REVIEW

Sugarcane bagasse-based biochar and its potential applications: a review

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Abstract
The effective management of agro-industrial waste plays a pivotal role in mitigating various forms of pollution. Sugarcane bagasse (SB), a substantial biomass waste generated in the sugar industry after cane juice extraction, necessitates sustainable handling. Although some sugar mills utilize wet sugarcane bagasse for fueling the milling process, a significant portion remains stockpiled and is often incinerated on-site, resulting in a highly flammable biomass that poses significant risks to the industry and its surroundings. Recognizing the importance of addressing this issue, researchers have identified the conversion of agricultural waste into biochar as an efficient means of harnessing energy following biomass devolatilization. There is scientific interest in the transformation of biomass into value-added products, including biochar, biogas, and biofuel. This comprehensive literature review delves into various pyrolysis processes applicable for converting sugarcane bagasse into char materials, showcasing its potential for diverse applications in line with current scientific interests.

Keywords Biochar · Sugarcane bagasse · Sustainable development · Environmental remediation · Waste reduction

1 Introduction

Sugarcane, a prominent cash crop on a global scale, plays a crucial role in providing not only sugar but also ethanol and jaggery. By-products of sugarcane find utility as animal feed in numerous countries. The cultivation of sugarcane has expanded to regions with warm climates worldwide. The largest contributor to the global sugarcane production is from the American continent including countries Brazil, Mexico, the USA, and others accounting for about 51% of the total output, closely followed by Asia (41.6%), Africa (5%), and Oceania (1.7%) [1]. The leading countries in sugarcane production are Brazil, India, China, Thailand, and Pakistan. These five nations are at the forefront when it comes to cultivating and harvesting sugarcane [2]. India surpasses other countries such as Brazil, Thailand, and China in sugarcane production, with an impressive output of 29.66 million metric tons as per some estimates. This significant production volume establishes India as a leading global player in the sugarcane industry [3]. As per a bi-annual report released in May 2022 by the Foreign Agricultural Service/USDA, the global sugar production has risen to 181.2 million tons. Notably, India stands out by contributing 2.1 million tons to the total sugar output of 8.4 million tons, primarily attributed to favorable weather conditions and increased crop yields. This significant increase in production further highlights India's noteworthy role in the global sugar industry [4] (Fig. 1).

Over the past few decades, there has been a notable rise in sugarcane production, driven by the increasing demand for sugar, ethanol, and jaggery derived from this versatile crop. Consequently, the sugar industry generates a significant amount of agricultural waste. This waste primarily takes the form of bagasse, which remains after sugarcane undergoes processing in factories to extract sucrose or alcohol. Without proper utilization, bagasse is commonly disposed of as solid waste or utilized as a fuel source for the milling process. For every ton of sugarcane, approximately 280 kg of wet bagasse is produced, highlighting the substantial quantity of this residue [5]. Sugarcane bagasse biomass (SB) has the potential to be transformed into energy, materials, and fine chemicals [6].

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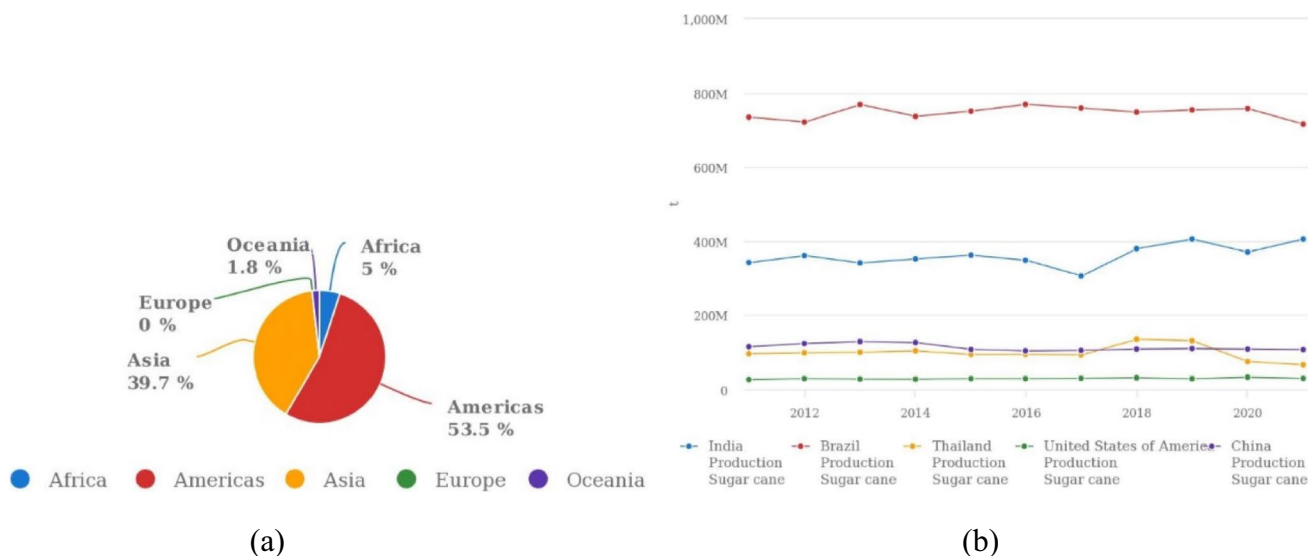
Fig. 1 **a** Production share of sugarcane by region averages from 2011 to 2021. **b** Production of sugarcane by 5 major sugarcane-producing countries' average from 2011 to 2021 [7]

Extensive research has revealed a promising avenue for enhancing energy recovery through the conversion of agricultural residues into biochar which is a solid product. This transformation is achieved by employing thermochemical and biochemical techniques following the devolatilization process of biomass. These innovative methods offer a compelling opportunity to harness greater energy potential from agricultural leftovers, paving the way for sustainable and efficient resource utilization [8–10]. Through the thermochemical process of pyrolysis, sugarcane biomass undergoes thermal decomposition at temperatures exceeding 300 °C in an oxygen-free environment. This process leads to the production of biochar, a solid material characterized by its carbon-rich composition. Additionally, volatile components may partially condense into a liquid form known as bio-oil. Alongside these outputs, flue gases containing CH_4, H_2, CO, and CO_2 are also generated [11]. Sugarcane bagasse holds the potential for producing a range of diverse materials, including biodiesel, bio-composites, and biochar. Biochars have some important physicochemical properties like higher surface area and porosity, low bulk density, higher cation exchange capacity (CEC), neutral to high pH, and higher carbon content. Such characteristics can effectively be utilized in various fields such as adsorption, as construction material, automobile, transportation, furniture making, household applications, cement, and the plastic industry [12–21]. The versatility of sugarcane bagasse opens up numerous possibilities for its application across multiple sectors, providing sustainable and eco-friendly alternatives in various industries [22–30]. Numerous review articles have been previously published, delving into the production of biochar and its diverse applications using various types of

agro-wastes (Table 1) [31, 32]. However, the current review aims to consolidate the extensive research conducted on sugarcane bagasse biochar and its wide-ranging applications. By focusing specifically on sugarcane bagasse, this review seeks to provide a comprehensive compilation of the work carried out in this field, shedding light on the potential uses and benefits of sugarcane bagasse biochar across different application domains.

2 Different techniques for biochar production from sugarcane bagasse

In recent years, extensive research has been conducted to explore various techniques, including thermochemical, chemical, and biological processes, for the conversion of biomass into biofuels, biochar, and syngas [8, 9, 46, 47]. Thermochemical techniques, such as pyrolysis, gasification, hydrothermal carbonization, torrefaction, and flash carbonization, have emerged as prominent methods for biochar production [48, 49]. Among these, pyrolysis is commonly employed to create biochar from sugarcane bagasse biomass, while hydrothermal carbonization is utilized for the production of hydrochar [50–52]. In addition to thermochemical processes, other techniques like hydrolysis, distillation, fermentation, and anaerobic digestion play vital roles in the production of biochar, bio-oil, and syngas (Fig. 2). This comprehensive overview highlights the diverse array of thermochemical techniques and complementary processes involved in biomass conversion for the generation of valuable biochar, bio-oil, and syngas products.

Table 1 Curated reviews highlighting applications of surface-engineered biochar

| Working title	Review compilation topics	Year review published	References
Biochar Application to Soils	This review compiles evidence on biochar's effects on soil properties and plant productivity, emphasizing its potential benefits and the need for more research, especially regarding potential priming effects on soil organic matter decomposition, which require urgent investigation	2010	[33]
Biochar-based catalysts in biomass	This review explores the versatile applications of biochar, an economical carbon-rich material produced from biomass degradation. It discusses its role as a catalyst or catalyst support in biomass upgrading processes, such as hydrolysis, biodiesel production, and biomass enhancement via pyrolysis and gasification	2017	[34]
Production and utilization of biochar from crop residues	This review article presents a compilation of information on the conversion of crop residues into biochar, which, when applied to soil, enhances its physiochemical properties and fertility, serving as a long-term carbon sequestration agent. It also discusses the production processes, feedstocks, characteristics, and the benefits of using biochar in soil	2019	[35]
Biochar production techniques, characterization, stability, and applications	The review comprehensively covers recent studies on biochar's capacity to remediate toxic pollutants, addressing production techniques, properties, stability, and environmental concerns. It also explores biochar applications in enhancing soil fertility and pollutant removal while highlighting the primary challenge of production costs	2020	[32]
Utilizing sugarcane bagasse as a biosorbent for dye removal	The review examines the efficacy of sugarcane bagasse (SB) as a biosorbent for dye removal, covering a range of activation and modification techniques, optimization conditions, and challenges in regeneration, offering valuable insights for future research on waste-derived adsorbents in wastewater treatment	2021	[36]
Biochar-based catalysts for biofuel production	This review covers various biofuel production techniques, including pyrolysis, hydrolysis, and trans-esterification, with a focus on the role of nano-catalysts and biochar-based catalysts to enhance production. It also addresses challenges like feedstock costs and technological efficiency in biofuel development	2021	[37]
Pyrolysis of sugarcane bagasse	This review covers biomass and pyrolysis fundamentals, highlighting advancements in sugarcane bagasse pyrolysis for bio-oil, biochar, and gas production, while also examining the impact of process conditions on product properties and yields	2021	[38]
Sugarcane Bagasse Ash and Rice Husk Ash as Cementitious Additives	The study evaluates bagasse ash's suitability in cement by comparing its characteristics with rice husk ash. Both bagasse ash and rice husk ash improve concrete strength and exhibit resistance against chloride, water, and air permeability up to optimal replacement levels	2021	[39]
Biochar for the removal of contaminants from soil and water	This review gives an outline of the significant potential of biochar in remediating water and soil through its production techniques, characteristics, and recent advancements in removing heavy metal ions and organic pollutants. It also highlights key factors influencing biochar's efficacy and underscores existing challenges and future research directions in this domain	2022	[40]

Table 1 (continued)

Working title	Review compilation topics	Year review published	References
Biochar-based adsorbents for CO_2 capture	This review compiles recent research on biochar-based adsorbents for carbon dioxide (CO_2) capture, highlighting the importance of enhancing biochar's properties for improved performance. It covers production methods, the impact of raw materials and processing conditions, as well as physical and chemical modification techniques while proposing future directions for more effective large-scale CO_2 capture	2022	[41]
Utilizing sugarcane bagasse for the remediation of heavy metals	This literature review offers crucial insights into the utilization of sugarcane bagasse (SCB) biosorbent, both in its natural and modified states, for the removal of heavy metals. The study delves into various SCB modifications, optimal operational conditions, and adsorption mechanisms, identifying key research gaps for future exploration in the realm of SCB as a potent bio-adsorbent for heavy metal ion removal	2022	[42]
Biochar as a filler in polymer composites	Reports emerging use of biochar as a filler in polymer composites. Explains how it enhances their physical, mechanical, and thermal properties. Offers insights into the potential of biochar as a renewable and superior filler for composites	2022	[13]
Biochar synthesis through the thermochemical conversion of sugarcane bagasse	This literature review provides a concise examination of thermochemical technologies employed for sugarcane bagasse (SCB) biochar production. The versatile applications of SCB biochar in agriculture, environmental remediation, and construction materials are explored, with identified research gaps including cost analysis and comparisons with bagasse utilization in sugar industries, highlighting the potential of SCB biochar as a versatile carbon material	2022	[43]
Biochar and its potential to reduce greenhouse gas emissions	This review highlights the significant role of pyrolysis in producing biochar from agricultural biomass waste, emphasizing its potential in greenhouse gas reduction. Additionally, it summarizes advancements in optimizing biochar yield using microwave-assisted pyrolysis	2023	[44]
Eco-friendly catalysts for biodiesel: CaO on sugarcane bagasse biochar	This review emphasizes the environmental and economic challenges in biodiesel production using homogeneous catalysts, highlighting the promise of CaO and biochar-derived catalysts. While studies show good activity and stability, there is a need to address leaching issues, particularly in CaO/biochar systems, and an evident gap exists in research on sugarcane bagasse biochar-derived catalysts	2023	[45]

When dealing with organic agro-wastes, such as sugarcane, pyrolysis is the preferred method for biochar production. It is essential to employ suitable fabrication techniques tailored to the specific biomass utilized, while optimizing process parameters like temperature and residence time to achieve the highest possible biochar yield. The nature of biochar derived from plant biomass can vary depending on the specific conditions, as the process involves the gradual weight loss of the biomass. Initially, weight loss occurs due to water evaporation at around 100 °C, followed by the degradation of fibers such as cellulose and hemicellulose

at temperatures exceeding 220 °C [32]. To provide a comprehensive overview, Table 2 presents the different thermochemical techniques employed for biomass conversion, along with the corresponding percentage yields of various products.

