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Chapter

Biochar Development as a Catalyst and Its Application

Stephen Okiemute Akpasi, Ifeanyi Michael Smarte Anekwe, Jeremiah Adedeji and Sammy Lewis Kiambi

Abstract

Biochar is a carbon-rich pyrogenic material that is made from carbon-neutral sources (i.e., biomass). It offers key strategies for carbon capture and storage (CCS) as well as being an environmentally friendly means of soil amendment. The recent recognition of biochar as a versatile media for catalytic applications has prompted preliminary research into biochar’s catalytic capacity and mechanistic practices via various routes. This chapter provides a review of biochar production technologies, biochar’s catalyst development, and its application in various catalytic processes as well as descriptions of the benefits and drawbacks of the various applications currently available. The characteristics of biochar-based catalysts, challenges of effective application of this catalyst system, emerging application, prospects, and future work consideration for effective utilization of biochar-based catalysts were presented.

Keywords: biochar, biodiesel, biomass, catalyst, pyrolysis, tar reforming, wastewater treatment

1. Introduction

With energy shortages and pollution escalating worldwide, renewable feedstocks are crucial for human long-term development. There are many natural sources of animal fats, including lignocellulosic biomass, crops, aquatic culture, biowaste generated by waste management, and domestic and urban waste recycling [1]. Utilizing thermochemical decomposition processes like gasification or pyrolysis, biofuels (bio-oil and syngas) can be produced from biomass and a carbon-based solid residue called biochar [2].

As a porous solid with high carbon content, biochar is formed during the thermal decomposition of biomass at moderate temperatures (e.g., 350–700°C) and under oxygen-limited conditions [3–7]. Despite its chemical and physical properties, biochar’s thermochemical process and the intrinsic properties of biomass feedstock are two of the factors that influence its properties [4]. Due to its porosity and large surface area, biochar is classified as activated carbon (AC), yet it also contains numerous surface functional groups (carbon monoxide, hydroxyl, carbonyl, carboxylic acid, among others) that can be easily tuned and used to make various functionalized
carbon materials. As well as being used for AC production and soil amendment, biochar serves as an adsorbent for pollutants in water and air [5].

Recent research has revealed that biochar is widely utilized as support for metals in catalysis, due to its feedstock availability, large surface area (for good metal phase dispersion and stability), low cost, and stability in basic and acidic media [6]. In addition to catalysis, biochar’s excellent performance in supporting and catalyzing a wide range of reactions has been demonstrated: electrochemical reactions, hydrolysis, gasification/pyrolysis, catalytic reforming/cracking, esterification/transesterification, peroxide/peroxynmonosulfate oxidation, and many more.

Biochar-based catalysts have been utilized for a variety of applications, including water and soil remediation. On the other hand, current perspectives tend to concentrate on applications designed to remediate soils, revegetate, and restore them, convert energy, and remove contaminants from water and wastewater. Despite this, there is still a lack of understanding regarding the synthesis, development, and novel applications of biochar-based catalysts. This chapter provides a comprehensive overview of recent developments in the production, application, and limitations of biochar-based catalysts. Various emerging catalytic applications of biochar-based catalysts are also addressed in this chapter. Further, the benefits of using biochar as catalysts and catalyst supports, as well as the correlations between structural and physical properties of biochar, which provide insights into the development of effective and promising biochar-based catalysts will be highlighted. The challenges and future advancements of using biochar-based catalyst materials are further discussed.

1.1 Properties of biochar

Biochar is a form of organic material that is mostly rich in carbon and other elements such as nitrogen (N), oxygen (O), and hydrogen (H). Biochar has a carbon (C) content ranging from 380 to 800g kg\(^{-1}\) and has both alkyl and aromatic structures [7]. Biochar is also composed of inorganic elements including phosphorus (P), calcium (Ca), aluminum (Al), potassium (K), and silicon (Si), whose quantities vary according to the feedstock used [8]. It has been reported that acidic pH can occur during pyrolysis, depending on conditions of production and the raw materials [9]. Other factors can affect the biochar pH, ranging from neutral to alkaline [10]. In general, biochar has a pH between 5 and 12, and its pH tends to increase in response to increased pyrolysis temperature as bionic acid decomposes, and mineral alkali elements increase [11]. Also, the high pH of biochar can be attributed to the functional organic groups present in it, namely hydroxyl-, aldehyde, and ketone- [12]. As a buffer between acid and bases, these functional organic groups influence biochar’s hydrophobicity and hydrophilicity as well as its adsorption properties [8]. The functional organic groups have the effect of lowering the negative charge on biochar, and therefore, enhancing its cation exchange capacity (CEC) [13].

Due to its high carbon content, biochar has a complex microstructure with numerous pores, which maximizes its surface area [14]. Biochar’s surface area and total pore volume typically range from 8 to 132 m\(^2\)/g and 0.016–0.083 cm\(^3\)/g, respectively. Using the right precursor and pyrolysis parameters, biochar can have surface areas and pore volumes as high as 490.8 m\(^2\)/g [15] and 0.25 cm\(^3\)/g [16]. Following effective post-treatments, such as potassium hydroxide (KOH) activation, the surface area and total pore volume of biochar can be enhanced to 3263 m\(^2\)/g and 1.772 cm\(^3\)/g, respectively [17], which is comparable to or even greater than commercial activated carbon.
Biochar’s surface area and porosity are greatly affected by the pyrolysis temperature [16]. Biochar with a higher pyrolysis temperature within a certain temperature range has a greater surface area [12]. As temperature rises in biochar pyrolysis, volatile substances are forced out of the char, causing pores to form a larger surface area [17]. Due to its high porosity/high amount of residual pores and large surface area, biochar can retain a large quantity of water [14, 18–20]. In contrast, a high pyrolysis temperature diminishes the polar functional groups found in biochar, thereby increasing its hydrophobicity [18]. According to the above characteristics, biochar can influence the pH, soil water-holding capacity, as well as base saturation, and CEC [14]. It is generally possible to modify the properties of biochar by modifying its conditions of preparation [19], as outlined in the next section.

1.2 Biochar production

To produce biochar from different feedstocks, several approaches have been developed. Torrefaction, pyrolysis, gasification, hydrothermal carbonization (HTC), and flash carbonization are the most prominent thermochemical conversion technologies (Figure 1).

