient cycling and ecosystem functioning. The long-term ecological impacts and the carbon stability under different environmental conditions are still poorly understood. (Yang *et al.,* 2024)

Aother important challenge is the scalability and integration of biochar production in existing sugar industries. For large scale continuous production, stable feedstock supply chains, efficient reactor systems and energy optimisation are required. Operational efficiency may be impacted by the availability of sugarcane bagasse in a season and the variability in biomass quality. Besides, the environmental management issues relating to the control of air emissions during pyrolysis and the safe disposal of gaseous by-products are still important.

There are also serious challenges in the verification and monitoring of the carbon credits. Biochar is a carbon sequestration material, but requires accurate monitoring, reporting and verification (MRV) systems, to ensure long-term carbon storage and environmental sustainability. The lack of harmonized international standards for carbon accounting introduces uncertainty to industries that wish to participate in carbon markets.(Ojo-kupoluyi *et al.,* 2024)

Future research should be directed towards the development of advanced and energy-efficient technologies of biochar production for improving the carbon yield, adsorption performance and environmental safety. Emerging techniques such as microwave-assisted pyrolysis, catalytic pyrolysis and engineered biochar modification can significantly improve the efficiency of pollutant removal and functional properties of sugarcane bagasse biochar. Functionalization with the use of nanoparticles, magnetic materials and chemical activators may widen its use in wastewater treatment, soil remediation and energy storage systems.(Sharma *et al.*, 2024). There is a great potential for the integration of biochar production in sugar mills and biorefineries to become part of circular bioeconomy systems . In such integrated systems, sugarcane bagasse can be used simultaneously for bioenergy production, carbon sequestration, soil improvement and environmental remediation, thus reducing the waste disposal problems and enhancing the resource efficiency. The joint manufacture of bio-oil, syngas and activated carbon can also improve economic profitability and industrial sustainability.(Ojo-kupoluyi *et al*., 2024).

The commercialization in future will largely depend on the government policies providing support, financial incentives and carbon credit mechanisms. Developing international standards on biochar quality, environmental safety and carbon accounting is essential to increase market confidence and attract industrial investment. Further development of life-cycle assessment (LCA) and techno-economic analysis studies is needed to assess the long-term sustainability and economic feasibility of sugarcane bagasse biochar systems under real industrial condition(Yang etal.,2025).

Long-term field experiments are needed to better understand the ecological effects of sugarcane bagasse biochar under different environmental conditions, interactions of nutrients, microbial responses, and stability of carbon sequestration. Further studies should also address the safe dosage limits and possible ecotoxicological consequences of repeated application of biochar. The development of biochar products that are both environmentally safe and free from contaminants will be important for sustainable applications in agriculture and the environment. Furthermore, interdisciplinary collaboration between researchers, policy makers, industries and environmental agencies will be important to accelerate the innovation and commercialization. Public awareness programmes and technology transfer initiatives can help farmers and industries adopt sustainable practices using biochar. With ongoing technological advancements and adequate regulatory support, sugarcane bagasse biochar has the potential to be a significant green material for pollution control, climate change mitigation, sustainable agriculture and circular waste management.(Zafeer *et al*., 2024)

IX. Recent Advancement

Recent breakthroughs like nano-modification, engineered biochar, alteration of functional groups, activation, magnetization in Biochar has greatly improved its use in varied domains like pollution abatement from environment, soil improvement. However, conventional biochar suffers from limited surface area and limited active adsorption sites. The researchers have, therefore, concentrated on modification of physicochemical properties of biochar for the enhancement of its adsorption efficiency, catalytic activity and environmental stability. High porosity and surface functionality have been achieved by advanced activation techniques using chemical agents (KOH, H3PO4, ZnCl2) and steam activation, which has enhanced the adsorption of heavy metals, dyes, pharmaceuticals and emerging contaminants from wastewater . Another approach is nanocomposite preparation process where immobilization of metal and metal oxide nanoparticle is carried out which enhances the surface area, porosity and surface functional groups, catalytic activity as well, which results to improve the adsorption and degradation capacity of biomass material.(Kumar *et al*., 2025; Kumari *et al*., 2025)

Another advancement is the magnetic nano-biochar which are comprised of iron oxides that can be easily separated and recovered after the treatment of waste water. The magnetized biochar is also reusable multiple times after use and has improved operational efficiency. The surface reactivity is increased due to the increased surface functional groups. The Fe-modified sugarcane bagasse biochar demonstrated excellent adsorption capacity for arsenic, chromium, phosphate and antibiotics contaminants due to the higher surface reactivity redox activity (Baharuddin *et al.,* 2022; Thakur & Chadar, 2025).

A next important development is the production of composite and hybrid biochar materials. Researchers have combined sugarcane bagasse biochar with graphene oxide, carbon nanotubes, biopolymers, clay minerals and layered double hydroxides to develop multi-functional adsorbents with enhanced mechanical strength and adsorption selectivity . These engineered composites have improved stability, adsorption kinetics and regeneration performance compared to that of pristine biochar. Moreover, heteroatom functionalization of biochars by sulfur, nitrogen and phosphorus resulted in the formation of more active binding sites and, therefore, higher affinity for toxic metals and organic pollutants (Shaheen *et al*., 2025; Zhang *et al*., 2025).

Furthermore, recent reports have shown the use of sugarcane bagasse biochar in advanced oxidation processes (AOPs) and catalytic degradation systems. Nano-modified biochar can activate oxidants such as persulfate and hydrogen peroxide to produce reactive oxygen species that can degrade persistent organic pollutants, pesticides and pharmaceutical residues. Photocatalytic biochar composites with TiO2 or ZnO nanoparticles have exhibited excellent efficiency in degradation of dyes and endocrine-disrupting compounds under visible light irradiation.(Fu *et al*., 2025) .

Engineered bagasse biochar has been applied to microbial immobilization, greenhouse gas mitigation, soil remediation and carbon sequestration, nutrient retention and slow release fertilizers . Surface modified biochar improves soil fertility, microbial activity and water holding capacity and reduces the mobility of toxic heavy metals in contaminated soils . Furthermore, recent advances in hydrothermal carbonization, microwave-assisted pyrolysis and plasma-assisted pyrolysis have enabled the production of biochar materials with high porosity, energy efficiency, controllable surface chemistry and enhanced environmental performance (Qureshi *et al*., 2026; Wada *et al*., 2026). Artificial intelligence and machine learning have also been applied in biochar engineering to enhance the biochar application by optimizing the pyrolysis conditions , predicting adsorption performance , and designing customized nano-biochar materials for targeted contaminant removal . AI-enabled strategies are expected to accelerate the commercialization and environmental application of engineered sugarcane bagasse biochar in wastewater treatment and soil remediation technologies (Frontiers in Soil Science, 2025; Wada *et al*., 2026).

X. Conclusion

Biochar produced from sugarcane bagasse has been recognized as a low cost, eco-friendly material to solve various environmental pollution problems. Sugarcane bagasse is an agricultural by-product which is abundantly available worldwide, hence, it is a low cost and sustainable feedstock for biochar production. The conversion of an agricultural waste into biochar is encouraging waste valorization and circular economy practices. Biochar possesses unique physicochemical properties including high surface area, porous structure and functional surface groups, which make it highly suitable for applications such as adsorption of heavy metals, dyes, organic pollutants and greenhouse gas mitigation. In addition, biochar application in soil systems improves soil fertility, capacity of water retention, microbial activity and carbon sequestration for sustainable agricultural development.