2.1 Pyrolysis

Pyrolysis, the oldest thermochemical technique for processing biomass, is widely employed in the production of biochar, bio-crude, or syngas from various biomass sources,
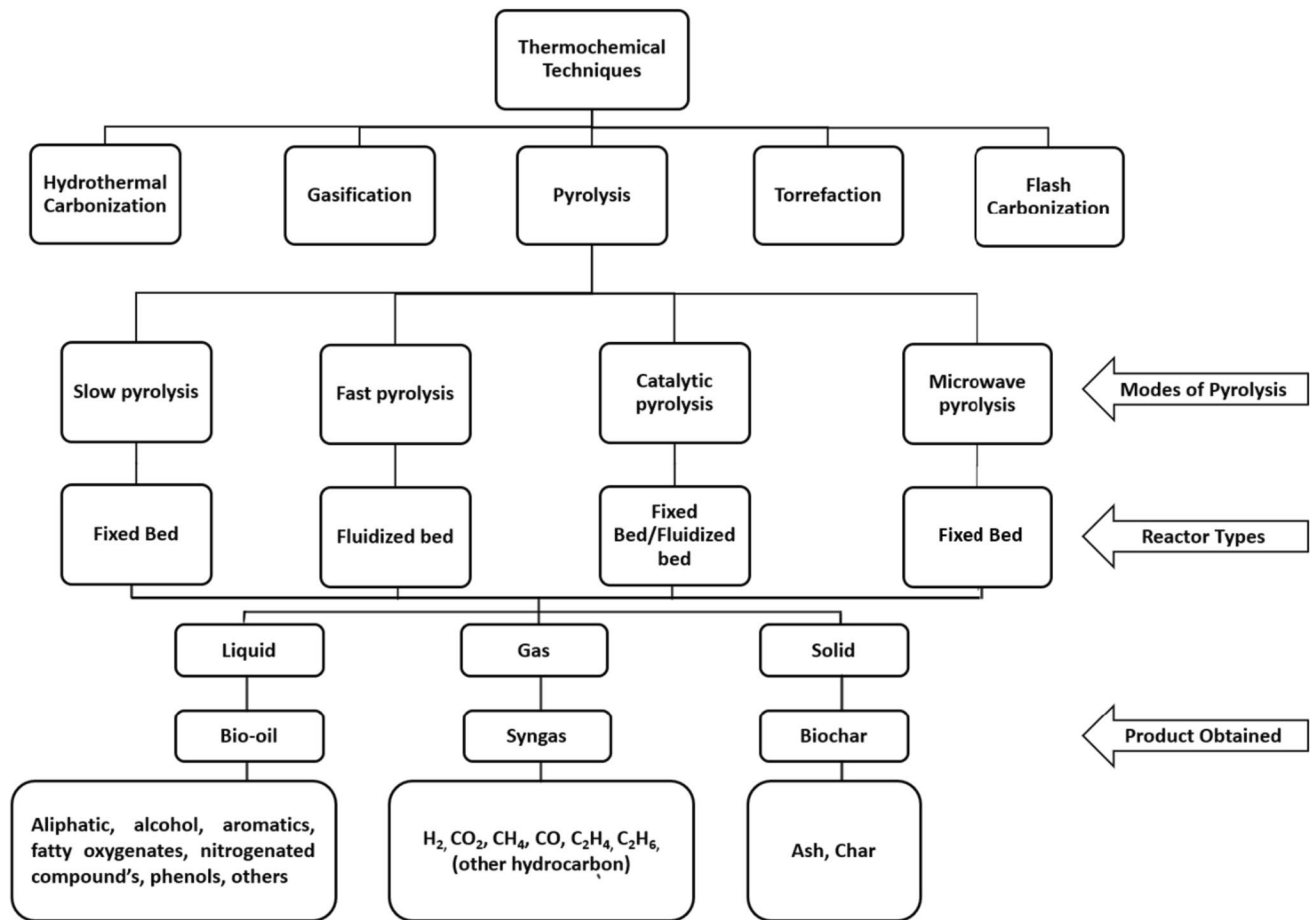
Fig. 2 Different thermochemical techniques and classification of different modes of pyrolysis

Table 2 Thermochemical processes showing the different percentages of yields of biochar, bio-oil, and syngas

Techniques	Temperature (°C)	Production of biochar (%)	Production of bio-oil (%)	Production of syngas (%)	References
Torrefaction	290	80	0	20	[53]
Hydrothermal carbonization	180–300	50–80	5–20	2–5	[54]
Flash arbonization	300–600	37	-	-	[55]
Pyrolysis	300–700 (Slow) 500–100 (Fast)	35 (Slow) 12 (Fast)	30 (Slow) 75 (Fast)	35 (Slow) 13 (Fast)	[56]
Gasification	750–900	10	5	85	[57]

operating at high temperatures and pressures. Pyrolysis can be defined as the carbonization of substances under extreme temperatures in an oxygen-depleted, enclosed chamber. During this process, the components of fibers, including lignin, hemicellulose, and cellulose, undergo different reaction mechanisms such as fragmentation, cross-linking, and depolymerization, resulting in a variety of product states such as solids, liquids, and gases. Gaseous products include carbon monoxide, carbon dioxide, hydrogen, and syngas (C1-C2 hydrocarbons), while solid and liquid products are represented by biochar and bio-oil, respectively. Generally, as the temperature of the pyrolysis process increases, the production of biochar decreases while the production of syngas increases. Figure 3 provides a visual representation of the diverse products obtained during the pyrolysis process.

Pyrolysis can be classified into three categories: flash, fast, and slow pyrolysis, depending on factors such as temperature range, residence duration, and heating rate [58]. Slow pyrolysis involves lower temperatures (300–500 °C), slower heating rates (0.1–1 °C/s), and a
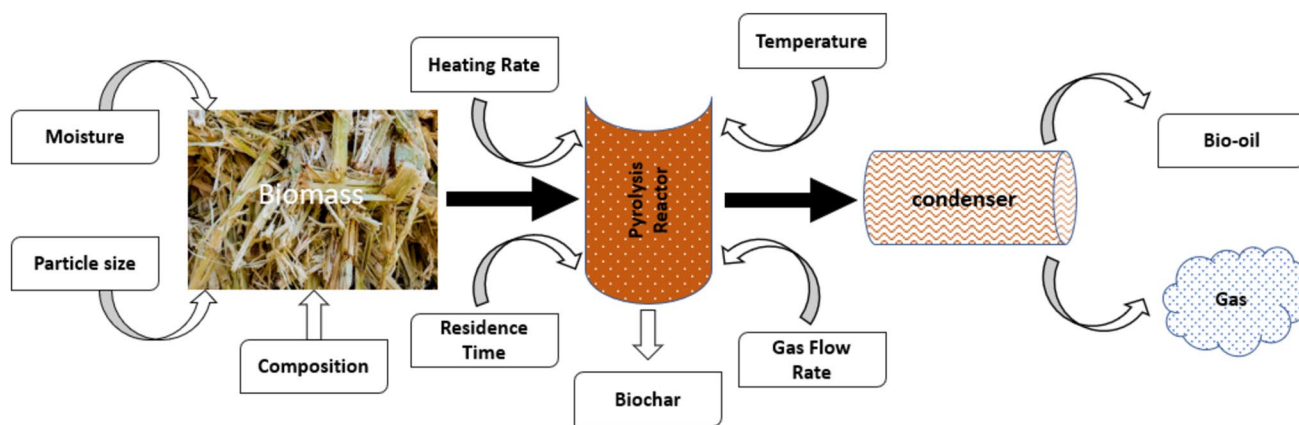
Fig. 3 Mechanism of pyrolysis demonstrating the formation of syngas, biochar, and bio-oil from bagasse biomass

maximum residence time of 2 h. These conditions promote a slower combustion process, resulting in higher solids production (up to 45%) and biochar as the primary output [59, 60]. In slow pyrolysis, the biomass particle size can be larger, ranging from 5 to 50 mm, as the primary focus is on biochar [58, 60].

On the other hand, fast pyrolysis occurs at higher temperatures (450–700 °C), shorter residence durations (about 20 s), and significantly faster heating rates (1–200 °C/s). This process yields up to 75% bio-oil as its main product [59]. Therefore, the biomass particle size needs to be smaller, typically less than 1 mm [61].

Flash pyrolysis, like gasification, aims primarily for gas generation. It requires even faster heating rates (over 1000 °C/s), shorter residence durations (1 s), and the highest temperatures among the three pyrolysis processes mentioned (above 800 °C). For this process, biomass particle size less than 0.2 mm is necessary [62]. Most of the gases produced in flash pyrolysis are non-condensable, including H_2, CO, CO_2, CH_4, C_2H_4, and C_2H_6 [58]. Table 3 provides an overview of the different types of pyrolysis and their corresponding working conditions, illustrating the variations in temperature, residence duration, heating rate, and desired outputs.

2.2 Hydrothermal carbonization

Hydrothermal carbonization (HTC), a thermochemical conversion technique, is employed to process wet biomass, characterized by its high moisture content, into charred biomass, also known as hydrochar [67]. HTC involves heating the biomass in the presence of water under high pressure, typically between 180 and 260 °C. The biomass is subjected to these conditions for a duration of 5 to 240 min under high pressure (2–6 MPa), ensuring effective conversion [68]. Within the hydrothermal process, two additional subcategories exist: hydrothermal vaporization and hydrothermal liquefaction. These methods are capable of generating liquid and gaseous fuels rather than solid fuels, as they are conducted at temperatures surpassing 260 °C [69].

The process known as artificial coalification, initially described by Bergius in 1913, imitates the natural transformation of cellulose into coal-like molecules. This process, also referred to as hydrothermal carbonization (HTC), subcritical water treatment, or wet torrefaction, has been rediscovered and extensively studied [70]. The hydrothermal carbonization process yields three main products: liquid bio-oil, hydro-char (solid carbonaceous material), and trace gases. The specific conditions employed during the process

Pyrolysis types	Temperature (°C)	Heating rate (°C/min)	Products/yield (%)	References
Slow pyrolysis	350–650	10–30	Biochar/29–37 Bio-oil/45–55 Biogas/16–32	[63, 64]
Fast pyrolysis	500 700	10	Bio-oil/20 Bio-oil/31	[65]
Flash pyrolysis	900–1300	1000	Bio-oil/60–75	[62, 66]

Table 3 Different types of pyrolysis used for sugarcane biomass to get different products

significantly impact the quality and distribution of these end products [71]. Among the various HTC products, hydrochar holds paramount importance due to its diverse applications. Hydrochar exhibits low ash content, hydrophobic properties, and advantages over the original feedstock in terms of mass, energy density, and combustion efficiency. On the other hand, biochar possesses a distinct advantage in applications relying on its porosity, as it exhibits a considerably larger surface area compared to hydrochar. Furthermore, hydrochar offers additional benefits, such as adsorption capabilities, soil improvement potential, and the ability to utilize various feedstocks in the HTC process [72, 73]. Figure 4 presents a standard hydrothermal carbonization reactor employed to produce biochar and bio-oil.

