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Agricultural Lignocellulose Biochar Material in Wastewater Treatment: A Critical Review and Sustainability Assessment

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Abstract

Globally, roughly 380 trillion liters of wastewater are generated annually, with a significant portion remaining untreated due to expensive treatment and lack of expertise, consequently, leading severe environmental and public health problems. This research aims to identify the most environmentally sustainable and eco-friendly approach to wastewater treatment. Results shows that, agricultural lignocellulose-based biomass (ALCB) biochar is highly effective for wastewater treatment due to its abundance, cost-effectiveness, and excellent adsorption properties. The ability of sustaining high carbon content makes it a valuable carbon sink beneficial for the carbon reduction. Annually, ALCB is widely available as a byproduct in developing countries like China 716 (million tons) Mt, India 605 Mt, Brazil 451 Mt, Pakistan 285 Mt as well as in developed regions U.S.A 682 Mt, and Europe 580 Mt. Pyrolysis, gasification, and torrefaction are mostly used methods for ALCB biochar production. Physicochemical properties including surface area, porosity, functional groups, pH, and elemental composition notably affected by production methods, feedstock types and reactor designs determine the adsorption performance and environmental safety of ALCB biochar. The adsorption mechanisms of the organic and inorganic pollutant on biochar are ion exchange, complexation, electrostatic attraction, pore-filings, and physical adsorption, etc. LCA assessment revealed that the utilization of ALCB biochar on wastewater treatment offers several economic, environmental, and educational benefits through the aspect of waste management, revenue generation, job creations, pollution control, trading and skill developments.

Keywords: Agricultural lignocellulose-based biochar, Pyrolysis; Pollutant adsorption; Sustainable water treatment; Environmental and economic benefits

1. Introduction

Since start of the 21st century many countries, including India, China, the United States, Canada, Bangladesh, Nigeria, and Pakistan are confronting significant wastewater challenges due to rapid industrialization and high population densities [1]. These regions contribute to the huge contamination of water sources with a wide range of organic pollutants (petroleum hydrocarbons, pesticides, polychlorinated biphenyls, plastics and microplastics, volatile organic compounds, natural organic matter), and inorganic pollutants (heavy metals (HMs), salts, acids and bases, oxides, and particulate matter) [2]. The high cost of wastewater treatment has led to the illegal discharge of untreated wastewater into rivers and canals, primarily from industries such as

55   pesticides, pharmaceuticals, textiles, leather, mining, and petroleum. Overall, around the world

56   the 75-80% (14 billion litres) of untreated wastewater discharge into the fresh water bodies that

57   significantly impacts environmental and human health risks [3].

58   Currently, inorganic pollutants like HMs (cadmium (Cd), chromium (Cr), mercury (Hg), phenol,

59   tetracycline, and dyes) are among the most persistent pollutants in aquatic ecosystems, as they

60   cannot be biologically degraded even under moderate temperatures [4]. Their presence in drinking

61   water poses significant health risks, including skin cancer, kidney diseases, neurological

62   dysfunction, and mental impairments [5]. So, removing of HMs from water can significantly

63   reduce environmental and health impacts. Many developing countries has limited treatment

64   options, intensified by factors such as lack of awareness, political instability, and economic

65   constraints, have led to the widespread use of contaminated groundwater for drinking and

66   irrigation purposes [6]. Besides, these countries are facing challenges in wastewater management

67   including water pollution, and improper disposal of untreated industrial, mining, and municipal

68   wastewater.

69   Moreover, several factors hinder the widespread adoption of modern wastewater treatment

70   technologies in low-income countries such as financial limitations, incomplete technical

71   expertise, inadequate infrastructure, energy demands, and insufficient educational institutional

72   capacity [7]. Despite these challenges, efforts are being made to adapt existing technologies and

73   develop innovative, cost-effective, and sustainable solutions tailored to resource-controlled

74   environments [8]. However, various organizations are actively addressing the unique challenges

75   and working to improve wastewater treatment techniques and management in these developing

76   countries.

77   Interestingly, in developing countries, agricultural lignocellulose-based biomass waste (ALCB)

78   serves as a readily available byproduct that can be utilized for biochar production. This approach

79   emerges as a cost-effective solution for wastewater treatment, offering an adsorption capacity of

80   over 80% for the removal of HMs from polluted water [9]. The ALCB-based biochar is highly

81   effective for wastewater treatment due to its abundance, cost-effectiveness, and excellent

82   adsorption properties. Its porous structure, high surface area, and functional groups enable it to

83   efficiently adsorb over 85-90% of HMs from wastewater. Besides, its production from agricultural

84   waste supports sustainable practices by reducing biomass disposal issues while addressing critical

85   environmental and health concerns [10].

86   Biochar is a multipurpose material used for wastewater treatment, because of its unique
87   adsorption and filtration properties across/present in various technologies, such as adsorption and
88   absorption, filtration systems, advanced oxidation processes (AOPs), and biological treatment
89   technologies [11]. Among these technologies, the adsorption technology by using ALCB base
90   biochar plays a significant role due to its unique physical and chemical properties, cost-
91   effectiveness, eco-friendliness, and easy availability. Agricultural residues such as corn cobs,
92   waste wood, sugarcane bagasse, rice husks, wheat straw, fruit peels, and cottonwood are
93   commonly used for biochar production [12]. However, biochar production depends on factors
94   such as the type and availability of biomass. Every year, a substantial amount of agricultural waste
95   is generated worldwide as a result of agricultural activities, particularly in developing countries.
96   According to the world health organization and the Grand University Center for Energy Policy
97   and Technology, the total land area dedicated to agricultural operations is currently around 13
98   Gha, with approximately 1.5-1.7 Gha allocated to these operations.

99   Agricultural biomass is typically composed of main three polymers like cellulose (30–60%),
100   hemicellulose (25–45%), and aromatic lignin (15–30%) which play a significant role in pollutant
101   treatment (Raji et al., 2023). Additionally, it contains minor quantities of proteins, pectin, ash, and
102   other extractives such as inorganics, waxes, fats, resin acids, and phenolics [13]. The composition
103   of these components is critical for biochar production, as lignin-rich crop residues are particularly
104   advantageous. Higher lignin content facilitates the manufacture of ALCB biochar with increased
105   fixed carbon content, enhancing both the yield and the adsorptive capacity of the biochar for
106   pollutant remediation [14]. Besides, the proportions of cellulose, hemicellulose, and lignin in
107   agricultural biomass polymers can vary significantly due to factors such as the type of biomass
108   (e.g., softwood, hardwood, grasses, or farm waste), soil type, environmental conditions [15],
109   fertilizer use, growing conditions, harvesting techniques, and other physical influences.
110   Understanding these variations is essential for optimizing biochar production and tailoring its
111   properties to effectively address specific environmental challenges, such as the adsorption and
112   degradation of organic and inorganic pollutants [16].

113   A range of traditional and modern techniques has been employed to produce biochar from
114   agricultural lignocellulosic base biomass. These methods include pyrolysis, gasification,
115   hydrothermal carbonization, and torrefaction [17]. Among these, pyrolysis emerges as a
116   particularly promising and widely applicable technique due to its versatility in processing diverse

117 biomass feedstocks and its relatively high biochar production efficiency, achieving yields of
118 approximately 25–35% as compare to other methods. Moreover, pyrolysis has stored significant
119 research attention as it involves the thermal decomposition of biomass at high temperatures in an
120 oxygen-free environment [18]. This process generates three primary products: bio-oil, syngas,
121 and biochar. Biochar produced through pyrolysis is notable for its high energy content, ranging
122 between 40–45 MJ/kg, making it a valuable material for production. It has the potential to serve
123 as a sustainable alternative to coal, further highlighting its significance in energy and
124 environmental applications [19].

125 Objective of this research is to explore the potential of agricultural lignocellulose-based biochar
126 as a sustainable and cost-effective solution for HM treatment from wastewater which offers
127 significant environmental and economic benefits. Specifically, this study aims to investigate the
128 types and quantitative availability of waste agricultural biomass in developed and developing
129 countries. Besides, researchers aim to explore biochar production methods and their mechanisms
130 to understand and optimize the processes that influence the yield, quality, and functional
131 properties of biochar. This exploration is crucial for several reasons like enhancing biochar yield
132 and pollutant adsorption properties. Analysis of biochar production mechanisms is very important
133 in that it primary talks about chemical, thermal, and physical transformations that occur during
134 the production process. A key component of this study includes analyzing the different adsorption
135 mechanisms of inorganic and organic pollutants specifically HMs by biochar to understand how
136 biochar interacts with these contaminants, understand the pollutant removal pathway, Improving
137 Functional Modifications, Bridging Knowledge Gaps in Biochar Applications, as well as optimize
138 its performance through enhancing adsorption efficiency for environmental and commercial
139 applications. Lastly, Techno-Economic Analysis (TEA) to assess the feasibility and scalability of
140 biochar production from agricultural residues as well as the life cycle assessment showing that the
141 synthesis of biochar from waste is a promising research direction through economic evaluation.
142 This comprehensive approach addresses existing gaps in the literature, as many studies focus
143 predominantly on biomass production without sufficient emphasis on its conversion to biochar or
144 its practical applications in environmental remediation. By bridging this gap, the research
145 contributes to advancing sustainable wastewater treatment methods, thereby supporting global
146 efforts toward resource recovery, pollution control, and economic sustainability.

2. Research methodology

2.1 Feedstock availability

In this research for annual production of ALCB base waste residues is considered for analysis. The data collection includes all information about composted agricultural waste residues (kg dry matter) from (https://data.worldbank.org) and (https://ourworldindata.org/transport). We use data from, those who measured the physical quantity of agricultural waste residues (kg wet or dry matter).

2.2 Biochar production technologies

The method of calculation of the contribution of lignin, celluloses, and hemicellulose in the final formed of biochar is predicted by using Cagnon equations 1, 2 and 3: Such as:

$$Y = 100 - (1 - x) \times 100 \qquad (1)$$

$$x = H \times y_{c,H} + C \times y_{c,C} + L \times y_{c,L} \qquad (2)$$

"Y" denoted the percentage yield of Biochar, while L, C, and H illustrate the ratio of lignin, cellulose, and hemicellulose in the forerunner and $y_{c,L}, y_{c,C}$ and $y_{c,H}$ are heat treatment yield of individually separate components [20]. By taking into account the primary mass of raw product, the influence of individual sections could be determined using the subsequent equation, with lignin serving as an illustrative example:

$$L_c = (1 - (x - \frac{L \times y_{c,L}}{x}) \times 100 \qquad (3)$$

Where L_c is manufacture of ALCB biochar from lignin in the example afterward pyrolysis (stated in wt%), x is the calculated biochar mass after heat treatment, $y_{c,L}$ is the yield of biochar from the pyrolysis of clean lignin (stated in %) [21]. The remaining celluloses and hemicellulose can be calculated by the same methodology.

Further, the overall biochar yield can be calculated by equation 4.

$$\text{Biochar yield (\%)} = \frac{W_f}{W_i} \times 100 \qquad (4)$$

Where W_f = mass (g) after pyrolysis; W_i = mass (g) before pyrolysis.

Moreover, from Table 3, it could be seen that ALCB biomass with high content of C and O_2 will produce higher biochar during pyrolysis as well as enhance the properties of higher heating value (HHMS). However, agricultural woody and non-woody biomass have higher proficiency and production capacity than aquatic biomass due to higher hydrogen and oxygen content.

176 **2.3 Biochar applications for wastewater treatment**

177 Metal-ion reserved on biochar, q_t (mg/g), and selected from adsorption dimensions calculate by

178 equation (5), and metal removal efficiency in % can be calculated by equation (6) [22].

179 $$q_t = \frac{C_O - C_t}{W} \times V \qquad (5)$$

180 $$\text{Removal efficiency} = \frac{C_O - C_t}{C_o} \times 100 \qquad (6)$$

181 ## 2.4 Techno-economic analysis

182 Techno-economic analysis (TEA) involves a systematic and comprehensive evaluation of various

183 technical and economic factors to assess the feasibility and viability of a technology or process

184 [23]. It can provide you with a general framework of the key steps involved in conducting a

185 techno-economic analysis: Identify inputs and outputs and identify the key inputs required for the

186 technology or process, such as raw materials, energy [24], labor, equipment, revenue assessment,

187 risk assessment and infrastructure. similarly, identify the outputs or products generated, such as

188 biochar or treated wastewater.

189

190 ## 3. Results and discussion

191 ### 3.1 Annually worldwide ALCB production

192 The efficient and cost-effective production of biochar heavily relies on the availability and

193 composition of feedstock. While there is a vast range of feedstocks available, it is crucial to

194 accurately classify and characterize them to ensure their suitable utilization in biochar production

195 [25]. Therefore, this section focuses on highlighting the resources, compositions, and global

196 availability of feedstocks. Some countries known for their abundant ALCB and potential for

197 biochar production which can be seen in Fig. 1(a) include China, India, the U.S.A, Pakistan,

198 Brazil, Indonesia Russia, Australia, and Canada.

199 China holds the title of the world's largest annual producer of agricultural biomass, generating a

200 staggering 716 MT [26]. The country has abundant crop residues and agricultural waste that can

201 be utilized for biochar production. Secondly, India has a large agricultural sector, resulting in

202 substantial amounts of crop residues. These residues can be converted into biochar for wastewater

203 treatment purposes. Additionally, India encompasses a total land area of 0.297 giga hectares

204   (Gha), with agricultural operations accounting for 10.57% (0.0314 Gha) of this land. In India, the

205   annual agricultural waste generation amounts to approximately 600 metric tons (MT) [27].

206   Besides, the United States has diverse biomass resources, including agricultural residues, forest

207   residues, and dedicated energy crops. Regions such as the Midwest, Southeast, and Pacific

208   Northwest have significant biomass availability [28]. Brazil is home to the Amazon rainforest,

209   which provides a vast amount of biomass resources and annually produces about 451 MT. The

210   country has a significant potential for biochar production from various organic materials.

211   Indonesia has ample biomass resources suitable for biochar production with its extensive forests

212   and agricultural sector. The country's large palm oil industry also generates significant amounts

213   of biomass [29].