The properties and environmental performance of the biochar are strongly affected by the different thermochemical conversion methods (pyrolysis, hydrothermal carbonization and torrefaction) and feedstocks. Recently, the process optimization, surface modification and composite formation have been proved to further improve the adsorption performance and environmental applicability of sugarcane bagasse biochar. However, despite these promising advantages, there are still challenges in terms of large scale production, regeneration, long term stability and economic feasibility. In conclusion, sugarcane bagasse biochar is green, environmental-friendly and multifunctional method for environmental remediation and sustainable resource management. Future research should emphasize on the development of cost-effective production technology, long-term environmental impacts and advanced functionalization approaches to maximize its efficiency in pollution control and climate change mitigation.

References:-

1. United States Department of Agriculture Foreign Agricultural Service.https://apps.fas.usda.gov/psdonline/circulars/sugar.pdf
2. Mishra, R. K., & Mohanty, K. (2023). A review of the next-generation biochar production from waste biomass for material applications. *The Science of the Total Environment*, *904*(167171), 167171. https://doi.org/10.1016/j.scitotenv.2023.167171

3. Fu, Y., Yi, Y., Wang, Y., Diao, Y., Diao, Z., & Chen, Z. (2025). A comprehensive review of modified biochar-based advanced oxidation processes for environmental pollution remediation: efficiency, mechanism, toxicity assessment. *Journal of Environmental Management*, *387*(125872), 125872. https://doi.org/10.1016/j.jenvman.2025.125872
4. Qureshi, M. A., Parveen, S., & Shabbir, M. (2026). Transforming natural waste into biochar for sustainable environmental remediation. *Discover Environment*, *4*(1). https://doi.org/10.1007/s44274-026-00701-8
5. Shaheen, S. M., Ullah, H., Wu, Y., Mosa, A., Fang, Y., Shi, Y., Liu, J., Kumar, M., Zhang, H., Zhang, B., Li, R., Wang, J., Antoniadis, V., Lee, S. S., & Rinklebe, J. (2025). Remediation of emerging inorganic contaminants in soils and water using pristine and engineered biochar: a review. *Biochar*, *7*(1). https://doi.org/10.1007/s42773-024-00407-1
6. Saleem, J., Moghal, Z. K. B., Pradhan, S., & McKay, G. (2024). High-performance activated carbon from coconut shells for dye removal: study of isotherm and thermodynamics. *RSC Advances*, *14*(46), 33797–33808. https://doi.org/10.1039/d4ra06287f
7. Baharudin, N. I. S., Mohamed Noor, N., Abdullah, E. C., Othman, R., & Nasibab Mujawar, M. (2022). Magnetically modified sugarcane bagasse biochar as cadmium removal agent in water. *IIUM Engineering Journal*, *23*(1), 294–309. https://doi.org/10.31436/iiumej.v23i1.1816
8. Zhang, Y., Chen, H., & Islam, S. (2025). Advances in biochar modification for environmental remediation with emphasis on iron functionalization. *Biochar X*, *1*(1), 0–0. https://doi.org/10.48130/bchax-0025-0010
9. Wang, Z., Xiang, Q., Zhang, D., Xue, A., Fang, Y., & Hu, S. (2026). Research progress on biochar-based photocatalytic materials for pollutant treatment: Structural regulation, electronic mechanisms, and engineering challenges. *Ecotoxicology and Environmental Safety*, *310*(119793), 119793. https://doi.org/10.1016/j.ecoenv.2026.119793
10. Wada, O. Z., McKay, G., Al-Ansari, T., & Mahmoud, K. A. (2026). AI-driven biochar engineering for emerging pollutants removal from water: performance, mechanisms, and environmental perspectives. *Biochar*, *8*(1). https://doi.org/10.1007/s42773-025-00565-w
11. Kumari, A., Yadav, M., Bhatia, A., Sharma, M., & Bhateria, R. (2025). A review and bibliometric analysis on recent modification of biochar for effective and sustainable remediation of heavy metals in aqueous medium. *Discover Chemical Engineering*, *5*(1). https://doi.org/10.1007/s43938-025-00088-7
12. Singh Thakur, D., & Narayan Chadar, S. (n.d.). Sugarcane Bagasse-Derived Nanobiochar via Optimized Pyrolysis: Synthesis, Characterizations and Application. *Progress Petrochem Sci*, *7*(4). https://doi.org/10.31031/PPS.2025.07.000669
13. Kumar, S., Kaur, P., Hsu, C.-Y., Mustafa, M. A., Rani, J., Kaur, J., & Kaushal, S. (2025). Advances in surface modification of biomass and its nanostructuring for enhanced environmental remediation applications. *Materials Advances*, *6*(23), 8774–8815. https://doi.org/10.1039/d5ma00494b
14. Sharma, P., Sharma, S., Sharma, S. K., Jain, A., & Shrivastava, K. (2024). Review on recent advancement of adsorption potential of sugarcane bagasse biochar in wastewater treatment. *Chemical Engineering Research & Design: Transactions of the Institution of Chemical Engineers*, *206*, 428–439. https://doi.org/10.1016/j.cherd.2024.04.055

15. Ojo-kupoluyi, O. J., Dele-Afolabi, T. T., & Tahir, S. M. (2024). Harnessing sugarcane bagasse for bioenergy production: Current status, optimization, and future directions. *Sustainable Energy Technologies and Assessments*, *72*(104074), 104074. https://doi.org/10.1016/j.seta.2024.104074
16. Yang, X., Hou, R., Fu, Q., Li, T., Li, M., Cui, S., Li, Q., & Liu, M. (2024). A critical review of biochar as an environmental functional material in soil ecosystems for migration and transformation mechanisms and ecological risk assessment. *Journal of Environmental Management*, *360*(121196), 121196. https://doi.org/10.1016/j.jenvman.2024.121196
17. Yameen, M. Z., Naqvi, S. R., Juchelková, D., & Khan, M. N. A. (2024). Harnessing the power of functionalized biochar: progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability. *Biochar*, *6*(1). https://doi.org/10.1007/s42773-024-00316-3
18. Wang, Z., Xiang, Q., Zhang, D., Xue, A., Fang, Y., & Hu, S. (2026). Research progress on biochar-based photocatalytic materials for pollutant treatment: Structural regulation, electronic mechanisms, and engineering challenges. *Ecotoxicology and Environmental Safety*, *310*(119793), 119793. https://doi.org/10.1016/j.ecoenv.2026.119793
19. Hiranobe, C. T., Gomes, A. S., Paiva, F. F. G., Tolosa, G. R., Paim, L. L., Dognani, G., Cardim, G. P., Cardim, H. P., dos Santos, R. J., & Cabrera, F. C. (2024). Sugarcane bagasse: Challenges and opportunities for waste recycling. *Clean Technologies*, *6*(2), 662–699. https://doi.org/10.3390/cleantechnol6020035
20. Zafeer, M. K., Menezes, R. A., Venkatachalam, H., & Bhat, K. S. (2024). Sugarcane bagasse-based biochar and its potential applications: a review. *Emergent Materials*, *7*(1), 133–161. https://doi.org/10.1007/s42247-023-00603-y
21. https://www.nfsm.gov.in/BriefNote/BN_Sugarcane.pdf National Food Security Mission , Government of India, Sugarcane data
22. Zafeer, M. K., Menezes, R. A., Venkatachalam, H., & Bhat, K. S. (2024). Sugarcane bagasse-based biochar and its potential applications: a review. *Emergent Materials*, *7*(1), 133–161. https://doi.org/10.1007/s42247-023-00603-y
23. Đukanović, N., Apostolović, T., Anojčić, J., Mutić, S., Marjanović Srebro, T., Kozma, G., Deák, C., Maletić, S., & Beljin, J. (2025). Comparative study of biochar from different biomass feedstocks: Toward sustainable resource utilization and environmental applications. *Molecules (Basel, Switzerland)*, *31*(1), 37. https://doi.org/10.3390/molecules31010037
24. Tsoutsa, E. K., Tolkou, A. K., Kyzas, G. Z., & Katsoyiannis, I. A. (2024). An update on agricultural wastes used as natural adsorbents or coagulants in single or combined systems for the removal of dyes from wastewater. *Water, Air, and Soil Pollution*, *235*(3). https://doi.org/10.1007/s11270-024-06979-9