2.3 Composition of sugarcane bagasse biochar

Among the different pyrolysis processes, fast pyrolysis results in the lowest biochar production, while slow pyrolysis yields the highest amount [74]. Biochar is primarily composed of carbon, typically ranging from 65 to 90%, along with oxygen and aromatic chemicals that contribute to its resistance against biological degradation [75]. Compared to sugarcane bagasse, biochar exhibits lower hydrogen levels (0.5–4.2 wt%), as the weaker bonds between its elements are broken during pyrolysis, whereas bagasse typically contains 5–7 wt% hydrogen. Similarly, the oxygen content follows a similar trend, with biochar ranging from 10 to 45 wt% compared to 27–56 wt% for sugarcane bagasse. In terms of carbon content, biochar surpasses bagasse, with biochar containing up to 82 wt% carbon, while bagasse can have up to 58 wt% carbon [38, 76, 77]. High-quality biochar is typically defined as having a carbon content of at least 75 wt%. Additionally, the nitrogen levels in biochar are comparable

to those found in bagasse, with both ranging up to 1.1 to 1.3 wt% [38, 78–80]. These higher carbon and nitrogen concentrations in biochar significantly impact soil quality by providing nutrients, enhancing crop yields over multiple harvests, and improving water retention capabilities.

In addition to the studies, the results of the proximate analysis demonstrate that the production of biochar is accompanied by an increase in fixed carbon and ash values, as well as a decrease in volatile matter contents during the biomass decomposition process. The high levels of carbon in biochar are correlated with the elevated trends in fixed carbon. Furthermore, due to the presence of mineral components remaining after carbonization, biochar exhibits higher ash levels (up to 23 wt%) compared to bagasse (1–6%) [79, 81–85]. Lastly, in contrast to bagasse, which typically contains volatile matter levels of up to 85 wt%, biochar displays a reduced volatile matter content of up to 57 wt%.

Due to its high fixed carbon content [93], the bagasse char has higher HHV (higher heat value) (22–36 MJ/kg) [90, 93] than bagasse (16–19 MJ/kg) [90, 94–96] and bio-oil (23 MJ/kg), suggesting its burning potential [38]. Table 4 illustrates the different compositions of sugarcane-based biochar in proximate and ultimate analysis.

2.4 Functional groups in biochar

The acidity/basicity of biochar is determined by the orientation of polyaromatic clusters, surface functional groups containing heteroatoms, and mineral components [97]. The backbone of the biochar produced at temperatures above 400 °C composed of four to six layers of graphene-like crystalline clusters, which are like coal-derived char and petroleum coke. The polyaromatic rings in these clusters have delocalized electrons that act as Lewis bases. The edge carbon of these clusters contains most of the oxygen, nitrogen,

Fig.4 A standard hydrothermal carbonization reactor for producing biochar from sugarcane bagasse biomass [31]

Sugarcane Bagasse Biomass

Valves
Pressure
Bio-oil
Biochar
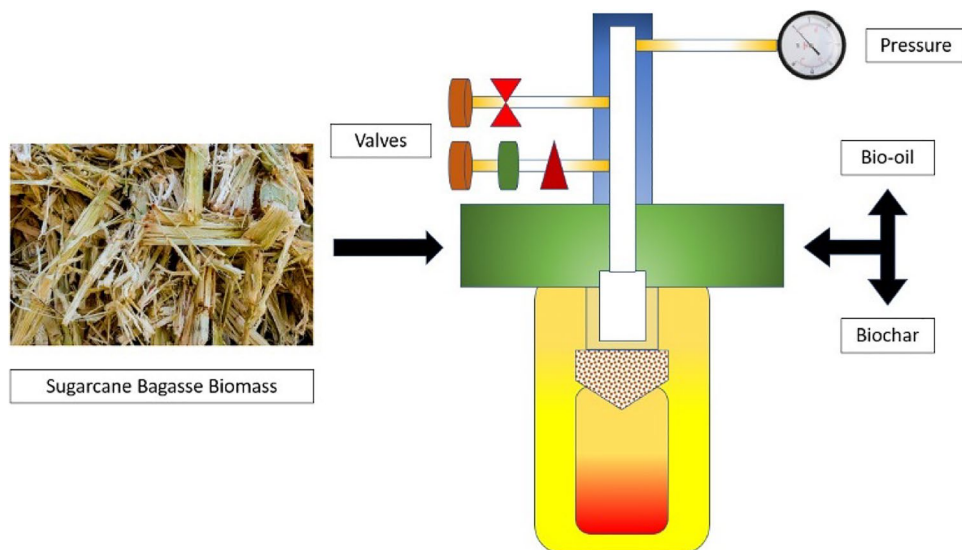
Table 4 Sugarcane bagasse-derived biochar's physicochemical characteristics

Proximate analysis				Ultimate analysis					HHV (MJ/kg)	Ref
Moisture	Ash	Volatile matter	Fixed carbon	N	S	O	H	C		
2.8–3.24	7.13–8.13	15.20–26.51	63.12–73.80	0.48	-	28.52	4.62	66.38	23–29	[77]
-	5.50–6.70	15.40–18.90	74.40–79.10	0.80–1.30	<0.10	10.20–14.60[a]	2.90–3.10	81.50–85.60	-	[76]
3.20	6.70	18.90	74.40	-	-	-	-	-	-	[86]
7.70	11.90–16.40	57.30	36.20	0.80–1.00	-	15.10–25.40[b]	1.50–2.20	60.40–65.30	-	[87]
1.98	8.91	34.65	54.46	0.54	0.05	21.66	0.45	77.30	-	[88]
-	22.73	-	-	0.95	-	14.77[c]	3.53	58.01	-	[89]
-	10.60–12.10	2.40–16.10	73.30–85.50	0.50–0.70	-	19.3–19.9[c]	0.70–2.20	77.20–79.50	22.2–23.1	[90]
-	3.60	-	-	-	-	18.10–22.60	3.90–4.40	73.00–78.00	-	[91]
-	18.50–22.96	26.46–37.04	16.52–22.98	0.004–0.009	0.053–0.089	45.55–57.10	2.25–3.76	40.48–51.47	-	[92]
-	5.50 ± 0.13	44.05 ± 0.30	50.44 ± 0.16	0.55 ± 0.01	-	24.72 ± 0.8[c]	4.19 ± 0.08	65.02 ± 0.93	24.35 ± 0.45	[93]

[a]O+ash (by difference)

[b]O+S (by difference)

[c]By difference

sulfur, and hydrogen containing functional groups, although intercalated oxygen has also been reported [98]. The surface acidity/basicity of carbon is primarily governed by the presence of oxygen and nitrogenous functional groups [99, 100]. According to Boehm's classification, functional groups can be categorized into acid, base, and neutral types [101]. Oxygen-containing groups are mainly acidic in nature [102].

Carboxylic acids, lactones, phenols, and lactol groups are among the well-established acidic functional groups that have been extensively researched. However, it is worth noting that not all oxygen-containing groups exhibit acidic properties. Take, for instance, pyrones, which are the primary oxygen functional groups dictating overall basicity. Pyrones form during the heat treatment of carbons exposed to air. Computational analyses have revealed that monocyclic ɣ-pyrones have relatively low basicity (with a *pKa* around − 1). In contrast, bicyclic pyrones display significantly greater basic characteristics compared to other surface oxide alternatives. Model compounds resembling polycyclic pyrones that span a wide range of basic strengths, with a difference of approximately 12 pKa units between them, were also reported [99] (Fig. 5).

Typically, when temperatures are raised from 100 to 700 °C, acidic oxygen functional groups like carboxyl, lactones, and phenols gradually break down, yielding CO_2 and CO (Fig. 6). On the other hand, basic oxygen functional groups tend to decompose at temperatures exceeding 600 °C. Consequently, subjecting BC to high temperatures allows for the effective elimination of most of its acidic oxygen functional groups, rendering the material more receptive to the adsorption of acidic compounds [97]. Functional groups containing nitrogen, such as amino groups, are typically associated with basic characteristics. However, it is important to note that raw biochar (BC) produced through pyrolysis at temperatures above 400 °C is unlikely to contain amino groups. In these raw BC materials, nitrogen atoms are incorporated into the aromatic structure, specifically of the pyridine type [97].

Montes-Morán et al. [99] have made an important observation that nitrogen present in the fused ring structure exhibits basicity akin to bicyclic pyrenes. Apart from these functional groups, the basal planes within the carbonaceous structure of BC demonstrate strong basic properties. This can be primarily attributed to the formation of hydrogen bonds between cations, notably H_3O^+, and π electrons on the basal planes. In this context, counter-ions are held at discrete distances to maintain electro-neutrality [103].

2.5 Utilization of sugarcane bagasse-based biochar for different applications

The preparation of sugarcane bagasse-based biochar using thermochemical processes attracted significant interest among researchers due to its versatile environmental
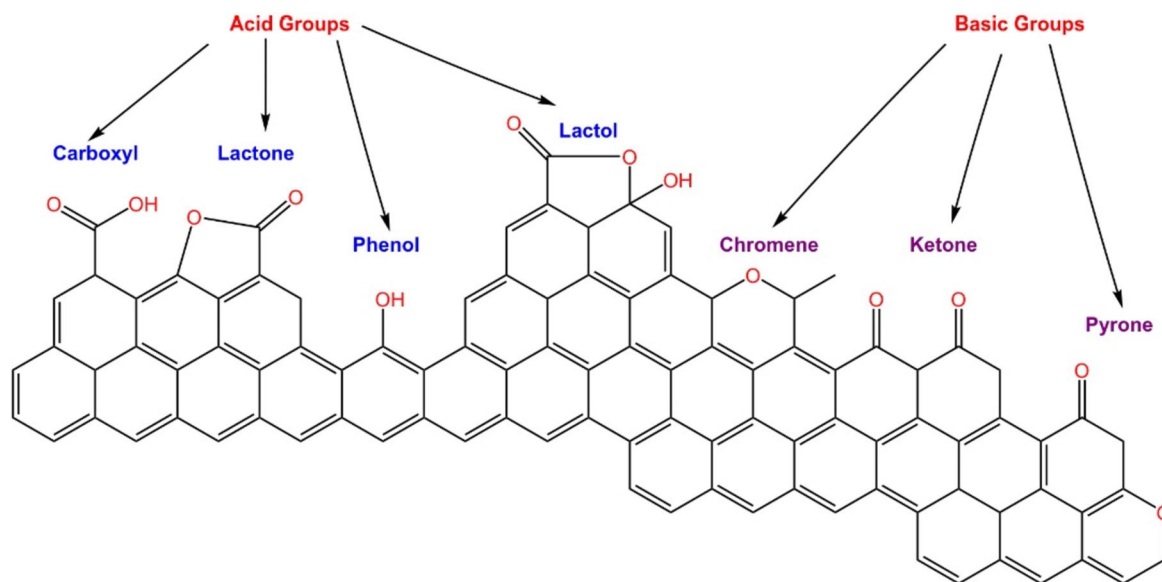
Fig. 5 Different acidic and basic sites in biochar [99]

applications. The choice of pyrolysis temperature and biomass type can determine the effectiveness of biochar in removing toxins and pollutants from soil and water. Biochar produced at higher pyrolysis temperatures reported to have rich carbon content exhibit enhanced properties such as porosity, surface area, and pH with reduced dissolved carbon content. They are also hydrophobic in nature, enabling it to effectively remove organic pollutants. Conversely, biochar produced at lower temperatures contains higher levels of dissolved organic carbon and oxygen-containing functional groups. These materials being less porous are better suited for the remediation of inorganic pollutants. The removal capacity of biochar is further influenced by factors such as residence duration and pH. In addition to pollutant removal, biochar finds diverse applications such as for energy storage, soil amendment for composting, carbon sequestration, catalysts, and in wastewater treatment [105].