1.2.1 Torrefaction

Torrefaction is a mild pre-treatment consisting of slow heating at 200–300°C, followed by a short retention time before gasification or pyrolysis [20]. Often, the resultant solid product is porous, low density, and carbon-enriched, with low moisture content and O/C ratio, an increase in energy density, and improved grindability, making it easier to store and deliver [21]. Its carbon yield can be affected by temperature, retention times, raw material types, and furnace atmosphere [22]. At 200°C, for example, beech lignin began to degrade, the majority of biomass developed at 230°C and cellulose only degraded over 270°C [22]. Using a pilot process, hardwood and

Figure 1.
Overview of biochar-based system production and applications.
switchgrass pellets produced solid yields above 77 wt% [23]. Oil palm fiber pellets were torrefied in an inert atmosphere for 30 min and in an oxidizing atmosphere for 30 min at 275–350°C to yield 43 and 65 wt% biochar, respectively [24].

1.2.2 Pyrolysis

Pyrogenic carbons are produced by the decomposition of biomass at 300–1200°C without oxygen (or with limited oxygen). During pyrolysis, biochar is produced at temperatures ranging from 300 to 700°C. A pyrolysis process can be classified into slow, fast, intermediate, flash, and vacuum modes [25].

1.2.2.1 Slow pyrolysis

In slow pyrolysis, the process temperature is lower (400–600°C), the heating rate is slower (~10°C min\(^{-1}\)), the vapor residence time is much longer (5–30 minutes), and the holding time is long (hours to days) [25]. Biochar typically yields 20–40 wt%, with yields decreasing with increasing pyrolysis temperature and heating rate [26], however, biochar characteristics are also affected by the procedure and feedstock used [27]. Comparing biochars derived from the wood stem and bagasse with palm kernel shell, paddy straw, and cocopeat, biochar derived from the wood stem and bagasse exhibited a wide range of pores and a high surface area. Biochar develops a significant surface area structure and pore structure at around 500°C [28] with a wide range of mineral compositions and high thermal stability [29].

1.2.2.2 Fast pyrolysis

Fast pyrolysis refers to the treatment of biomass at high temperatures without oxygen [30]. It is usually necessary to dry and grind the feedstock to facilitate effective heat exchange and conversion. This technique produces high liquid yields (bio-oil) rather than solid char (15–25 wt%) [31]. In contrast to the slow pyrolysis of wheat straw, fast pyrolysis generated biochar with a labile un-pyrolyzed carbohydrate fraction (8.8%) rather than carbonized completely [32]. There was a significant difference in the pH, particle size, and specific surface area for biochars produced using these two methods at 400°C, as well as a significant increase in surface area at 500°C (175.4 m\(^2\) g\(^{-1}\)), in comparison to 300°C (2.9 m\(^2\) g\(^{-1}\)) and 400°C (4.8 m\(^2\) g\(^{-1}\)) [21, 33].

1.2.2.3 Intermediate pyrolysis

Intermediate pyrolysis produces 15–35 wt% dry and brittle biochar at temperatures between slow and fast pyrolysis, i.e., solid residence durations of 0.5–25 min, vapor residence times of 2–4 s, and moderate temperatures up to 500°C [34]. Utilizing barley straw and wood pellets, a pilot-scale production yielded 30 wt% char with a carbon content of 75 wt% [25]. The process produces 51.7 wt% char from the organic fraction of municipal solid waste as a result of inert fractions in the biomass [35]. Table 1 illustrates the product yield of pyrolysis processes.

1.2.3 Gasification

Carbonaceous materials are turned into char, tars, and syngas through gasification at high temperatures (~800°C) in the presence of a gaseous active medium (e.g., carbon
Biochar Development as a Catalyst and Its Application
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During this process, the material is dried, pyrolyzed, partially oxidized, and reduced. Generally, char only makes up 5–10 wt% of the mass of the feedstock [39]. As a by-product of large-scale processes, biochar is produced in large quantities every day. Biochar produced through gasification usually has smaller particles than biochar produced by pyrolysis, lower surface area, and a lower total pore volume [40]. Since the aromatic rings are condensed, gasification chars contain little carbon (20–60 wt%) but are highly stable, preventing microbial mineralization and chemical oxidation; however, their surface chemistry is constrained by their absence of functional groups [34]. Biodiesel generation, catalytic tar decomposition, soil amendment, anode materials for direct carbon fuel cells, and anaerobic digestion additives are just a few of the uses for gasification char [41].

1.2.4 Hydrothermal carbonization

Biomass can be processed using a thermochemical process called hydrothermal carbonization (HTC). In closed vessels with liquid water and autogenous pressure of 2–10 MPa, the feedstock is heated from 200 to 300°C and hydrochar is produced [42]. The thermal stability of hydrochar is improved by high temperatures (300°C). Wet torrefaction or wet pyrolysis are other terms for HTC [43, 44]. In comparison with biochar, hydrochar contains less carbon, ash, surface area, and a smaller pore volume [39].

1.2.5 Flash carbonization

Through flash carbonization, biomass can be transformed into biocarbon (i.e., charcoal) rapidly and efficiently, typically by starting and controlling a flash fire at a high temperature within a packed bed (~1 MPa) [45]. The biomass is transformed into gas and charcoal in less than 30 min when the combustion flame flows in the opposite direction of the airflow. Charcoal yields are typically approximately 40 wt% [45].

1.3 Biochar as a promising catalyst

Biochar can serve as catalyst support. Besides stabilizing and dispersing nanoparticles, biochar can also provide more active sites for catalytic degradation reactions [46].

<table>
<thead>
<tr>
<th>Process</th>
<th>Bio-oil (liquid)</th>
<th>Biochar [37]</th>
<th>Syngas (gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast pyrolysis</td>
<td>75% (25% water)</td>
<td>15–25%</td>
<td>10–25%</td>
</tr>
<tr>
<td>Short hot residence time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-500°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate pyrolysis</td>
<td>50% (50% water)</td>
<td>25%</td>
<td>20–30%</td>
</tr>
<tr>
<td>Moderate hot vapor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>residence time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-moderate temperature</td>
<td>(300–400°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow pyrolysis</td>
<td>50% (50% water)</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td>Long residence time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-moderate temperature</td>
<td>(200–300°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasification</td>
<td>5% tar (5%)</td>
<td>10%</td>
<td>85%</td>
</tr>
<tr>
<td>Long vapor residence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature (-700°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of product yield of pyrolysis processes [36].

dioxide, air, nitrogen, oxygen, steam, or gas mixtures) [37, 38].
Biochar’s mesoporous structure enhances the proper dispersion of immobilized metal particles while also preventing particle aggregation owing to intra-particle interaction [47]. The incorporation or fixing of metal elements, for example, magnesium (Mn), copper (Cu), cobalt (Co), and iron (Fe) into biochar pores result in no or minimal metal escape into the aqueous phase [48].