25. Iwuozor, K. O., Chizitere Emenike, E., Ighalo, J. O., Omoarukhe, F. O., Omuku, P. E., & George Adeniyi, A. (2022). A Review on the thermochemical conversion of sugarcane bagasse into biochar. *Cleaner Materials*, *6*(100162), 100162. https://doi.org/10.1016/j.clema.2022.100162

26. Zhao, J., Shen, X.-J., Domene, X., Alcañiz, J.-M., Liao, X., & Palet, C. (2019). Comparison of biochars derived from different types of feedstock and their potential for heavy metal removal in multiple-metal solutions. *Scientific Reports*, *9*(1), 9869. https://doi.org/10.1038/s41598-019-46234-4

27. Rasaq, W. A., Okpala, C. O. R., Igwegbe, C. A., & Białowiec, A. (2024). Navigating pyrolysis implementation-A tutorial review on consideration factors and thermochemical operating methods for biomass conversion. *Materials*, *17*(3), 725. https://doi.org/10.3390/ma17030725

28. dos Santos, W. M., Gonzaga, M. I. S., da Silva, A. J., & de Almeida, A. Q. (2022). Improved water and ions dynamics in a clayey soil amended with different types of agro-industrial waste biochar. *Soil & Tillage Research*, *223*(105482), 105482. https://doi.org/10.1016/j.still.2022.105482
29. Prasannamedha, G., Kumar, P. S., Mehala, R., Sharumitha, T. J., & Surendhar, D. (2021). Enhanced adsorptive removal of sulfamethoxazole from water using biochar derived from hydrothermal carbonization of sugarcane bagasse. *Journal of Hazardous Materials*, *407*(124825), 124825. https://doi.org/10.1016/j.jhazmat.2020.124825
30. Prasannamedha, G., Senthil Kumar, P., & Shankar, V. (2022). Facile route for synthesis of Fe0/Fe3C/γ-Fe2O3 carbon composite using hydrothermal carbonization of sugarcane bagasse and its use as effective adsorbent for sulfamethoxazole removal. *Chemosphere*, *289*(133214), 133214. https://doi.org/10.1016/j.chemosphere.2021.133214
31. Sharma, R., Jasrotia, K., Singh, N., Ghosh, P., Srivastava, S., Sharma, N. R., Singh, J., Kanwar, R., & Kumar, A. (2020). A comprehensive review on hydrothermal carbonization of biomass and its applications. *Chemistry Africa*, *3*(1), 1–19. https://doi.org/10.1007/s42250-019-00098-3
32. Van, H. T., Nguyen, L. H., Dang, N. V., Chao, H.-P., Nguyen, Q. T., Nguyen, T. H., Nguyen, T. B. L., Van Thanh, D., Nguyen, H. D., Thang, P. Q., Thanh, P. T. H., & Hoang, V. P. (2021). The enhancement of reactive red 24 adsorption from aqueous solution using agricultural waste-derived biochar modified with ZnO nanoparticles. *RSC Advances*, *11*(10), 5801–5814. https://doi.org/10.1039/d0i.org/10.1039/d0ra09974k
33. Chen, B., Chen, Z., & Lv, S. (2011). A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. *Bioresource Technology*, *102*(2), 716–723. https://doi.org/10.1016/j.biortech.2010.08.067
34. Chen, Y., Hassan, M., Nuruzzaman, M., Zhang, H., Naidu, R., Liu, Y., & Wang, L. (2023). Iron-modified biochar derived from sugarcane bagasse for adequate removal of aqueous imidacloprid: sorption mechanism study. *Environmental Science and Pollution Research International*, *30*(2), 4754–4768. https://doi.org/10.1007/s11356-022-22357-6
35. Hamoud, Y. A., Saleem, T., Zia-Ur-Rehman, M., Shaghaleh, H., Usman, M., Rizwan, M., Alharby, H. F., Alamri, A. M., Al-Sarraj, F., & Alabdallah, N. M. (2024). Synergistic effect of biochar with gypsum, lime, and farm manure on the growth and tolerance in rice plants under different salt-affected soils. *Chemosphere*, *360*(142357), 142357. https://doi.org/10.1016/j.chemosphere.2024.142357
36. Vimal, V., Karim, A. A., Kumar, M., Ray, A., Biswas, K., Maurya, S., Subudhi, D., & Dhal, N. K. (2022). Nutrients enriched biochar production through Co-Pyrolysis of poultry litter with banana peduncle and phosphogypsum waste. *Chemosphere*, *300*(134512), 134512. https://doi.org/10.1016/j.chemosphere.2022.134512
37. Zafar-ul-Hye, M., Wasim, M. M., Munir, T. M., Aon, M., Shaaban, M., Abbas, M., Hussain, M., & Ahmad, M. (2020). Co-application of sugarcane bagasse biochar, farmyard manure and mineral nitrogen improved growth indices of corn grown in alkaline calcareous soil. *Journal of Plant Nutrition*, *43*(9), 1293–1305. https://doi.org/10.1080/01904167.2020.1727509
38. Inyang, M., & Dickenson, E. (2015). The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review. *Chemosphere*, *134*, 232–240. https://doi.org/10.1016/j.chemosphere.2015.03.072
39. Komkiene, J., & Baltrenaite, E. (2016). Biochar as adsorbent for removal of heavy metal ions [Cadmium(II), Copper(II), Lead(II), Zinc(II)] from aqueous phase. *International Journal of Environmental Science and Technology: IJEST*, *13*(2), 471–482. https://doi.org/10.1007/s13762-015-0873-3