2.6 Pollutant remediations

Current applications of biochar primarily focus on its effectiveness in removing both organic and inorganic contaminants from soil and water systems. When applied to soil, biochar acts as a binding agent for pre-existing organic contaminants. Examples of organic contaminants include cationic dyes like methylene blue, rhodamine, and methylene violet, as well as industrial chemicals like polycyclic aromatic hydrocarbons (PAHs), which encompass phenanthrene, catechol, pyrene, naphthalene, and anthracene. Additionally, organic contaminants may include antibiotics and medications like acetaminophen, tetracycline, diclofenac, naproxen, and ibuprofen [106, 107]. On the other hand,

inorganic pollutants, such as metals including copper, zinc, cadmium, lead, nickel, and mercury, pose significant threats to both human health and the environment due to their toxicity and non-biodegradable nature, particularly in high concentrations. Heavy metals are particularly harmful and can have carcinogenic effects. These inorganic contaminants are often released into the environment through industrial effluents or municipal wastewater [108].

Recent advancements in the utilization of sugarcane bagasse-based biochar have demonstrated its efficacy in adsorbing ciprofloxacin hydrochloride (CPF) [96]. The process involved conversion of sugarcane bagasse into carbon through hydrothermal carbonization (HTC), followed by activation using alkali impregnation in an inert gas environment. The activation was conducted at high temperatures as HTC typically results in limited surface area and porosity development. Comprehensive characterizations have been performed to investigate the physical, chemical, thermal, surface morphology, and surface area properties of the resulting material [96]. The HTC-derived biochar exhibited a spherical structure, with hydrophobic functional groups in the inner core and hydrophilic functional groups on the outer surface. The material displayed less porous structures, leading to a reduced surface area. However, these functional groups and increased porosity facilitated the adsorption of the target pollutant through surface/chemical adsorption mechanisms. Although the strength of the functional groups diminished after activation, the use of KOH led to the creation of a rough surface on the activated carbon spheres (ACSs), which enhanced the removal of CPF from water. Batch adsorption experiments demonstrated that CPF was effectively removed from water by the biochar, following

Fig. 6 Analysis of carbon's surface oxygenated functional groups and their decomposition via temperature-programmed desorption (TPD) [104]
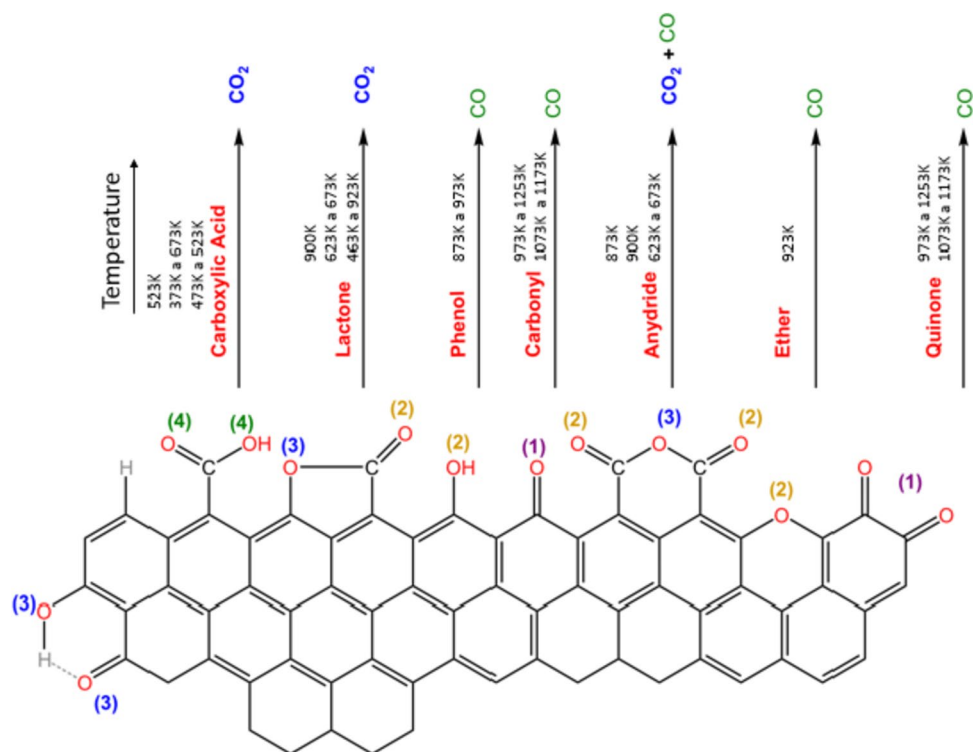
pseudo-second-order kinetics with a multilayer heterogonous mode. The maximal adsorption capacity of ACS for CPF was determined to be 110.008 mg/g [96].

In a similar study, HTC-derived biochar was chemically activated with NaOH in an inert atmosphere, and its ability to adsorb sulfamethoxazole (SMX) from water was investigated. The synthesized biochar exhibited abundant hydrophobic and hydrophilic groups both internally and externally within its sphere-like structure. The primary mechanisms for extracting SMX from water involved charge-assisted hydrogen bonding, adsorbate pore filling, and π-π interactions with the heterogeneous surface of the sorbent. The ionization effect influenced by pH facilitated these interactions. The results indicate that activated biochar is an effective adsorbent with a strong affinity for removing contaminants from water, while also being environmentally acceptable [109].

In a study by Inyang et al. [110], biochar derived from anaerobically processed sugarcane bagasse demonstrated ability to adsorb inorganic lead ions. Two types of sugarcane bagasse biochar, namely raw biochar (BC) and anaerobically digested biochar (DBC), for their effectiveness in removing lead from water were reported. Batch sorption studies were conducted, comparing the lead-binding capacities of BC, DBC, and commercial activated carbon (AC). These results indicated neither DBC nor BC exhibited the same level of lead removal efficiency as AC. DBC exhibited a significantly higher maximum lead sorption capacity (653.9 mmol/kg) compared to BC (31.3 mmol/kg), with DBC's capacity being approximately twice that of AC (395.3 mmol/kg). While

surface adsorption was identified as the primary mechanism for lead retention by BC, lead sorption by DBC occurred through a precipitation mechanism, which was confirmed using techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) [110].

In another comparative study involving sugarcane bagasse biochar and orange peel biochar, the efficiency of biochar in removing Pb(II) from aqueous solutions was examined. The sorption capacities of SC-BC (sugarcane bagasse biochar) and OP-BC (orange peel biochar) were evaluated, with SC-BC exhibiting a significantly higher removal capacity of 86.96 mg/g compared to OP-BC (27.86 mg/g). This higher sorption capacity of SC-BC was attributed to its larger surface area compared to OP-BC. Additionally, batch adsorption experiments were conducted to investigate the effects of various parameters such as pH, contact duration, initial concentration of Pb(II) ions, and temperature on the sorption process and optimization of Pb removal efficiency [111].

The removal of Cr(VI) ions 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. Additionally, different iron oxides such as FeO, Fe_2O_3, and Fe_3O_4 were employed to remove Cr(VI), highlighting the significant contribution of FeO in the magnetic biochar. The physicochemical properties of the magnetic biochar and its efficiency in Cr(VI) removal were influenced by changes

in the iron content [113]. In another related study, 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 suggested approach offered advantages such as low cost and excellent reproducibility of BMBC application. 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. Various parameters including ionic strength, BMBC dosage, pH, adsorption duration, initial Cr ion concentration, and coexisting ions were modified. The main components of BMBC were found to be amorphous Fe_2O_3 and Fe_3O_4 on bagasse biochar. The maximum percentage of Cr(VI) removal was achieved with a dosage of 0.20 g of BMBC in a 50 mL solution at pH 2. BMBC exhibited excellent adsorption capabilities for Cr(VI) in aqueous solutions. Compared to conventional biochar sorbents, BMBC showed a maximum Cr(VI) adsorption capacity of 29.08 mg/g at 25 °C. The desorption of Cr(VI) using a 0.2 mol/L NaOH solution resulted in a capacity of 8.21 mg/g. The removal efficiency of Cr(VI) remained above 80.36% even after three reuse cycles [114].

In a related study, the sorption and detoxification of malachite green (MG) dye were investigated using biochar produced by pyrolyzing agricultural and industrial waste at temperatures of 800 °C, 600 °C, and 400 °C. The highest sorption capacity for MG dye (3000 mg/L) was observed with sugarcane bagasse biochar (SCB) produced at 800 °C (Fig. 7). Response surface methods (RSM) were employed to analyze the relationships 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 mg/L, contact duration of 51.89 min, temperature of 60 °C, and pH of 7.5 [112]. The effectiveness of sugarcane-based biochar in adsorbing different types of pollutants is summarized in Table 5.

2.7 Sugarcane bagasse-based biochar in CO_2 adsorption

The increasing global energy consumption has led to a rise in anthropogenic CO_2 emissions. To address this, sugarcane bagasse biochar has emerged as a low-cost and sustainable alternative for CO_2 adsorption [125]. In their study, Han et al. [126] pyrolyzed sugarcane bagasse to produce biochar, which was subsequently doped with nitrogen using the urea-KOH method. The synthesized adsorbent exhibited excellent CO_2 adsorption of 4.88 mmol/g at 25 °C and 1 bar pressure. The adsorbent was prepared at 600 °C with the addition of 15 wt% urea and a carbon/KOH ratio of 2.0. The resulting biochar,

known as SB-AC, possessed consistent micropores with a size of 0.55 nm contributing to remarkable CO_2/N_2 selectivity. The CO_2 absorption capacity of the adsorbent remained stable and reproducible over five cycles of CO_2 adsorption/desorption, demonstrating its strong adsorption stability [126].

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 prepared at 600 °C, exhibiting a capacity of 73.55 mg/g at 25 °C. Although HW600 had a larger surface area than BG600, the CO_2 adsorption curve of HW600 showed a slightly steeper trend at both 25 °C and 75 °C adsorption conditions. This research suggests that, in addition to surface area, interactions with surface functional groups may also influence the adsorption of CO_2 on biochars [127].

In another report, various activating conditions like air, H_3PO_4, CO_2, and NaOH were employed to produce porous activated carbon adsorbents from sugarcane bagasse. Table 6 demonstrates the experimental variables and CO_2 adsorption capacity of different sugarcane bagasse-based biochar. The resulting adsorbents exhibited excellent CO_2 adsorption capabilities, large pore volumes, and high specific surface areas [128]. Specifically, the adsorbent prepared with NaOH activation showed remarkable static CO_2 absorption (4.28 mmol CO_2/g at 25 °C and 1 bar) as well as dynamic CO_2 adsorption capacity (1.31 mmol CO_2/g at 60 °C and 10% CO_2 concentration) [128]. In the context of biogas purification, the combination of sugarcane bagasse-based biochar with natural zeolites demonstrated effective adsorption capabilities. The adsorption process was conducted at room temperature within the pressure range of 5–7 bar. Notably, when biochar was utilized as a substitute for zeolite at a 50% volume ratio, a significant reduction in CO_2 content was observed (Fig. 8). The mixture of 50% naturally occurring zeolite and 50% sugarcane bagasse-based biochar exhibited the most favorable CO_2 reduction [129].