As a heterogeneous catalyst or support, biochar offers many advantages including large surface area, lower cost, functional group tailoring, etc., which makes it highly beneficial for many catalytic applications. There are several intrinsic properties of biochar that contribute to its effectiveness as a catalyst [49]. It has a good thermal, stable structure, mechanical stability, and a chemically hierarchical structure that originates from biomass. Biochar-based catalysts have the following distinctive characteristics: (i) heterogeneity, i.e., the reaction mixture can be easily isolated from other reactants; (ii) bifunctionality, i.e., transesterification and esterification are involved; (iii) recyclable; (iv) porous; (v) non-graphitizable, i.e., it does not form crystal at high temperatures [50]. Comparing biochar-based catalysts with other solid-based catalysts, biochar has the advantages of being cost-effective, eco-friendly, easy to produce, reusable, and biodegradable.

Furthermore, biochar as a catalyst can be used in many different fields, including agriculture, environment, and energy, for biodiesel production, tar removal, waste management, production of syngas, production of chemicals, and removal of contaminants, etc. [45, 51]. Biochar is an excellent catalyst with several beneficial properties. Biochar, for instance, is catalytically active in cracking tar because of its presence of inorganic elements including Fe and K [47]. A biochar-supported metal catalyst can be synthesized by adsorbing metal precursors on its surface functional groups [52]. Despite this, biochar has some properties that preclude it from functioning as a catalyst, such as poor porosity and low surface area. Considering that biochar contains more functional groups, it must have a large surface area for catalysis. A functional group, such as OH, adsorbs norfloxacin. Adsorption of ammonium is possible through C··O and ··OH groups. To endow biochar with specific properties, it is necessary to develop a variety of modification strategies. Furthermore, several processes can be used to activate feedstocks, control synthesis conditions, functionalize materials on the surfaces, form composites with other materials [53], etc.

1.4 Characteristics of biochar based catalyst

In addition to its properties, biochar’s potential for specific applications is dependent on both the biomass source and the conditions of preparation. Biochar, for instance, is suitable as an electrode material because it is electrically conductive and porous [54]. It has been proven that structurally bound nitrogen groups and high porosity biochar make superior supercapacitor electrode materials [55]. However, the intrinsic inorganics, matrix nature, and surface functionality of biochar have a significant influence on its catalytic performance.

1.4.1 Bulk element and inorganics

The carbon content of activated carbon from coal is approximately 80–95%; however, that content is lower for biochar (45–60 wt%) than carbon black (98%) [5]. Biochar also contains substantial amounts of hydrogen and oxygen. Another characteristic of biochar is that it contains small amounts of inorganic elements like potassium, sodium, calcium, magnesium, sodium, iron, and calcium. The nature of raw
biomass greatly affects the amount and composition of inorganics. Woody biomass, as well as herbaceous and hydrophyte biomass, usually have a much lower inorganic content than biochar made from these sources [56, 57].

The inorganic components of biochar are crucial to many of the biochar’s catalytic applications [47], including tar cracking [58], methane decomposition, and bio-oil upgrading [59].

1.4.2 Chemistry of biochar matrix

Amorphous crystalline sheets of high-conjugated aromatics make up most of the biochar matrix. As shown in Figure 2, these aromatic sheets are crosslinked randomly. In response to rising processing temperatures, biochar crystallites increase in size, and order is created throughout the entire structure [62]. The aromatic structure of biochar may also contain heteroatoms, including N, P, and S. These heteroatoms have a different electronegativity from the aromatic C, which results in biochar’s chemical heterogeneity. This plays a key role in catalytic applications [58].

1.4.3 Surface functional groups

Comparing biochar to other carbon materials including (activated carbon and carbon black), Figure 3 shows that it typically contains large numbers of surface functional groups. Biochar can be functionalized using its surface functional groups. Moreover, biochar has been shown to facilitate the loading of metal precursors onto metal catalysts as part of the synthesis of a metal catalyst supported by biochar [52]. Biochar-based catalysts can also work better for certain reactions if they contain some surface functional groups. Biochar-based solid-acid catalysts are typical examples. Kitano, Yamaguchi [63] demonstrated that sulfonated carbon is more effective at hydrolyzing cellohexaose, than sulfonic acid (SO\textsubscript{3}H)—bearing resins. Adsorption sites, in this case, were found in the carboxylic acid (COOH) and hydroxyl (OH) groups of phenolic groups in the carbon material. Researchers found that the combination of functional groups on biochar-based solid acids was efficient for hydrolyzing cellulose and 1,4-glucan.

Figure 2.
Chemical structures of (a) pyrochar and (b) hydrochar (adapted from Shi & Lee) [60, 61].
2. Preparation of biochar-based catalyst

Biochar has been activated and functionalized in various ways to adjust its physicochemical properties, leading to enhanced reactivity in a range of processes and applications [48]. Impregnation and physical or chemical activation are the most popular methods. In-situ or post-synthesis methods are employed in such modifications. Biochar-based catalysts have the potential to be a feasible alternative to metal-based catalysts and carbon catalysts driven by fossil fuels. Table 2 lists the types of biomass used to make biochar-based catalysts.

2.1 Impregnation

This technique involves mixing feedstock and metallic precursors (in-situ) into biochar structures to incorporate active metallic species into them [64]. With the use of biochar, lignin magnetite pellets were synthesized into zero-valent iron at 900°C [64]. It was possible to remove trichloroethylene by both adsorptive and degradative mechanisms due to the macro-porosity developed. Rice straw biochar was impregnated with cobalt nitrate ($\text{Co(NO}_3\text{)}_2$), then hydrothermally treated and calcined to produce the composite [65]. In comparison to pure biochar ($43.0 \text{ m}^2 \text{ g}^{-1}$, $0.081 \text{ cm}^3 \text{ g}^{-1}$) and cobalt (II, III) oxide ($\text{CO}_3\text{O}_4$ $37.0 \text{ m}^2 \text{ g}^{-1}$, $0.184 \text{ cm}^3 \text{ g}^{-1}$), the composite showed greater SBET (62.7 $\text{ m}^2 \text{ g}^{-1}$) and total pore volume (0.207 $\text{ cm}^3 \text{ g}^{-1}$). The catalyst was shown to be effective for oxidatively degrading ofloxacin (over 90% removal in 10 min) using peroxymonosulfate (PMS). An X-ray photoelectron spectrometer (XPS) study revealed that the rich mesoporous support contains many CO−OH groups, which are important for activation. The obtained pristine biochar may also contain metal species varying in amounts and characteristics, depending on the biomass source. Despite this, impregnation typically produces composites rather than carbonaceous biochar, so one could compare biochar with impregnated composites and exhausted catalysts.