40. Chen, W.-H., Ye, S.-C., & Sheen, H.-K. (2012). Hydrothermal carbonization of sugarcane bagasse via wet torrefaction in association with microwave heating. *Bioresource Technology*, *118*, 195–203. https://doi.org/10.1016/j.biortech.2012.04.101
41. Nguyen, H. N., Khuong, D. A., Tran-Nguyen, P. L., & Tsubota, T. (2022). Towards sustainable biomass gasification: Evolution of bagasse char characteristics throughout gasification. *Biomass & Bioenergy*, *158*(106384), 106384. https://doi.org/10.1016/j.biombioe.2022.106384
42. Zhang, S., Lyu, H., Tang, J., Song, B., Zhen, M., & Liu, X. (2019). A novel biochar supported CMC stabilized nano zero-valent iron composite for hexavalent chromium removal from water. *Chemosphere*, *217*, 686–694. https://doi.org/10.1016/j.chemosphere.2018.11.040
43. Raul, C., Bharti, V. S., Dar Jaffer, Y., Lenka, S., & Krishna, G. (2021). Sugarcane bagasse biochar: Suitable amendment for inland aquaculture soils. *Aquaculture Research*, *52*(2), 643–654. https://doi.org/10.1111/are.14922
44. Mansee, A. H., Abdelgawad, D. M., El-Gamal, E. H., Ebrahim, A. M., & Saleh, M. E. (2023). Influences of Mg-activation on sugarcane bagasse biochar characteristics and its PNP removing potentials from contaminated water. *Scientific Reports*, *13*(1), 19153. https://doi.org/10.1038/s41598-023-46463-8
45. Liang, M., Ding, Y., Zhang, Q., Wang, D., Li, H., & Lu, L. (2020). Removal of aqueous Cr(VI) by magnetic biochar derived from bagasse. *Scientific Reports*, *10*(1), 21473. https://doi.org/10.1038/s41598-020-78142-3
46. Lefebvre, D., Williams, A., Kirk, G. J. D., Meersmans, J., Sohi, S., Goglio, P., & Smith, P. (2021). An anticipatory life cycle assessment of the use of biochar from sugarcane residues as a greenhouse gas removal technology. *Journal of Cleaner Production*, *312*(127764), 127764. https://doi.org/10.1016/j.jclepro.2021.127764

47. Kumi, A. G., Ibrahim, M. G., Fujii, M., & Nasr, M. (2022). Petrochemical wastewater treatment by eggshell modified biochar as adsorbent: Atechno-economic and sustainable approach. *Adsorption Science & Technology: Interface Science for Advanced Materials & Technologies*, *2022*, 1–13. https://doi.org/10.1155/2022/2323836

48. Kumar, A., Singh, E., Khapre, A., Bordoloi, N., & Kumar, S. (2020). Sorption of volatile organic compounds on non-activated biochar. *Bioresource Technology*, *297*(122469), 122469. https://doi.org/10.1016/j.biortech.2019.122469
49. Kulkarni, R. M., Dhanyashree, J. K., Varma, E., & Sirivibha, S. P. (2022). Batch and continuous packed bed column studies on biosorption of nickel (II) by sugarcane bagasse. *Results in Chemistry*, *4*(100328), 100328. https://doi.org/10.1016/j.rechem.2022.100328
50. Konde, K. S., Nagarajan, S., Kumar, V., Patil, S. V., & Ranade, V. V. (2021). Sugarcane bagasse based biorefineries in India: potential and challenges. *Sustainable Energy & Fuels*, *5*(1), 52–78. https://doi.org/10.1039/d0se01332c
51. Komkiene, J., & Baltrenaite, E. (2016). Biochar as adsorbent for removal of heavy metal ions [Cadmium(II), Copper(II), Lead(II), Zinc(II)] from aqueous phase. *International Journal of Environmental Science and Technology: IJEST*, *13*(2), 471–482. https://doi.org/10.1007/s13762-015-0873-3
52. Khan, A. Z., Khan, S., Ayaz, T., Brusseau, M. L., Khan, M. A., Nawab, J., & Muhammad, S. (2020). Popular wood and sugarcane bagasse biochars reduced uptake of chromium and lead by lettuce from mine-contaminated soil. *Environmental Pollution (Barking, Essex: 1987)*, *263*(Pt A), 114446. https://doi.org/10.1016/j.envpol.2020.114446

53. Kameyama, K., Miyamoto, T., Shiono, T., & Shinogi, Y. (2012). Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcaric dark red soil. *Journal of Environmental Quality*, *41*(4), 1131–1137. https://doi.org/10.2134/jeq2010.0453
54. Jatav, S. S., Singh, S. K., Patra, A., Jatav, H. S., Mohapatra, K. K., & Singh, P. (2021). Characterization of sewage sludge for quality assessment and its safe utilization in agriculture. *Current Journal of Applied Science and Technology*, 28–35. https://doi.org/10.9734/cjast/2021/v40i2531511
55. Ighalo, J. O., Yap, P.-S., Iwuozor, K. O., Aniagor, C. O., Liu, T., Dulta, K., Iwuchukwu, F. U., & Rangabhashiyam, S. (2022). Adsorption of persistent organic pollutants (POPs) from the aqueous environment by nano-adsorbents: A review. *Environmental Research*, *212*(113123), 113123. https://doi.org/10.1016/j.envres.2022.113123
56. He, L., Liu, Z., Hu, J., Qin, C., Yao, L., Zhang, Y., & Piao, Y. (2021). Sugarcane biochar as novel catalyst for highly efficient oxidative removal of organic compounds in water. *Chemical Engineering Journal (Lausanne, Switzerland: 1996)*, *405*(126895), 126895. https://doi.org/10.1016/j.cej.2020.126895
57. Haghighatjou, M., & Shirvani, M. (2020). Sugarcane bagasse biochar: Preparation, characterization, and its effects on soil properties and zinc sorption-desorption. *Communications in Soil Science and Plant Analysis*, *51*(10), 1391–1405. https://doi.org/10.1080/00103624.2020.1763383
58. Gwenzi, W., Chaukura, N., Wenga, T., & Mtisi, M. (2021). Biochars as media for air pollution control systems: Contaminant removal, applications and future research directions. *The Science of the Total Environment*, *753*(142249), 142249. https://doi.org/10.1016/j.scitotenv.2020.142249
59. Guo, Y., Tan, C., Sun, J., Li, W., Zhang, J., & Zhao, C. (2020). Porous activated carbons derived from waste sugarcane bagasse for CO2 adsorption. *Chemical Engineering Journal (Lausanne, Switzerland: 1996)*, *381*(122736), 122736. https://doi.org/10.1016/j.cej.2019.122736
60. Farid, I. M., Siam, H. S., Abbas, M. H. H., Mohamed, I., Mahmoud, S. A., Tolba, M., Abbas, H. H., Yang, X., Antoniadis, V., Rinklebe, J., & Shaheen, S. M. (2022). Co-composted biochar derived from rice straw and sugarcane bagasse improved soil properties, carbon balance, and zucchini growth in a sandy soil: A trial for enhancing the health of low fertile arid soils. *Chemosphere*, *292*(133389), 133389. https://doi.org/10.1016/j.chemosphere.2021.133389
61. Divband Hafshejani, L., Hooshmand, A., Naseri, A. A., Mohammadi, A. S., Abbasi, F., & Bhatnagar, A. (2016). Removal of nitrate from aqueous solution by modified sugarcane bagasse biochar. *Ecological Engineering*, *95*, 101–111. https://doi.org/10.1016/j.ecoleng.2016.06.035
62. de Castro, A. E., Penido, E. S., Souza, T. F., Camargos, J. B., Lobato, R. L. M., Ribeiro-Soares, J., Ferreira, G. M. D., & Ferreira, G. M. D. (2023). Biochars from modified sugarcane bagasse for manganese removal from mining effluents. *Journal of Environmental Chemical Engineering*, *11*(5), 110761. https://doi.org/10.1016/j.jece.2023.110761
63. Chen, W.-H., Hsu, H.-J., Kumar, G., Budzianowski, W. M., & Ong, H. C. (2017). Predictions of biochar production and torrefaction performance from sugarcane bagasse using interpolation and regression analysis. *Bioresource Technology*, *246*, 12–19. https://doi.org/10.1016/j.biortech.2017.07.184
64. Carrier, M., Hardie, A. G., Uras, Ü., Görgens, J., & Knoetze, J. (hansie). (2012). Production of char from vacuum pyrolysis of South-African sugar cane bagasse and its characterization as activated carbon and biochar. *Journal of Analytical and Applied Pyrolysis*, *96*, 24–32. https://doi.org/10.1016/j.jaap.2012.02.016
65. Candido, R. G., Godoy, G. G., & Gonçalves, A. R. (2017). Characterization and application of cellulose acetate synthesized from sugarcane bagasse. *Carbohydrate Polymers*, *167*, 280–289. https://doi.org/10.1016/j.carbpol.2017.03.057
66. Bashir, S., Hussain, Q., Akmal, M., Riaz, M., Hu, H., Ijaz, S. S., Iqbal, M., Abro, S., Mehmood, S., & Ahmad, M. (2018). Sugarcane bagasse-derived biochar reduces the cadmium and chromium