214   Russia owns large fertile agricultural and forest areas and an abundant supply of biomass from

215   these sectors. These resources can be utilized for biochar production and wastewater treatment

216   [30]. In addition, Canada has vast areas of forests and agrarian land, providing abundant biomass

217   resources. For the creation of biochar, biomass materials such as tree trimmings, crop by-products,

218   and agricultural waste can be employed. The annual agricultural biomass residue generated about

219   105 MT. Resulting, the country's agricultural sector also contributes to biomass availability.
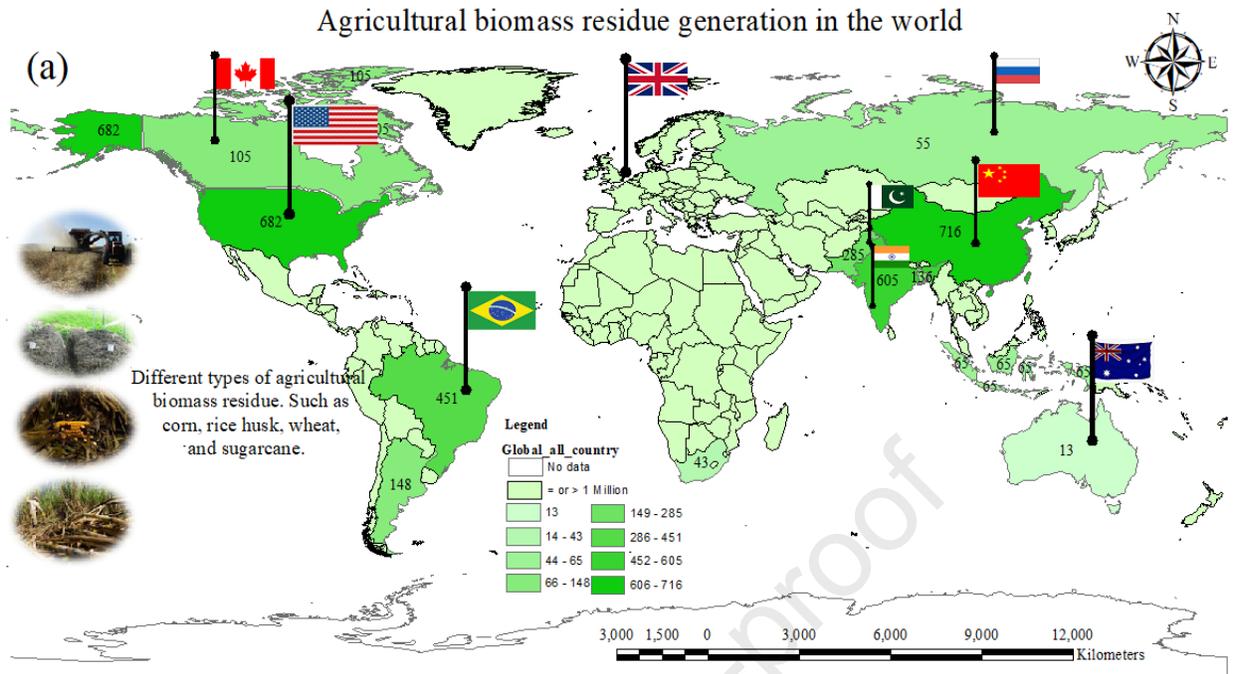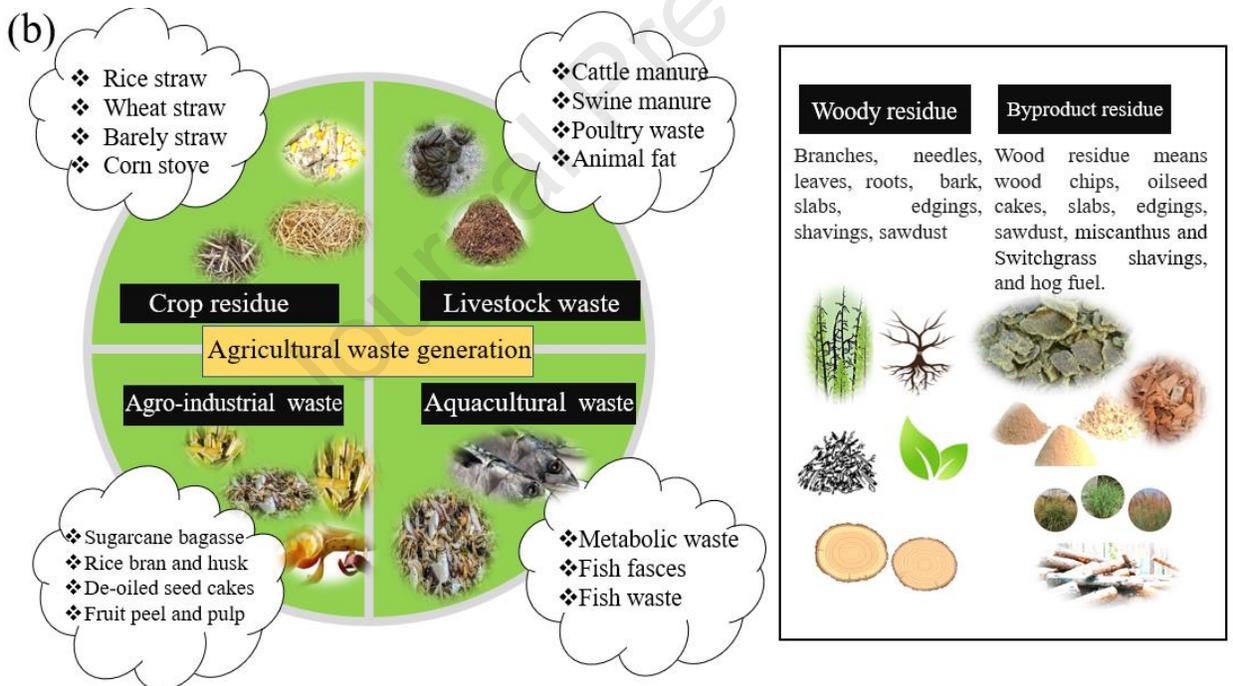
Fig. 1. (a) Shows the world annual production of agricultural biomass residues. (b) Shows the distribution of agricultural woody, nonwoody and by-product waste which can be used for production of biochar.

Agricultural biomass from various crop residues left after harvesting agricultural crops is a significant source of biochar production. In Fig. 1(b) can be seen these residues can include straws, stalks, husks, and leaves from crops such as rice, wheat, maize, sugarcane, soybean, and

228   cotton. Crop residues are often readily available and can be effectively used to produce biochar.

229   Despite the fact that bagasse is fibrous waste residue that is available afterward sugarcane stalks

230   are crushed in order to extract the juice [31]. It is a widely available biomass waste and can be

231   utilized by way of a feedstock for biochar manufacture. Bagasse biochar has been studied for its

232   potential in agriculture and soil improvement. Moreover, pruned branches and twigs from

233   orchards, vineyards, and fruit tree plantations can be utilized as biomass for biochar production

234   [32].

235   These pruning's are typically collected during regular maintenance activities and can provide a

236   sustainable source of biomass for biochar. In woody and by-product agricultural residues the

237   Nutshells, oilseed cake, also known as oilseed meal or oil cake, is a byproduct obtained after

238   extracting oil from oilseeds like soybeans, sunflower seeds [33], rapeseeds, or cottonseeds. It is

239   rich in organic matter and can be used as a feedstock for biochar manufacture. It is noteworthy

240   selection of agricultural biomass for biochar production depends on factors such as regional

241   availability, cost, desired biochar characteristics, and specific application requirements [34].

242   Additionally, the use of agricultural biomass for biochar production can contribute to waste

243   valorization, carbon sequestration, and sustainable agricultural practices.

244   **3.2 Biochar production and formation mechanism**

245   **3.2.1 Pre-treatment technologies**

246   Pre-treatment is the first step for biochar production from different raw materials. In general, these

247   methods can be classified physical, chemical, and biological pre-treatment technologies the

248   detailed informations can be seen in Table 1 and Fig. 2(a). The pretreatment of ACLB for the

249   production of biochar involves several physical, chemical, and biological processes [35]. These

250   pretreatment methods are employed to enhance the efficiency of the biochar production process

251   and improve the quality of the final product. Physical pretreatment methods involve mechanical

252   or thermal processes to alter the structure and size of the biomass. Biomass is mechanically

253   chopped, shredded, or ground by using hammer mill to reduce the particle size, which increases

254   the surface area and facilitates subsequent processes, and usually dried at 90-105 °C to reduce its

255   moisture content, improving the efficiency of the subsequent pyrolysis process [36]. Chemical

256   pretreatment involves the use of chemicals to modify the structure and composition of the

257   biomass. Commonly biomass is treated with dilute acids such as sulfuric acid or hydrochloric

258   acid. Moreover, biomass is subjected to oxidation using agents like hydrogen peroxide or ozone

259 to break down complex organic compounds, increase the release of volatile components, and

260 enhance the biochar's stability.

261 Biological pretreatment involves the use of microorganisms, such as bacteria or fungi, to degrade

262 and modify the biomass. Microorganisms are used to break down complex organic compounds in

263 the biomass, such as lignin and cellulose, making them more accessible for subsequent processing

264 steps [37]. Moreover, certain biomass types, such as lignocellulosic materials, can undergo

265 fermentation processes where microorganisms convert sugars into products like ethanol or

266 organic acids. These pretreatment methods can be applied individually or in combination,

267 depending on the specific biomass feedstock and desired characteristics of the biochar. The

268 selection of pretreatment approaches depends on factors such as biomass type, desired biochar

269 properties, process economics, and environmental considerations [38]. Notable, the content of

270 biomass components such as cellulose, hemicellulose, and lignin can significantly affect or

271 interfere with the pretreatment process, and their interaction with pretreatment methods must be

272 carefully considered to optimize biochar production.

273 **Table 1** Describe physical, chemical, and biological pretreatment methods for biochar production from ALCB

274 waste.

Method	Description	Purpose/Benefits	Examples	Limitations
Physical	Mechanical processes: grinding, shredding, sieving.	Reduces particle size, improves heat transfer.	Milling rice husks, chopping wheat straw.	Energy-intensive, may produce dust.
Chemical	Use of acids, alkalis, or oxidizing agents to modify biomass.	Enhances surface area, porosity, and reactivity.	Acid washing sugarcane bagasse, NaOH-treated corn stover.	Residual chemicals, costly, environmental concerns.
Biological	Microbial or enzymatic degradation of lignin and hemicellulose.	Makes biomass more accessible for pyrolysis.	Fungal treatment of wheat straw using white-rot fungi.	Time-intensive, requires controlled conditions.

275

276 3.2.2 Biochar production by thermal carbonization technologies

277 To achieve the maximum biochar yield, the choice of production methodologies should be

278 appropriate and optimized for the specific biomass type and process conditions such as heating

279 rate, temperature, residence time, etc [39]. These conditions play a crucial role as they can impact

280 the physical and chemical properties of the biochar during the production process. Such as the

281 morphology of biochar derived from plant biomass can vary depending on the process conditions

282   since it involves the loss of weight from the biomass. Initially, there is a weight loss due to water

283   evaporation around 100 °C, followed by the degradation of cellulose, hemicellulose, and lignin

284   occurring above 220 °C. Mainly there are two types (i), traditional approaches and (ii) modern

285   approaches for production of biochar. Traditional approaches such as Slow pyrolysis, Fast

286   pyrolysis, and Gasification to biochar production refer to age-old methods that have been used by

287   various cultures throughout history [40]. These approaches often rely on simple and low-cost

288   techniques, using locally available materials and traditional knowledge can be seen in Table 1 and

289   Table 2. Moreover, these traditional approaches have been adapted to suit local conditions and

290   available resources. While they may lack the efficiency and control of modern approaches, they

291   highlight the long history of biochar production and the sustainable utilization of biomass for

292   various purposes.

293   3.2.2.1 Biochar production by pyrolysis

294   Biochar from ALCB source materials begins with pre-treatment. Fig. 2(a) shows these approaches

295   as physical, chemical, and biological. These pre-treatment approaches are employed to recover

296   the productivity of the ALCB biochar manufacture process and improve the quality of the final

297   product. Physical pre-treatment methods involve mechanical or thermal procedures to alter the

298   structure and size of the biomass [41]. Biomass is mechanically chopped, shredded, or ground by

299   using hammer mill to reduce the particle size which rises the surface zone besides facilitates

300   subsequent processes, and usually dried at 90-105 °C to reduce its moisture content, improving

301   the efficiency of the subsequent pyrolysis process. Chemical pre-treatment involves the usage of

302   chemicals to modify the structure and configuration of ALCB biomass. Commonly biomass is

303   treated with dilute acids for example sulfuric acid or hydrochloric acid. Chemical pretreatment of

304   biomass for production of biochar does not merely improve its stability, it can also enhance

305   several other properties such as, enhanced adsorption capacity, improved catalytic properties,

306   hydrophilicity or hydrophobicity, thermal and chemical stability, as well as optimized porosity

307   and surface area. However, it depending on the type of pretreatment method and its intended

308   application. Such as, certain chemical treatments (e.g., acid or alkali treatments) can modify the

309   biochar's pore structure, increasing its surface area and making it more effective for applications

310   like gas storage or water treatment. Moreover, biomass is subjected to oxidation using agents like

311   hydrogen peroxide or ozone to break down complex organic compounds, increase the release of

312   volatile components, and enhance the biochar's stability [42].

313   Biological pre-treatment includes the usage of microorganisms, for example bacteria or fungi, to
314   degrade and modify the biomass. Microorganisms are used to collapse multifaceted organic
315   compounds in biomass [43], such as lignin and cellulose, making them more accessible for
316   subsequent processing steps. Moreover, certain biomass types, such as lignocellulosic materials,
317   can undergo fermentation processes where microorganisms convert sugars into products like
318   ethanol or organic acids. These pre-treatment procedures can be useful separately or in grouping,
319   dependent on the specific biomass feedstock and desired characteristics of the biochar. The
320   selection of pre-treatment approaches depends on aspects for example biomass category, desired
321   biochar properties, process economics, and environmental considerations [44]. Currently, biochar
322   production by thermal carbonization technologies are promising methods to achieve the
323   maximum biochar yield, the choice of production methodologies and process circumstances for
324   example heating amount, temperature, residence period, etc., should be appropriate. Some
325   thermochemical conversion techniques can be seen in Table 2 and Table 3.