2.2 Physical activation

A physical activation process involves exposing the pyrolyzed biochar materials to a streamflow control or carbon dioxide or a mixture of both when temperatures...
Biochar Development as a Catalyst and Its Application
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Exceed 700°C. Gaseous activation agents, depending on the degree of C–H₂O and/or C–CO₂ gasification that occurs at such high temperatures, are capable of partially eroding carbon atoms in the as-prepared biochar matrix [66]. By physically activating the carbonized material, most of the reactive carbon parts can be eliminated and the enclosed pores in the biochar matrix can be opened and interconnected [67]. Consequently, the surface area of biochar increases significantly, resulting in an improved micropore structure and a lower mesopore content [68]. Figure 4 illustrates the process for producing biochar-based catalysts.

Activated biochars differ significantly from one another in terms of a specific area, pore size distribution, and porosity based on the type of biomass, reaction parameters, and activating gas [66]. Lima et al. [62] for example, evaluated the effects of steam activation on the surface areas and porosities of different biochars, as well as their metal ion adsorptive capabilities. They found that steam-activating biochars at 800°C for 45 minutes dramatically increased the surface area and micropore volume from less than (5 m² g⁻¹) to (136–793) m² g⁻¹. In addition, due to the increased porosity and surface area, these biochars were able to improve their metal ion adsorption performance to varying degrees after activation [69]. In addition, Kołtowski et al. [60] utilized steam and CO₂ to activate biochar produced from the slow pyrolysis of willow. Their findings revealed that both steam and carbon dioxide activation considerably increased the porosity and surface area of biochar. Additionally, steam-activated biochar (840.6 m² g⁻¹) and CO₂-activated biochar (512.0 m² g⁻¹) showed significantly larger surface areas than those of unactivated biochar (11.4 m² g⁻¹). In contrast with the CO₂-activated biochar, steam-activated biochar was found to have higher specific surface areas and pores [60].

2.3 Chemical treatment

Chemical activation involves mixing freshly prepared biochar with activation agents (e.g., KOH, ZnCl₂, K₂CO₃, H₂SO₄, H₃PO₄, etc.). The biochar is subsequently heated at high temperatures in an inert gas flow [70]. While the mechanism for chemical activation is still unclear, chemical activation is more corrosive than physical activation [71]. However, high temperatures can significantly enhance the corrosion properties of chemical activation substances. Aside from removing some carbon atoms from the biochar matrix, these chemicals might suppress tar formation and/or

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Production method (biochar)</th>
<th>Production method (catalyst)</th>
<th>Type of catalyst</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana</td>
<td>Carbonization</td>
<td>Wet impregnation</td>
<td>Solid alkali</td>
<td>[49]</td>
</tr>
<tr>
<td>Vegetable oil asphalt, coconut shell, oat hull, glucose, peanut shell</td>
<td>Carbonization</td>
<td>Sulfonation</td>
<td>Solid acid</td>
<td>[50]</td>
</tr>
<tr>
<td>Rice husk</td>
<td>Carbonization</td>
<td>Chemical activation</td>
<td>Solid acid</td>
<td>[51]</td>
</tr>
<tr>
<td>Peat</td>
<td>Carbonization</td>
<td>Wet impregnation</td>
<td>Solid alkali</td>
<td>[52]</td>
</tr>
<tr>
<td>Irul wood saw dust</td>
<td>Slow pyrolysis</td>
<td>Sulfonation</td>
<td>Solid acid</td>
<td>[53]</td>
</tr>
<tr>
<td>Pamelo peel, shelled palm kernel</td>
<td>Carbonization</td>
<td>Wet impregnation</td>
<td>Solid alkali</td>
<td>[54]</td>
</tr>
</tbody>
</table>

Table 2. Production methods and feedstocks for biochars and biochar-based catalysts.
facilitate the formation of volatile compounds [67]. It was reported by Liu et al. [59], that chemical erosion and physical activation lead to large surfaces and high porosities in KOH-activated biochar, and metallic K intercalation. Chemical activation generally results in a higher activation efficiency than physical activation, and chemical activation may be performed at a relatively lower temperature, resulting in a more porous and higher surface area biochar [43]. Although chemical activation leaves biochar with improved surface area and porosity, it is usually necessary to wash it to remove impregnating agents and salts [50]. The use of chemical activation is, therefore, affected to some extent by several factors, including corrosion of equipment, chemical recycling, secondary pollution, etc. [43].

Several factors affecting the chemically activated biochar, including the temperature of activation, feedstock type, the type, and concentration of the activating agent, etc., are significant [66]. Biochar impregnated with KOH solution has been investigated by Dehkhoda et al. [65] to determine how activation temperature (685–700°C) influenced the electrosorption performance, porosity, and surface area. In their study, there was an increase in the surface area of the biochar from (1.66 m² g⁻¹) to (614–990 m² g⁻¹), as well as its porosity, which increased from negligible to 0.6–0.9 m³ g⁻¹. Additionally, as the temperature rises, a decrease in biochar surface area is observed, by collapsing and burning off the micropore walls or causing the formation of graphite-like structures in the matrix. Since biochar activated at 675°C contains more micropores and oxygen-containing functional groups, its overall electrosorption capacitance was more than twice as high as that of activated biochar at 1000°C [68].

3. Application of biochar catalyst

The growing discovery of biochar as a diverse material for catalytic activities has prompted preliminary study into the catalytic potential of biochar as well as applications in different processes.

3.1 Biodiesel production on biochar catalysts

It has been demonstrated that biodiesel can be used as a renewable alternative to traditional petrochemical-derived diesel [67, 72]. The application of traditional catalysts in the synthesis of biodiesel from biomass (vegetable oils) has been extensively explored. However, the manufacture of such catalysts necessitates the use of costly metal precursors. Because of their low cost and versatility, sulfonated biochars have been utilized to produce biodiesel. It has been demonstrated that sulfonated biochar
Biochar Development as a Catalyst and Its Application

Biochar can produce the maximum productivity (88%) of biodiesel products from vegetable oil in the esterification of FFAs (free fatty acids) and transesterification of TGs (triglycerides) carried out simultaneously at 100°C for 15 h [72–74]. It was observed that after five recycles of the catalyst, the output of methyl esters reduced from 88% to 80%, due to the leaching of $\cdot SO_3^\cdot$ functional groups [74]. Using a biochar catalyst made from palm kernel shells to transesterify sunflower oil, Kostić et al. [69] investigated the catalytic activity. With the deposition of 3 wt% catalysts into a reaction, the production of methyl esters was 99% at 65°C [75]. The solid acid/base biochar catalysts mentioned above resulted in a significant synthesis of biodiesel from a variety of edible oils. In contrast, both catalysts exhibited signs of deactivation after many re-uses in the laboratory. While transesterification was taking place, the base catalyst was contaminated by undesired secondary products formed by CaO and the feed oil interactions [75]. The ester output (from TGs and FFAs) is comparable to that obtained from non-biochar catalysts. However, to make biochar catalysts for biodiesel generation more realistic, the stability of biochar catalysts must be increased to prevent the need for post-treatment processes to remove S or Ca from the catalyst [75]. The biodiesel production efficiency of different biochar and non-biochar-based catalysts is shown in Table 3.