bioavailability to mash bean and enhances the microbial activity in contaminated soil. *Journal of Soils and Sediments*, *18*(3), 874–886. https://doi.org/10.1007/s11368-017-1796-z

67. Bai, X., Zhang, M., Niu, B., Zhang, W., Wang, X., Wang, J., Wu, D., Wang, L., & Jiang, K. (2022). Rotten sugarcane bagasse derived biochars with rich mineral residues for effective Pb (II) removal in wastewater and the tech-economic analysis. *Journal of the Taiwan Institute of Chemical Engineers*, *132*(104231), 104231. https://doi.org/10.1016/j.jtice.2022.104231

68. Bai, L., Su, X., Feng, J., & Ma, S. (2021). Preparation of sugarcane bagasse biochar/nano-iron oxide composite and mechanism of its Cr (VI) adsorption in water. *Journal of Cleaner Production*, *320*(128723), 128723. https://doi.org/10.1016/j.jclepro.2021.128723

69. Saleh, Y., Ali, L., & Altarawneh, M. (2025). Recent advances in biomass valorization through thermochemical processes, bio-oil production and AI strategies: a concise review. *RSC Advances*, *15*(54), 45943–45978. https://doi.org/10.1039/d5ra05770a

70. Alves, B. S. Q., Zelaya, K. P. S., Colen, F., Frazão, L. A., Napoli, A., Parikh, S. J., & Fernandes, L. A. (2021). Effect of sewage sludge and sugarcane bagasse biochar on soil properties and sugar beet production. *Pedosphere*, *31*(4), 572–582. https://doi.org/10.1016/s1002-0160(21)60003-6

71. Abdelhafez, A. A., & Li, J. (2016). Removal of Pb(II) from aqueous solution by using biochars derived from sugar cane bagasse and orange peel. *Journal of the Taiwan Institute of Chemical Engineers*, *61*, 367–375. https://doi.org/10.1016/j.jtice.2016.01.005
72. Nie, C., Yang, X., Niazi, N. K., Xu, X., Wen, Y., Rinklebe, J., Ok, Y. S., Xu, S., & Wang, H. (2018). Impact of sugarcane bagasse-derived biochar on heavy metal availability and microbial activity: A field study. *Chemosphere*, *200*, 274–282. https://doi.org/10.1016/j.chemosphere.2018.02.134
73. Moradi-Choghamarani, F., Moosavi, A. A., Sepaskhah, A. R., & Baghernejad, M. (2019). Physico-hydraulic properties of sugarcane bagasse-derived biochar: the role of pyrolysis temperature. *Cellulose (London, England)*, *26*(12), 7125–7143. https://doi.org/10.1007/s10570-019-02607-6
74. Montero, J. I. Z., Monteiro, A. S. C., Gontijo, E. S. J., Bueno, C. C., de Moraes, M. A., & Rosa, A. H. (2018). High efficiency removal of As(III) from waters using a new and friendly adsorbent based on sugarcane bagasse and corncob husk Fe-coated biochars. *Ecotoxicology and Environmental Safety*, *162*, 616–624. https://doi.org/10.1016/j.ecoenv.2018.07.042
75. Moharm, A. E., El Naeem, G. A., Soliman, H. M. A., Abd-Elhamid, A. I., El-Bardan, A. A., Kassem, T. S., Nayl, A. A., & Bräse, S. (2022). Fabrication and characterization of effective biochar biosorbent derived from agricultural waste to remove cationic dyes from wastewater. *Polymers*, *14*(13), 2587. https://doi.org/10.3390/polym14132587

76. Moradi-Choghamarani, F., Moosavi, A. A., Sepaskhah, A. R., & Baghernejad, M. (2019). Physico-hydraulic properties of sugarcane bagasse-derived biochar: the role of pyrolysis temperature. *Cellulose (London, England)*, *26*(12), 7125–7143. https://doi.org/10.1007/s10570-019-02607-6
77. Ograk, S., Griffin, G. J., & Pannirselvam, M. (2019). Potential use of biochar from sugarcane bagasse for treatment of textile wastewater. In *Water Scarcity and Ways to Reduce the Impact* (pp. 115–133). Springer International Publishing.
78. Praipipat, P., Ngamsurach, P., & Sanghuayprai, A. (2023). Modification of sugarcane bagasse with iron(III) oxide-hydroxide to improve its adsorption property for removing lead(II) ions. *Scientific Reports*, *13*(1), 1467. https://doi.org/10.1038/s41598-023-28654-5

79. Raj, V., Chauhan, M. S., & Pal, S. L. (2022). Potential of sugarcane bagasse in remediation of heavy metals: A review. *Chemosphere*, *307*(Pt 2), 135825. https://doi.org/10.1016/j.chemosphere.2022.135825
80. Rajabi, H., Hadi Mosleh, M., Prakoso, T., Ghaemi, N., Mandal, P., Lea-Langton, A., & Sedighi, M. (2021). Competitive adsorption of multicomponent volatile organic compounds on biochar. *Chemosphere*, *283*(131288), 131288. https://doi.org/10.1016/j.chemosphere.2021.131288
81. Raul, C., Bharti, V. S., Dar Jaffer, Y., Lenka, S., & Krishna, G. (2021). Sugarcane bagasse biochar: Suitable amendment for inland aquaculture soils. *Aquaculture Research*, *52*(2), 643–654. https://doi.org/10.1111/are.14922
82. Rodier, L., Villar-Cociña, E., Ballesteros, J. M., & Junior, H. S. (2019). Potential use of sugarcane bagasse and bamboo leaf ashes for elaboration of green cementitious materials. *Journal of Cleaner Production*, *231*, 54–63. https://doi.org/10.1016/j.jclepro.2019.05.208
83. Sadegh, F., Sadegh, N., Wongniramaikul, W., Apiratikul, R., & Choodum, A. (2024). Adsorption of volatile organic compounds on biochar: A review. *Process Safety and Environmental Protection : Transactions of the Institution of Chemical Engineers, Part B*, *182*, 559–578. https://doi.org/10.1016/j.psep.2023.11.071