326   **Table 2** Comparative study of thermochemical conversion techniques.

Process	Resources	Status	Cost	Pre-treatment	Emission product	Reference
Pyrolysis	Solid biomass	Developing	High	Required	Biochar, syngas Bio-oil	[45]
Gasification	---	Commercial	---	---	---	[46]
HTC	---	---	Low	---	---	[47]
Torrefaction	---	---	Moderate	Not required	---	[48]

327

328   **Table 3** The distribution of products and reaction parameters for different pyrolysis modes

Process	Temperature (°C)	Contact time	Biochar (Solid)	Bio-oil (Liquid)	Syngas (Gas)
			Percentage Yields		
Slow pyrolysis	400–500	Several hours to days	33%	32%	40%
Intermediate pyrolysis	400–650	One min to one hour	25%	40%	355%
Fast pyrolysis	850–1250	More than 2 sec	15%	60%	25%
Gasification	~750–900	15–25 sec	10%	10%	80%
HTC	150–280	4–18 hours	50–80%	5–20%	2–5%
Torrefaction	~280	~15–55 min	70%	10%	20%

329

330   Pyrolysis is a thermochemical procedure that decomposes organic materials like biomass or trash
331   in the absence or with minimal oxygen. It is a type of thermal decomposition where high
332   temperatures typically ranging from 300-1000 °C are applied to the material, causing it to undergo

333   chemical and physical changes, including thermal cracking [49], vaporization, and condensation.

334   In the sequence of process, the constituents of lignocellulosic material, for example cellulose,

335   hemicellulose, and lignin, involvement numerous responses, with depolymerization,

336   fragmentation, and cross-linking, under specific temperature conditions resulting in the

337   breakdown of the organic material into three main products like biochar, bio-oil, and syngas. The

338   overall procedures, temperature, residence time and percentage production are addressed in Fig.

339   2(a) and Table 4.

340   *(1) Slow Pyrolysis*: This process characterized by a relatively small heating amount and long

341   residence time. ALCB biomass is heated gradually to temperatures typically extending since 400-

342   500 °C over an extended period, often several hours to days [50]. The slow heating rate allows

343   for a controlled thermal breakdown of biomass, subsequent in a higher produce of biochar (solid

344   product) compared to other pyrolysis variants. The biochar yield in slow pyrolysis can be as high

345   as 35-50% or more by weight, contingent on the feedstock and procedure circumstances. The

346   process also produces bio-oil and syngas, albeit in lesser quantities compared to faster pyrolysis

347   methods.

348   *(2) Intermediate Pyrolysis*: This occurs at lower heating and extensive residence times compared

349   to fast pyrolysis. Biomass is typically heated to temperatures between 400-650 °C and maintained

350   at these temperatures for a longer duration, usually several minutes to hours [51]. The slower

351   heating rate and lower temperatures result in a more controlled decomposition process, promoting

352   the formation of a higher proportion of biochar (solid product) relative to bio-oil. The biochar

353   yield in intermediate pyrolysis can range from 30-40% by weight, while bio-oil and syngas are

354   also produced but in lesser quantities compared to fast pyrolysis [52].

355   *(3) Fast Pyrolysis*: It is a pyrolysis process conducted at relatively high temperatures and rapid

356   heating rates. Typically, biomass is heated to temperatures between 850-1250 °C in a matter of

357   seconds to minutes. The fast-heating rate and high temperatures promote the rapid thermal

358   breakdown of ALCB, resulting in the production of a low ratio of biochar 12% compared to other

359   pyrolysis variants. The biochar yield can range from 10-12% by weight, contingent on the

360   biomass feedstock and procedure circumstances. The remaining products include bio-oil and

361   syngas [53].

362   *(4) Flash Pyrolysis*: Flash pyrolysis, also known as rapid or vacuum pyrolysis, is a pyrolysis

363   process that involves extremely fast heating rates and short residence times. Biomass is rapidly

364 heated to high temperatures, typically above >1200 °C within milliseconds to seconds [54]. The

365 rapid heating and short residence time prevent secondary reactions, such as significant biochar

366 formation, and promote the production of a higher proportion of bio-oil (liquid product). The bio-

367 oil yield in flash pyrolysis can range from 60-80% by weight, depending on the biomass feedstock

368 and process conditions. Flash pyrolysis also yields syngas and a smaller amount of biochar [55].

369 All pyrolysis has its unique characteristics, advantages, and applications. slow and intermediate

370 pyrolysis is frequently favored for ALCB biochar manufacture, which finds usage in soil

371 amendment, carbon sequestration, and filtration. While fast and flash pyrolysis is often favored

372 for manufacture of bio-oil, which can be further processed into biofuels or used as a feedstock for

373 chemical production [56].

3.2.2.2 Hydrothermal carbonization process

375 The HTC is a thermochemical process that involves the conversion of biomass into biochar under

376 high temperature and pressure conditions in the presence of water. It is an alternative method for

377 producing biochar that utilizes wet or low-quality biomass, such as agricultural residues, organic

378 waste, or algae [57]. During hydrothermal carbonization, biomass is typically mixed with water

379 to form a slurry or paste-like mixture. The mixture is then heated in a closed system, such as an

380 autoclave or reactor, at temperatures typically ranging from 180-250 °C under high pressure. The

381 high temperature and pressure conditions promote the breakdown of the biomass, leading to

382 chemical reactions including hydrolysis, dehydration, decarboxylation, and polymerization. As

383 biomass undergoes hydrothermal carbonization, various physical and chemical transformations

384 occur, resulting in the production of biochar [58]. The whole mechanism of biochar production

385 can be seen in Fig. 2(b).

386 Moreover, the time required for biochar preparation by the hydrothermal method depends on the

387 reaction conditions (temperature range, water content, biomass characteristics) and type

388 feedstock. Such as, corn stover or wheat straw at 240 °C might require 4 to 8 hours to achieve

389 complete carbonization [59]. For sawdust treated at 200 °C, a reaction time of 6 hours might do

390 to produce biochar with suitable stability and porosity [60]. Adjusting the time is crucial for

391 balancing process efficiency and the quality of the resulting biochar. The resulting biochar has a

392 unique structure with a high carbon content, porous nature, and increased stability compared to

393 the original biomass.

394   Hydrothermal carbonization offers several advantages for biochar production. It can handle a

395   wide range of feedstocks, including biomass with high moisture content or low energy density.

396   Additionally, HTC can retain more nutrients in biochar compared to other pyrolysis methods. The

397   process can also be coupled with wastewater treatment, as it effectively removes contaminants

398   and reduces the volume of organic waste [61]. The produced biochar from hydrothermal

399   carbonization can be used in various applications, including soil amendment to enhance soil

400   fertility and carbon sequestration, as well as in water treatment processes to remove pollutants

401   and improve water quality. Overall, hydrothermal carbonization provides a promising method for

402   the production of biochar from wet or low-quality biomass, offering opportunities for resource

403   utilization and environmental sustainability.

404 3.2.2.3 Gasification process

405   The gasification process for the production of biochar from agricultural biomass involves the

406   conversion of biomass into a combustible gas known as syngas, along with the simultaneous

407   production of biochar as a byproduct. Fig. 2(c) shows the overall process of biochar production

408   by the gasification method. In the first stage the ACLB biomass, such as crop residues, wood

409   chips, or energy crops, is collected and prepared under 100-150 °C for gasification. This may

410   involve shredding, chipping, or drying the biomass to achieve the desired moisture content. In the

411   second stage the prepared biomass is fed into a gasifier reactor [62], which is a high-temperature

412   200-500 °C reactor where the biomass undergoes partial combustion in an oxygen-limited

413   environment. Gasifiers can be of different types, such as fixed-bed, fluidized-bed, or entrained-

414   flow gasifiers. Pyrolysis Zone in gasifier, the biomass is subjected to intense heat in the absence

415   of sufficient oxygen, leading to a thermochemical decomposition process called pyrolysis. The

416   biomass is transformed into three main products tar and charcoal. In the third stage at 650-900 °C

417   these products convert into syngas, biochar, and ash [63].

418   The primary product of gasification is syngas, which consists of carbon monoxide (CO), hydrogen

419   (H_2), methane (CH_4), and other trace gases. Syngas can be used as a fuel for heat and power

420   generation or further processed to produce synthetic fuels or chemicals. During the pyrolysis

421   process, a solid residue known as biochar is produced. Biochar is a carbon-rich material that

422   retains the carbon from the biomass. It has a high carbon content, stable structure, and can be used

423   for wastewater treatment as a removal of heavy metals and organic pollutant as well as soil

424   amendment to improve fertility and sequester carbon. The syngas generated in the gasification

425 process contains impurities like tars [64], particulates, and contaminants. Therefore, it undergoes

426 a series of cleaning steps, including filtration, cooling, and scrubbing, to remove these impurities

427 and ensure the syngas meets the desired specifications for further use.

### 3.2.2.4 Torrefaction process

429 Currently, torrefaction is an emerging technology used for the production of biochar. It involves

430 a low heating process, often referred to as mild pyrolysis, where the prepared biomass is fed into

431 a torrefaction reactor, which is typically a rotary kiln, fluidized bed, or fixed-bed reactor. The

432 steps involved in the torrefaction process are represented in Fig. 2(d). In the first stage "team

433 torrefaction", the reactor operates at a temperature between 100-150 °C and a residence time of

434 about 10-15 min in an oxygen-limited or oxygen-free environment. In the second stage of the

435 "wet torrefaction" also called the hydro-carbonization process [65], the biomass undergoes

436 heating and degassing. During this stage, the moisture and volatile components of the biomass

437 are removed, leading to the release of water vapor, gases, and other volatile organic compounds.

438 In oxidative torrefaction the temperature increases 200-300 °C and residence time is less than 30

439 min, the biomass undergoes physical and chemical changes.

440 These changes include depolymerization, devolatilization, and partial carbonization of the

441 biomass, resulting in the formation of torrefied biochar. Lastly, after the torrefaction process [66],

442 the torrefied biochar is cooled to reduce its temperature and stabilize the product. The biochar is

443 then collected and stored for further use of wastewater treatment. Moreover, the torrefied biomass

444 produced through this process has several advantages over raw biomass, such as improved grind

445 ability, increased energy density, reduced moisture content, and enhanced hydrophobicity. These

446 properties make torrefied biomass suitable for co-firing with coal in power plants, as a feedstock

447 for bioenergy production, or as a renewable replacement for fossil fuels in various industrial

448 applications.

449 **Table 4** The biomass used as feedstocks for production of biochar's and their constituent elements

Feedstock	Operating conditions	Reactor	C%	N%	H%	S%	O%	HHMS (MJ/kg)	Yield (wt.%)	Reference
Rice husk	Temp: 500, and 650 ∘C H.R.: 10 ∘C/min Holding Time: 2 h	Muffle furnace	42.95–47.09	2.11–5.27	0.57–0.73	0.02–0.03	46.01–54.41	24.76	29.02–50.67	[67]
Wheat straw	Temp: 500 ∘C H.R.: 50 ∘C/min Particle size: 1 mm	Vertical tube pyrolyze	44.35	--	0.45	--	39.69	23.89	21.13	[68]
Sugarcane baggage	Temp: 600 and 900 ∘C H. T.: 30 and 60 min	Semi-batch reactor	43.20	0.40	6.20	0.80	43.20	17.20	26.13	[69]
Hardwood	Temp: 800 and 900 ∘C H. T.: 20–80 min	Vertical tube pyrolyze	46.78	--	5.54	0.87	--	16.45	29.11	[70]
Celery	Temp: 500 ∘C H.R.: 50 ∘C/min Particle size: 1 mm	Muffle furnace	56.53	--	--	--	46.78	--	27.12	[71]
Corn straw	Temp: 800 and 900°C H. T.: 20–80 min	Vertical tube pyrolyze	37.80	0.30	5.50	Less-than1.00	39.30	18.98	15.30	[72]
Pine-wood	Temp: 50, 500, and 650°C H.R.: 10 ∘C/min. Holding Time: 2 h	Semi-batch reactor	44.11	0.70	7.98	--	46.75	12.08	29.11	[73]
Orange peel	Temp:500∘C H.R.:50∘C/min Particle size: 1 mm	Muffle furnace	--	0.68	--	0.45	--	--	10.71	[74]
Hardwood	Temp: 50, 500, and 650 ∘C H.R.: 10 ∘C/min Holding Time: 2 h	Pyrolizer (1dm^3)	43.20	0.52	5.89	0.16	50.53	18.21	19.23	[75]
Switchgrass	Temp: 800 and 900 ∘C H. T.: 20–80 min	Muffle furnace	43.21	0.35	4.98	--	49.89	--	26..17	[76]
Corn cob	Temp: 500 ∘C H.R.: 50 ∘C/min Particle size: 1 mm	Pyrolizer (1dm^3)	46.21	--	--	0.19	--	21.32	29.61	[77]
Samanea seeds	Temp:500∘C.H.R.:50∘C/min Particle size: 1 mm	Semi-batch reactor	62.66	2.06	3.45	0.02–0.03	31.83	23.14	32	[78]

450 **Note:** C, N, H, S, O, and HHMS represent carbon, nitrogen, hydrogen, sulfur, oxygen, ash and higher heating value.