### 3.2 Biomass hydrolysis on biochar catalysts

Biochar catalysis has been applied in biomass hydrolysis. The fact that most biochar-based catalysts are more effective than commercially available and traditional catalysts has long been recognized. According to Ormsby et al. [75], pinewood chips and peanut hulls that were sulfonated with $H_2SO_4$ were used as the raw materials for biochar. When used to hydrolyze xylan, the sulfonated pine chip-biochar catalyst demonstrated an 85% transformation rate in 2 h at 393 K. On the other hand, while having a greater surface area (1391 $m^2g^{-1}$) than the biochar catalyst (365 $m^2g^{-1}$), industrial activated carbon only achieved a 57% transformation in 24 hours [84]. Furthermore, biochar catalysts showed greater starting process rates for the hydrolysis of cellobiose and xylan when compared to other catalysts (activated carbon and Amberlyst-15) [84], indicating that they were more efficient than the other two catalysts. Moreover, the hydrolysis of maize stover, switchgrass, and prairie cordgrass

<table>
<thead>
<tr>
<th>Biochar-based catalyst</th>
<th>Feedstock</th>
<th>Temp. (K)</th>
<th>Biodiesel yield</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood biochar-mixture</td>
<td>Canola oil</td>
<td>423</td>
<td>44%</td>
<td>[76]</td>
</tr>
<tr>
<td>Peanut hull-biochar</td>
<td>Palmitic + stearic acid + soybean oil</td>
<td>333</td>
<td>70%</td>
<td>[77]</td>
</tr>
<tr>
<td>Husk of rice</td>
<td>Oleic acid + canola oil</td>
<td>423</td>
<td>48%</td>
<td>[78]</td>
</tr>
<tr>
<td>Rice husk-biochar</td>
<td>Cooking oil waste</td>
<td>383</td>
<td>88%</td>
<td>[79]</td>
</tr>
<tr>
<td>Biochar-palm kernel shell</td>
<td>Sunflower oil</td>
<td>333</td>
<td>99%</td>
<td>[80]</td>
</tr>
<tr>
<td><strong>Non-biochar catalysts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al(HSO$_4$)$_3$</td>
<td>Vegetable oil waste</td>
<td>493</td>
<td>81%</td>
<td>[81]</td>
</tr>
<tr>
<td>Zeolite beta</td>
<td>Cooking oil waste</td>
<td>353</td>
<td>25%</td>
<td>[82]</td>
</tr>
<tr>
<td>SO$_4^{2-}$/ZrO$_2$</td>
<td>Cooking oil waste</td>
<td>353</td>
<td>44%</td>
<td>[83]</td>
</tr>
</tbody>
</table>

Table 3. A comparison of biochar and non-biochar-based catalysts for biodiesel production.

Biochar catalysis has been applied in biomass hydrolysis. The fact that most biochar-based catalysts are more effective than commercially available and traditional catalysts has long been recognized. According to Ormsby et al. [75], pinewood chips and peanut hulls that were sulfonated with $H_2SO_4$ were used as the raw materials for biochar. When used to hydrolyze xylan, the sulfonated pine chip-biochar catalyst demonstrated an 85% transformation rate in 2 h at 393 K. On the other hand, while having a greater surface area (1391 $m^2g^{-1}$) than the biochar catalyst (365 $m^2g^{-1}$), industrial activated carbon only achieved a 57% transformation in 24 hours [84]. Furthermore, biochar catalysts showed greater starting process rates for the hydrolysis of cellobiose and xylan when compared to other catalysts (activated carbon and Amberlyst-15) [84], indicating that they were more efficient than the other two catalysts. Moreover, the hydrolysis of maize stover, switchgrass, and prairie cordgrass.
biomass was accomplished using a corn stover-biochar mixture [85]. Compared to a traditional homogeneous H\textsubscript{2}SO\textsubscript{4} catalyst, the catalyst exhibited a stronger preference for glucose and xylose, confirming its superior efficiency in biomass hydrolysis. The existence of sulfonated corn stover-based biochar increased the production of glucose and xylose from lignocellulosic biomass [48]. The glucose output was 8–10% and the xylose yield was 23–41% when compared to the equivalent polysaccharide [85]. The findings were equivalent to those obtained from the hydrolysis of model substances using a similar catalyst: cellulose yielded 3% glucose and xylan yielded 40% xylose. This indicated that the biochar was able to sustain good efficiency even when exposed to contaminants and a complex matrix of biomass materials. The performance of different biochar based catalysts for hydrolysis is shown in Table 4.

### Table 4. Biochar catalyst for hydrolysis.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Condition of catalyst preparation</th>
<th>Feedstocks</th>
<th>Condition of reaction</th>
<th>Catalyst performance</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forestry wood waste</td>
<td>Slow pyrolysis at 700°C for 15 h; sulfonated with 30 w/v% H\textsubscript{2}SO\textsubscript{4}.</td>
<td>Fructose or maltose</td>
<td>C\textsubscript{cata} = 25 w/v%, T = 1 h (maltose: 160°C and fructose: 180°C), C\textsubscript{F} = 5 w/v%</td>
<td>Selectivity = 60.4%; HMF yield = 42.3%; selectivity = 88.2%; Glucose yield = 85.4%</td>
<td>[86]</td>
</tr>
<tr>
<td>Palm kernel shells</td>
<td>Carbonized at 550°C for 4 h; sulfonated at 120°C for 6 h with concentrated sulfuric acid</td>
<td>Cellulbiose</td>
<td>C\textsubscript{cata} = 50 g/L, T = 24 h, Temp. = 110°C</td>
<td>Glucose yield = 100%</td>
<td>[87]</td>
</tr>
<tr>
<td>Bamboo</td>
<td>Carbonates of alkali molten at 450°C; pyrolyzed at 450°C; sulfonated at 150°C for 6 h</td>
<td>Cellulose</td>
<td>C\textsubscript{cata} ≈ 16.67 g/L, T = 12 h, Temp. = 150°C</td>
<td>RSs yield = 52.8%, Glucose yield = 43.5%</td>
<td>[88]</td>
</tr>
<tr>
<td>Bamboo</td>
<td>80% sulfuric acid treatment; immersion in oleum and heating with N\textsubscript{2}; ultrasonic vibration treatment with NaCl saturated aqueous solution; treatment with an excess of IL-Cu in anhydrous MeCN</td>
<td>Bamboo and cellulose</td>
<td>C\textsubscript{cata} ≈ 133.33 g/L, C\textsubscript{F} ≈ 66.67 g/L, T = 2 h, Temp. = 90°C, Microwave radiation = 350 W</td>
<td>TON: 3.54 (cellulose), 2.42 (bamboo), RSs yield = 35.6% (cellulose), 22.5% (bamboo)</td>
<td>[89]</td>
</tr>
</tbody>
</table>

Hydroxymethyl furfural = HMF, reducing sugars = RSs, TON = turnover number, temperature = Temp, time = T, catalyst amount = C\textsubscript{cata}, feedstocks concentration = C\textsubscript{F}, imidazolium chloride = IL-Cu; anhydrous MeCN = anhydrous acetonitrile.