84. Samhan, F. (2020). Sugarcane bagasse biochar with nanomagnetite: a novel composite for heavy metals pollutants removal. *Egyptian Journal of Chemistry*, *0*(0), 0–0. https://doi.org/10.21608/ejchem.2020.43158.2870
85. Sun, E., Zhang, Y., Xiao, Q., Li, H., Qu, P., Yong, C., Wang, B., Feng, Y., Huang, H., Yang, L., & Hunter, C. (2022). Formable porous biochar loaded with La-Fe(hydr)oxides/montmorillonite for efficient removal of phosphorus in wastewater: process and mechanisms. *Biochar*, *4*(1). https://doi.org/10.1007/s42773-022-00177-8
86. Kalifa, M. A., Habtu, N. G., Jembere, A. L., & Genet, M. B. (2024). Characterization and evaluation of torrefied sugarcane bagasse to improve the fuel properties. *Current Research in Green and Sustainable Chemistry*, *8*(100395), 100395. https://doi.org/10.1016/j.crgsc.2023.100395
87. Sun, R., Lu, F., Yu, C., Yang, Y., Qiao, L., & Liu, A. (2022). Peanut shells-derived biochars as adsorbents for the pipette-tip solid-phase extraction of endocrine-disrupting phenols in water, milk and beverage. *Journal of Chromatography A*, *1673*(463101), 463101. https://doi.org/10.1016/j.chroma.2022.463101
88. Sun, Y., Wang, T., Sun, X., Bai, L., Han, C., & Zhang, P. (2021). The potential of biochar and lignin-based adsorbents for wastewater treatment: Comparison, mechanism, and application—A review. *Industrial Crops and Products*, *166*(113473), 113473. https://doi.org/10.1016/j.indcrop.2021.113473
89. Tang, M., Snoussi, Y., Bhakta, A. K., El Garah, M., Khalil, A. M., Ammar, S., & Chehimi, M. M. (2023). Unusual, hierarchically structured composite of sugarcane pulp bagasse biochar loaded with Cu/Ni bimetallic nanoparticles for dye removal. *Environmental Research*, *232*(116232), 116232. https://doi.org/10.1016/j.envres.2023.116232
90. Trakal, L., Veselská, V., Šafařík, I., Vítková, M., Číhalová, S., & Komárek, M. (2016). Lead and cadmium sorption mechanisms on magnetically modified biochars. *Bioresource Technology*, *203*, 318–324. https://doi.org/10.1016/j.biortech.2015.12.056
91. Verma, V., & Sharma, Y. C. (2023). Facile preparation, characterization and application of novel sugarcane bagasse-derived nanoceria-biochar for defluoridation of drinking water: kinetics, thermodynamics, reusability and mechanism. *Environmental Science and Pollution Research International*. https://doi.org/10.1007/s11356-023-30993-9

92. Vikash, P. V., Mandade, P. V., & Shastri, Y. (2018). Assessment of bagasse and trash utilization for ethanol production: A case study in india. *Environmental Progress & Sustainable Energy*, *37*(6), 2165–2174. https://doi.org/10.1002/ep.12900
93. Vyavahare, G. D., Gurav, R. G., Jadhav, P. P., Patil, R. R., Aware, C. B., & Jadhav, J. P. (2018). Response surface methodology optimization for sorption of malachite green dye on sugarcane bagasse biochar and evaluating the residual dye for phyto and cytogenotoxicity. *Chemosphere*, *194*, 306–315. https://doi.org/10.1016/j.chemosphere.2017.11.180
94. Xu, Q., Ji, T., Gao, S.-J., Yang, Z., & Wu, N. (2018). Characteristics and applications of sugar cane bagasse ash waste in cementitious materials. *Materials*, *12*(1), 39. https://doi.org/10.3390/ma12010039
95. Yaashikaa, P. R., Kumar, P. S., Varjani, S., & Saravanan, A. (2020). A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnology Reports (Amsterdam, Netherlands)*, *28*(e00570), e00570. https://doi.org/10.1016/j.btre.2020.e00570
96. Yao, Y., Zhang, Y., Gao, B., Chen, R., & Wu, F. (2018). Removal of sulfamethoxazole (SMX) and sulfapyridine (SPY) from aqueous solutions by biochars derived from anaerobically digested bagasse. *Environmental Science and Pollution Research International*, *25*(26), 25659–25667. https://doi.org/10.1007/s11356-017-8849-0
97. Yi, Y., Tu, G., Zhao, D., Tsang, P. E., & Fang, Z. (2020). Key role of FeO in the reduction of Cr(VI) by magnetic biochar synthesised using steel pickling waste liquor and sugarcane bagasse. *Journal of Cleaner Production*, *245*(118886), 118886. https://doi.org/10.1016/j.jclepro.2019.118886
98. Yu, K. L., Lee, X. J., Ong, H. C., Chen, W.-H., Chang, J.-S., Lin, C.-S., Show, P. L., & Ling, T. C. (2021). Adsorptive removal of cationic methylene blue and anionic Congo red dyes using wet-torrefied microalgal biochar: Equilibrium, kinetic and mechanism modeling. *Environmental Pollution (Barking, Essex: 1987)*, *272*(115986), 115986. https://doi.org/10.1016/j.envpol.2020.115986
99. Yu, S., Liao, Y., Guan, X., Gao, H., & Li, Y. (n.d.). *One-Step Pyrolysis Fabrication of Magnetic Bagasse Biochar Composites with Excellent Lead Adsorption Performance Jinming Chang*.
100. Zhang, S., Lyu, H., Tang, J., Song, B., Zhen, M., & Liu, X. (2019). A novel biochar supported CMC stabilized nano zero-valent iron composite for hexavalent chromium removal from water. *Chemosphere*, *217*, 686–694. https://doi.org/10.1016/j.chemosphere.2018.11.040
101. Aragón-Briceño, C. I., Pozarlik, A. K., Bramer, E. A., Niedzwiecki, L., Pawlak-Kruczek, H., & Brem, G. (2021). Hydrothermal carbonization of wet biomass from nitrogen and phosphorus approach: A review. *Renewable Energy*, *171*, 401–415. https://doi.org/10.1016/j.renene.2021.02.109
102. Bonelli, P. R., Buonomo, E. L., & Cukierman, A. L. (2007). Pyrolysis of sugarcane bagasse and co-pyrolysis with an Argentinean subbituminous coal. *Energy Sources Part A Recovery Utilization and Environmental Effects*, *29*(8), 731–740. https://doi.org/10.1080/00908310500281247
103. Chen, W.-H., Ye, S.-C., & Sheen, H.-K. (2012). Hydrothermal carbonization of sugarcane bagasse via wet torrefaction in association with microwave heating. *Bioresource Technology*, *118*, 195–203. https://doi.org/10.1016/j.biortech.2012.04.101
104. David, G. F., Perez, V. H., Rodriguez Justo, O., & Garcia-Perez, M. (2017). Effect of acid additives on sugarcane bagasse pyrolysis: Production of high yields of sugars. *Bioresource Technology*, *223*, 74–83. https://doi.org/10.1016/j.biortech.2016.10.051
105. Doumer, M. E., Arízaga, G. G. C., Silva, D. A. da, Yamamoto, C. I., Novotny, E. H., Santos, J. M., Santos, L. O. dos, Wisniewski, A., Jr, Andrade, J. B. de, & Mangrich, A. S. (2015). Slow pyrolysis of different Brazilian waste biomasses as sources of soil conditioners and energy, and for environmental protection. *Journal of Analytical and Applied Pyrolysis*, *113*, 434–443. https://doi.org/10.1016/j.jaap.2015.03.006