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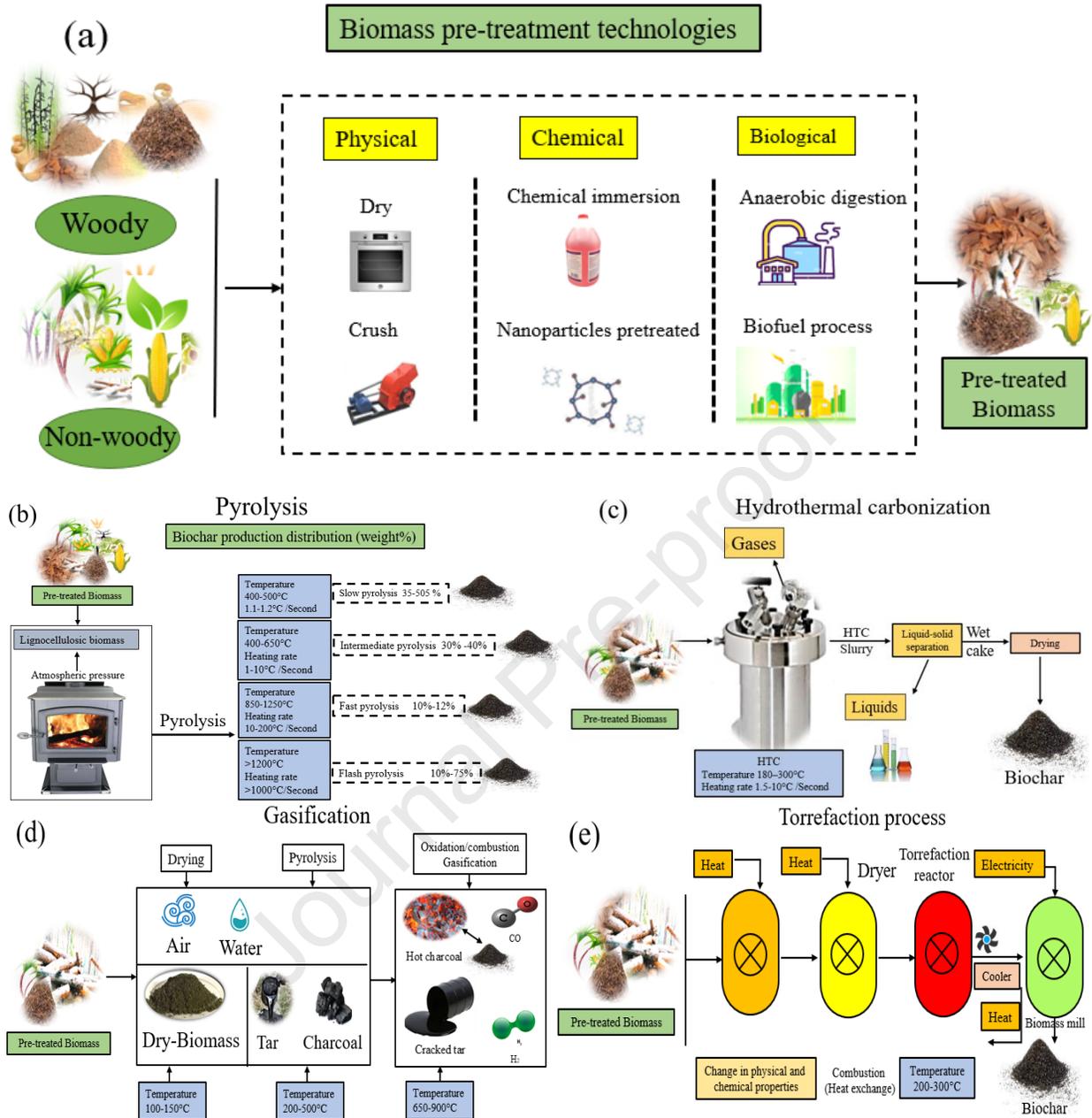
Fig. 2. (a) shows the different pre-treatment technologies of ACLB and thermal methods of (b) pyrolysis, (c) hydrothermal, (d) gasification, and (e) torrefaction for biochar production.

3.3 Biochar production mechanism

The process of producing biochar from agricultural biomass waste, such as lignin, cellulose, and hemicellulose, involves the thermal decomposition of these complex organic compounds. This decomposition leads to the formation of several products, including biochar, syngas, and bio-oil. However, the specific composition and content of lignin, cellulose, and hemicellulose have a direct impact on the production of these products. Table 5 presents the cellulose, hemicellulose,

462 lignin, as well as ash content in numerous kinds of ALCB feedstocks. It is noteworthy relative

463 proportions of these polymers can vary across different ALCB biomasses because of factors such

464 as biomass kind (soft and hard wood, lawn grass, and farmhouse waste left-over), soil category,

465 weather, manure custom, rising situations, reaping methods, and additional physical features.

466 **Table** 5 Percentage of different agricultural lignocellulose ALCB biomass feedstocks

| Biomass	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	Ash%	Reference
Eucalyptus	41.58	15.85	29.4	3.76	[79]
Spruce sawdust	55.4	1.4% arabinose, 4.2% xylose	28.7	19.80	[80]
Oat flakes	21	38%	27	0.98	[81]
Rice husk	56.1	16.15	19.11	0.20	[82]
Sugarcane bagasse	38.6	20 %	24.68	4.00	[83]
Waste cotton heterophorias	49.98	7.61% arabinose, 14.18% xylose	17.6	7.20	[84]
Wheat	38.6	2.1% galectin 1.7% arabinan	24.68	0.20	[85]
Sunflower stalks	27.22	11.94	24.68	1.30	[86]
Oil palm trunk	55.2	19.10	18.13	3.60	[87].
Oak sawdust	43.8	1.3% arabinose, 14.8% xylose	26.7	3.43	[88]
Pine	36.2	23	32.8	0.20	[89]
Cup plant	39	21	21	1.30	[90]
Sun hemp fiber	74.8	9.01	11.35	--	[91]
Watermelon rind	39.67	23.21	10.6	--	[92]
Peanut shell	36.9% glucan	2.1% galectin, 1.7% arabinan	18	--	[93]
Corn stover	31.5% glucan	14.8% xylose	32.8	3.67	[94]
Switchgrass	41	22.6	21	5.00 –6.00	[93]
Barley straw	31.1 ± 0.8	27.2 ± 0.4	18.8 ± 0.2	--	[95]

467

468 Fig. 3 demonstrations of general overview of structural mechanism of each component like lignin,

469 cellulose, and hemicellulose during pyrolysis. In the context of biochar production, lignin serves

470 as a binder and structural component. The presence of lignin in the feedstock used for biochar

471 production can affect the characteristics of the resulting biochar. Biomass with a higher lignin

472 content tends to produce biochar with advanced carbon ratio, greater stability, besides a advanced

473 degree of aromaticity. These properties can influence biochar's ability to sequester carbon and its

474 suitability for specific applications.

475   Lignin $[C_9H_{10}O_3(OCH_3)_{0.9-1.7}]_n$ is a primary and crucial component of the plant that complex

476   polymer which provides rigidity and structural support to plant cell walls. Depending on the plant

477   type and extraction technique, the composition of these components shows significant variations.

478   Softwood typically exhibits higher lignin percentages (25-31 wt%), while hardwood tends to have

479   relatively lower percentages (16-24 wt%) [96]. When integrated with the cellulose and

480   hemicellulose components of ALCB, lignin forms a three-dimensional cross-linked network.

481   Lignin is characterized by various interunit bonds, including β-aryl ether retinol, phenyl

482   coumarin, dibenzodioxin, β-1,4-O-50, and α-O-40 linkages. Among these, ether bonds are the

483   most common type of bond, constituting approximately 60-75% of all lignin bonding and

484   accountancy for about 45-62% of all joining categories used to connect different structural units.

485   During pyrolysis, lignin undergoes depolymerization and decomposition into smaller aromatic

486   compounds such as phenols, guaiacols, and syringes. The breakdown of lignin occurs through the

487   cleavage of various bonds, including β-O-4, β-5, β-β, and 5-5 linkages. The exact products and

488   mechanisms of lignin pyrolysis depend on factors such as temperature, heating rate, and lignin

489   composition.

490   Cellulose $(C_6H_{10}O_5)_x$, another important component of plant cell walls and 30-50 wt% of the

491   whole dry mass. It plays a role in the production of biochar. Cellulose-rich feedstocks tend to

492   produce biochar with higher porosity, which can enhance its water-holding capacity and provide

493   a habitat for beneficial microorganisms in the soil. Biochar derived from cellulose-rich materials

494   can also have a higher ash content which may impact its potential agricultural or environmental

495   applications. Cellulose, a glucose-based polymer, supports plants [97]. Biochar is made by

496   thermally decomposing cellulose and other biomass components. Carbon dioxide, water vapor,

497   and other organic compounds are produced when cellulose is pyrolyzed. These gases are

498   generated when heat decomposes cellulose into smaller molecules in absence of oxygen.

499   Moreover, the composition of these gases can be prejudiced by influences for example of heating

500   amount, temperature, as well as time duration of pyrolysis procedure. Specific conditions used

501   during pyrolysis can be adjusted to optimize the yield and composition of the desired byproducts

502   including biochar and bio-oil.

503   Hemicelluloses $(C_5H_8O_4)_m$, like cellulose and lignin, is a component of plant cell walls founds

504   around 15-40 wt% (dry mass base) of whole ALCB biomass which is composed of heteropolymer

505   composed of various sugar units, including xylose, glucose, mannose, and arabinose. It is a

506 branched polysaccharide that is more easily depolymerized than cellulose during the pyrolysis
507 process used for biochar production. Hemicellulose is crucial to biochar production. It
508 decomposes faster than cellulose and lignin and impact the physical and chemical characteristics
509 of ALCB biochar [98]. The pyrolysis releases furfurans, aldehydes, ketones, and acids from their
510 sugar units at lower temperatures. These molecules contribute to generate bio-oil or pyrolysis
511 gases. The specific composition of the gases can be influenced by the type and structure of the
512 hemicellulose present in the biomass feedstock. As hemicellulose decomposes and releases
513 volatile compounds, it contributes to the formation of pores and channels within the biochar
514 structure. Hemicellulose increases biochar porosity. Porosity increases water retention, nutrient
515 retaining capacity, and wastewater pollutant habitat. Moreover, biochar derived from
516 hemicellulose-rich materials tends to have a higher ash content, which can impact its nutrient
517 content and interactions with soil [99]. Overall, it is noteworthy that pyrolysis of lignocellulosic
518 biomass waste which contains lignin, cellulose, and hemicellulose, is a complicated process.
519 These components decompose simultaneously but at distinct rates and conditions. Temperature,
520 heating rate, residence duration, and catalysts or additions affect pyrolysis. Consequently,
521 depending on biomass type and pyrolysis circumstances, processes and product distributions can
522 be complicated.

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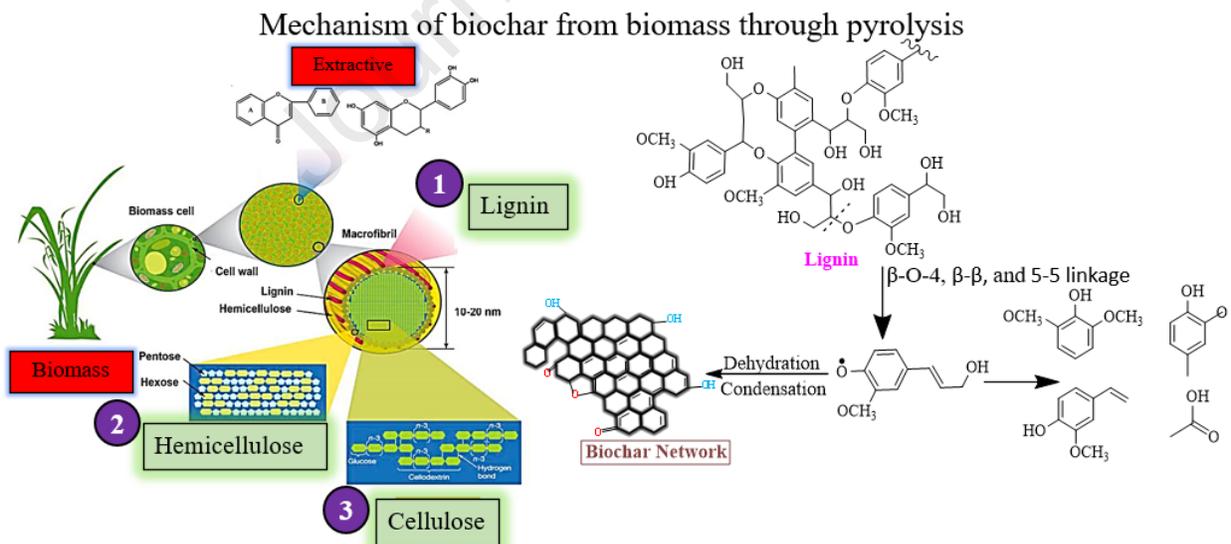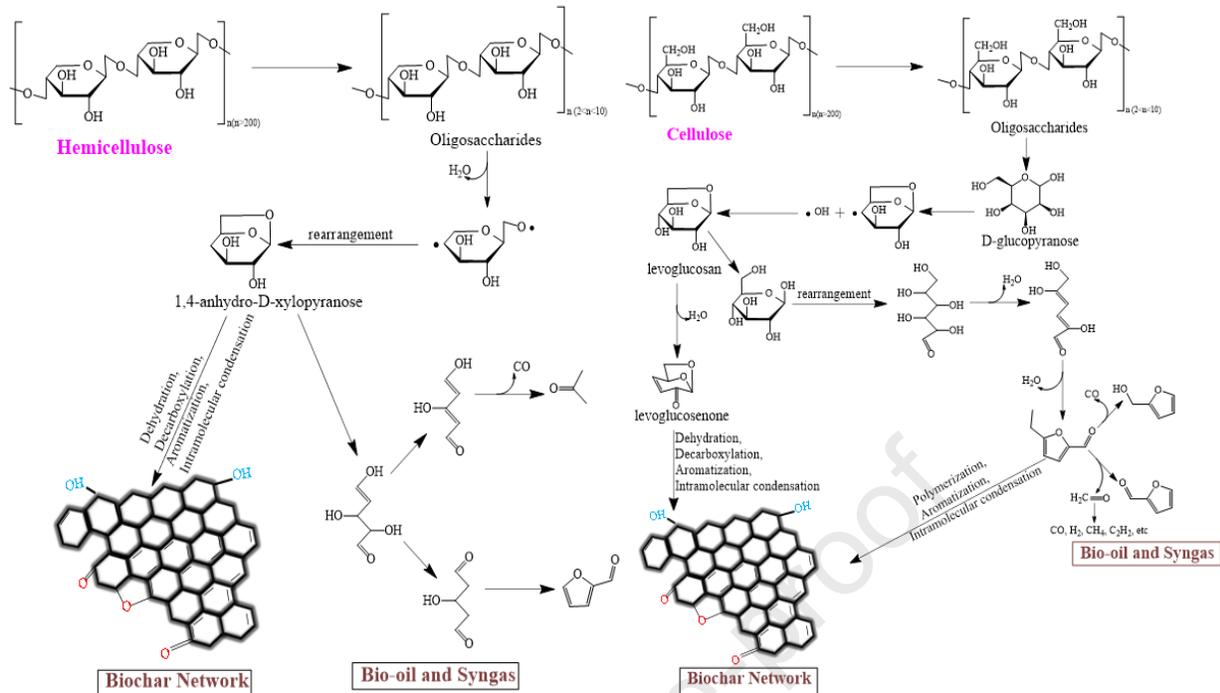
Fig. 3 Shows the formation mechanism of agricultural lignocellulosic biomass waste through pyrolysis.