Source: Adapted from Shan et al. [90].
3.3 Production of biogas

3.3.1 Tar reforming (syngas synthesis)

Tar reforming is the process of converting the hydrocarbon combination that is inevitably generated following the gasification and pyrolysis of biomass into useful syngas (combination of CO and H₂). Syngas is a multipurpose intermediate and/or beginning raw material for the synthesis of fuels and chemicals. As a result of this fact, several studies have investigated the potential involvement of biochar catalysts in the generation of syngas in recent years [58]. Biochar comprises catalytic centers that are similar to those found in traditional catalysts, such as dolomites (MgCO₃·CaCO₃), olivine ((Mg²⁺, Fe²⁺)₂SiO₄), and Ni- and alkali metal-based catalysts, could be efficient for tar reforming [78]. The switchgrass biochar that had been activated by KOH demonstrated the highest efficacy, with around 90% elimination of toluene. This was likely owing to the increased surface area of the switchgrass biochar. Iron calcined biochar [79] and nickel nanoparticle-embedded biochar [80] have also been shown to be efficient. Ren et al. [58] noted that the application of a biochar catalyst improved the quantity of syngas produced during biomass pyrolysis. At 480°C, it was discovered that the syngas output increased from 15 wt% to 46 wt% in the absence and presence of biochar catalyst respectively. According to Ren et al. [58, 81], the hydrogen content in syngas rose significantly with the addition of the biochar catalyst (27 vol%), in contrast to when the catalyst was not employed. A current investigation shows that biochar can be applied in the dry reforming process [82]. The dry reforming of CH₄ was carried out on a tungsten carbide [83] Based on a biochar (WC-biochar) catalyst. As the CH₄/CO₂ ratio rose, the CH₄ transformation reduced, while the CO₂ transformation improved. Increases in the CH₄/CO₂ ratio and temperature resulted in greater H₂ production, and the WC-biochar catalyst remained stable for 500 hours after being introduced into the system [82].

3.3.2 Tar elimination

The gasification of biomass is a viable sustainable energy pathway since it has the potential to enhance the generation of large quantities of syngas. A consequence of its synthesis, however, is the formation of condensable hydrocarbons (tar). Tars can accumulate in pipelines throughout a system, causing them to become clogged and potentially inhibiting downstream operations [84]. To commercialize biomass gasification for syngas generation, the elimination and/or mitigation of tar is a vital first stage in the procedure [85, 90]. In reality, catalytic tar cracking was carried out at 823–1173 K, with dolomite, olivine, and base metals including nickel [78], serving as catalysts. These conventional tar cracking catalysts, on the other hand, were susceptible to deactivation as a result of coking and contamination [91]. It has been attempted numerous times to degrade tars using a secondary reactor containing noble metal catalysts (e.g., platinum, palladium, and rhodium) [92], but the restoration of the catalyst has remained a difficult process. The introduction of an affordable catalyst for tar breakdown is therefore preferable in this situation. In this regard, biochar was found to be superior to traditional catalysts when used as a catalyst to remove tar [93]. The tar removal efficiency of biochar catalysts is summarized in Figure 5. The majority of investigations have relied on model processes of tar disintegration with toluene, naphthalene, and phenol. Moreover, the biochar-based metal catalysts (e.g., Nickel and Iron) outperformed the typical mineral catalysts in terms of tar removal.
efficiency. For example, a catalyst constituted of a combination of NiO and wood-biochar eliminated 97% of the genuine tars formed during sawdust gasification, resulting in an improvement in syngas synthesis attributed to the catalytic reforma-
tion of the tars [94]. According to Shen et al. [79], bimetallic catalysts based on rice
husk-biochar generated seven times fewer tars in the biomass combustion process
than monometallic catalysts and raw biochars during the pyrolysis of biomass. The
NiO-biochar catalyst combination remained stable for an 8-h time in the stream
(TOS). One of the limitations linked to biochar and metal-biochar catalysts for tar
reduction is the process temperature, as tar elimination occurs at >973 K. At reduced
temperatures (i.e., 843 K) with the typical nickel catalyst, tar removal can be com-
menced [92], however, biochar is not yet efficient at these lower temperatures [95].
To overcome these restrictions and broaden the scope of biochar’s application as a
catalyst, future work must concentrate on overcoming these constraints.

3.4 Wastewater treatment

Due to its ability to remedy environmental pollutants, biochars are becoming
highly significant for enhancing environmental quality in the world today [96].
Wastewater, which is a result of household, commercial, and agricultural operations,
has long been a global concern since it affects everyone. Biochars offer a significant
deal of promise for use in wastewater remediation applications. Biochar’s applications
in the cleanup of different wastewaters are the primary focus of this section.

3.4.1 Industrial wastewater remediation

Industrial wastewater originates from a variety of sources. In addition, heavy metals
and organic contaminants are the most prevalent contaminants in industrial wastewa-
ter. It has been demonstrated that biochars can be used in the treatment of industrial
effluent. It is possible to cast membranes, beads, and solutions from a biochar-chitosan
combination that has been cross-linked. It has the potential to be used efficiently as an
adsorbent for the adsorption of heavy metals in industrial wastewater. The amount of
chitosan and biochar used in the adsorption of Cu, Pb, As, Cd and other heavy metals in industrial wastewater would depend on the ratio of the two materials [97]. Gliricidia biochar has shown promise in the elimination of crystal violet (CV) from aquatic environments in dye-based industries. A biochar’s pH value, surface area, and pore volume are all important factors to consider throughout the CV sorption process [98]. Biochar made from bagasse was employed to absorb lead from the effluent of the battery production sector. The maximal adsorption ability can attain 13 mg/g, and the adsorptive activity is dependent on the moderate pH value, contact time, and concentration [99]. So far, the majority of the trials on the utilization of biochar in the clean-up of contaminants from industrial wastewater have been carried out in a laboratory environment; however, additional study and deployment in the actual situation are required.