In a separate investigation, the objective was to quantify CO_2 capture using carbonaceous materials derived from sugarcane bagasse. The first material, CA-1, was impregnated into biochar and subsequently pyrolyzed at 350 °C, while the second material, CA-2, was directly impregnated into dry biomass, resulting in two distinct carbonaceous materials (CA-1 and CA-2, respectively). Chemical activation with KOH was applied to the biochar, and thermal analysis revealed two primary stages of carbonization: the first occurring around 150 °C and the second between 150 and 600 °C. CO_2 capture was evaluated through thermogravimetric testing, and both samples exhibited comparable physicochemical properties. However, the CA-2 sample demonstrated superior CO_2 adsorption performance, with a value of 1.22 mmol CO_2/g [130]

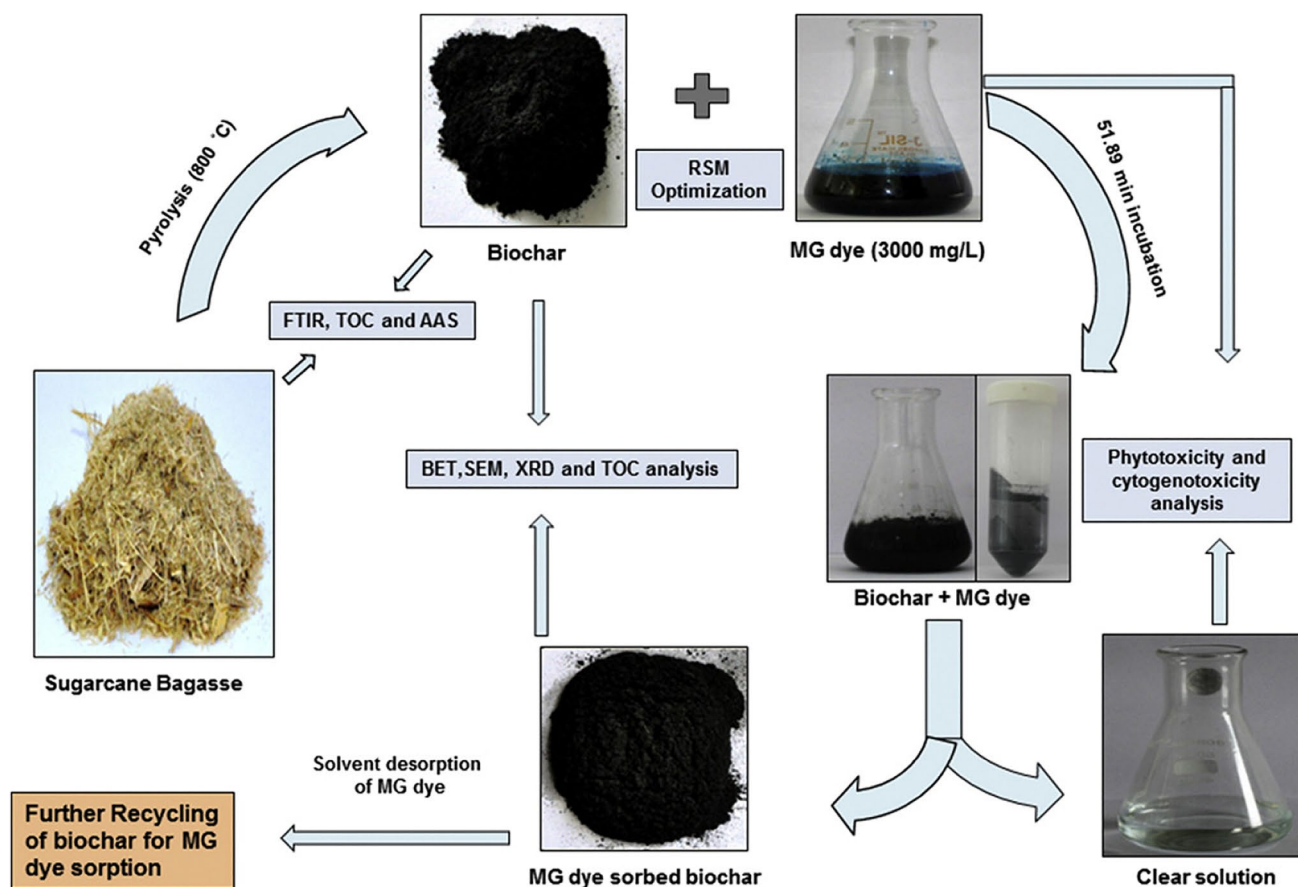جامعة قطر QATAR UNIVERSITY

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Fig. 7 A schematic diagram illustrating the sequential stages involved in the adsorption of MG dye by sugarcane bagasse biochar [112]

2.8 Sugarcane bagasse-based biochar as an additive in composites

The rapid increase in population and evolving lifestyles has led to the generation of large quantities of solid waste. In China, the addition of biochar to composting regulations has been proposed to enhance the composting process by improving water retention, promoting better aeration, and reducing gas emissions [131–133]. Sugarcane bagasse-derived biochar has been utilized to develop polymer additives as potential substitutes for carbon blacks. These additives can be effectively combined with other readily available renewable resources. By modifying the surface chemistry of the particles, the interaction between the particles and the polymer matrix is improved, resulting in enhanced quality of the composites. Polyethylene composites with 5% loading of annealed biochar samples exhibited mechanical, calorimetric, and thermal properties like those prepared with commercial carbon black [134].

In a study conducted by Biswas et al. [135] on a new composite adsorbent for the removal of methylene blue dye from aqueous solutions. They developed composite adsorbent beads using sugarcane bagasse biochar (SB) encapsulated in calcium-alginate (CASB). Batch and closed-circuit semi-fluidized bed column experiments were carried out to evaluate the performance of the composite adsorbent. The closed-circuit bed experiment investigated the impact of initial dye concentration, bed height, and liquid feed flow rate on dye removal. The maximum bed capacity of 30.13 mg/g and a 95.47% removal efficiency were achieved at an initial solute concentration of 40 mg/L, feed flow rate of 2.5 LPM, and bed height of 10 cm [136].

In another study, nanocomposites were developed using sugarcane bagasse-based biochar for the removal of metal ions such as Fe and Zn from aqueous solutions. The novel adsorbent, called SCB-BC/Fe_3O_4, was created by combining nano-magnetite with sugarcane bagasse biochar. The synthesized nanocomposite exhibited high removal efficiencies of 90% for Fe and 96% for Zn, effectively eliminating these metal ions from water [137]. Furthermore, a sugarcane bagasse biochar/nano-iron oxide composite was prepared using a one-pot pyrolysis technique for the absorption of Cr(VI) from water. The composite was characterized using various techniques such as BET, XRD, FT-IR, and TEM. The composite mainly consisted of amorphous carbon, Fe_3O_4, and Fe_2O_3. The iron oxides were uniformly

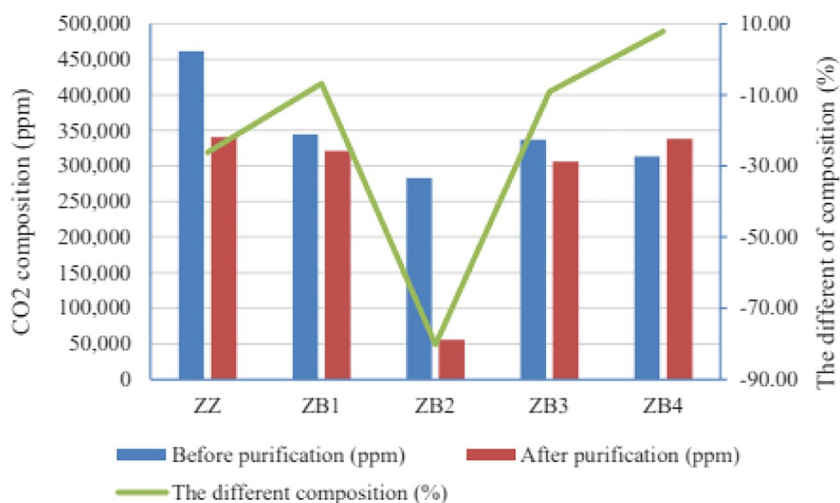**Table 5** Sugarcane bagasse-based biochar for different pollutants adsorptions

Adsorbent types	Mode of experiment	Experimental variables				Adsorbates	Maximum adsorptions (mg/g)	Ref
		pH	Initial adsorbate conc. (ppm)	Adsorbent dose (g/L)	Contact time (min)			
Sugarcane bagasse	Batch and fixed column	6	100	10	60	Ni(II)	3.008	[115]
Sugarcane bagasse Fe-coated biochar	Batch	-	-	-	-	As(III)	20	[116]
Modified SCB biochar	Batch	4.64	1–100	2	60	Nitrate	28.21	[117]
Anaerobically digested bagasse biochar	Digestion vessel	2	10	0.1 g*	-	Sulfamethoxazole (SMX) and sulphapyridine (SPY)	SMX and SPY 54.38 and 8.60, respectively	[118]
Sugarcane bagasse biochar (SB500)	Batch and Fixed Bed	2	4.5	2	35	Carbofuran	19	[119]
Modified Sugarcane bagasse biochar	Batch	2	10	0.5 g*	60	Chlorpyrifos	3.20	[120]
Activated bagasse biochar	Batch	2	300	4	-	C.I. Reactive Blue 19 Dye	58.1	[121]
KOH-activated magnetic sugarcane bagasse biochar	Batch	-	-	-	-	Imidacloprid	313	[122, 123]
Sugarcane bagasse biochar B600	Batch	7	0.2	-	-	p-benzoquinone, tetracycline, and polyvinyl alcohol	-	[124]

*Units in grams

Table 6 Sugarcane bagasse-based biochar's CO_2 adsorption capacity

Adsorbent types	Biochar activation/ bagasse treatments	Experimental variables		CO_2 adsorption capacity	Surface area	Reference
		Temperature	Pressure			
Sugarcane bagasse (waste biomass)	15 wt% urea additions and KOH/carbon ratio of 2.0	25 °C	1 bar	4.8 mmol/g	1113 m^2/g	[126]
Sugarcane bagasse (BG) and hickory wood (HW)	Slow pyrolysis of sugarcane bagasse in N_2 environment at different temperatures (BG 600)	25 °C	-	73.55 mg/g	388 m^2/g	[127]
Sugarcane bagasse	Chemically and physically activated biochar (NaOH-activated carbon)	at 0 °C and 25 °C	1 bar	5.50 and 4.28 mmol/g	1149 m^2/g	[128]
Sugarcane bagasse	Sugarcane bagasse biochar combine with zeolites (50%/50%) by volume	Room temperature	5–7 bar	-	35.45 m^2/g	[129]
Sugarcane bagasse	Biochar activated chemically with KOH (CA-1 and CA-2)	-	-	1.08 and 1.22 CO_2 mmol/g	1.81 and 5.47 m^2/g	[130]

Fig. 8 Purification of biogas using natural zeolites and bagasse biochar using in different ratios [129]. (According to the information presented in Fig. 8, ZB2 exhibits the most significant reduction in carbon dioxide emissions, achieved through a combination of 50% sugarcane bagasse-derived biochar and 50% natural zeolite)

embedded on the surface of the carbon layer through van der Waals forces. This composite demonstrated potential for the removal of Cr (VI) from wastewater [138].

2.9 Sugarcane bagasse-based biochar as a catalyst

Biodiesel, a renewable alternative to conventional diesel fuel, is produced through a chemical process called transesterification. This process involves the reaction of alcohol with fats or oils in the presence of a catalyst. The alcohol reacts with the triglycerides in the fat or oil resulting in the formation of methyl esters, which are valuable biofuels, and glycerol as a by-product [139]. Figure 9a provides an overview of the general transesterification reaction, which leads to the production of glycerol and biodiesel from triglycerides. This transesterification reaction can be catalyzed by biochar-based catalysts derived from various feedstocks, such as sugarcane bagasse including rice husk and sunflower oil, as discussed in previous literature [140–142].

In a study by Niju et al. [143], sugarcane bagasse-based biochar was employed as a catalyst for biodiesel production using waste cooking oil (WCO) as a cost-effective source of lipids. They achieved a maximum biodiesel conversion of 98.94% by using a catalyst concentration of 10%, a methanol-to-oil volumetric ratio of 1:2, a reaction time of 120 min, and a reaction temperature of 65 °C (Fig. 9b).

In another study, Hidayat et al. [144] investigated the use of sugarcane bagasse biochar as a solid catalyst for biodiesel production from waste residue of the palm oil industry. They created the catalyst by sulfonating the sugarcane bagasse biochar, introducing sulfonate functional groups. At a reaction temperature of 65 °C and a mass ratio of 4:1 for PFAD (palm fatty acid distillate) to methanol, the highest FFA (free fatty acid) concentration of 86.1% was achieved with a PFAD catalyst content of 5%.

Biodiesel production encounters challenges with both homogeneous and heterogeneous catalysts, marked by issues such as challenging catalyst recovery and product purification for homogeneous catalysts, and extended reaction times, stringent conditions, and elevated production costs for heterogeneous catalysts. In their study, Nazir et al. [145] tackle biodiesel production challenges by exploring a sulfonated catalyst derived from activated carbon originating from sugarcane bagasse lignin. The optimized catalyst demonstrated exceptional features, including a surface area of 30.31 m^2/g, acidic density of 4.74 mmol/g, pore volume of 0.03 cm^3/g, pore size of 9.44 nm, and well-defined functional groups, surface morphology, and crystallographic structure. Microwave heating was utilized for transesterification of waste cooking oil with methanol using this catalyst, presenting a promising avenue for improving efficiency and sustainability in biodiesel synthesis [146].