106. Gayathri, R., Gopinath, K. P., & Kumar, P. S. (2021). Adsorptive separation of toxic metals from aquatic environment using agro waste biochar: Application in electroplating industrial wastewater. *Chemosphere*, *262*(128031), 128031. https://doi.org/10.1016/j.chemosphere.2020.128031
107. Gonçalves, E. V., Seixas, F. L., de Souza Scandiuzzi Santana, L. R., Scaliante, M. H. N. O., & Gimenes, M. L. (2017). Economic trends for temperature of sugarcane bagasse pyrolysis. *The Canadian Journal of Chemical Engineering*, *95*(7), 1269–1279. https://doi.org/10.1002/cjce.22796
108. Guo, Y., Tan, C., Sun, J., Li, W., Zhang, J., & Zhao, C. (2020). Porous activated carbons derived from waste sugarcane bagasse for CO2 adsorption. *Chemical Engineering Journal (Lausanne, Switzerland: 1996)*, *381*(122736), 122736. https://doi.org/10.1016/j.cej.2019.122736
109. Inyang, M., & Dickenson, E. (2015). The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review. *Chemosphere*, *134*, 232–240. https://doi.org/10.1016/j.chemosphere.2015.03.072
110. Komkiene, J., & Baltrenaite, E. (2016). Biochar as adsorbent for removal of heavy metal ions [Cadmium(II), Copper(II), Lead(II), Zinc(II)] from aqueous phase. *International Journal of Environmental Science and Technology: IJEST*, *13*(2), 471–482. https://doi.org/10.1007/s13762-015-0873-3
111. Leng, L., Huang, H., Li, H., Li, J., & Zhou, W. (2018). Biochar stability assessment methods: A review. *The Science of the Total Environment*, *647*, 210–222. https://doi.org/10.1016/j.scitotenv.2018.07.402
112. Mohanty, S. K., Valenca, R., Berger, A. W., Yu, I. K. M., Xiong, X., Saunders, T. M., & Tsang, D. C. W. (2018). Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment. *The Science of the Total Environment*, *625*, 1644–1658. https://doi.org/10.1016/j.scitotenv.2018.01.037
113. Nwajiaku, I. M., Olanrewaju, J. S., Sato, K., Tokunari, T., Kitano, S., & Masunaga, T. (2018). Change in nutrient composition of biochar from rice husk and sugarcane bagasse at varying pyrolytic temperatures. *International Journal of Recycling of Organic Waste in Agriculture*, *7*(4), 269–276. https://doi.org/10.1007/s40093-018-0213-y
114. Parihar, M. F., Kamil, M., Goyal, H. B., Gupta, A. K., & Bhatnagar, A. K. (2007). An experimental study on pyrolysis of biomass. *Process Safety and Environmental Protection : Transactions of the Institution of Chemical Engineers, Part B*, *85*(5), 458–465. https://doi.org/10.1205/psep07035
115. Qi, F., Yan, Y., Lamb, D., Naidu, R., Bolan, N. S., Liu, Y., Ok, Y. S., Donne, S. W., & Semple, K. T. (2017). Thermal stability of biochar and its effects on cadmium sorption capacity. *Bioresource Technology*, *246*, 48–56. https://doi.org/10.1016/j.biortech.2017.07.033
116. Raul, C., Bharti, V. S., Dar Jaffer, Y., Lenka, S., & Krishna, G. (2021). Sugarcane bagasse biochar: Suitable amendment for inland aquaculture soils. *Aquaculture Research*, *52*(2), 643–654. https://doi.org/10.1111/are.14922
117. Saeed, A. A. H., Harun, N. Y., Sufian, S., Bilad, M. R., Zakaria, Z. Y., Jagaba, A. H., Ghaleb, A. A. S., & Mohammed, H. G. (2021). Pristine and magnetic Kenaf fiber biochar for Cd2+ adsorption from aqueous solution. *International Journal of Environmental Research and Public Health*, *18*(15), 7949. https://doi.org/10.3390/ijerph18157949
118. Samhan, F. (2020). Sugarcane bagasse biochar with nanomagnetite: a novel composite for heavy metals pollutants removal. *Egyptian Journal of Chemistry*, *0*(0), 0–0. https://doi.org/10.21608/ejchem.2020.43158.2870
119. Sanna, A., Li, S., Linforth, R., Smart, K. A., & Andrésen, J. M. (2011). Bio-oil and bio-char from low temperature pyrolysis of spent grains using activated alumina. *Bioresource Technology*, *102*(22), 10695–10703. https://doi.org/10.1016/j.biortech.2011.08.092

120. Seyedsadr, S., Šípek, V., Jačka, L., Sněhota, M., Beesley, L., Pohořelý, M., Kovář, M., & Trakal, L. (2022). Biochar considerably increases the easily available water and nutrient content in low-organic soils amended with compost and manure. *Chemosphere*, *293*(133586), 133586. https://doi.org/10.1016/j.chemosphere.2022.133586
121. Sohaib, Q., Muhammad, A., & Younas, M. (2017). Fast pyrolysis of sugarcane bagasse: Effect of pyrolysis conditions on final product distribution and properties. *Energy Sources Part A Recovery Utilization and Environmental Effects*, *39*(2), 184–190. https://doi.org/10.1080/15567036.2016.1212292
122. Wu, L., Zhang, S., Wang, J., & Ding, X. (2020). Phosphorus retention using iron (II/III) modified biochar in saline-alkaline soils: Adsorption, column and field tests. *Environmental Pollution (Barking, Essex: 1987)*, *261*(114223), 114223. https://doi.org/10.1016/j.envpol.2020.114223
123. Yi, S., He, X.-M., Lin, H.-T., Zheng, H., Li, C.-H., & Li, C. (2016). Synergistic effect in low temperature co-pyrolysis of sugarcane bagasse and lignite. *The Korean Journal of Chemical Engineering*, *33*(10), 2923–2929. https://doi.org/10.1007/s11814-016-0129-z
124. Zafar-ul-Hye, M., Wasim, M. M., Munir, T. M., Aon, M., Shaaban, M., Abbas, M., Hussain, M., & Ahmad, M. (2020). Co-application of sugarcane bagasse biochar, farmyard manure and mineral nitrogen improved growth indices of corn grown in alkaline calcareous soil. *Journal of Plant Nutrition*, *43*(9), 1293–1305. https://doi.org/10.1080/01904167.2020.1727509
125. Zafeer, M. K., Menezes, R. A., Venkatachalam, H., & Bhat, K. S. (2024). Sugarcane bagasse-based biochar and its potential applications: a review. *Emergent Materials*, *7*(1), 133–161. https://doi.org/10.1007/s42247-023-00603-y
126. Zhang, S., Lyu, H., Tang, J., Song, B., Zhen, M., & Liu, X. (2019). A novel biochar supported CMC stabilized nano zero-valent iron composite for hexavalent chromium removal from water. *Chemosphere*, *217*, 686–694. https://doi.org/10.1016/j.chemosphere.2018.11.040