3.4.2 Treatment of municipal wastewater

Biochar can be employed alone or in combination with other techniques for municipal wastewater treatment, resulting in the retrieval of labile nitrogen and phosphorus [100]. Engineered biochar containing aluminum oxyhydroxides (AlOOH) was used to recover and restore phosphorus from tertiary remediated wastewater [101]. The adsorption strategy of phosphorus is mostly based on electrostatic interaction. Phosphorus adsorbed on manufactured biochar has the potential to be used as a slow-release fertilizer for agricultural activities. Biochar generated from digested sludge was employed as an adsorbent for the elimination of NH₄ from municipal wastewater. Biochar produced at 723 K has the maximum NH₄ reduction capability due to its increased functional group density and surface area, and the procedure is governed by chemisorption [102]. This shows that biochar derived from waste sludge can be utilized to ozonate refinery effluent and achieve a significant reduction rate of total organic carbon (TOC) [103].

3.4.3 Wastewater treatment in the agricultural sector

Because of the rapid development of the agriculture sector, agricultural pollution is getting extremely serious. As a result, pesticides and toxic heavy metals are released into croplands in large quantities, the situation is becoming increasingly worrisome [104, 105]. The use of biochar and its modified forms in the remediation of agricultural wastewater pollution has been investigated. Pesticides such as atrazine and pentachlorophenol are two of the most often used in agriculture. Adsorption of atrazine and imidacloprid from agricultural wastewater by rice straw biochar and phosphoric acid-modified rice straw biochars is much higher than that of adjusted rice straw biochar [106]. Corn straw and soybean biochars both exhibit strong atrazine reduction potentials, with the adsorption efficiency owing mostly to the pH value and pore volume of the biochars [107]. Steam-activated biochar is efficient at eliminating sulfamethazine, and the rate at which it absorbs the substance is reliant on the pH value [108]. The presence of hazardous heavy metals in agricultural wastewater is yet another widespread issue.

4. Emerging advances in the applications of biochar catalyst

Recent advancements in the use of biochar for processes other than agriculture have been linked to biochar’s various properties. Among other characteristics that are
suitable for electrode materials, biochar has high porosity and high electrical conductivity [54]. It is preferred to use biochar with structurally bound nitrogen groups and high porosity as electrode materials for supercapacitors [55]. During catalysis, surface functionality, matrix nature, and intrinsic inorganic components are all important factors [49]. Unlike activated carbon derived from coal, biochar has a considerable amount of other organics present in it based on the biomass feedstock. These organics aid its compatibility, utilization, and effectiveness for varying applications than activated carbon.

There are several advantages to using biochar as a catalyst or catalyst support. Firstly, since biomass resources are sustainable and synthesis techniques have been developed, the process for producing biochar is simple and inexpensive. Secondly, the physicochemical properties of biochar can be easily tuned through a variety of methods. As a third consideration, biochar may be of interest in catalytic applications because of its surface functional groups, a hierarchical structure derived from the biomass matrix, and the presence of inorganic species [48]. Additionally, active metals and biochar support may, in some cases, have synergistic effects on catalysis [49].

4.1 Energy storage and conversion

Due to excess energy generation, energy storage is becoming more popular in some developed countries, and stored energy can also be used as a backup in the event of an emergency. The increased use of electric vehicles necessitates the continuous development of batteries with greater energy storage capacity. Despite continuous battery development, there are times when an unplanned situation may occur in electric vehicles. To alleviate such a situation, supercapacitors, which are energy storage devices primarily made of carbon materials, have been applied as continuous power sources in digital communications systems and electric vehicles. Because of its wide availability and low environmental impact, carbon materials with a high surface area and a rich porous structure are the primary raw materials for making super-capacitors [98]. It is crucial to the development of the supercapacitor industry to produce attractive, high-quality carbon materials at a reasonable price [99].

The utilization of biochar as material for supercapacitors has been tested by researchers with incredible results obtained. Biochar is made from paper cardboard and woody biomass. Based on the pyrolysis of woody biomass, the biochar supercapacitor electrodes exhibited a potential window of about 1.3 V, and fast charging-discharging behaviors with about 14 F/g gravimetric capacitance [100]. The authors also enhanced the performance of woody biochar by activating it with nitric acid. According to the researchers, the nitric acid treatment helped increased the capacitance from 14 to 115 F/g with 5000 usage cycles [100]. Likewise, Liu et al. [98] also created a high-performance supercapacitor out of biochar-derived carbon monolith, which was created by pyrolyzing poplar wood at 900℃ for 6 h and then surface-modifying with nitric acid. The supercapacitor was discovered to have a highly consistent structure as well as a high porosity. The maximum specific capacitance was high (234 F/g) and cyclic stability was excellent [98, 99].

With the recent development of direct carbon fuel cell (DCFC) which converts carbonaceous material directly into electricity. The DCFC directly oxidizes solid carbon to produce electricity by using the chemical energy contained therein. Fuel utilization can reach nearly 100% if fuel feed and product gases are separated easily. The use of biochar as an energy source for this fuel cell has shown tremendous results. In a study by Kacprzak et al. [101], nine different carbonaceous fuels were tested, including
commercial graphite, a carbon black, two commercial types of hard coal, and four biochars made by the authors, and one commercial biochar. At 0.5 V, commercial biochar had the second-highest current density (64.22 mA/cm$^2$) and the third-highest power density (32.8 mW/cm$^2$). Biochar produced in the laboratory had a high current density (36–44.6 mA/cm$^2$) and power density (18–22.4 mW/cm$^2$) [102].

4.2 Challenges and prospects of biochar-based catalyst applications

The use of biochar just as any other material has some limitations in its application for energy storage, conversion, and electrocatalyst. In terms of energy storage, the performance efficiency of tested biochar is still low when compared to its counterparts, though the biochar is easy to access and economical. Likewise, in the use of biochar in DCFC, it has been reported that upon consumption of the carbon content, the ash content present in biochar blocks the active surface area thereby impeding the effectiveness of the whole process [102]. In terms of reusability as a catalyst, further work still needs to be done as biochar from some feedstocks is reusable after the second attempt. For electrochemical oxidation of fuel, an ideal anode should have a large surface area, high porosity, and a continuous frame to ensure mechanical strength. Boosting the DCFC's power output and durability is therefore possible by improving its anode material [99].

Along with biochar’s widespread use in wastewater remediation, scientists should consider its possible adverse impact on the ecosystem. To effectively employ biochar, one of the most significant features that must be considered is its capacity to maintain its stability throughout time. The aromaticity and extent of aromatic condensation of biochar are two factors that influence the stability of biochar [103]. When biochar is employed for wastewater detoxification, the possible emission of carbon from the biochar can cause the carbon concentration of the solution to be treated to rise. Moreover, the discharge of heavy metals from biochar formed from sludge is a possibility, particularly for biochar generated from sludge. Huang et al. [105] demonstrated that the dissolution of organic materials from biochar into an aqueous solution is caused by the biochar’s instabilities. In addition, it was discovered that the stability of the biochar deteriorated after multiple cycles when it was employed as a support for a catalyst. This can be attributed to variations in the carbon framework of the biochar. It is usually acknowledged that the stability of biochar relies on the type of the starting feedstock as well as the experimental settings utilized during its thermal transformation. As a result, it is required to establish a relationship between these two factors and the stability of the biochar. Another significant element to consider is the renewal and restoration of biochar after it has been utilized. The adsorption procedure is characterized by the transition of pollution from the liquid stage to the solid material/adsorbent phase in most cases. As a result, it is critical to transforming the hazardous pollutants that are bonded to biochar into non-toxic conditions to control them effectively [101].

5. Challenges, prospects, and future perspectives

5.1 Challenges and prospects of effective application of biochar-based catalyst

The use of biochar-based catalysts can be beneficial in several catalytic processes, including biodiesel production, bio-oil up-gradation, reforming, and
various organic reactions involving specialty or functional chemicals. These are currently in their infancy and must be scaled up. Biochar production systems must be set up on an industrial scale to enable the scaling up of these processes. The biggest barriers to scaling up biochar production are multiple competing end-users, as well as the collection and transportation of raw materials to the facilities that manufacture biochar. Homagain [107] studied the sensitivity of transportation distance and distinct carbon offset values and found that the system is financially viable at 200 km with good biomass availability. Furthermore, the seasonal biomass production cycle makes it difficult to maintain a steady supply of sustainable and reliable fuel.

The moisture content and particle size are other critical parameters in the synthesis of biochar. The biochar production method requires a lot of energy to process feedstocks with a high moisture content or large particle size. During biochar production, it is necessary to pre-process feedstock by drying and reducing its size. The heat resistance of feedstocks, on the other hand, limits heat transfer during biochar formation. Due to temperature differences, this phenomenon causes unconverted feedstock to accumulate on the inner walls of reactors, posing a significant barrier to the widespread production of uniform biochar [103].

Biochar's properties can also be difficult to fine-tune once it has been produced to achieve the required transformation. Following the proper design of biochar-based catalysts, the resulting materials will have real-world applications and will be able to replace catalysts that are expensive, non-renewable, and harmful to the environment. These conditions can be met by conducting mechanistic investigations during the char activation/synthesis/loading of necessary metals and catalytic processes. It is critical to comprehend two key factors in the catalytic process. The first is the interaction between biochar's physicochemical properties and its catalytic activity. The second step is to tune physicochemical parameters during the char production and activation process based on catalytic activity. Regarding this, the investigation of high surface area, active sites, and optimal pores is critical to managing the combined impacts of important production process variables (e.g., reagent gas, duration, heating rate, and temperature) and activation process variables (e.g., chemical, and physical). Just a few experiments have been conducted to control the physicochemical parameters of biochar for catalytic applications. However, the biorefinery of the future will require a single-step method for producing biochar with effective porous structure and functionality that is closely related to the production of biochemicals, biogas, and biofuels.

5.2 Future perspectives

Although biochar has many applications, biochar-based catalysts are still in the very early stages of development. Therefore, it is imperative to develop a method that can maximize catalytic activity. Researchers are currently exploring the modifications that can be carried out on biochar-based catalysts to apply them in future fields such as catalysis, environmental pollution, energy storage and conservation, and even chromatography.

Laboratory research is still underway for biochar-based catalysts. A purpose-driven synthesis and modification will be necessary for the future of an industrial application. Mechanistic studies may help to achieve this. A first step would be to investigate how biochar's catalytic properties relate to its physicochemical properties. To accomplish this, advanced characterization techniques of catalytic
materials can be combined with theoretical modeling of the mechanisms involved. Second, it is critical to determine how biochar's properties are affected by synthesis conditions and feedstock. It is extremely difficult to work with biomass because of its complex composition and complex formation mechanism. The application of advanced characterization techniques, such as pyrolysis/gas chromatography/mass spectrometry (Py/GC/MS), and thermogravimetric analysis/Fourier-transform infrared spectroscopy/mass spectrometry (TGA/FTIR/MS), is potentially vital for the future.

In terms of process optimization, the role of catalysts in biochar synthesis must be given much more thought. The presence of some inorganic species in biomass feedstock can catalyze pyrolysis. However, their autocatalysis is not enough to ignite the process. A catalyst must achieve at least one of the following goals: (1) to reduce reaction temperature or residence time so that biochar can be produced more efficiently; (2) to make biochar with desirable properties in a single step instead of having modification and synthesis done separately. In the future, we may be able to produce biochar-supported catalysts directly from biomass using catalysts that can produce effective functional groups and porous structures in a single step. A biomass refinery would also be able to produce biofuels and biochemicals in close coordination with manufacturing biochar-based catalysts, allowing for a more integrated and environmentally sustainable process for using biomass.

Biochars intended for use as catalysts require a functionalization and/or activation process because of their limited porosity, surface area, and surface functional groups. According to the activation technique, biochar can have varying physicochemical properties, such as surface area or porosity. Activated biochar can be endowed with specialized properties via the addition of functional groups or substances, such as selectivity, catalysis, and selective adsorption. Although biochars vary significantly according to the type of biomass they are produced from, as well as their production conditions and functionalization or activation. Future research should focus on the production of biochar with stable properties on an industrial scale.

6. Conclusion

The use of biochar-based catalysts in environmental applications has excellent catalytic properties. Recent achievements of biochar catalyst preparation procedures, as well as their performance, were examined from a range of applications. Additionally, the catalytic properties of biochar were examined further by its production and activation methods. Through various chemical and/or physical treatments, biochar can be modified in terms of morphology and surface functionality. Therefore, biochar has a strong potential for replacing costly and non-renewable conventional catalysts.

It has been demonstrated that biochar-derived catalysts are effective in a variety of reactions, including the production of biodiesel from biomass, removal of tars from bio-oil and syngas, and production of syngas. However, biochar catalyst properties (including surface functionality, surface area, porosity, and acidity) vary widely with biomass origin, biochar synthesis conditions, and pre/post-treatment. Yet, there is limited information about how biochar's properties can be controlled to enable its catalytic applications. Therefore, further research is needed to develop the catalytic properties of biochar to design active, stable, and selective biochar catalysts. Also, if biochar is to be considered as an industrial heterogeneous catalyst, the development
of a method that allows for the manufacture of biochar on an industrial scale is extremely desirable. For large-scale production, it is also challenging to secure stable sources of raw biochar materials. To meet these challenges, biochar catalysts must be stimulated and facilitated to be used in real-world applications to replace costly, non-environmentally benign catalysts, which have been used for a wide range of applications until now.
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