3.4 Biochar characteristics

Physicochemical properties of biochar refer to the characteristics and attributes of biochar that are related to its physical and chemical nature. These properties encompass various measurable features that describe biochar's structure, composition, reactivity, and interactions with pollutants and surrounding. They provide valuable insights into how biochar behaves and functions in different applications [100]. Moreover, the surface properties of biochar refer to the characteristics of its outer surface, which play a crucial role in its performance and interactions with pollutants. Currently, numerous modern characterization techniques have been reported such as scanning electron microscopy (SEM), fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermo-gravimetric analysis (TGA) [101], nuclear magnetic resonance spectroscopy (NMR), brunauer-Emmett-teller (BET), proximate and ultimate analysis, Raman spectroscopy, etc as shown in (Fig. 4-5).

(i) Physical and chemical properties

(1) pH: pH is a measure of the acidity or alkalinity of a substance. In the case of biochar, it refers to the pH of its aqueous extract. pH influences biochar's interactions with soils and its potential to affect soil pH when applied as an amendment.

542 (2) Cation Exchange Capacity (CEC): Cation exchange capacity is the ability of biochar to attract,

543 retain, and release positively charged ions (cations). It represents the capacity of biochar to hold

544 and supply essential nutrients to plants and mitigate nutrient leaching.

545 (3) Electrical Conductivity: Biochar itself is typically a poor electrical conductor. It primarily

546 consists of carbon, which is not highly conductive. However, the electrical conductivity of biochar

547 can be influenced by factors such as the presence of ash content and conductive minerals. If

548 biochar contains significant levels of ash, particularly minerals like potassium, calcium, or

549 phosphorus, it may exhibit some degree of electrical conductivity [102]. The ash content can

550 provide conductive pathways within the biochar structure, allowing for the flow of electric

551 current.

552 (4) Surface area: high surface area of biochar, due to its hierarchical porous structure comprising

553 micro-, meso-, and macropores, provides a substantial contact area for chemical reactions and

554 enhances its ability to adsorb and retain substances like nutrients and pollutants [103]. This pore

555 structure not only supports microbial colonization and gas exchange but also facilitates the

556 retention of water and nutrients, making biochar highly effective in environmental and

557 agricultural applications.

558 (5) Particle size distribution: The particle size distribution of biochar refers to the range of particle

559 sizes present in a sample. The particle size can be characterized using various metrics, including

560 mean particle size, median particle size, or the distribution of particle sizes within different size

561 ranges [104].

562 (6) Bulk Density: Biochar's bulk density refers to the mass of biochar per unit volume, typically

563 expressed in grams per cubic centimeter (g/cm^3) or kilograms per cubic meter (kg/m^3) [105]. The

564 bulk density of biochar can vary depending on factors such as feedstock, pyrolysis conditions,

565 and post-treatment processes [106]. Generally, biochar has a lower bulk density compared to the

566 original biomass feedstock due to the removal of volatile components during pyrolysis. The bulk

567 density of biochar typically ranges from 0.1 to 0.6 g/cm^3 or 100 to 600 kg/m^3.

568 *(ii) Surface and molecular properties*

569 The undertaking of surface and molecular properties of biochar to understand and enhance its

570 potential applications across various fields, such as environmental remediation, adsorption of

571 HMs from wastewater, and agricultural soil remediation etc. There are many analytical techniques

572 designed to examine its physical structure, chemical composition, and functional groups. These

573 methods provide insights into the biochar's porosity, surface area, elemental makeup, and
574 chemical functionalities. There are some examples how such analyses can be conducted.

575 (1) Scanning electron microscopy (SEM)

576 The SEM analysis is commonly used to examine the surface morphology and structure of biochar.
577 By using SEM picture, researchers can gain detailed insights into the physical characteristics of
578 biochar, including its particle size, porosity, and surface features [107]. The SEM allows for high-
579 resolution imaging of the surface morphology of biochar particles. It can reveal the external
580 structure, surface texture, and shape of the biochar particles. The common SEM picture of rick
581 huck is used in Fig. 4(a), for understand the function of SEM. This information is important for
582 understanding the physical properties and performance of biochar in different applications.
583 Additionally, SEM can be equipped with energy-dispersive X-ray spectroscopy (EDS) detectors,
584 which allow for the elemental analysis of biochar before and after the adsorption of pollutant.
585 [108].

586 (2) SEM and EDS analysis

587 Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS) analysis
588 is a technique used for the characterization of biochar before and after the adsorption of pollutants.
589 It combines high-resolution imaging capabilities with elemental analysis to provide detailed
590 information about the surface morphology, elemental composition, and spatial distribution of
591 elements in biochar samples. Moreover, help to Contaminant identification such as HMs after
592 adsorption [109]. EDS enables the identification and mapping of different elements present on
593 the biochar surface. This analysis provides insights into the mineral content, elemental
594 composition, and distribution within the biochar particles. The main drawback is SEM-EDS is
595 not suitable for organic contaminants. The common SEM-EDS picture of rick huck is used in Fig.
596 4(a-b), for understand the function of SEM-EDS.

597 (3) FTIR and Raman analysis

598 FTIR (Fourier Transform Infrared Spectroscopy) and Raman analysis are two analytical
599 techniques used to characterize biochar. FTIR analysis is used to identify the functional groups
600 present on the surface of biochar and provide information about its chemical composition. It
601 works based on the principle that different chemical bonds in a molecule vibrate at specific
602 frequencies, resulting in characteristic infrared absorption patterns. Moreover, increase the

603 temperature about 600-800 °C huge changing happens and lose of aromatic compounds. By

604 subjecting a biochar sample to infrared radiation and measuring the intensity of the absorbed light,

605 FTIR can identify the types of chemical bonds and functional groups present in the biochar

606 sample. This information helps in understanding the organic composition of biochar, such as the

607 presence of functional groups like hydroxyl (-OH), carboxyl (-COOH), or carbonyl (-C=O)

608 groups, which can influence its properties and potential applications.

609 While Raman spectroscopy involves the scattering of laser light by a sample. The scattered light

610 undergoes energy shifts that provide information about the vibrational modes of the sample's

611 molecules. Raman analysis can provide valuable insights into the structural and chemical

612 properties of biochar [110]. Both FTIR and Raman analysis techniques are valuable tools for

613 studying the chemical composition, functional groups, and molecular structure of biochar. They

614 help researchers understand its properties, assess its quality, and optimize its applications in

615 various fields, such as agriculture, environmental remediation, and energy storage. The common

616 FTIR-Raman analysis picture of rick huck is used in Fig. 4(c-d), for understand the function of

617 SEM

618 (4) TGA and TEM analysis

619 Thermo-gravimetric (TGA) is applied for thermal analysis to observe the physical and chemical

620 properties of materials which are measured as a function of a temperature rise. The TGA analysis

621 has been generally utilized to portray and think about the warm conduct of various examples. This

622 examination is planned to look at the ignition attributes of biochar and the biomass/biochar mixes

623 by thermogravimetric examination. Additionally, the normal weighted average of the individual

624 part was inspected whether synergic activity happened between the segments of the blends [111].

625 The outcomes may assist with bettering comprehending the warm procedure and attributes of the

626 examples from a major perspective and for the examination of tests. During this process, the

627 heating of biochar initiates from room temperature and is increased up to 1000 °C. Many

628 researchers have reported using different temperatures such as 10 and 20 °C /min, 10 K/min, and

629 less than 1000 °C. The common TGA and TEM analysis picture of rick huck is used in Fig. 4(e-

630 f), for understand the whole function.

631 (5) XRD and NMR analysis

632 XRD analysis is used to determine the crystallographic structure and phase composition of a

633 material, including biochar. It works based on the principle of X-ray diffraction, where X-rays are

634 diffracted by the atomic planes within a crystalline material [112]. By measuring the angles and

635 intensities of the diffracted X-rays, XRD can provide information about the arrangement of atoms

636 within the crystal lattice and the crystalline phases present in the biochar sample. Biochar derived

637 from different biomass sources or produced under different pyrolysis conditions may exhibit

638 different crystalline structures [112], such as graphitic or amorphous carbon, or may contain

639 crystalline mineral phases originating from the biomass feedstock. XRD analysis helps to

640 characterize these structural properties of biochar and can provide insights into its thermal

641 stability and potential applications. The common XRD analysis picture of rick huck is used in

642 Fig. 4(g), for understand the whole function.

643 Nuclear magnetic resonance (NMR) spectroscopy is a powerful characterization technique used

644 for the characterization of biochar. NMR spectroscopy provides information about the chemical

645 structure, composition, and functional groups present in biochar. It is particularly useful in

646 analyzing the carbonaceous components of biochar, including its aromaticity, degree of

647 carbonization, and surface properties. Overall, theses analyses are complementary techniques that

648 offer valuable information about the chemical composition, functional groups, and

649 crystallographic structure of biochar, helping researchers and scientists understand its properties

650 and explore its potential applications in various fields, including agriculture, environmental

651 remediation, and energy storage [113]. Moreover, there are many types of NMR analysis such as,

652 ^{1}H NMR: Analyzes hydrogen nuclei, ^{13}C NMR: Analyzes carbon-13 nuclei, ^{2}D NMR: Provides

653 information about spatial relationships between atoms, and solid-state NMR: Studies materials in

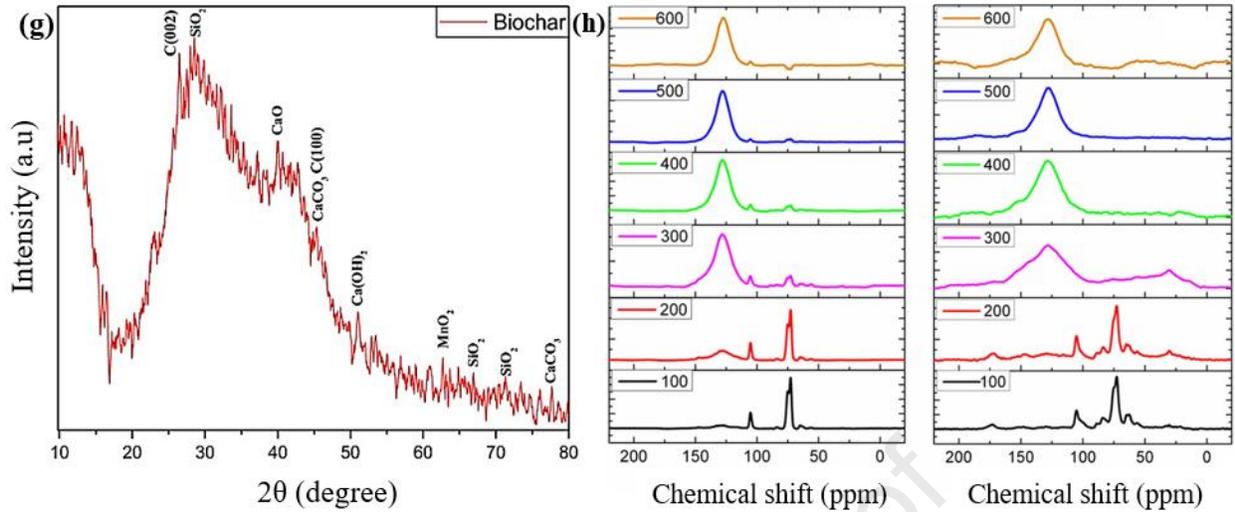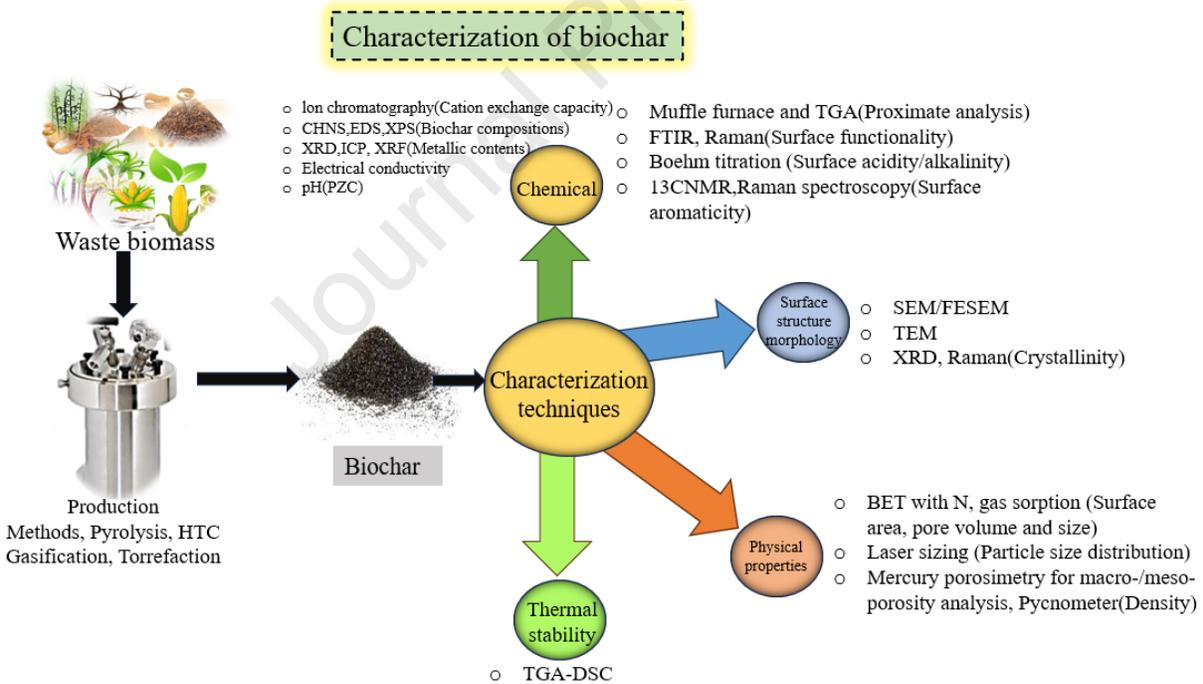654 solid form. In the Fig. 4(h), ^{13}C NMR has been used for as a example.