127. Vimal, V., Karim, A. A., Kumar, M., Ray, A., Biswas, K., Maurya, S., Subudhi, D., & Dhal, N. K. (2022). Nutrients enriched biochar production through Co-Pyrolysis of poultry litter with banana peduncle and phosphogypsum waste. *Chemosphere*, *300*(134512), 134512. https://doi.org/10.1016/j.chemosphere.2022.134512

128. Navarro, J., Salazar, J., Kang, J. J., Parsons, J., Cheng, C.-L., Castillo, A., & Pujol Pereira, E. I. (2020). Compost and biochar to promote soil biological activities under sweet potatoes cultivation in a subtropical semiarid region. *Applied and Environmental Soil Science*, *2020*, 1–11. https://doi.org/10.1155/2020/7230595
129. Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, *2*(4), 421–438. https://doi.org/10.1007/s42773-020-00067-x
130. Di Domenico, G., Bianchini, L., Di Stefano, V., Venanzi, R., Lo Monaco, A., Colantoni, A., & Picchio, R. (2024). New frontiers for raw wooden residues, biochar production as a resource for environmental challenges. *C – Journal of Carbon Research*, *10*(2), 54. https://doi.org/10.3390/c10020054
131. Praipipat, P., Ngamsurach, P., & Sanghuayprai, A. (2023). Modification of sugarcane bagasse with iron(III) oxide-hydroxide to improve its adsorption property for removing lead(II) ions. *Scientific Reports*, *13*(1), 1–23. https://doi.org/10.1038/s41598-023-28654-5
132. Montero, J. I. Z., Monteiro, A. S. C., Gontijo, E. S. J., Bueno, C. C., de Moraes, M. A., & Rosa, A. H. (2018). High efficiency removal of As(III) from waters using a new and friendly adsorbent based

on sugarcane bagasse and corncob husk Fe-coated biochars. *Ecotoxicology and Environmental Safety*, *162*, 616–624. https://doi.org/10.1016/j.ecoenv.2018.07.042

133. Saravanan, A., Senthil Kumar, P., Jeevanantham, S., Karishma, S., Tajsabreen, B., Yaashikaa, P. R., & Reshma, B. (2021). Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. *Chemosphere*, *280*(130595), 130595. https://doi.org/10.1016/j.chemosphere.2021.130595
134. Hao E Ting, K. (2020). China b Department of Pulmonary and Critical Care Medicine, China-Japan Friendship Hospital, Beijing 100029, China c National Clinical Research Center for Respiratory Diseases, Beijing 100029, China d Institute of Respiratory Medicine, Chinese Academy of Medical Sciences. In *Air pollution and chronic obstructive pulmonary disease Rui-Rui Duan a,b* (Vol. 100029).
135. Dehhaghi, M., Sik Ok D, Y., Nizami E Benyamin Khoshnevisan F, A.-S., Mussatto G Mortaza Aghbashlo H, S. I., & Tabatabaei A, M. (Eds.). (n.d.). *A comprehensive review of engineered biochar: Production, characteristics, and environmental applications Hamed Kazemi Shariat Panahi a*.
136. David, E. (2022). Production of activated biochar derived from residual biomass for adsorption of volatile organic compounds. *Materials*, *16*(1), 389. https://doi.org/10.3390/ma16010389
137. Hou, M., He, Y., Yang, X., Yang, Y., Lin, X., Feng, Y., Kan, H., Hu, H., He, X., & Liu, C. (2023). Preparation of biomass biochar with components of similar proportions and its methylene blue adsorption. *Molecules (Basel, Switzerland)*, *28*(17). https://doi.org/10.3390/molecules28176261
138. Ge, S., Zhao, S., Wang, L., Zhao, Z., Wang, S., & Tian, C. (2024). Exploring adsorption capacity and mechanisms involved in cadmium removal from aqueous solutions by biochar derived from euhalophyte. *Scientific Reports*, *14*(1), 450. https://doi.org/10.1038/s41598-023-50525-2
139. Braghiroli, F. L., Bouafif, H., Neculita, C. M., & Koubaa, A. (2018). Activated biochar as an effective sorbent for organic and inorganic contaminants in water. *Water, Air, and Soil Pollution*, *229*(7). https://doi.org/10.1007/s11270-018-3889-8
140. Ariho, A., Aja, L., Muhammad, T., & Mohammad, L. (2024). Water pollution: causes, impacts and current efforts to address the issues of water pollution along river Meizimera-kihihi, Kanugu District,Uganda. *F1000Research*, *13*, 1298. https://doi.org/10.12688/f1000research.155162.1
141. Yadav, S. C. (2024). Water pollution: The problems and solutions. *Science Insights*, *44*(2), 1245–1251. https://doi.org/10.15354/si.24.re905
142. Warren-Vega,W.M.; Campos-Rodríguez, A.; Zárate-Guzmán, A.I.; Romero-Cano, L.A. A Current Review ofWater Pollutants in American Continent: Trends and Perspectives in Detection, Health Risks, and Treatment Technologies. Int. J. Environ. Res.Public Health 2023, 20, 4499. https://doi.org/10.3390/ijerph20054499
143. Kiliç, Z. (2021). Su Kirliliği Nedenleri, Olumsuz Etkileri ve Önleme Yöntemleri. *İstanbul Sabahattin Zaim Üniversitesi Fen Bilimleri Enstitüsü Dergisi*. https://doi.org/10.47769/izufbed.862679
144. Vyavahare, G. D., Gurav, R. G., Jadhav, P. P., Patil, R. R., Aware, C. B., & Jadhav, J. P. (2018). Response surface methodology optimization for sorption of malachite green dye on sugarcane bagasse biochar and evaluating the residual dye for phyto and cytogenotoxicity. *Chemosphere*, *194*, 306–315. https://doi.org/10.1016/j.chemosphere.2017.11.180
145. Sierra-Vargas, M. P., & Teran, L. M. (2012). Air pollution: impact and prevention: Prevention studies for air pollution. *Respirology (Carlton, Vic.)*, *17*(7), 1031–1038. https://doi.org/10.1111/j.1440-1843.2012.02213.x
146. Van Tran, V., Park, D., & Lee, Y.-C. (2020). Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality. *International Journal of Environmental Research and Public Health*, *17*(8), 2927. https://doi.org/10.3390/ijerph17082927