Akinfalabi et al. [6] developed a reusable nano-catalyst from sulphonated sugarcane bagasse-based biochar for biodiesel production from waste feedstock. The SCB-SO_3H catalyst exhibited exceptional performance due to its superior acid density of 5.63 mmol/g, pore volume of 1.17 (cm^3/g), pore diameter of 3.21 nm, and specific surface area of 298 (m^2/g). The catalyst could be reused for up to seven reaction cycles, with a decrease in FAME (fatty acid methyl ester) yield from 98.6 to 79.1% while retaining approximately 19% of its conversion strength.

2.10 Sugarcane bagasse-based biochar in building construction

The utilization of biochar derived from agricultural waste offers significant potential as it does not have detrimental effects on the environment, unlike agro-waste ashes. Incorporating biochar into cementitious materials can provide

(a)

(b)
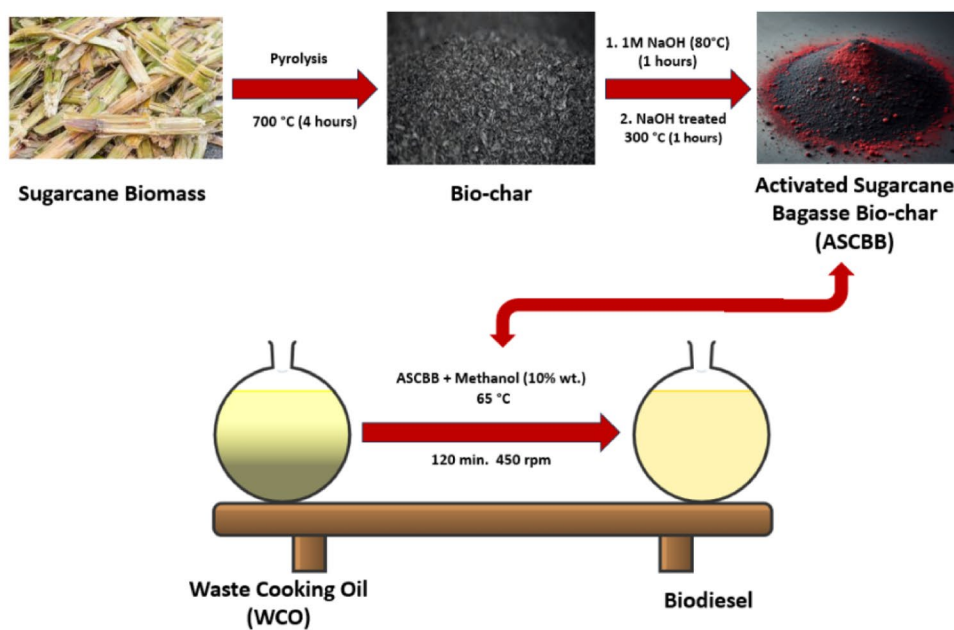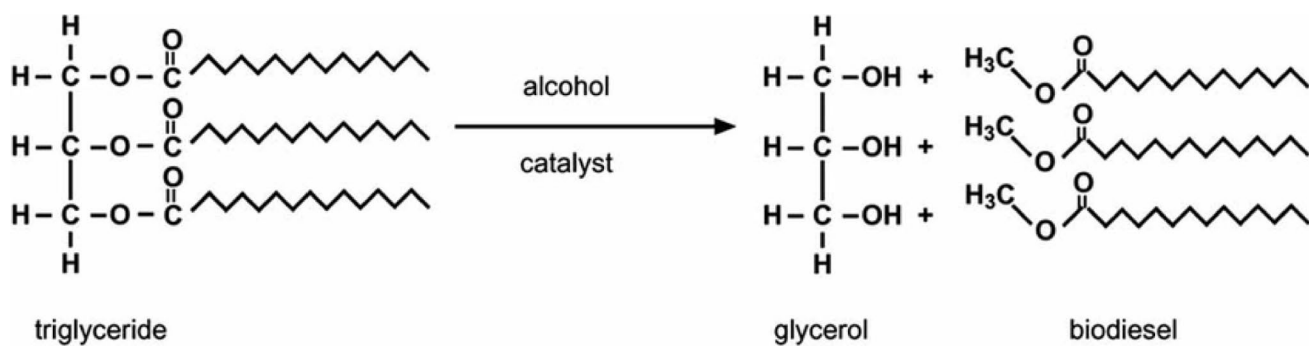
Fig. 9 **a** Transesterification reaction [139]. **b** Schematic diagram showing the activated sugarcane bagasse biochar (ASCBB) used as catalyst in conversion of waste cooking oil into biodiesel following the mechanism of transesterification reactions [143]

opportunities for carbon sequestration from agricultural biomass waste, mitigating methane and CO_2 emissions that would occur during disposal. Previous studies have investigated biochar-cement applications using various agro-wastes [147–149]. Asadi Zeidabadi et al. [150] examined the mechanical properties of concrete by adding 0%, 5%, and 10% (by mass) of rice husk and bagasse biochar to the cement. The synthesized samples were referred to as TRHB, RHB, TBB, and BB for pretreated rice husk biochar, unpretreated rice husk biochar, pretreated bagasse biochar, and unpretreated bagasse biochar, respectively. The tensile strength of the concrete sample with 5% treated bagasse biochar increased by 78% compared to concrete without

biochar (Fig. 10). The maximum compressive strength was achieved by incorporating 5% bagasse biochar and 5% rice husk biochar.

In another study by Khan et al. [151], 10% of the cement in concrete was replaced with sugarcane bagasse ash and micro silica by weight to enhance resistance against sulfate and chloride attacks. Rodier et al. [152] investigated the influence of pyrolyzed sugarcane bagasse biochars on the thermal and mechanical characteristics of cement-based composites. Addition of 2% by weight of biochar improved the hydration of cement, resulting in 36% less water absorption compared to using sugarcane bagasse alone. Thermal conductivity tests revealed that incorporating 4% by weight
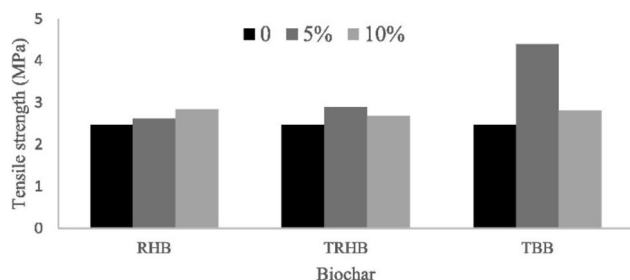
Fig. 10 Tensile strength evaluation in concrete specimens incorporating varying proportions of biochar derived from bagasse and rice husk [150]

of biochar reduced the thermal conductivity of cement-based materials by 25% compared to composites with sugarcane bagasse [153].

2.11 Sugarcane bagasse-based biochar in soil amendments

Unsound agricultural practices have resulted in increased CO_2 emissions and accelerated the decomposition of organic soil compounds. Previous experiments have explored the augmentation of organic carbon in soil by incorporating biomass into crop cultivation and utilizing livestock manure [154]. In clayey soil, various types of biochar have shown improvements in water distribution and infiltration. Biochar has a preferential attraction for cations and anions in the soil [155]. The application of sugarcane biochar has been found to enhance the removal of Na + from the soil [155]. Furthermore, the interaction between biochar particles and soil components influences water and ion dynamics, which is crucial for rehabilitating salt-affected soils [155].

Combining synthetic fertilizers with organic soil amendments can enhance crop productivity and improve soil quality [156]. The use of sugarcane bagasse and leaf residue biochar has demonstrated positive effects on soil health, water-holding capacity, and sugarcane yields when applied alongside commercial fertilizers. The application of biochar to sugarcane fields offers several benefits, including increased soil carbon content, improved drainage and aeration, and enhanced nutrient uptake for the sugarcane crop [157]. The water retention capacity of the soil is also influenced by the pyrolysis temperature and the amount of biochar incorporated. In clay soil amended with biochar at rates exceeding 3% wt/wt, a significant improvement of over 60% in available water capacity was observed [158]. Haghighatjou et al. [159] conducted sorption and desorption studies, which revealed that the addition of biochar enhanced the soil's capacity to retain Zn compared to naturally acidic soil. The amended soils exhibited higher cation exchange capacities (up to 42%), increased electrical conductivity (up to 2.66 times), and elevated pH values (up to 2.5 pH units) compared to the unmodified acidic soil. Furthermore, the addition of biochar significantly improved the levels of exchangeable calcium, potassium, sodium, and magnesium cations in the soil.

Sugarcane bagasse biochar has been reported to enhance microbial activity in soil, although it does not have a significant impact on soil pH and potassium content [160]. Raul et al. [161] conducted a study on the modification of physicochemical characteristics in inland saline aquaculture pond sediments using biochar. The application of biochar led to an increase in organic carbon, available phosphorus, available potassium, calcium, magnesium, and water-holding capacity, but a decrease in pH, electrical conductivity, and bulk density.

Azadi et al. [162] investigated the effects of sugarcane bagasse biochar treatment on enzymatic activities, microbial activity, and biomass in lead- and cadmium-contaminated soil during an incubation experiment. In salinized soils, biochar reduced metal availability, while in saline co-polluted soils, it enhanced enzyme and microbial activity. Zhang et al. [163] produced mesoporous biochar by calcining bagasse with KOH, followed by activation with persulfate for the degradation of phenol. The synthetic biochar demonstrated excellent removal effectiveness in the degradation of organic contaminants in soil and water, offering potential applications due to its high removal rate, relative stability, low cost, and low dosage. With a relatively little dosage (0.066 g/L), the synthetic biochar showed an exceptional clearance rate of 90% in 60 min. Due to its excellent removal effectiveness, relative stability, low cost, and relatively smaller dosage, it offers an application potential in the degradation of organic contaminants in soil and water [163]. Sugarcane bagasse biochar has also shown promising results in increasing the organic matter content of organic carbon-deficient alluvial soils [164].

In another study on soil remediation, the use of poplar wood biochar and sugarcane bagasse biochar resulted in reduced uptake of chromium (Cr) and lead (Pb) in lettuce, demonstrating their effectiveness in cleaning up contaminated agricultural soil (Fig. 11) [165]. Alves et al. [166] investigated the effect of mixed biochar, combining sewage sludge and sugarcane bagasse biochar, on soil properties. The treated soil showed increased total carbon and pH, as well as a decrease in nutrient concentrations except for potassium (K) and chromium (Cr), leading to overall improvements in soil fertility. Similarly, co-composted biochar from sugarcane bagasse and rice straw has shown an increase in soil organic content [167]. Previous studies have indicated that the amendment of sugarcane bagasse biochar to soil not only enhances sugarcane crop yield but also improves sugar content [168]. In separate study, Pereira Lopes et al. [169] carried out work on bagasse biochar as

Fig. 11 The bioaccumulation of chromium (Cr) and lead (Pb) in lettuce cultivated in both untreated soil (referred to as the "Control") and soil amended with various biochars: PWB3 and PWB7 correspond to poplar wood biochar applied at 3% and 7%, respectively, while SCBB3 and SCBB7 denote sugarcane bagasse biochar applied at 3% and 7%, respectively [165]
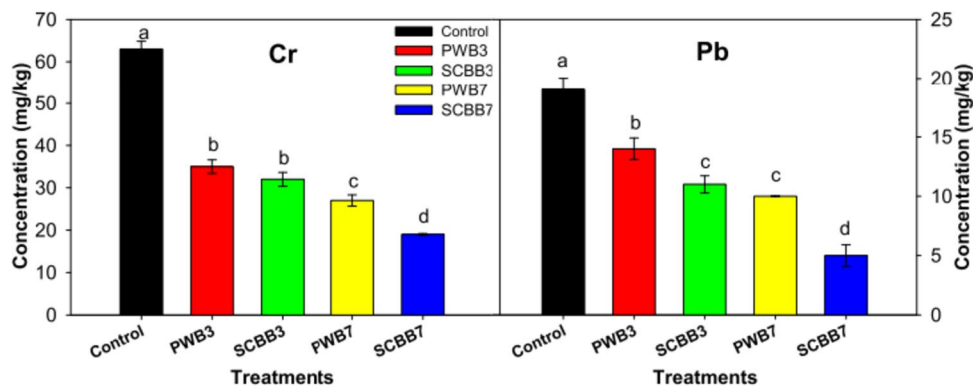
support for the reactive Ni/Fe bimetallic catalyst for the remediation of decabromodiphenyl-contaminated soil. BC@Ni/Fe demonstrated a removal efficiency of 87.7% for BDE209 after 72 h, surpassing the combined efficiency of pure Ni/Fe and biochar.