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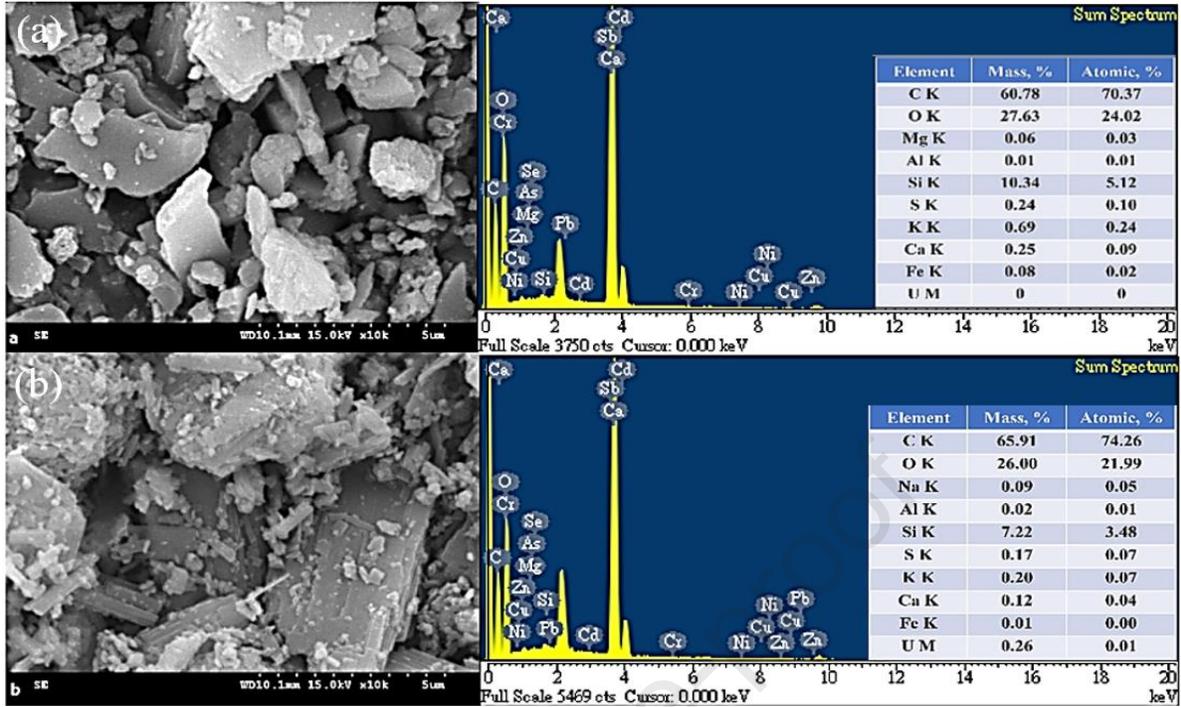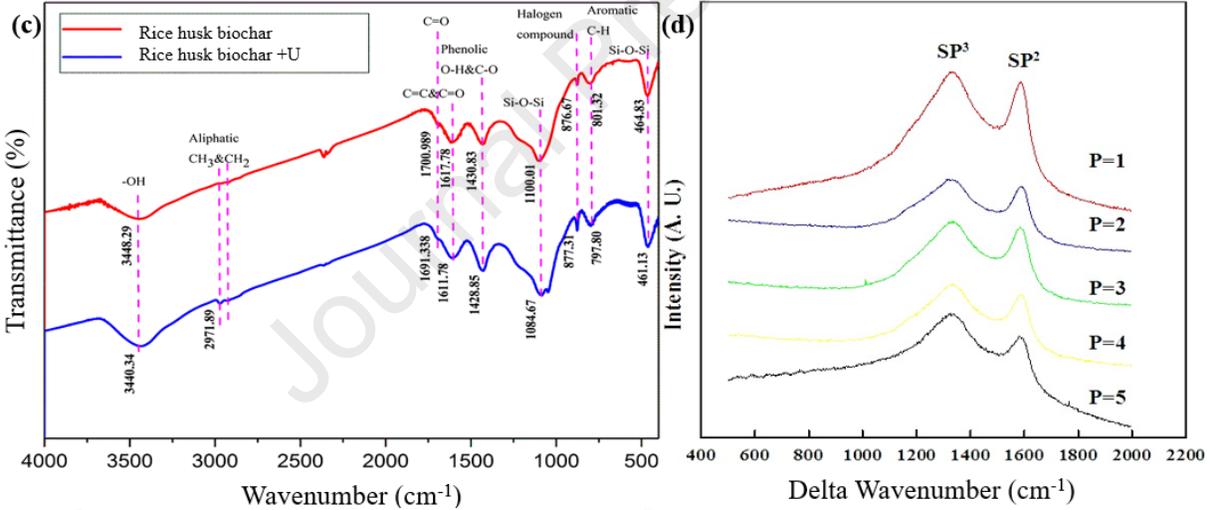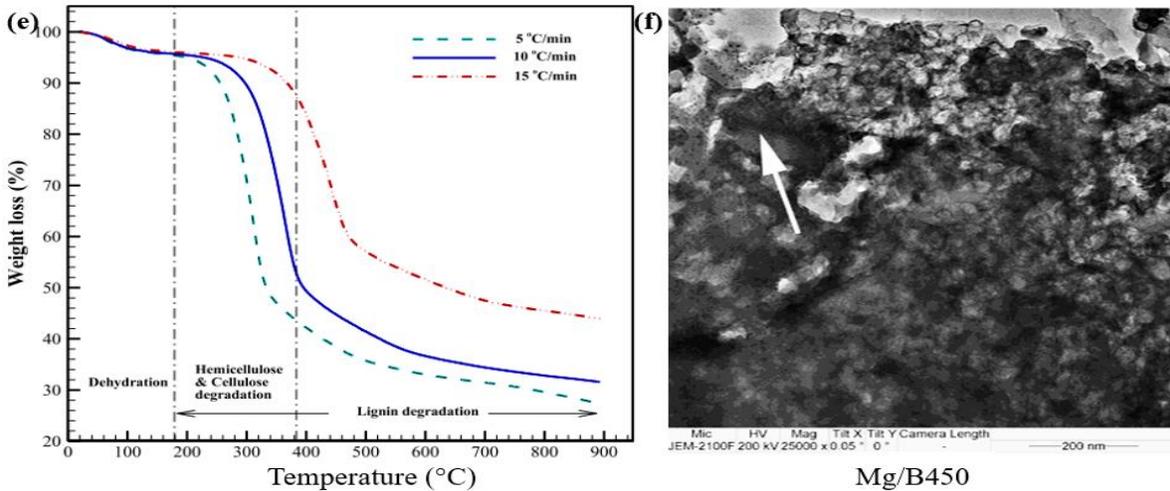
Fig. 4. (a,b) shows the SEM and EDS[114], (c) FTIR (d) Raman,[115] (e) TGA [116], (f) TEM [117], (g) XRD [118], and (h) NMR analysis or characteristic pictures of rice huck [119] biochar. **Note**: The rice huck biochar analysis pictures are used just as a example for understand the whole mechanism characteristics of biochar's.

Fig. 5. Physicochemical, surface and structural characterization of biochar.

3.5 Biochar applications for wastewater treatment
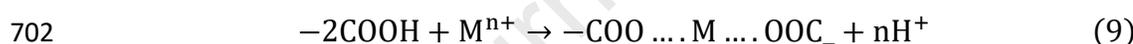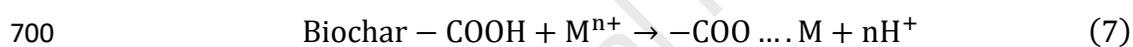
3.5.1 Adsorption mechanism of HMs by ACLB biochar

With the intention of assess the effectiveness of the overall adsorption performance of biochar in removing contaminants, it is crucial to know the fundamental mechanisms involved in adsorption procedure. Adsorption behavior of ACLB biochar varies dependent on detailed contaminants being targeted, for example HMs, organic pollutants, and other pollutants [120]. Moreover, this behavior is strongly linked characteristics of ALCB biochar, with its surface functional groups, detailed surface area, porous structure, and mineral mechanisms. For example, activated carbon-based ALCB biochar, resulting from carbon-rich materials for example rice husks, sugarcane bagasse, corn stalk, coconut shells or wood, often exhibits high adsorption capacity it can be seen in Table 6 because its big surface and functional groups [121]. These functional groups, including carboxyl, hydroxyl, and phenolic groups, donate to the removal of HMs over ion exchange, complexation, and surface chelation. The mechanism of adsorption of HMs onto solid adsorbents involves various kinds of connections for example co-precipitation, ion exchange, electrostatic attraction, surface complexation, physical adsorption, and other mechanisms. Fig. 6(a) provides a summary of the numerous processes that have been proposed to explain the interaction between biochar and heavy metals.

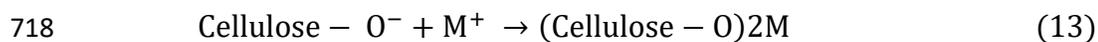683 **Table 6** Wastewater treatment for the elimination of metals and metalloids.

Adsorbates	Initial concentration	Adsorbents	Pyrolysis temperature	Applied dose	Removal efficiency	Reference
Cu^{2+}	1 mM	Corn straws	850 °C	1.25 g	98%	[122]
Cd^{2+}	1 mM	Rice husk	800-900 °C	--	87%	[123]
Cd^{2+}	150 mg/L	Wheat straw	600-750 °C	--	91.2%	/
Pb^{2+}	150 mg/L	Sawdust	800 °C	--	53%	/
Zn^{2+}	30 mg/L	Orange peel	400 °C	1.25 g	30-40%	[124]
Pb^{2+}	1 mM	Rice husk	500-550 °C	1.5 g	30-40%	[125]
As^{5+}	30 mg/L	Pinewood	390 °C	1.25 g	67-72%	[126]
Ni^{2+}	30 mg/L	Wheat straw	450-480 °C	1 g	87 %	/
Pb^{2+}	1 mM	Sugar cane bagasse	650 °C	1.25 g	98%	[127]
Cu^{2+}	0.09 mg/L	Orange peel	400 °C	--	87%	/
Cu^{2+}	150 mg/L	Pinewood	800-900 °C	--	91.2%	[128]
Cu^{2+}	30 mg/L	Sugar cane bagasse	650-700 °C	1.5 g	30-40%	[129]
Ag^{+}	30 mg/L	Gasifier biochar	650-700 °C	1.5 g	30-40%	/
Zn^{2+}	1 mM	Celery	800-850 °C	0.5 g	53%	[130]
As^{5+}	30 mg/L	Activated Biochar	500-550 °C	--	87%	/
Cr^{3+}	25 mg/L	Magnetic biochar	390 °C	--	91.2%	[131]
Ni^{2+}	30 mg/L	Corn straw	800 °C	4 g	53%	[132]
Cd^{2+}	1 mM	Sugar cane bagasse	400 °C	3 g	30-40%	/
Zn^{2+}	30 mg/L	Hardwood	500-550 °C	2 g	67-72%	[133]
Cr^{6+}	100 mg/L	Celery	390 °C	1.75 g	67-72%	[134]
As^{5+}	1 mM	Corn straw	650 °C	4 g	83%	[135]

684

685 Functional groups present on the surface of ALCB biochar show a crucial part in the removal of

686 HMs from wastewater. These functional groups contain atoms for instance oxygen (O), nitrogen

687 (N), sulfur (S), and phosphorus (P), which hold singular pairs of electrons that can form chemical

688 bonds with HMs ions [136]. Functional groups help in removal method by electrostatic attraction,

689 ion exchange, and surface complexation. Ion exchange is a reversible chemical process wherein

690 ions freely moving within insoluble solids are exchanged with ions of same charge present in a

691 solution. This mechanism theatres a vital role in elimination of HMs from wastewater entire the

692 use of biochar. Biochar possesses various functional groups, for instance carboxyl (-COOH),

693 hydroxyl (-OH), amino (-NH$_2$), in addition sulfhydryl (-SH) groups, which harbor exchangeable

694 ions. These functional groups undergo ion exchange reactions with HMs ions in the polluted

695 sewer water, causing the substitution of metal ions with other ions derived from the functional

696 groups. Consequently, this process effectively reduces the adsorption of HMs in the wastewater.

