# BIOCHAR PRODUCTION: IT'S APPLICATIONS IN AGRICULTURE

## Abstract

In India, agriculture is the main basic occupation provides food, fodder as well as biomass for the generation of energy. Biochar a black carbon plays an important role in the recent decades. Due to its potential advantages for agriculture and the environment as well as its capacity to store soil water, the manufacture of biochar from agro-environmental waste biomass is generating a great deal of attention as a low-cost supplement. This chapter reveals the various process of producing biochar like gasification and different types of pyrolysis. Many analysts have thought about using biochar to increase their capacity to clean up pollution. Several characterization methods that were used in earlier investigations have gained more and more recognition. The various applications of biochar in the agriculture is discussed along with the future perspectives.

**Keywords:** Biomass, Gasification, Pyrolysis, Biochar and Agriculture

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## I. INTRODUCTION

A solid byproduct of the combustion of high carbonaceous residues can also be referred to as "char." Typically, char products have a high carbon content; charcoal is one such product and is arguably the first invention that humans made using fire or heat[1]. Biochar is another striking illustration of char. In contrast to charcoal, the substance under investigation in this instance is made of organic chemicals such as those found in wood, plants, or animals[2]. As a result, biochar is produced by burning biomass at comparatively low temperatures of less than 700 °C while there is a partial or no supply of oxygen[3]. The earliest documented that the biochar was used for soil applications, like the sequestration or storage of carbon available in the soil; enhancement of soil functionality, such as an increase in nutrient availability, a decrease in soil compactness, an increase in pH of the soil; and filtration of soil water[4]. Recently biochar uses include energy generation, stabilization and enhancement of biological processes, mitigation of climate change, and building additive. The properties of carbonized organic matter are determined by the source material, as are the production-related operational parameters[5]. The two primary processes for producing biochar are pyrolysis (slow or quick) and gasification. The chemical make-up of the biomass feedstock has a direct impact on the physical characteristics of the biochar generated. At temperatures above 120 °C, the majority of organic stuff starts to thermally degrade[6]. Between the temperature of 200 and 260°C, hemicelluloses break down, cellulose degraded between 240 and 350°C, and lignin occurs between 280 and 500°C[7][8]. The ratios of these components will therefore impact the level of reactivity and, consequently, the degree of physical structure modification after processing. High porosity and pores that range in size from micro to macro are characteristics of biochar[9]. Because they can serve as habitats for symbiotic microorganisms, large holes are crucial for enhancing soil quality. The vascular bundles of the raw biomass are where these holes are located. The main components of biochar are carbon, ash, volatile matter, and moisture. The feedstock material and operation settings have an impact on the percentage content of each component[10][11]. The carbon content of biochar made from plant-based sources is higher and ranges from 51% to a high percentage[12]. Understanding the main mechanisms generating changes in biochar's physicochemical properties during processing for diverse feedstock sources and operating conditions is necessary to assess its potential for application both today and in the future. Therefore, the decomposition of biomass is covered in this chapter along with how biochar is produced.

## II. BIOCHAR PRODUCTION TECHNOLOGIES

A growth in its conversion into biochar has been prompted by an ever-increasing appetite for employing it in various applications. Making biochar involves a standard method called thermochemical conversion. Pyrolysis, hydrothermal carbonization (HTC), gasification, torrefaction, and hydrothermal liquefaction are examples of thermochemical conversion processes. The process flow charts for pyrolysis and gasification is shown in the figure 1.
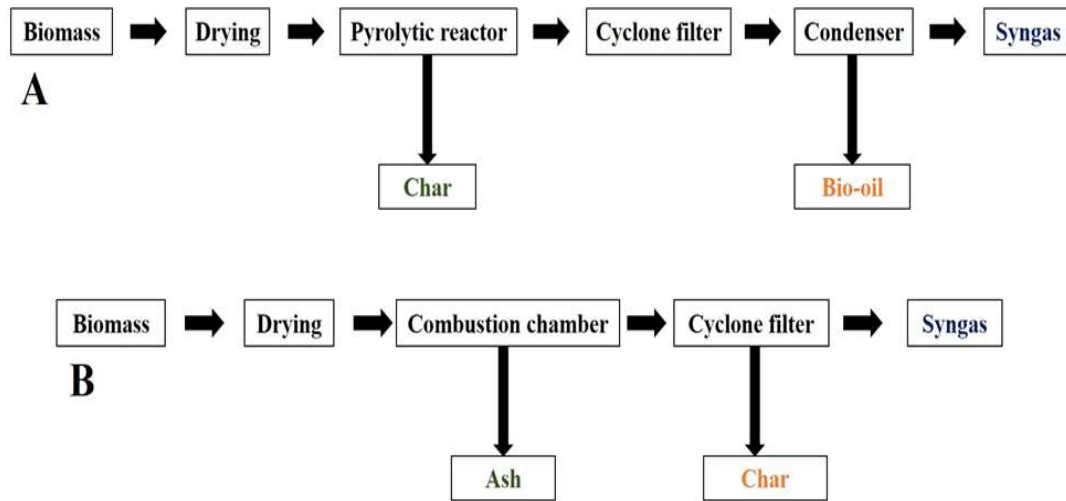
**Figure 1:** Process Flow Chart For A) Pyrolysis And B) Gasification for the Production of Biochar