2.12 Analytical technique use in characterization of sugarcane bagasse biochar

The characterization of biochar is conducted to assess its capacity for pollutant removal and surface functional group modifications or explore potential alternative uses. Evaluating the structural and elemental properties of biochar is instrumental in predicting its potential ecological impact [170]. Additionally, the interaction of metals and other pollutants with biochar is contingent on pH, as evidenced by the following: (i) the role of biochar varies with pH and (ii) the speciation of metal contaminant ions changes with pH. These attributes of biochar illustrate its effectiveness as a highly efficient biosorbent for removing a substantial portion of caffeine and diclofenac [171]. Biochar characterization methods revolve around the assessment of its structure, surface functional groups, and elemental composition [172, 173]. Various technological characterization methods, as illustrated in Fig. 12, encompass SEM, FTIR, XRD, NMR, BET, thermogravimetric analysis (TGA), proximate and ultimate analysis, and Raman spectroscopy. Veiga et al. [174] employed a range of techniques for the characterization of bagasse biochar samples, including FTIR, determination of functional group pKa, elemental analysis, zeta potential measurements, Raman spectroscopy, EPR, and SEM.

2.13 Fourier-transform infrared spectroscopy

Fourier transform infrared technology is a vibrational spectroscopic technique used to examine the functional groups that exist on the surface of biochar [176, 177]. The biochar within the mixture and additional settings underwent substantial changes with increasing temperature. To effectively monitor these transformations, a non-destructive FTIR

instrument would be necessary [178]. The spectra revealed a substantial reduction in aromatic groups at higher temperature ranges between 650 and 800 °C. Another technique, diffuse reflectance infrared Fourier transform spectroscopy, is applied after pelletizing the sample with KBr. In this method, the sample comes into contact with an attenuated total reflectance crystal (ATR), allowing for the detection of functional groups in ATR-FTIR spectroscopy [178]. Numerous researchers have employed FTIR to characterize biochar produced from biomass. However, ATR (attenuated total reflectance) is often favored due to its user-friendly operation and time-saving advantages when compared to conventional FTIR analysis [179].

Furthermore, as noted by Alfattani et al. [180], the FTIR spectra revealed distinct peaks at wavenumbers of 3428, 3465, 3442, and 3411 cm^{-1} for biochar obtained from thin-shelled walnut, paper-shelled walnut, hard-shelled walnut, and medium-shelled walnut. These peaks clearly indicated the stretching vibrations of phenolic –OH hydroxyl groups. In another study, Adekanye et al. [181] conducted a characterization of maize cob biochar using FTIR. They focused on the analysis of functional groups in biochars prepared at temperatures of 300, 400, and 500 °C. Their findings revealed that an increase in temperature led to the expansion of the O–H group, located within the band range of 3383–3402 cm^{-1}. As reported by Sahoo et al. [182], FTIR analysis proves valuable for examining how temperature impacts the functional groups of biochar during the pyrolysis process. Their research indicated that the temperature exerted a significant influence on the functional groups of biochar when pyrolysis occurred within the temperature range of 300–750 °C.

2.14 Raman spectroscopy

Raman spectroscopy is extensively employed for the structural analysis of carbon-based solid materials. This is attributed to its notable advantages, which include straightforward sample preparation, high sensitivity, excellent resolution, and the ability to perform nondestructive testing [183,
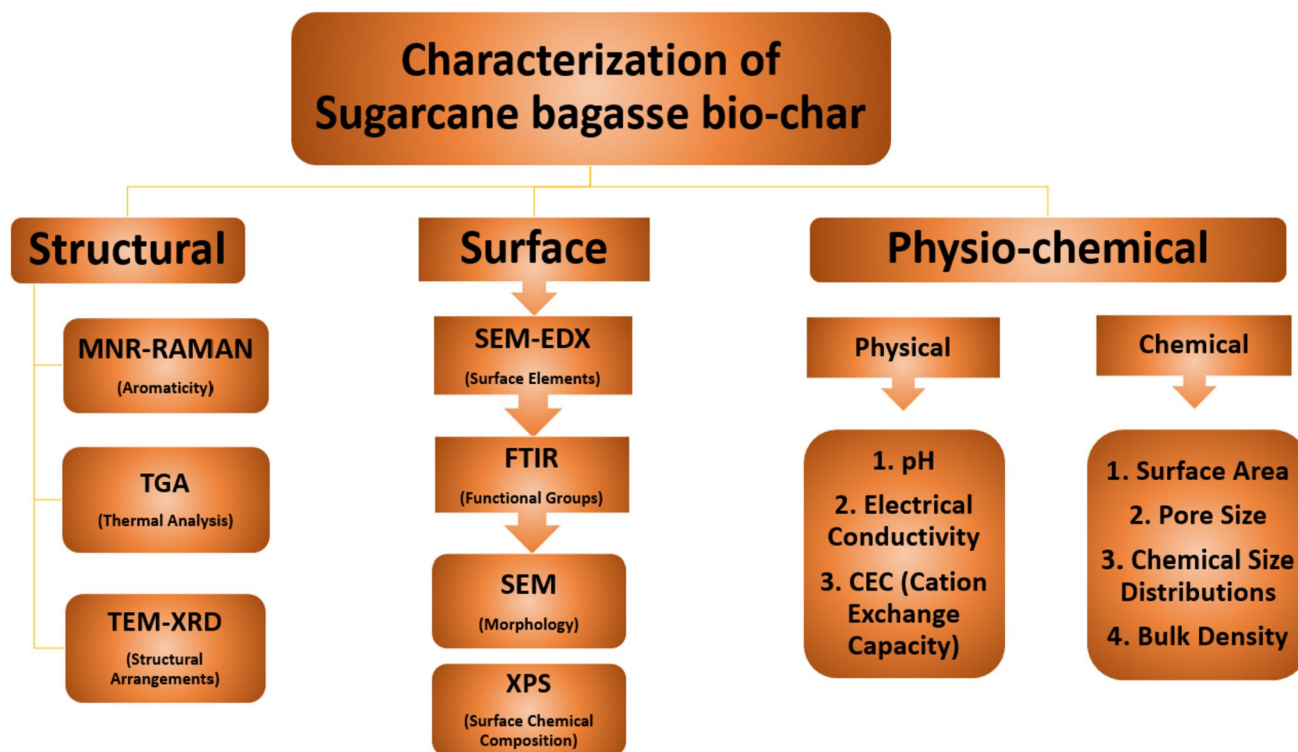
Fig. 12 Structural, surface, and physio-chemical biochar characterization [175]

184]. Biochars produced through the pyrolysis of different agro-waste like sugarcane bagasse, rice husk, pine wood, and rice straw can be also effectively characterized using Raman spectroscopy. The alterations in Raman band positions and bandwidths signify that the carbon structure of biochar becomes more ordered as the pyrolysis temperature rises. Furthermore, it is important to note that the detailed chemical composition of biochar can substantially vary depending on the source of the raw biomass [185]. The features observed in the positions and widths of Raman bands indicate that the degree of carbon order in biochar steadily rises as the pyrolysis temperature increases. Additionally, the detailed chemical composition of biochar originating from different source materials can exhibit significant variations [185]. In a study conducted by Veiga et al. [174] on the transition from a batch to a continuous flow process for the pyrolysis of sugarcane bagasse, the results indicated that the elemental analyses (H/C ~ 0.31) and Raman spectra (ID/IG ~ 0.55) affirmed a higher degree of carbonization and reduced structural disorder in the material generated through the continuous flow process.

Several researchers have employed Raman spectroscopy to investigate the structure and properties of biochar derived from the pyrolysis of biomass. Tsaneva et al. [186] utilized Raman spectroscopy to study the graphitizing and

non-graphitizing structural changes in two distinct types of biochar. Their research unveiled alterations in Raman spectral characteristics that correlated with changes in the biochar structures. In another work, Yu et al. [187] employed Raman spectroscopy to investigate the structural changes in biochar as beechwood underwent pyrolysis. They observed that the intensity ratio of the D band to the G band consistently shifted with the pyrolysis temperature, indicating an increase in the number and/or size of aromatic rings and carbon crystallites in the biochar as the pyrolysis temperature increased. In separate study, Smith et al. [188] employed Raman spectroscopy to conduct structural analysis of chars formed during biomass pyrolysis. Their investigation revealed that as the pyrolysis temperature increased, there was a formation of polyaromatic hydrocarbons, a reduction in oxygen content, and the development of non-hexagonal ring systems during the deconvolution of cellulose. In a recent study, Guizani et al. [189] introduced a novel structure characterization method that combines Raman spectroscopy with ultimate analysis. They observed a strong linear relationship between the intensity ratio of Raman bands and the atom ratio of O, H to C. However, it is worth noting that these findings were derived from a limited range of biochar samples, which were exclusively prepared from a single type of biomass at pyrolysis temperatures exceeding 600 °C.

2.15 Scanning electron microscopy

Scanning electron microscopy (SEM) is a useful tool for exploring the surface structures and morphological characteristics of synthesized biochar (BC). SEM analysis of BC has shown that variations in temperature and different processing methods result in significant differences in the shape and size of the initial biomass particles. Furthermore, in biochar experiments, elevating the system's temperature can significantly enhance the pore properties of the biochar.

SEM was employed to characterize the surface structures of the biochar [174, 190]. SEM images offer a detailed insight into the distribution of mesopores and micropores, as well as the characteristics of pores found within the biochar particles. SEM images revealed a honeycomb-like which resulted from the development of a carbonaceous framework that mimicked the capillary structure found in sugarcane biomass [176] (Fig. 13).

SEM can be employed to anticipate the surface morphology both before and after the adsorption process [191]. Additionally, SEM, in conjunction with EDX (energy-dispersive X-ray) analysis, can be utilized to investigate the composition and properties of biochar [192]. SEM–EDX analysis is valuable for identifying the different components present on the surface of biochar. This technique has been frequently utilized in research on biochar applications to assess the biochar's surface characteristics after adsorbing pollutants. It is important to note, however, that SEM–EDX is not suitable for the analysis of organic pollutants [193].