697 However, the adsorption capacity and efficiency of metals primarily depend on the availability of

698 exchangeable sites on the functional groups and the size of the targeted metal ions. The ion

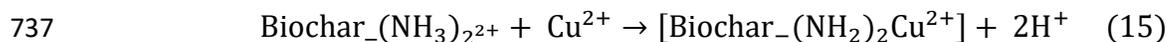699 exchange reaction mechanism is outlined in equations (7) to (11).

$$Biochar - COOH + M^{n+} \rightarrow -COO \dots M + nH^+ \qquad (7)$$

$$-OH + M^{n+} \rightarrow -O \dots M + nH^+ \qquad (8)$$

$$-2COOH + M^{n+} \rightarrow -COO \dots M \dots OOC\_ + nH^+ \qquad (9)$$

$$-2OH + M^{n+} \rightarrow -O \dots M \dots O\_ + nH^+ \qquad (10)$$

$$-COOH + M^{n+} + \_OH \rightarrow -COO \dots M \dots O\_ + nH^+ \qquad (11)$$

705 In the equation, *M* represents the metal ions, and n indicates their respective ionic charges.

706 Electrostatic attraction happens when the positively charged metal ions are involved to negatively

707 charged surface of adsorbent material. HMs typically carry a positive ion in a solution and the

708 surface of the adsorbent such as carbon, clay minerals or metal oxide carry negative charge, in

709 the form of functional group such as hydroxyl (OH-) or carboxyl (COO-) groups. As a result, the

710 HMs ions adsorb onto the surface of the adsorbent, forming a layer or a monolayer [137]. Strength

711 of electrostatic attraction concern on several factors, including magnitude of the charges on the

712 metal ions and adsorbent surface, distance among the ions and the surface, and the dielectric

713 constant of the medium. Other factors like pH and the occurrence of other ions in the solution can

714 similarly affect the electrostatic interaction [138]. The researcher indicated that the electrostatic
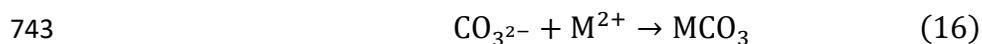
715 interaction reaction be contingent on the pH or cationic and ionic condition of the adsorbent

716 surface.

717 $$\text{Cellulose} - \text{OH} \rightarrow \text{Cellulose} - \text{O}^- + \text{H}^+ \qquad (12)$$

718 $$\text{Cellulose} - \text{O}^- + \text{M}^+ \rightarrow (\text{Cellulose} - \text{O})2\text{M} \qquad (13)$$
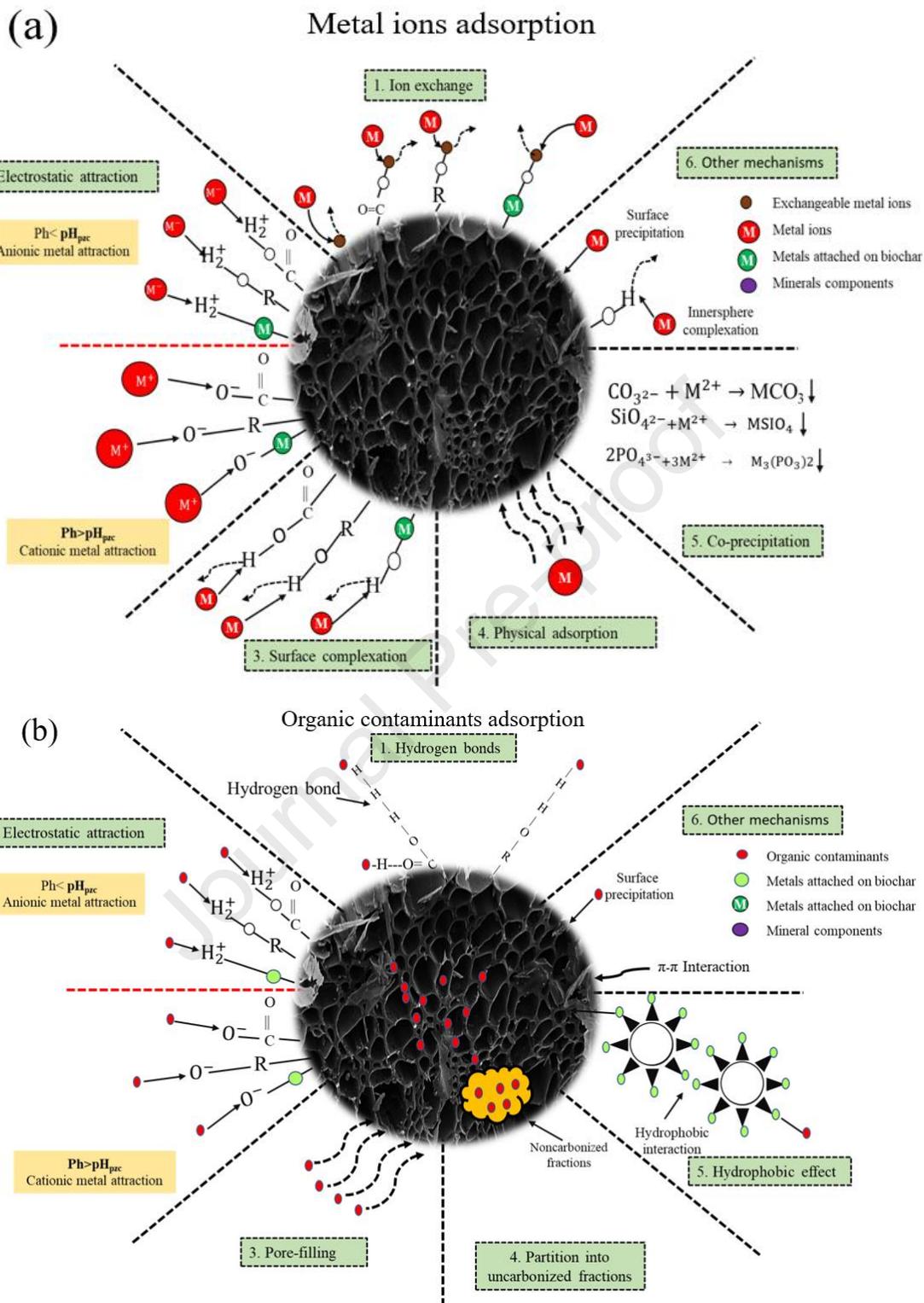
719 Besides, surface area also porous texture of ALCB biochar significantly influence the diffusion

720 kinetics and adsorption capacity of HMs from wastewater. A higher surface area allows for a

721 larger number of active places, such as functional groups or mineral components, that can interact

722 with the heavy metal ions. While micropores, with their small size, provide a larger surface area

723 per unit volume, promoting intimate contact with heavy metal ions. Mesopores and macropores

724 facilitate carriage of metal ions to interior of the biochar, increasing the accessibility of adsorption

725 sites. Surface complexation (SC) development is extensively acknowledged as the group of

726 cations with molecules or anions with single couples of electrons. Functional groups -COO-, R-

727 O-R, -R$_3$N etc., can form coordination bonds with heavy metal ions, forming complexes. These

728 complexes are generally stable and insoluble, which allows them to be effectively adsorbed onto

729 the biochar surface. The functional groups act as ligands, coordinating with the heavy metal ions

730 through electron pairs and reducing their mobility in the wastewater. The SC mechanism offers a

731 deeper understanding of the physicochemical interactions among HMs ions and the surface of

732 biomaterials. Techniques such as FTIR, EDX, or XPS analysis were utilized to explore the

733 possibility of binding by examining the functional groups. These analyses revealed the existence

734 of a favorable binding site between Cu(II) and the amine group, as indicated in equations 14 to

735 15.

736 $$(\text{COOH})_2 + \text{Cu}^{2+} \rightarrow [\text{Biocha}\_(\text{COO})_2] + 2\text{H}^+ \qquad (14)$$

737 $$\text{Biochar}\_(\text{NH}_3)_2{}^{2+} + \text{Cu}^{2+} \rightarrow [\text{Biochar}\_(\text{NH}_2)_2\text{Cu}^{2+}] + 2\text{H}^+ \quad (15)$$

738 Co-precipitation Precipitation or co-precipitation: Over time, the attentiveness of HMs ions on

739 ALCB biochar surface increases, leading to formation of metal-rich particles. These metal-

740 bearing biochar particles can undergo precipitation or co-precipitation, depending on the specific

741 circumstances, such as pH, temperature, and the attendance of other chemical species in the

742 wastewater [139].

743 $$\text{CO}_3{}^{2-} + \text{M}^{2+} \rightarrow \text{MCO}_3 \qquad (16)$$

744 $$\text{SiO}_4{}^{2-} + \text{M}^{2+} \rightarrow \text{MISO}_4 \qquad (17)$$

745 $$2\text{PO}_4{}^{3-} + 3\text{M}^{2+} \rightarrow \text{M}_3(\text{PO}_3)_2 \qquad (18)$$

746

747

Fig. 6 The hypothesized pathways for the adsorption of (a) HMs ion and (b) organic pollutants on biochar are summarized.

3.5.2 Adsorption mechanism of organic pollutant

Organic pollutants in wastewater, such as fats, oils, and grease (FOG), surfactants, solvents, drugs and individual care products (DICPs), endocrinal disorderly compounds (EDCs), chlorinated organic compounds (polychlorinated biphenyls (PCBs), chlorinated pesticides (e.g., DDT)), aromatic hydrocarbons (e.g., benzene, toluene, ethylbenzene, and xylene), dyes, pesticides, and herbicides, originate from various sources including households, industries, and agriculture. The presence and concentration of these specific organic contaminants in wastewater depend on the sources, and characteristics of the wastewater. It is necessary to employ appropriate treatment methods to effectively eliminate these pollutants before discharge or reuse. In wastewater treatment, organic contaminants bind to biochar through various adsorption mechanisms, which involve interactions such as hydrogen bonds, electrostatic attractions, pore filling, hydrophobic connections, Van der Waals forces, and π-π loading. These connections facilitate the easy removal of organic contaminants with ALCB biochar [140]. The proposed interactions of biochar with organic pollutants are illustrated in Fig. 5(b).

$$(AM) + (OP) + \rightleftharpoons \text{Adsorbed Complex } (A \bullet\bullet\bullet B) \quad (19)$$

Where "AM" adsorbent material such as biochar and "OP" represent the organic pollutants present in the wastewater. While Adsorbed Complex (A ••• B) is interaction bonding reaction than can be perform by hydrophobic interactions, van der Waals forces, hydrogen bonds, electrostatic attractions and π-π stacking mechanisms.

It is noteworthy relative contribution of each adsorption mechanism can vary depending on influences for example the nature of organic contaminants, temperature, solution conditions (pH, ionic strength), and temperature, biochar properties (surface area, pore structure, surface chemistry), as well as, biomass components such as cellulose, hemicellulose, and lignin significantly affect the adsorption mechanism. These components contribute distinct chemical and structural properties that influence the adsorption capacity and specificity. For instance, the crystalline structure of cellulose can contribute to the surface area available for adsorption. Its highly porous nature facilitates the trapping of pollutants. Chemically, cellulose contains hydroxyl (-OH) groups, which can form hydrogen bonds or participate in electrostatic interactions with adsorbates. The same form is applying on other two hemicellulose and lignin components.

The consequences of dissimilar research collected suggested that electrostatic attraction was main procedure for the adsorption of organic pollutants onto the biochar than other adsorption

781 mechanisms. Research was showed that examine the mechanism of dye adsorption on biochar

782 produced from straw. The findings revealed that the adsorption process is influenced by several

783 interactions [141]. The adsorption process involves various interactions, including π-π

784 interactions between dye molecules and the graphene layers of biochar. Moreover, electrostatic

785 attraction/repulsion and intermolecular hydrogen bonding contribute to the overall adsorption

786 mechanism.

787 Furthermore, pore-filling has been identified as an important mechanism for adsorption of organic

788 composites onto ALCB biochar. Adsorption procedure is inclined because of surface

789 characteristics of biochar, and the adsorption volume is directly correlated with the surface area

790 of micropores. Carbonaceous materials, known for their abundant surface areas and pore volumes,

791 effectively enhance the adsorption of organic pollutants, primarily through the pore-filling

792 phenomenon. The phenomenon of pore-filling has been extensively studied, particularly in

793 research exploring the adsorption of phenol and methylene blue from wastewater using biochar.

794 It has been observed that high-temperature biochar demonstrates greater effectiveness compared

795 to low-temperature biochar, indicating its superior adsorption capability and enhanced reliability.

796 **3.6 Life cycle analysis**

797 The life cycle assessment (LCA) of biochar production from agricultural waste residues,

798 illustrated in Fig. 7, evaluates the environmental and economic impacts of the process. It considers

799 the benefits across the entire life cycle, including the collection and transportation of agricultural

800 residues, production through pyrolysis, and the final application or disposal of biochar.

801 The economic analysis of biochar production from agricultural waste residues involves key stages

802 contributing to costs and revenue. Feedstock collection and transportation account for

803 approximately 15–25% of the total economic cost, influenced by factors like residue type (e.g.,

804 wheat straw, rice husks), distance, fuel costs, and infrastructure. Secondly, biochar production via

805 pyrolysis, the most significant cost contributor at 50–65%, includes capital investments in

806 installations of pyrolysis units, operational costs like energy, maintenance, and labor. It is usually

807 largest contributor to the overall cost due to technological and energy requirements. The

808 application of biochar contributing 10–20% of costs, encompasses expenses related to

809 application, such as using it for water filtration or spreading on fields for some purpose (adds

810 value through soil productivity improvement or crop yield increases) with potential savings from

811 reduced fertilizer usage. On the revenue side, biochar sales generate 40–60% of total income, the

812   revenue potential depending on market demand and application type like wastewater treatment,

813   soil improvement or industrial uses. The price per ton of biochar significantly impacts the

814   economic balance. Lastly, additional revenue (15–30%) comes from carbon credits such as

815   Income from carbon credits in regulated or voluntary markets for biochar's carbon sequestration

816   and environmental benefits like savings from reduced waste management and mitigation costs,

817   demonstrating biochar's economic and environmental potential.