1. **Gasification:** This thermochemical process converts carbon-rich materials into syngas, which is a mixture of gaseous output products such carbon monoxide (CO), carbon-di-oxide ($CO_2$), methane ($CH_4$), hydrogen ($H_2$), and traces of some hydrocarbons[13]. In an environmental factors with few oxidizing materials, such as oxygen, carbon dioxide, nitrogen, steam, or a different combination of these gaseous products of gasification occurs at high temperatures between 700 to 900°C, at limited supply of air[14]. It was found that when the temperature climbed, the generation of carbon monoxide and hydrogen increased while that of other substances including methane, carbon dioxide, and hydrocarbons decreased. Syngas, which contains primarily hydrogen, is the process' primary output; char, together with ash, tar, and some pyro-oil, is considered as a by-product with a lesser yield. The contrary to burning, partial oxidation of biomass transfers the energy present in the biomass into chemical bonds in the form of gaseous products[15]. Combustible gases of fuel, which are highly effective as well as practical to use than raw biomass, are created from the congenital chemical energy of the carbon in any biomass[16]. The gasification technology has also been used commercially. Gasification surpasses other conventional methods including pyrolysis, combustion, and fermentation due to its low level emissions and high volume of syngas. In order to achieve high gasification efficiency, the O/C ratio is essential. When gasifying biomass, a low O/C ratio is used for the achievement of high gasification process efficiency[17]. The process of torrefaction can lower the O/C ratio of biomass. Torrefaction could be thought of as a pretreatment for enhanced product quality prior to conventional gasification. Depending on the kind and composition of the biomass, this process is carried at low-temperature process between 300-350 °C with an approximate heating rate of 50 °C/min. Gasification and pyrolysis are processes that are interconnected[18]. There is no discernible difference between gasification and pyrolysis when they are combined. The partial oxidation of the biomass brought on by the small amount of oxygen utilized in gasification alters the properties of the finished product[19]. One of the most important differences between pyrolysis and gasification is the product type. About 85% of the results of gasification are gases, 10% are solid char, and 5% are liquids[20]. The working

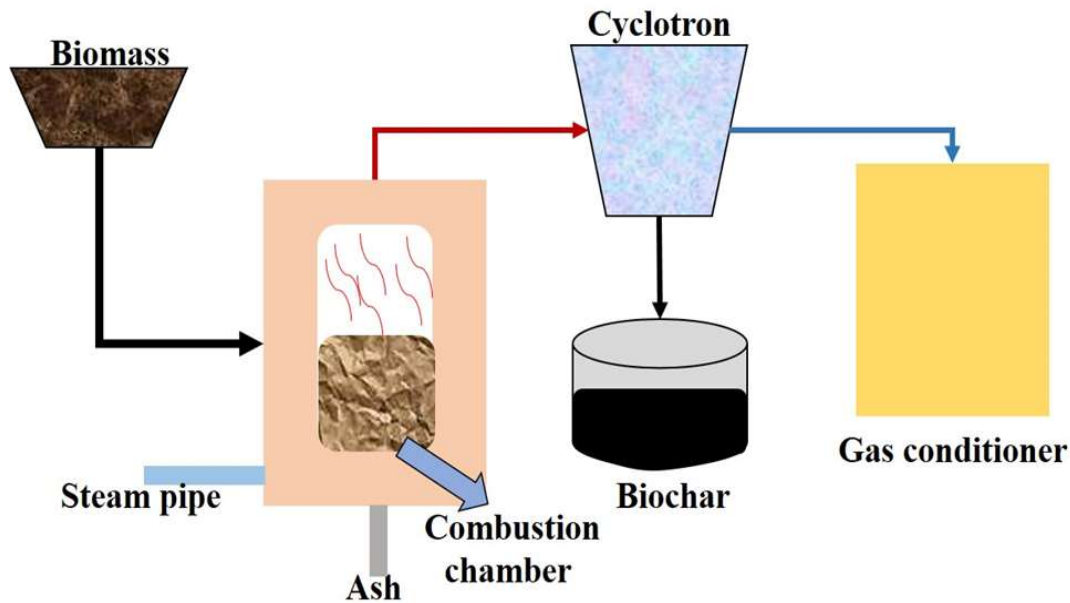diagram of the gasification process showed in the figure 2 and it involves four stages discussed below.



**Figure 2:** Schematic Working Diagram of Gasification Process for Biochar and Syngas Production

- **Drying:** There is no energy will recover during the process of completely removing the moisture from the biomass. Different biomass types having different moisture contents during initial stage. When the biomass has more moisture, gasification process uses drying as a separate step.

- **Pyrolysis:** During the pyrolysis process, the biomass is heated between 200 and 700°C with a small amount of oxygen or air. Under these conditions, the biomass' volatile components evaporate[21]. The volatile vapour is made up of gases including $CO$, $CO_2$, $CH_4$, $H_2$, tar (a heavier hydrocarbon content), as well as vaporized water along with the production of tar and char.

- **Combustion/Oxidation:** The main energy sources in the gasification process are oxidation and combustion reactions of the gasification agents. These gasification agents combine with the combustible species in the gasifier to produce $CO_2$, $CO$, and water.

- **Reduction:** The oxygen supplied to the gasifier for gasification of biomass reacts with the combustibles to produce $CO_2$ and $H_2O$, some of which are converted to $CO$ and $H_2$ also called as syngas upon contact with the char produced by pyrolysis, and the hydrogen in the biomass can be oxidized to produce water[20]. The reduction reactions which occurs inside the reactor are endothermic in nature and the energy required for them was comes from the combustion of char and volatiles obtained from the process.

- **Cracking:** Additionally, the tar and gases obtained during the pyrolysis step of the process are cracked during the gasification process, producing non-condensable gases, light hydrocarbons, and unconverted tar. This equation, roughly speaking, describes the cracking stage.

$$aC_nH_x \rightarrow bC_mH_y + CH_2$$
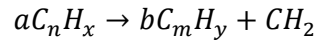
Where,
$C_nH_y$ is tar content and $C_mH_y$ is dehydrogenated hydrocarbons in the output, a, b and are molecular ratios.

2. **Pyrolysis:** The biochar, bio-oil, and syngas are products of the thermochemical process known as pyrolysis, which is used to process biomass[4]. The technique involves heating biomass to temperatures between 400°C and 1200°C and then thermally decomposing the products under anaerobic circumstances or with little oxygen ($O_2$) present[22]. Without oxygen, biomass can be heated over its thermal stability limit, producing more durable byproducts like solid residues. This is also insured that the combustion process will not take place when the biomass is heated by establishing an anaerobic environment[23]. It is a very intricate procedure that involves a wide variety of unique reactions in the reacting zone. In a different investigation, pyrolysis was found to occur at low temperatures between 250°C to 900°C. Silica, lignin, cellulose, and hemicelluloses make up agricultural biomass. The melting point of lignin is much higher than 350°C, but cellulose typically pyrolyzes at this temperature[24]. Although there are several operating factors that affect product yield, char formation is often favoured by low temperatures and lengthy residence times. Thus, it may be deduced that the pyrolysis's optimal temperature range was between 300 and 700°C[25]. In secondary pyrolysis, heavy chemicals are cracked, converting biomass into charcoal or gases. The overall view of the pyrolysis is shown in the figure 3.
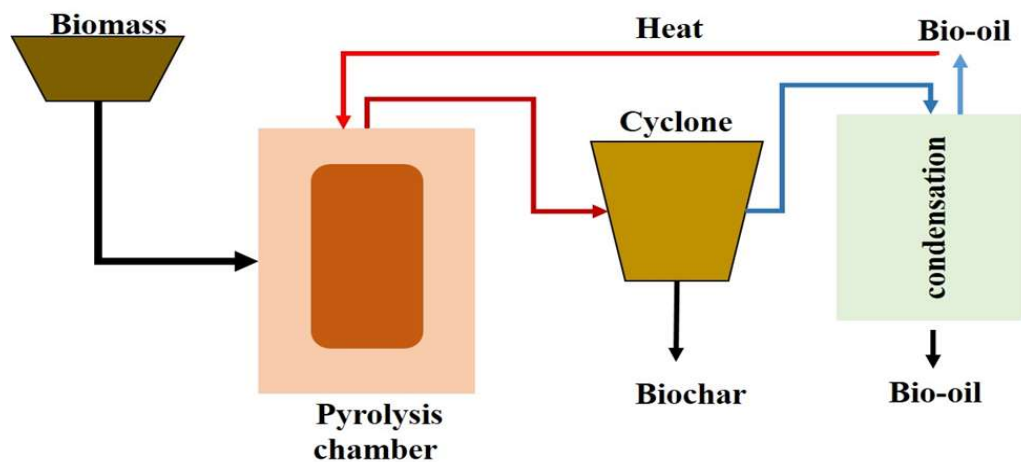


**Figure 3:** Pyrolysis Process Representation for the Production of Biochar, Bio-Oil and Syngas

In essence, this is an alternative strategy for turning biomass into goods like charcoal, syngas, and oil. At particular temperature points during the process, depolymerization, fragmentation, and cross-linking are chemical mechanisms that take place, resulting in a different product state for lignocellulosic components like cellulose and hemicellulose (solid, liquid, or gas)[26]. While $CO_2$, $CO$, and $H_2$ (together known as syngas) are produced as the gaseous byproducts ($C_1$-$C_2$ hydrocarbons), biochar and bio-oil are the solid and liquid byproducts. There are various types of reactors used to make biochar, including the waggon reactor, bubbling fluidized bed, paddle kiln, and agitated sand rotating kiln[27]. The type of biomass used and its nature impact the yield of biochar during the pyrolysis process. The temperature is the main operating factor that affects a product's efficiency. The yield of biochar drops and syngas production rises as the pyrolysis temperature rises[28]. The first portion of the product side, which includes a variety of gases produced throughout the process as given in the equation, is a representation of the gas yield.

$$(C_6H_6O_6)_n \rightarrow (H_2 + CO + CH_4 + \ldots + C_5H_{12}) + (H_2O + CH_3OH + CH_3COOH + \ldots) + C$$
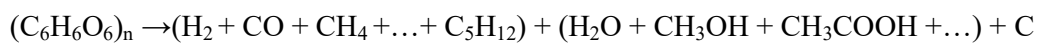
The second section of the products' side displays the mixing of various liquid outputs, and the final section displays the solid output. One of this technology's most important strengths is its ability to be optimized in order to get the required results[1][29]. For instance, slow pyrolysis can be used to generate a sizable amount of biochar, whereas quick pyrolysis is ideal for primarily generating bio-oil.

- **Types of Pyrolysis:** The temperature, heating rate, and residence time are the key operating parameters that determine pyrolysis. Pyrolysis is further divided into six subclasses by these operating circumstances. These subclasses include hydropyrolysis, intermediate pyrolysis, vacuum pyrolysis, fast pyrolysis, flash pyrolysis, and slow pyrolysis[30]. Each type of pyrolysis has distinct known advantages and disadvantages. The aforementioned subclasses support an environment where varied reaction mechanisms and situations can result in a variety of products[31][32].

  ➢ **Slow Pyrolysis:** Slow pyrolysis, as its name suggests, requires a lengthy residence time (more than an hour) to be completed, and the main output is charcoal. Conventional pyrolysis, also known as slow pyrolysis, involves heating biomass at a pace of 5-7°C/min while maintaining temperatures between 300 and 600°C[33]. The secondary reactions can proceed with the help of a favourable environment and enough time provided by a slower heating rate and a longer vapour residence period. Additionally, a prolonged residence time enables the evacuation of vapours produced during the secondary reaction[34]. In the end, this results in the production of solid carbonaceous biochar. Char development is favoured by slow pyrolysis, however small amounts of liquid oils and gaseous products called syngas are also produced. Along with secondary products like bio-oil (25–35%) and syngas (20–30%), biochar is produced as the main product in the process (35–45%)[35].

  ➢ **Fast Pyrolysis:** A direct thermochemical method known as fast pyrolysis is used to transform the biomass into high-energy content liquid bio-oil. A thermal

conversion process with great efficiency that yields biofuels derived from biomass while producing less solid waste and gas[36]. Without oxygen, fast pyrolysis occurs at temperatures higher than 500 °C and heating rates greater than 300 °C/min. A quick method for producing biochar is fast pyrolysis, which only needs a few seconds[37]. According to other studies, fast pyrolysis yields 60% bio-oil, 20% charcoal, and 20% syngas. Several investigations have reported even higher temperatures between 850 and 1250 °C with heating rates between 10 and 200 °C and short dwell times between 1 and 10 s[38]. A typical pyrolysis process yields 60%–75% of liquid products, 15%–25% of biochar, and 10%–20% of non-condensable gaseous fuel products[39]. Fast pyrolysis reduces exposure time while bringing biomass to this temperatures where thermal cracking of biomass can take place, supporting the creation of biochar.

- **Flash Pyrolysis:** Fast pyrolysis is said to be improved and modified by this. At temperatures of 1000 °C and above, biomass decomposes swiftly, typically in less than a minute. On occasion, heating rates more than 1000°C/sec have been seen[10]. Temperatures between 900 and 1200 °C attained in less than a second (often between 0.1 and 1 s), are required for flash pyrolysis. High heating rates, high temperatures, and short vapour residence times result in a high bio-oil production[40]. However, because of the procedure the biochar yield will decrease. The distribution of the products in flash pyrolysis is influenced by biomass phase transition behaviour, reaction chemical kinetics, heat and mass transfer mechanisms, and reaction kinetics[41]. The construction of the reactor necessitates that it operate at a high temperature with a very fast heating rate, which limits the commercial use of flash pyrolysis even though it can be accomplished in a fluidized bed reactor and a twin-screw mixing reactor[42].

- **Intermediate Pyrolysis:** As the name implies, this is a combination of fast and slow pyrolysis processes, and it is essential when solid and liquid products need to be balanced. This indicates that slow pyrolysis is more effective at producing huge volumes of char but produces fewer liquid products, whereas quick pyrolysis is the opposite[43]. Pressure is typically maintained at 1 bar throughout the procedure. With the different heating rates between 0.1 and 10°C/min and varying residence times between 5 and 17 minutes, intermediate pyrolysis occurs at temperatures between 500 and 650°C[44]. The usual composition of finished products is 40–60% liquid, 20–30% non–condensable gases, and 15–25% biochar. By using intermediate pyrolysis settings, it is possible to avoid the production of highly reactive tar and produce the dry biochar, which can be used in boilers and engines alone or in conjunction with high-quality bio-oil[45].

- **Hydropyrolysis:** By injecting hydrogen ($H_2$) or a hydrogen-based substance into the pyrolysis reactor at high pressure between 50 bar and 200 bar above atmospheric pressure and it is a relatively new method for turning biomass into high-quality goods. The temperature (350-600°C), residence duration (over 15 sec), and the heating rate of (10-300°C/s) do not depart much from fast pyrolysis[46]. In essence, hydropyrolysis can be viewed as a specific form of fast pyrolysis that is subjected to high pressure in an environment that is rich in hydrogen or materials derived from hydrogen. The injection of hydrogen at high

temperatures and pressure works as a reducing agent, lowering the oxygen concentration in the resulting bio-oils and concomitantly impeding the creation of biochar, making this approach unsuitable for making biochar[47]. Hydropyrolysis is frequently associated with the use of a catalyst to remove oxygen, water, and COx from the liquid product. Depolymerization and coking processes are also decreased by catalysts. However, creating the catalyst for this purpose continues to be a glaring illustration of the challenging nature of catalytic hydropyrolysis[48].

- ➢ **Vacuum Pyrolysis:** The vacuum pyrolysis is a thermal breakdown of biomass in zero oxygen atmosphere under vacuum or low pressure. Temperature is normally kept between 450°C and 600°C, while pressure is typically controlled between 0.5 and 2 bar.[49]. Like slow pyrolysis, vacuum pyrolysis has comparably low heating rates. However, these two techniques, in comparison, yield significantly different products. In addition to greatly reducing the vapour residence period, the quick evacuation of organic vapours produced during primary pyrolysis also ensures a high yield of liquid products during secondary pyrolysis by minimizing the occurrence of secondary reactions[50]. Because inorganic devolatilization is prevented by using solely vacuum or low-pressure extraction, the quality and yield of the product are significantly impacted[51].

3. **Biomass Degradation:** The majority of the materials used in the pyrolysis process to produce biochar contain multiple types of carbohydrates (cellulose, hemicellulose, and lignin), and these react differently depending on the operating conditions they are exposed to, affecting the pyrolysis's output yield[52]. More specifically, the bulk of biomass is made up of lignin and cellulose. When cellulose is pyrolyzed, it primarily yields tar, which is a mixture of isolated ketones, aldehydes, organic liquids, and char, whereas lignin primarily yields char and a negligible amount of water[53]. The output of gaseous content rises as cellulose content increases while char and tar content decreases. Additionally, it has been found that structural variations in the biomass affect how the pyrolysis product is composed.

- **Cellulose Decomposition:** The process of cellulose degradation, which consists of two main processes, is identified by reducing the degree of polymerization. In slow pyrolysis, cellulose is broken down gradually over time at a decreased heating rate[54]. Levoglucosan is formed as a result of rapid pyrolysis, which takes place at high heating rates by rapid volatilization. Levoglucosan is dehydrated to create hydroxymethylfurfural, which can break down to create liquid and gaseous products including bio-oil and syngas, in addition to the solid result biochar. In order to produce solid biochar, the hydroxymethylfurfural can also go through a number of processes, such as aromatization, condensation, and polymerization[55]. A lot of char is produced as cellulose degrades to a very stable anhydrocellulose at low temperatures, but it also breaks down into volatiles.

- **Hemicellulose Decomposition:** The process by which hemicellulose degrades is similar to that of cellulose. Hemicellulose depolymerization results in the synthesis of oligosaccharides. Biochar can be created through decarboxylation, intramolecular rearrangement, depolymerization, and aromatization processes, or the substance can

break down into syngas and bio-oil[27][56]. The char yield of the cellulose and hemicellulose components in biomass is caused by the volatile compounds and lignin.

- **Lignin Decomposition:** The breakdown of lignin is more difficult than that of cellulose and hemicellulose. Char is produced from lignin by the production of a more compact solid structure and the dissolution of relatively weak linkages[57]. The 🔲-O-4 lignin link is broken, which results in the release of free radicals. These free radicals absorb the protons coming from other particles, which results in the synthesis of chemicals or materials that have undergone degradation[53]. By travelling to other molecules, free radicals help the chain to grow. Different lignin contents in connection with various wood kinds result in various breakdown rates. It has been found that coniferous lignin is more stable than deciduous lignin, and the former produces more char[58].

## III. BIOCHAR APPLICATIONS IN AGRICULTURE

The small scale in the lab and on a large scale in the field use of biochar in agriculture has been investigated in recent studies. Among these uses are as a component of chemical fertilizer, to promote soil microbial activity, as a soil amendment to increase crop yield by increasing nutrient availability, and to increase soil's capacity to hold water[59]. Additionally, biochar has been shown to reduce the release of heavy metals into the soil while also having a limiting impact that helps to raise the pH of extremely acidic soils[60]. Despite being a different kind of soil conditioner than compost, biochar has different production processes. Agricultural and other biomass are thermally decomposed to create biochar in the absence of oxygen, whereas organic substrates naturally biodegrade to create compost in an aerobic environment by the microbial population[61]. Compost benefits are also relatively short-lived compared to those of biochar, which remains in the soil for longer periods of time. Another distinction is that compost dissolves quickly[62].

1. **Biochar as an Adsorbent:** All kinds of life are negatively impacted by the problem of heavy metals/metalloids (HMS) and polycyclic aromatic hydrocarbons (PAHs) present in soil and water[63]. These pollutants cause negative environmental issues and poor agricultural practices. These contaminants are poisonous, enduring, non-biodegradable, and may bioaccumulate[64]. Biochar is among the greatest bioremediation strategies used to address the HMS and PAHs problem because of its benefits[65]. These benefits include affordability, carbon sequestration, and sustainability. Biochar has been utilized to adsorb various contaminants due to its physical and chemical properties, including its pore structure, specific surface area, and functional groups[66].

2. **Soil Water Dynamics Improvement Through Biochar:** In dry places with narrow water supplies and highly changeable water quality, biochar makes a considerable positive contribution. The biochar preparation technique has an impact on the soil's ability to retain water[67]. Because biochar has a large total pore space, it can hold onto water in its micropore space and help water move through bigger pores from the lower soil horizon to the upper soil (0–15 cm) right after a heavy rain. This increases water holding capacity. A study was conducted for different soils only 25 out of 60 soil types exhibited an increased capacity to store water after biochar was applied at various

rates[68]. It has been discovered that applying biochar to drought-stressed plants increased their photosynthetic rate[69].

3. **Biochar Impact on Soil Biological Properties:** Carbon, phosphorus, nitrogen, carbon mineralization, and a number of enzymatic processes in soil can all be improved by biochar[70]. In general, many types of enzyme behaviour were considerably improved when being incubated with fresh pyrolyzed biochar. Heavy metals have a negative impact on soil biological and biochemical parameters such soil enzyme activity, according to numerous reports[71]. However, it has also been claimed that adding biochar to soil can lessen the toxic effects of heavy metals, altering the soil enzymes in the process. A major factor in systemic acquired resistance is biochar[72]. Various types of biochar have various recommended application rates for disease suppression. There isn't yet a "one concentration fits all" concept that can be used for adding biochar to soilless systems[73].

## IV. FUTURE PERSPECTIVES OF BIOCHAR

Future research must clarify how the production process impacts biochar's characteristics because applications rely heavily on them. The type of biochar used in water treatment would be different from that utilized in agriculture or energy. The impacts of biochar on agriculture, notably on crop yield due to various soils, are also the subject of a variety of literature results. For instance, depending on the soil type and fertilizer management, adding charcoal might either boost or decrease crop yields. Additionally, it has been discovered that the chemical behavior of biochar with heavy metal ions is unpredictable. It is clear that the interactions between biochar, soil, and plants are important but poorly understood. Thus, further work is still required to understand how the characteristics of biochar affect soil and crop responses both in the field and in climate-controlled environments.

## V. CONCLUSION

The biochar derived from different processes can lowering acidity and improving nutrient availability, biochar has been used to repair polluted agricultural soil and increase soil fertility. Thus, one of the finest practices for reducing biotic stress in soil and boosting crop yield, particularly in the agricultural sector, is the addition of biochar to soils. Processes like pyrolysis and gasification could have been covered in this chapter, have had a big impact on the characteristics of biochar. So it looks that biochar is a very promising choice for pollutant elimination. When creating recoverable biochar for numerous environmental applications, economic effects and recyclability should be taken into account. The relationship between various approaches to managing trash and producing energy differs in terms of parameters, production methods, and economic, social, and ecological restrictions. This review paper outlined the most recent data that might be useful in identifying potential areas for scientific innovation in the study of biochar.

# REFERENCES

[1] M. Raza *et al.*, "Progress of the pyrolyzer reactors and advanced technologies for biomass pyrolysis processing," *Sustain.*, vol. 13, no. 19, 2021, doi: 10.3390/su131911061.

[2] L. Dai *et al.*, "A review on selective production of value-added chemicals via catalytic pyrolysis of lignocellulosic biomass," *Sci. Total Environ.*, vol. 749, 2020, doi: 10.1016/j.scitotenv.2020.142386.

[3] S. Y. Lee *et al.*, "Waste to bioenergy: a review on the recent conversion technologies," *BMC Energy*, vol. 1, no. 1, 2019, doi: 10.1186/s42500-019-0004-7.

[4] S. Bolognesi, G. Bernardi, A. Callegari, D. Dondi, and A. G. Capodaglio, "Biochar production from sewage sludge and microalgae mixtures: properties, sustainability and possible role in circular economy," *Biomass Convers. Biorefinery*, vol. 11, no. 2, pp. 289–299, 2021, doi: 10.1007/s13399-019-00572-5.

[5] M. B. Asif, R. Habib, S. Iftekhar, Z. Khan, and N. Majeed, "Optimization of the operational parameters in a submerged membrane bioreactor using Box Behnken response surface methodology: Membrane fouling control and effluent quality," *Desalin. Water Treat.*, vol. 82, no. September, pp. 26–38, 2017, doi: 10.5004/dwt.2017.20998.

[6] R. Mahendiran *et al.*, "Instrumental evidence for biodegradation of tannery fleshings during anaerobic digestion and proteolytic enzyme hydrolysate study," *Vib. Spectrosc.*, p. 103530, 2023.

[7] G. Enaime, A. Baçaoui, A. Yaacoubi, and M. Lübken, "Biochar for wastewater treatment-conversion technologies and applications," *Appl. Sci.*, vol. 10, no. 10, 2020, doi: 10.3390/app10103492.

[8] H. Luo *et al.*, "Solar pyrolysis of waste plastics with photothermal catalysts for high-value products," *Fuel Process. Technol.*, vol. 230, 2022, doi: 10.1016/j.fuproc.2022.107205.

[9] F. L. Braghiroli *et al.*, "The conversion of wood residues, using pilot-scale technologies, into porous activated biochars for supercapacitors," *J. Porous Mater.*, vol. 27, no. 2, pp. 537–548, 2020, doi: 10.1007/s10934-019-00823-w.

[10] G. S. Ghodake *et al.*, "Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy," *J. Clean. Prod.*, vol. 297, 2021, doi: 10.1016/j.jclepro.2021.126645.

[11] K. M. Qureshi, F. Abnisa, and W. M. A. Wan Daud, "Novel helical screw-fluidized bed reactor for bio-oil production in slow-pyrolysis mode: A preliminary study," *J. Anal. Appl. Pyrolysis*, vol. 142, no. January, p. 104605, 2019, doi: 10.1016/j.jaap.2019.04.021.

[12] F. Cheng, H. Luo, and L. M. Colosi, "Slow pyrolysis as a platform for negative emissions technology: An integration of machine learning models, life cycle assessment, and economic analysis," *Energy Convers. Manag.*, vol. 223, p. 113258, 2020.

[13] S. Dasappa and A. M. Shivapuji, "Biomass gasification: Thermochemical route to energetic bio-chemicals," *Adv. Biofuel Technol. Present Status, Challenges Futur. Prospect.*, pp. 305–332, 2021, doi: 10.1016/B978-0-323-88427-3.00022-2.

[14] G. A. Lisbet, S. L. Electo, V. A. Rubenildo, Y. G. Sandra, L. J. René, and M. C. Vladimir, "Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality," *Biomass and Bioenergy*, no. 61, pp. 236–2244, 2014.

[15] D. Prabakar *et al.*, "Advanced biohydrogen production using pretreated industrial waste: Outlook and prospects," *Renew. Sustain. Energy Rev.*, vol. 96, pp. 306–324, 2018, doi: 10.1016/j.rser.2018.08.006.

[16] G. Maitlo *et al.*, "Thermochemical Conversion of Biomass for Syngas Production: Current Status and Future Trends," *Sustain.*, vol. 14, no. 5, 2022, doi: 10.3390/su14052596.

[17] T. R. Sarker, S. Nanda, A. K. Dalai, and V. Meda, "A Review of Torrefaction Technology for Upgrading Lignocellulosic Biomass to Solid Biofuels," *Bioenergy Res.*, vol. 14, no. 2, pp. 645–669, 2021, doi: 10.1007/s12155-020-10236-2.

[18] A. S. Bisht and N. S. Thakur, "Pine Needles Biomass Gasification Based Electricity Generation for Indian Himalayan Region: Drivers and Barriers," pp. 47–59, 2020, doi: 10.1007/978-981-15-1063-2_4.

[19] S. Safarian, R. Unnþórsson, and C. Richter, "A review of biomass gasification modelling," *Renew. Sustain. Energy Rev.*, vol. 110, pp. 378–391, 2019, doi: 10.1016/j.rser.2019.05.003.

[20] H. Shahbeig, A. Shafizadeh, M. A. Rosen, and B. F. Sels, "Exergy sustainability analysis of biomass gasification: a critical review," *Biofuel Res. J.*, vol. 9, no. 1, pp. 1592–1607, 2022, doi: 10.18331/BRJ2022.9.1.5.

[21] Md Waliul Islam, "A review of dolomite catalyst for biomass gasification tar removal," *Fuel*, 2020.

[22] Z. Kwoczynski and J. Čmelík, "Characterization of biomass wastes and its possibility of agriculture utilization due to biochar production by torrefaction process," *J. Clean. Prod.*, vol. 280, p. 124302, 2021, doi: 10.1016/j.jclepro.2020.124302.

[23] Y. H. Chan *et al.*, "An overview of biomass thermochemical conversion technologies in Malaysia," *Sci.*

*Total Environ.*, vol. 680, pp. 105–123, 2019, doi: 10.1016/j.scitotenv.2019.04.211.

[24] A. Parihar and S. Bhattacharya, "Cellulose fast pyrolysis for platform chemicals: assessment of potential targets and suitable reactor technology," *Biofuels, Bioprod. Biorefining*, vol. 14, no. 2, pp. 446–468, 2020.

[25] J. Li *et al.*, "A critical review on energy recovery and non-hazardous disposal of oily sludge from petroleum industry by pyrolysis," *J. Hazard. Mater.*, vol. 406, p. 124706, 2021.

[26] S. Y. Foong *et al.*, "Valorization of biomass waste to engineered activated biochar by microwave pyrolysis: Progress, challenges, and future directions," *Chem. Eng. J.*, vol. 389, 2020, doi: 10.1016/j.cej.2020.124401.

[27] A. T. Hoang *et al.*, "Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability," *Fuel Process. Technol.*, vol. 223, 2021, doi: 10.1016/j.fuproc.2021.106997.

[28] M. Heidari, A. Dutta, B. Acharya, and S. Mahmud, "A review of the current knowledge and challenges of hydrothermal carbonization for biomass conversion," *J. Energy Inst.*, vol. 92, no. 6, pp. 1779–1799, 2019, doi: 10.1016/j.joei.2018.12.003.

[29] E. S. K. Why, H. C. Ong, H. V. Lee, Y. Y. Gan, W. H. Chen, and C. T. Chong, "Renewable aviation fuel by advanced hydroprocessing of biomass: Challenges and perspective," *Energy Convers. Manag.*, vol. 199, 2019, doi: 10.1016/j.enconman.2019.112015.

[30] L. D. M. S. Borel, A. M. Reis Filho, T. P. Xavier, T. S. Lira, and M. A. S. Barrozo, "An investigation on the pyrolysis of the main residue of the brewing industry," *Biomass and Bioenergy*, vol. 140, 2020, doi: 10.1016/j.biombioe.2020.105698.

[31] J. W. Gabhane, V. P. Bhange, P. D. Patil, S. T. Bankar, and S. Kumar, "Recent trends in biochar production methods and its application as a soil health conditioner: a review," *SN Appl. Sci.*, vol. 2, no. 7, 2020, doi: 10.1007/s42452-020-3121-5.

[32] J. Wei *et al.*, "Assessing the effect of pyrolysis temperature on the molecular properties and copper sorption capacity of a halophyte biochar," *Environ. Pollut.*, vol. 251, pp. 56–65, 2019, doi: 10.1016/j.envpol.2019.04.128.

[33] A. Inayat *et al.*, "Activated Carbon Production from Coffee Waste via Slow Pyrolysis Using a Fixed Bed Reactor," *Environ. Clim. Technol.*, vol. 26, no. 1, pp. 720–729, 2022, doi: 10.2478/rtuect-2022-0055.

[34] C. del Pozo *et al.*, "The effect of reactor scale on biochars and pyrolysis liquids from slow pyrolysis of coffee silverskin, grape pomace and olive mill waste, in auger reactors," *Waste Manag.*, vol. 148, pp. 106–116, 2022, doi: 10.1016/j.wasman.2022.05.023.

[35] G. Albor, A. Mirkouei, A. G. McDonald, E. Struhs, and F. Sotoudehnia, "Fixed Bed Batch Slow Pyrolysis Process for Polystyrene Waste Recycling," *Processes*, vol. 11, no. 4, p. 1126, 2023.

[36] W. A. Rasaq, M. Golonka, M. Scholz, and A. Białowiec, "Opportunities and challenges of high-pressure fast pyrolysis of biomass: A review," *Energies*, vol. 14, no. 17, p. 5426, 2021.

[37] J. Liang, G. Shan, and Y. Sun, "Catalytic fast pyrolysis of lignocellulosic biomass: Critical role of zeolite catalysts," *Renew. Sustain. Energy Rev.*, vol. 139, p. 110707, 2021.

[38] C. Chang *et al.*, "Study on products characteristics from catalytic fast pyrolysis of biomass based on the effects of modified biochars," *Energy*, vol. 229, 2021, doi: 10.1016/j.energy.2021.120818.

[39] Y. K N *et al.*, "Lignocellulosic biomass-based pyrolysis: A comprehensive review," *Chemosphere*, vol. 286, 2022, doi: 10.1016/j.chemosphere.2021.131824.

[40] M. Tripathi, A. Bhatnagar, N. M. Mubarak, J. N. Sahu, and P. Ganesan, "RSM optimization of microwave pyrolysis parameters to produce OPS char with high yield and large BET surface area," *Fuel*, vol. 277, 2020, doi: 10.1016/j.fuel.2020.118184.

[41] B. H. Caudle, M. B. Gorensek, and C. Chen, "A rigorous process modeling methodology for biomass fast pyrolysis with an entrained-flow reactor," *J. Adv. Manuf. Process.*, vol. 2, no. 1, 2020, doi: 10.1002/amp2.10031.

[42] S. S. Lam *et al.*, "Microwave vacuum pyrolysis conversion of waste mushroom substrate into biochar for use as growth medium in mushroom cultivation," *J. Chem. Technol. Biotechnol.*, vol. 94, no. 5, pp. 1406–1415, 2019, doi: 10.1002/jctb.5897.

[43] F. Campuzano, R. C. Brown, and J. D. Martínez, "Auger reactors for pyrolysis of biomass and wastes," *Renew. Sustain. Energy Rev.*, vol. 102, pp. 372–409, 2019, doi: 10.1016/j.rser.2018.12.014.

[44] B. Nyoni and S. Hlangothi, "Intermediate pyrolysis of Scenedesmus microalgae in a rotary kiln pyrolyser: Effect of temperature on bio-oil yields and composition," *Biomass Convers. Biorefinery*, 2022, doi: 10.1007/s13399-022-03378-0.

[45] A. Suresh *et al.*, "Microwave pyrolysis of coal, biomass and plastic waste: a review," *Environ. Chem. Lett.*, vol. 19, no. 5, pp. 3609–3629, 2021, doi: 10.1007/s10311-021-01245-4.

[46]   M. Z. Stummann, M. Høj, J. Gabrielsen, L. R. Clausen, P. A. Jensen, and A. D. Jensen, "A perspective on catalytic hydropyrolysis of biomass," *Renew. Sustain. Energy Rev.*, vol. 143, 2021, doi: 10.1016/j.rser.2021.110960.

[47]   M. Sekar *et al.*, "A review on the pyrolysis of algal biomass for biochar and bio-oil – Bottlenecks and scope," *Fuel*, vol. 283, 2021, doi: 10.1016/j.fuel.2020.119190.

[48]   F. Melligan, M. H. B. Hayes, W. Kwapinski, and J. J. Leahy, "A study of hydrogen pressure during hydropyrolysis of Miscanthus x giganteus and online catalytic vapour upgrading with Ni on ZSM-5," *J. Anal. Appl. Pyrolysis*, vol. 103, pp. 369–377, 2013, doi: 10.1016/j.jaap.2013.01.005.

[49]   A. Andooz, M. Eqbalpour, E. Kowsari, S. Ramakrishna, and Z. A. Cheshmeh, "A comprehensive review on pyrolysis of E-waste and its sustainability," *J. Clean. Prod.*, vol. 333, 2022, doi: 10.1016/j.jclepro.2021.130191.

[50]   F. Wang, X. Zeng, G. Kang, K. Li, J. Ma, and G. Xu, "Secondary reactions suppression during fuel fast pyrolysis in an infrared heating apparatus for the fixed bed pyrolysis process with internals," *J. Anal. Appl. Pyrolysis*, vol. 156, p. 105163, 2021.

[51]   J. W. Gabhane, V. P. Bhange, P. D. Patil, S. T. Bankar, and S. Kumar, "Recent trends in biochar production methods and its application as a soil health conditioner: a review," *SN Appl. Sci.*, vol. 2, no. 7, 2020, doi: 10.1007/s42452-020-3121-5.

[52]   P. Jagnade, N. L. Panwar, and C. Agarwal, "Experimental Investigation of Kinetic Parameters of Bamboo and Bamboo Biochar Using Thermogravimetric Analysis Under Non-isothermal Conditions," *Bioenergy Res.*, pp. 0–27, 2022, doi: 10.1007/s12155-022-10497-z.

[53]   H. G. Wise, A. B. Dichiara, and F. L. P. Resende, "Ex-situ catalytic fast pyrolysis of Beetle-killed lodgepole pine in a novel ablative reactor," *Fuel*, vol. 241, pp. 933–940, 2019, doi: 10.1016/j.fuel.2018.12.101.

[54]   M. Movva and R. Kommineni, "Extraction of cellulose from pistachio shell and physical and mechanical characterisation of cellulose-based nanocomposites," *Mater. Res. Express*, vol. 4, no. 4, 2017, doi: 10.1088/2053-1591/aa6863.

[55]   T. Y. A. Fahmy, Y. Fahmy, F. Mobarak, M. El-Sakhawy, and R. E. Abou-Zeid, "Biomass pyrolysis: past, present, and future," *Environ. Dev. Sustain.*, vol. 22, no. 1, pp. 17–32, 2020, doi: 10.1007/s10668-018-0200-5.

[56]   D. Zhong *et al.*, "Characteristics and evolution of heavy components in bio-oil from the pyrolysis of cellulose, hemicellulose and lignin," *Renew. Sustain. Energy Rev.*, vol. 157, p. 111989, 2022.

[57]   C. G. Yoo, X. Meng, Y. Pu, and A. J. Ragauskas, "The critical role of lignin in lignocellulosic biomass conversion and recent pretreatment strategies: A comprehensive review," *Bioresour. Technol.*, vol. 301, 2020, doi: 10.1016/j.biortech.2020.122784.

[58]   Z. Ma *et al.*, "In-depth comparison of the physicochemical characteristics of bio-char derived from biomass pseudo components: Hemicellulose, cellulose, and lignin," *J. Anal. Appl. Pyrolysis*, vol. 140, pp. 195–204, 2019, doi: 10.1016/j.jaap.2019.03.015.

[59]   J. S. Cha *et al.*, "Production and utilization of biochar: A review," *J. Ind. Eng. Chem.*, vol. 40, pp. 1–15, 2016, doi: 10.1016/j.jiec.2016.06.002.

[60]   N. A. de Figueredo, L. M. da Costa, L. C. A. Melo, E. A. Siebeneichlerd, and J. Tronto, "Characterization of biochars from different sources and evaluation of release of nutrients and contaminants," *Rev. Cienc. Agron.*, vol. 48, no. 3, pp. 395–403, 2017, doi: 10.5935/1806-6690.20170046.

[61]   X. Yang, W. Ng, B. S. E. Wong, G. H. Baeg, C. H. Wang, and Y. S. Ok, "Characterization and ecotoxicological investigation of biochar produced via slow pyrolysis: Effect of feedstock composition and pyrolysis conditions," *J. Hazard. Mater.*, vol. 365, pp. 178–185, 2019, doi: 10.1016/j.jhazmat.2018.10.047.

[62]   D. Wang, P. Jiang, H. Zhang, and W. Yuan, "Biochar production and applications in agro and forestry systems: A review," *Sci. Total Environ.*, vol. 723, 2020, doi: 10.1016/j.scitotenv.2020.137775.

[63]   M. Kah, G. Sigmund, F. Xiao, and T. Hofmann, "Sorption of ionizable and ionic organic compounds to biochar, activated carbon and other carbonaceous materials," *Water Res.*, vol. 124, pp. 673–692, 2017, doi: 10.1016/j.watres.2017.07.070.

[64]   S. Ambika *et al.*, "Modified biochar as a green adsorbent for removal of hexavalent chromium from various environmental matrices: Mechanisms, methods, and prospects," *Chem. Eng. J.*, vol. 439, 2022, doi: 10.1016/j.cej.2022.135716.

[65]   M. Burachevskaya *et al.*, "Fabrication of biochar derived from different types of feedstocks as an efficient adsorbent for soil heavy metal removal," *Sci. Rep.*, vol. 13, no. 1, 2023, doi: 10.1038/s41598-023-27638-9.

[66]    B. Qiu, X. Tao, H. Wang, W. Li, X. Ding, and H. Chu, "Biochar as a low-cost adsorbent for aqueous heavy metal removal: A review," *J. Anal. Appl. Pyrolysis*, vol. 155, 2021, doi: 10.1016/j.jaap.2021.105081.

[67]    D. Wang, C. Li, S. J. Parikh, and K. M. Scow, "Impact of biochar on water retention of two agricultural soils – A multi-scale analysis," *Geoderma*, vol. 340, pp. 185–191, 2019, doi: 10.1016/j.geoderma.2019.01.012.

[68]    H. Bohara *et al.*, "Influence of poultry litter and biochar on soil water dynamics and nutrient leaching from a very fine sandy loam soil," *Soil Tillage Res.*, vol. 189, pp. 44–51, 2019, doi: 10.1016/j.still.2019.01.001.

[69]    A. Obia, G. Cornelissen, V. Martinsen, A. B. Smebye, and J. Mulder, "Conservation tillage and biochar improve soil water content and moderate soil temperature in a tropical Acrisol," *Soil Tillage Res.*, vol. 197, 2020, doi: 10.1016/j.still.2019.104521.

[70]    E. Mahmoud, M. Ibrahim, N. Ali, and H. Ali, "Effect of Biochar and Compost Amendments on Soil Biochemical Properties and Dry Weight of Canola Plant Grown in Soil Contaminated with Heavy Metals," *Commun. Soil Sci. Plant Anal.*, pp. 1561–1571, 2020, doi: 10.1080/00103624.2020.1763395.

[71]    P. D. Somerville, C. Farrell, P. B. May, and S. J. Livesley, "Biochar and compost equally improve urban soil physical and biological properties and tree growth, with no added benefit in combination," *Sci. Total Environ.*, vol. 706, 2020, doi: 10.1016/j.scitotenv.2019.135736.

[72]    M. S. Zaheer *et al.*, "Potential effects of biochar application for improving wheat (Triticum aestivum l.) growth and soil biochemical properties under drought stress conditions," *Land*, vol. 10, no. 11, 2021, doi: 10.3390/land10111125.

[73]    M. Daniele *et al.*, "Soilless tomato grown under nutritional stress increases green biomass but not yield or quality in presence of biochar as growing medium," *Hortic. Environ. Biotechnol.*, vol. 60, no. 6, pp. 871–881, 2019.