2.16 Nuclear magnetic resonance microscopy

Nuclear magnetic resonance microscopy (NMR) spectroscopy, a well-established technique, serves as a valuable tool for examining the structural composition of biochar (BC) molecules. In this method, a robust radiofrequency (RF) pulse is employed to measure the resonance frequencies of specific nuclei within the molecule. NMR is also capable of revealing the composition of BC particles. In the context of solid-state NMR, this approach helps identify the carbon functional groups present in BC. Furthermore, it provides insights into the molecular structure of char and the overall extent of aromatic ring formation. Additionally, NMR spectroscopy has been employed to analyze the composition of both aromatic and aliphatic hydrocarbons in BC. Recent studies have also employed NMR to compare the degree of carbonization of BC and its stability [194]. NMR can be effectively utilized to assess and compare the stability and degree of carbonization in different biochar samples [195]. The main drawback associated with using NMR spectroscopy is the possible interference of NMR signals by the presence of ferromagnetic minerals in biochar. Additionally, biochar produced through high-temperature pyrolysis tends to exhibit a low signal-to-noise ratio in NMR measurements
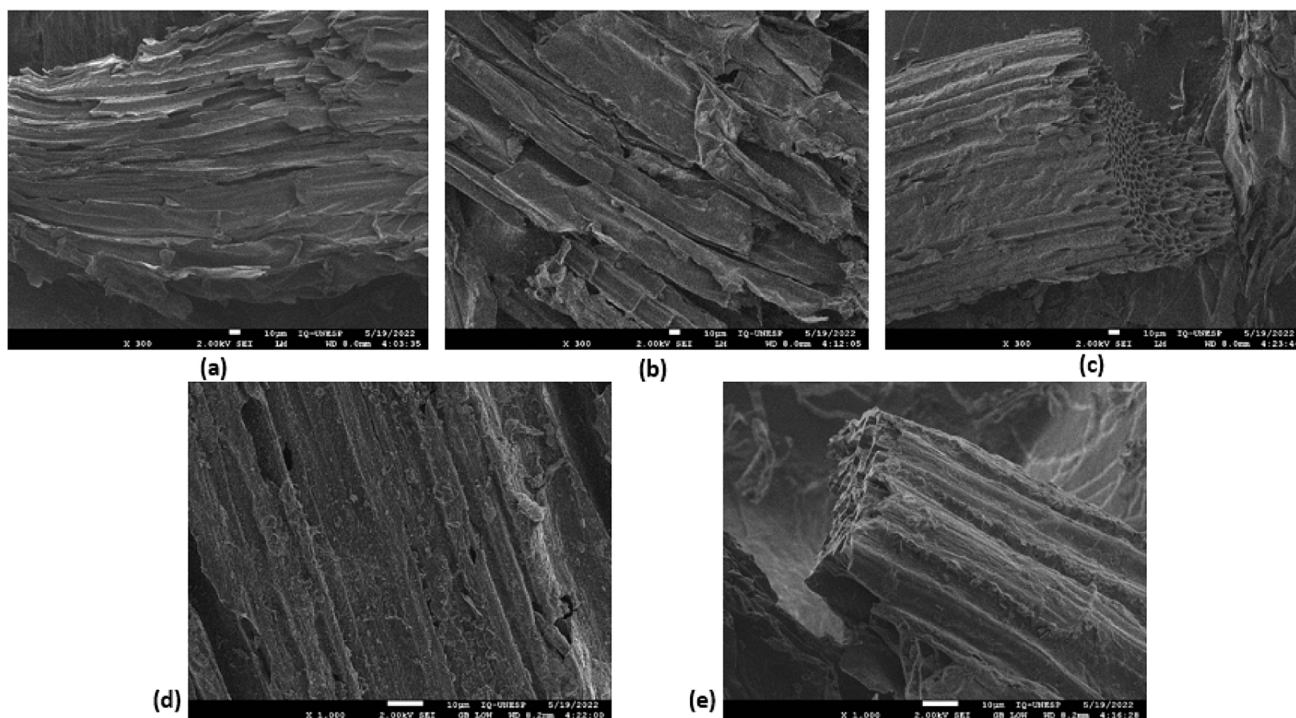
Fig. 13 Scanning electron microscopy (SEM) images at a magnification of 300× and 1000× for bagasse biochar after pyrolysis at different pyrolytic temperatures: **a** 300×B450, **b** 300×B550, **c** 300×B650, **d** 1000×B550, and **e** 1000×B650 [176]

[196]. Solid-state techniques are valuable for quantifying the total number of carbon functional groups in biochars, estimating the extent of aromatic ring formation, and revealing the overall structure of char molecules [191].

2.17 X-ray diffraction

X-ray diffraction (XRD) is a highly versatile technique extensively employed to assess the crystallinity and structure of biochar [197]. Franklin conducted one of the earliest systematic structural analyses of carbon materials, employing X-ray diffraction (XRD) to scrutinize diverse carbon crystallites and categorize them into two main groups. One group is graphitizing carbon, identified by narrow and sharp (002) reflection patterns in XRD after thermal treatment. The other group is non-graphitizing carbon, characterized by broad (002) reflection patterns in XRD after thermal treatment [198]. The XRD diffractogram has revealed distinct characteristics of the amorphous material formed at temperatures exceeding 350 °C, and its reliability has been established in the study by Zoroufchi et al. [199]. A computerized XRD system consists of essential components, including a monochromator, a radiation source, and a stepping motor for precise measurements. The nanocrystals formed exhibit a crystalline structure, which is evident from the sharp and well-defined XRD peaks. Notably, the particle size tends to increase with the passage of time [200, 201]. Therefore, XRD patterns enable the efficient and non-destructive production of high-quality biochar, known for its substantial sorption capacity.

2.18 Brunauer–Emmett–Teller analysis

The transformation of biomass into biochar results in the creation of more pores, which in turn leads to a significantly larger surface area compared to the initial raw biomass. The BET (Brunauer–Emmett–Teller) method, a widely studied technique, is employed to quantify the specific surface area of these particles. A multitude of reports have detailed the utilization of biochar for investigating surface area [130]. The specific surface area is a critical attribute for any adsorbent when it comes to efficiently removing pollutants from soil and aquatic environments. Biochar, due to the release of volatile materials during its formation, acquires high porosity with diverse pore structures and lower density. When comparing raw samples to their biochar counterparts, a substantial increase in the BET surface area is observed after pyrolysis. Natural biomasses typically lack physical micropores, but during pyrolysis, biochar is generated with new micropores. Porosity characteristics for both biomass types, encompassing the BET surface area and micropore region, showed enhancements as the power level increased from 2100 to 2400 W. This was evidenced by a rapid release

of volatile components and an increased formation of micropores at higher heating rates [202, 203].

2.19 X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy (XPS) is a commonly employed technique for determining the elemental composition of biomaterials like biochar. The traditional approach focuses on elements within a bulk sample, while spectroscopic techniques like XPS specifically analyze elements present on the surface of a sample [204]. XPS is capable of discerning and quantifying functional groups as well as constituents present in biochar. Changes in oxygen-containing functional groups serve as an indicator of the biochar's short-term stability. Additionally, XPS can ascertain the elemental O/C ratio, serving as a representative measure for biochar stability [205]. XPS, in addition, cannot distinguish between alcohols and phenols and necessitates the use of costly instrumentation. XPS and FT-IR spectroscopy enable a preliminary characterization of surface functional groups, yet they lack the ability to differentiate between aliphatic and aromatic OH groups [206]. Moreover, the outcomes from XPS can aid in illustrating and comprehending that the complexation between oxygenated groups and the metal constitutes a significant adsorption mechanism. XPS plays a pivotal role in the findings of metal remediation by biochar, revealing the formation of MnO and cation exchange as additional mechanisms for manganese removal [207].

2.20 Thermogravimetric analysis

Thermal analysis, which includes techniques like TGA (thermogravimetric analysis), is employed to assess the physiochemical properties of materials as they undergo changes with increasing temperature [176]. TGA is a valuable technique for examining the thermal behavior of biomass across different temperature ranges. It is known for its reliability, simplicity, and speed, making it an excellent analytical method for studying the kinetics of the pyrolysis process. TGA provides information about how the mass of a biomass sample changes with both temperature and time [208, 209]. TGA has frequently been employed to characterize and analyze the thermal behavior of various samples. In this particular experiment, conducted by Labiadh and Kamali [210], the aim was to assess the ignitibility of biochar and mixtures of biomass and biochar using thermogravimetric analysis. When examining the pyrolysis and gasification properties of sugarcane bagasse using the TGA-MS (thermogravimetric analysis-mass spectrometry) method and kinetic analysis, the findings revealed significant variations in gas release and char yield during pyrolysis depending on the heating rates [211]. In another investigation, biochar derived from different biomass sources, such as bamboo, was subjected to

thermogravimetric analysis. The analysis was conducted in an inert environment at heating rates of 10, 20, and 30 °C/min. Additionally, vacuum pyrolysis was utilized in the production of bamboo biochar, as reported in the study [212].

3 Knowledge gaps and anticipated futures

This literature review delves into the utilization of biochar produced from sugarcane bagasse and its potential applications in tackling environmental issues like soil and water contamination. While this article presents an overview of the current state of knowledge, it identifies several gaps in knowledge and outlines future research directions:

Sugarcane bagasse biochar significantly enhances soil quality and pollutant remediation through sorption, demonstrating higher potential in lab settings compared to field conditions influenced by variables like rainfall and temperature. Further research is imperative for a comprehensive understanding of SCB biochar behavior in natural environments. The absence of concrete evidence for optimal biochar application necessitates targeted efforts in specifying biochar characterisitcs, preparation conditions, timing, and application rates. Elevating its redox potential requires advanced production techniques and post-treatments to introduce more functional groups onto the SCB biochar surface. The evaluation of redox-mediated potential and long-term stability against industrial wastewaters is critical for advancing commercial-scale remediation. Additionally, biochar presents a potential solution for addressing water and nutrient deficiencies, offering growers economic benefits as a "carbon credit" for carbon sequestration and potentially nitrogen credits in the future [213].

Before implementing SCB-based biofuels commercially, a thorough economic and environmental assessment is crucial. Evaluations should encompass pretreatment costs, water consumption, and product yield to determine SCB's viability for biofuel production. The potential advantages of heterogeneous catalysts in biodiesel production depends on their washability and reactivation capabilities, countering the inactivation issues seen in homogeneous catalysts and enhancing the competitiveness of biodiesel. Despite promising outcomes in terms of activity and reusability, leaching remains a concern, particularly with CaO catalysts in a biochar matrix, as the permissible Ca^{2+} limit in biodiesel is low. Limited attention has been given to assessing Ca^{2+} content in biodiesel, necessitating further investigation into this aspect [45]. Various activation methods, such as physical, chemical, and biological approaches, are employed to enhance sugarcane bagasse biochar for applications like alternative fuel production, pollutant remediation, CO_2 adsorption, and construction. Key methods include steam activation, CO_2 activation, alkali and acid-based activation, as well as metal composite activation. Despite their importance, optimizing the parameters and conditions of these activation strategies is essential for efficient catalyst modification. Additionally, exploring cost-effective activation methods is crucial for synthesizing economically viable catalysts and enhancing their applications [214].

Efforts are underway to enhance microbial immobilization by optimizing the surface characteristics of biochar through improved feedstock selection and pyrolyzing conditions. Additionally, the potential recovery and reuse of "spent" microorganism-immobilized biochar is being investigated using magnetic biochar. Critical evaluation of microorganism selection is underway to determine its impact on the success of biochar-based inoculants for agricultural and environmental applications. Large-scale field experiments are set to demonstrate the agronomic and environmental remediation benefits of biochar-based microbial immobilization technology. The exploration of opportunities for immobilizing microbial extracellular enzymes onto biochar is underway to directly enhance soil health and environmental remediation [215].

Further work is necessary to quantify the yield of SCB biochar while also exploring innovative technologies for increased biochar yield. Encouraging studies on the impact of temperature and other parameters, such as oxygen levels on SCB biochar properties and application, is essential. Additionally, the production of electro-modified SCB biochar, involving chemical impregnation, proves more effective for adsorption and soil amendment. Magnetic SCB biochar for environmental remediation should be promoted as they provide more efficiency. Untapped applications, like SCB biochar filters replacing carbon filters in water treatment and activated carbon in raw sugar purification, warrant investigation, potentially offering efficient, cost-effective carbon materials for various industries. Notably, no published paper has explored the techno-economic analysis of SCB biochar, a crucial aspect that could be valuable when compared with bagasse costs for electricity generation [216].

The creation of novel material via eco-friendly synthesis using sugarcane bagasse biochar as support for catalyst is of considerable interest, given its utilization of recycled waste, reduced use of chemical reagents, and the generation of an environmentally sustainable catalyst for the degradation of dyes and other pollutants in wastewater treatments [217–220]. To promote the broader adoption and application of sugarcane bagasse biochar, it is imperative to bridge knowledge gaps and emphasize future perspectives, particularly concerning standard characterization procedures. This can be achieved through knowledge transfer and dissemination, advancements in technology, and comprehensive assessments of its environmental and economic aspects. By addressing these knowledge gaps and embracing future perspectives, researchers and stakeholders can enhance the

accessibility and economic feasibility of sugarcane bagasse biochar as an alternative resource. This, in turn, will facilitate the wider implementation of biochar technology, leading to positive environmental outcomes and sustainable development.

4 Conclusion

Sugarcane bagasse biochar presents a wide array of applications, serving as an adsorbent, ion exchange resin, briquettes, ceramics, concrete, catalyst, and even aiding in CO_2 capture as well as biofuel production. This versatility positions of SCB biochar makes a promising resource to address global energy needs while promoting environmental and economic sustainability. This study delves into various pyrolysis techniques for SCB biochar production, exploring its utility in soil amendment, water and air purification, and catalysis. Physical and surface characteristics, including surface area and functional groups, significantly influence its suitability for diverse applications, leading to the use of activation techniques for enhancement. Biochar's efficacy in pollutant removal from aqueous solutions surpasses alternative methods, making it a scalable wastewater treatment solution. While success stories abound, widespread adoption awaits improved life cycle analysis and cost evaluations, strengthening sugarcane bagasse biochar's case as a sustainable material for new product development.

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Data availability The data from literature has been used and discussed within the manuscript.

Declarations

Ethics approval No ethical approvals required as the study involve no human subjects or animal studies.

Competing interests The authors declare no competing interests.

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