818   More preciously to understand of the net economic contribution of biochar production is

819   influenced by various factors, including feedstock availability, transportation efficiency, market

820   prices of biochar and carbon credits, production scale, and operational efficiency. Profitability is

821   contingent on these variables, with potential net profit margins ranging from 20–40%, depending

822   on subsidies, incentives, and market dynamics. For example, in a $1,000 economic distribution,

823   feedstock collection and transportation constitute $150–$250 (15–25%), biochar production costs

824   amount to $500–$650 (50–65%), and utilization costs range from $100–$200 (10–20%). On the

825   revenue side, biochar sales generate $400–$600 (40–60%), while carbon credits contribute $150–

826    $300 (15–30%). This balance highlights the economic viability and potential for optimizing

827   biochar production systems.
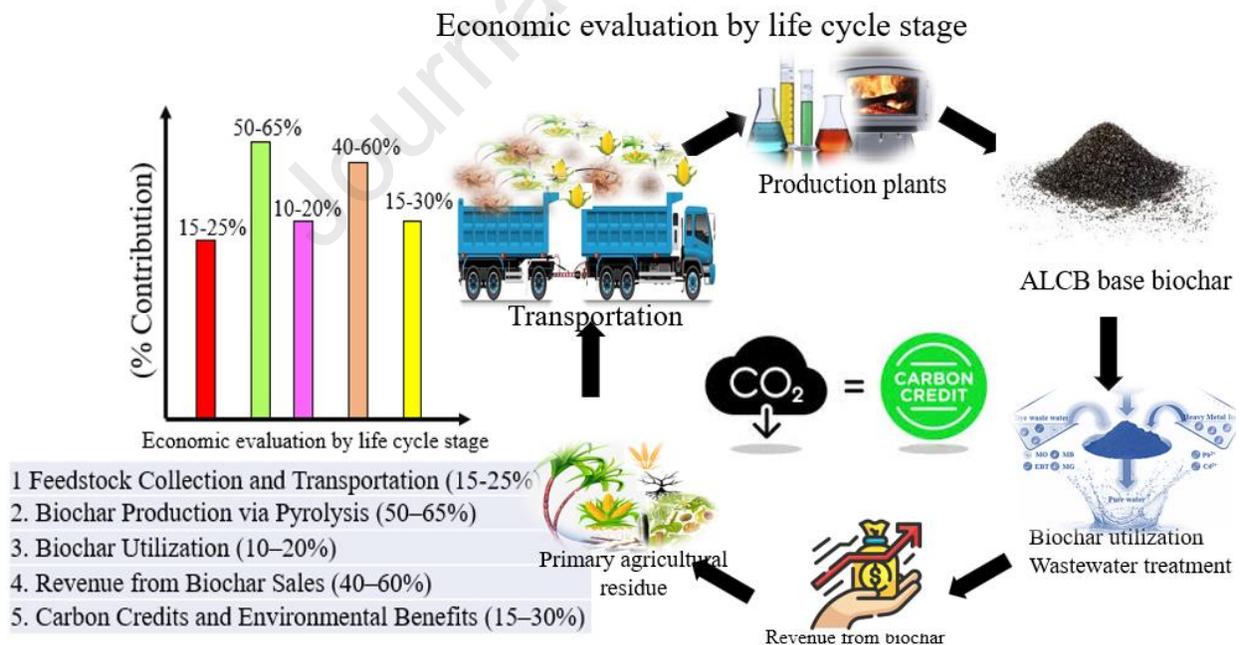
828

829   **Fig. 7.** The life cycle assessment showing that the synthesis of biochar from waste is a promising research

830   direction through economic evaluation.

831

3.6 Complications, sustainability, and potential use of biochar

3.6.1 Potential negative effects

Usage of ALCB biochar for treatment of wastewater can have some potential negative effects, including pH changes, long-term stability, clogging and reduced flow, nutrient leaching, and contaminant release. It is noteworthy the negative influence can be mitigated through proper selection of biochar properties, careful system design, and monitoring of water quality parameters during wastewater treatment [142]. Conducting comprehensive studies and pilot tests specific to the target contaminants and wastewater characteristics can help optimize the use of biochar for efficient and environmentally sustainable wastewater treatment.

3.6.2 Sustainable use of biochar

International Biochar Initiative (IBI) has recognized standards known as the "Standardized Product Definition and Product Testing Guidelines for Biochar" to provide a common framework for characterizing and evaluating biochar for sustainable production, and its safe use for biochar producers, researchers, regulators, and consumers. These standards help ensure consistency and transparency in biochar production, testing, and quality assessment. The key components of these standards include: physical and chemical characteristics, contaminant limits, testing protocols, quality control and labeling. the standardized product meaning and creation challenging rules for biochar by the IBI serve as a reference for biochar producers, researchers, regulators, and consumers to establish a common understanding and promote quality assurance in the biochar industry. Adhering to these standards enhances the credibility and reliability of biochar products and facilitates their safe and effective use in various applications.

3.6.3 Potential application of biochar

Currently, there is a shortage of data concerning the usage of biochar for treating contaminated sediment. Given the remarkable adsorption capacity of biochar towards water pollutants, it presents a promising opportunity as a novel *in-situ* amendment sorbent for managing contaminated sediment [143]. Consequently, it is crucial to prioritize further research activities that examine the viability of this hypothesis, as it presents a attractive prospect and opportunity for environmental remediation, soil amendment, building materials, renewable energy, livestock and poultry industry and carbon sequestration.

4. Techno-Economic analysis of biochar

Techno-economic analysis (TEA) is a methodology used to assess the economic possibility and viability of a particular technology or process. In the context of ALCB biochar manufacture also the elimination of HMs from wastewater, TEA would involve assessing the technical aspects and costs associated with these processes to determine their economic potential.

(1) Biochar production:

The ALCB biochar is a carbon-rich solid material formed by heating waste residue in a low-oxygen atmosphere (a procedure calls as pyrolysis). To conduct a TEA for biochar production, the following factors would typically be considered: feedstock cost, pyrolysis equipment and infrastructure, operational costs, biochar yield and quality, market demand and pricing, and environmental benefits.

The cost of acquiring the biomass feedstock, such as agricultural residues or dedicated energy crops, would be evaluated. The capital costs associated with acquiring and installing the pyrolysis equipment, as well as any additional infrastructure requirements, would be assessed. In cost operating include costs related to energy consumption, labor, maintenance, and other operational expenses. Moreover, the amount and quality of biochar produced per unit of biomass input would be evaluated, as they impact the potential market value. While, the current and projected demand for biochar, along with the prevailing market prices, would be considered to estimate the potential revenue. Lastly, environmental Benefits: The potential environmental benefits, for example carbon sequestration and soil improvement, would also be factored into the analysis.

(2) Removal of HMs

The removal of HMSs from wastewater typically includes various treatment procedures, for example precipitation, ion exchange, adsorption, and membrane filtration. Conducting a TEA for HMs removal would involve the following aspects: Treatment technology selection, capital and operating costs, metal removal efficiency, regulatory compliance, disposal of metal-rich residues, and potential revenue streams.

The selection of an appropriate treatment technology or combination of technologies based on their effectiveness in removing heavy metals from wastewater. The capital investment required to implement the chosen treatment technology, along with the associated operating costs (e.g., energy, chemicals, maintenance), would be assessed. While The efficiency of the chosen treatment method(s) in removing heavy metals would be evaluated, considering factors like the

892   concentration of metals in the wastewater, treatment time, and any limitations or potential

893   regeneration requirements. Furthermore, compliance with regulatory standards and guidelines

894   related to heavy metal discharge limits would be considered to ensure the treated wastewater

895   meets the required quality standards. On the other hand, the costs associated with proper disposal

896   or management of the metal-rich residues generated during the treatment process would be

897   accounted for. Lastly, potential Revenue Streams: If the removed heavy metals have commercial

898   value, the possibility of generating revenue through metal recovery or recycling would be

899   explored. Overall, techno-economic analysis provides a comprehensive assessment of costs

900   profits, and potential risks related with ALCB biochar manufacture and the removal of HMs from

901   wastewater, aiding decision-making processes and investment planning.

5. Limitations of current research and what needs to be done in future

903   Considering the declining availability of chemical resources, the application of second-generation

904   biochar derived by ACLB feedstock emerges as a sustainable and environmentally friendly

905   alternative, environmentally friendly and decrease treatment prices. However, current challenges

906   and future prospectives need to be addressed such as Feedstock selection, Genetic modification

907   of feedstocks Pyrolysis process optimization, Scalability and cost-effectiveness, Integrated

908   biorefinery approaches, and Biochar properties and quality control, value-added applications, and

909   artificial intelligence and machine learning. The availability, consistency, and quality of

910   lignocellulosic biomass pose challenges for biochar production and its cost for

911   commercialization.

912   Achieving optimal pyrolysis circumstances, for instance temperature, residence time, besides

913   heating rate, for different lignocellulosic feedstocks is challenging to improve biochar production

914   efficiency, reduce energy requirements, and enhance biochar properties. Moreover, process

915   optimization is crucial to maximize biochar yield, stability, and adsorption capacity while

916   minimizing energy consumption and emissions. Genetically engineering or selectively breeding

917   lignocellulosic biomass could improve biomass quality, biochar yields, biochar physical and

918   chemical characteristics making it more effective in heavy metal treatment and other uses.

919   Subsequently, the usage of artificial intelligence and machine learning techniques can improve

920   process optimization, the prediction of biochar properties, and real-time monitoring, resulting in

921   the manufacture of biochar by agricultural waste biomass that is more efficient and reliable.

922   Addressing these challenges and capitalizing on future prospects will contribute to the continued

923 advancement and adoption of biochar production from agricultural lignocellulosic biomass,
924 unlocking its full potential as a sustainable solution for heavy metal treatment and other
925 environmental applications.

926 Recent advancements in ALCB research have demonstrated its potential as a sustainable and cost-
927 effective solution for wastewater treatment. Studies have focused on optimizing pyrolysis
928 processes and engineering biochar with chemical modifications or nanoparticle integration to
929 enhance adsorption properties for removing heavy metals, organic pollutants, and emerging
930 contaminants [144]. Moreover, in the published research the valorization of agri-food residues
931 into ALCB supports circular economy initiatives by addressing waste management challenges
932 while providing efficient adsorbents for environmental remediation [145,146]. Furthermore, a
933 deeper understanding of pollutant removal mechanisms and the development of tailored biochar
934 materials have expanded its applicability in diverse wastewater treatment systems, highlighting
935 its innovative and timely role in addressing global water quality issues [147,148]

936 Moreover, the focus on the utilization of agricultural waste in biochar research often overshadows
937 or less detailed discussion about the cost of adsorbent preparation for several reasons such as
938 research objectives and scope which primary focus on applications, and scientific emphasis.
939 Besides, complexity of cost such as generalized challenges: Researchers may avoid detailed cost
940 discussions because they would require extensive economic modeling specific to each region or
941 application, making the findings less generalizable. Parenthetically, by incorporating cost
942 analysis, researchers can make biochar studies more relevant to practical applications while
943 maintaining their focus on sustainability and resource efficiency.

6. Conclusion

945 The present work emphasized the role of ALCB base biochar represent a transformative solution
946 for wastewater treatment offer viable solutions to biomass waste management that prevent the
947 pollution threats to humans as well as the environment. The results prove that the quantitatively
948 biomass waste present in an excessive form worldwide. From the various investigations, the
949 following conclusions were made:

950 ▪ ALCB is an abundant, renewable, and low-cost feedstock for biochar production, which
951 is available in both developed and developing countries. The high annual generation of
952 agricultural residues worldwide ensures a reliable feedstock supply, addressing issues of
953 waste management as well as promoting resource recovery.

954 ▪ In efficient production techniques the pyrolysis remains the most promising method for

955 biochar production, due to its versatility, relatively high yield, and ability to process

956 diverse biomass types. The physicochemical properties of biochar including surface area,

957 porosity, functional groups, and carbon content can be tailored by optimizing feedstock

958 selection, reactor designs, and pyrolysis conditions.

959 ▪ LCB biochar demonstrates excellent adsorption capabilities for a range of pollutants,

960 including heavy metals, organic compounds, and other contaminants. The mechanisms,

961 such as ion exchange, electrostatic attraction, and pore-filling, contribute to its high

962 efficacy in pollutant removal. These properties make biochar a valuable tool for mitigating

963 environmental and public health risks associated with untreated wastewater.

964 ▪ Utilizing agricultural residues for biochar production aligns with circular economy

965 principles by converting waste into a valuable resource. Additionally, ALCB biochar

966 contributes to carbon sequestration and reduction, enhancing its role as a carbon sink and

967 supporting global efforts to combat climate change.

968 ▪ ALCB biochar technology not only benefits the environment but also drives economic

969 growth through revenue generation, job creation, and support for local industries.

970 ▪ The life cycle assessment and Techno-Economic analysis underscore the feasibility of

971 integrating biochar production into existing wastewater treatment systems. By addressing

972 economic and technical challenges, this approach can bridge the gap between laboratory

973 research and real-world applications.

974 Lastly, future research should focus on enhancing biochar's functional properties, exploring

975 advanced production methods, and scaling up implementation to maximize its global impact on

976 water quality, resource conservation, and environmental sustainability.

977

978

979 **Author's contribution**

980 **Aqib Zahoor:** Methodology, Conceptualization, Formal analysis, Writing, and original draft.

981 **Xiao Liu:** Writing and Conceptualization, **Yuxin Liu:** Writing and Conceptualization**,**

982 **Shengyong Liu:** Methodology, Conceptualization**,** and Writing**, Wang Yi:** Methodology,

983 Conceptualization**,** and Writing**, Shahdev Sajnani:** Methodology, Conceptualization**,** and

984 Writing, **Lingyu Tai:** Methodology, Formal analysis, Investigation, Supervision, editing the

998

Competing interest

1000 The authors state unequivocally that they do not have any known conflicting financial interests
1001 or personal relationships with third parties that would have given the appearance of influencing
1002 the work disclosed in this study.

Availability of data and materials

Data is available on reviewers and journals requirements.

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Highlights

- Current research on treatment of heavy metals by biochar has been summarized.

- Biochar production and formation mechanism from agricultural biomass.

- Biochar is derived from agricultural waste biomass using pyrolysis techniques examine.

- Complexation, electrostatic interaction, and ion exchange are sorption mechanisms

- Discussion on adsorption behaviors and mechanism of biochar for heavy metal

- Adsorption capacity and mechanisms i.e., Complexation, electrostatic interaction, and ion exchange summarized

- It seeks to offer a rational assessment of what needs to be done in future research

- TEA of agricultural biochar has been studied and discussed in depth

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: