



Recent trends in biochar production methods and its application as a soil health conditioner: a review

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Abstract

Interest in biochar production from organic waste has been growing in recent years due to its broad applicability, availability, and smoother production. Biochar production techniques are being continuously modernized to improve the production rate and quality. Though numerous methods have been reported in the recent past, a systematic classification of the same is yet to be explored. Based on the advancement of the techniques being employed for biochar production and modification of conventional methods, we have categorized all major techniques of biochar production into two primary classes. In the traditional approach, ancient methods and conventional pyrolysis techniques (Slow and Fast pyrolysis) are included, whereas, in modern approaches, several advanced technologies such as Gasification, Torrefaction, Hydrothermal carbonization, Electro-modification, along with modified traditional methods (Flash pyrolysis, Vacuum pyrolysis, and Microwave pyrolysis) are comprised. Further, the systematic review was intended to evaluate various types of feedstocks (agricultural biomass, forest/woody biomass, aquatic biomass, urban waste, and paper waste) with their potential to produce biochar. It was observed that the feedstock containing high cellulose was found to be helpful in improving the overall properties of biochar, including enhanced adsorptive action and retention of nutrients.

Keywords Biochar · Adsorbent · Soil amendment · Biochar production techniques · Pyrolysis · Gasification

1 Introduction

Population explosion, rapid industrialization, and urbanization result in the massive generation of organic wastes, including agro-wastes, municipal solid waste (MSW), industrial waste, sea waste, forestry waste, etc. A small fraction of agro and forestry waste is utilized in domestic and in-farm activities such as cattle feeding, cooking, composting, and biogas production [1]. However, a major portion gets disposed of either by burning or dumping in the fields or landfill that results in air, water, and soil pollution. Thus, several researchers recommended the composting of organic wastes [1–4]. However, its slow degradation rate

and laborious operation make it an unattractive choice [5]. Therefore, the utilization of organic wastes for biochar production could offer a solution to the existing issues. Biochar production is a rapid process that is also economically feasible due to the value of the final product obtained in the process. Further, it has other potential benefits such as improving soil fertility, encouraging seed germination, enhancing vegetative growth of plants, increasing disease resistance of soil, adsorbing toxic pollutants, improving water retention capacity of the land, etc. [6, 7]. Besides, biochar can be used as energy fuel and carbon sink. Biochar is a carbon-rich solid by-product produced through high-temperature pyrolysis or degasification of organic

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material under low or no oxygen environment, which prevents combustion. The relative yield of product formation in pyrolysis varies with temperature. More char is produced at temperatures between 400–500 °C (752–932 °F), while temperature above 700 °C (1292 °F) favors the yield of liquid and gas fuel components [8]. High-temperature pyrolysis (above 700 °C), which is also known as gasification, can produce biochar as well. However, the yield in gasification was found to be relatively low [9, 10].

The production and application of biochar for improving soil fertility is an old tradition commonly used by farmers from India, Europe, China, Japan, and America. It is being produced by smoldering agricultural waste in pits or trenches [11]. As per their views, the amelioration of soil with biochar can improve the retention of nutrients in the soil, which ultimately increases soil fertility [11, 12]. Several reports suggested that the effect of biochar on soil fertility and crop productivity showed a positive impact, especially where the biochar is mixed with fertilizers [13, 14]. Biochar amendment also improved the seasonal NPP (net primary production) accumulation arising from atmospheric CO₂ assimilation [15]. Mosses, which generally grow on peatland, need phosphorus for the vegetative growth. Phosphate rock fertilization is generally used for such peatland restoration [16]. However, the use of biochar could significantly assist the ecological restoration that helps the recovery of the degraded, damaged, or destroyed ecosystem. Further, soil amendment with biochar enhances the nutrient uptake, which reduces dependency on chemical fertilizer and is essentially important in developing countries such as India, where most of the farmers cannot afford chemical fertilizers. Nevertheless, there are several reports surfaced in the recent past stating neutral or negative plant growth responses to the soil amended with sole biochar [17, 18]. Therefore, research needs to be focused concerning the effects of biochar on the increment of nutrient availability, seed germination, vegetative growth, and enhancement in protein and chlorophyll content. Feedstock composition, pyrolysis conditions, and biochar production methods are the vital factors controlling the physical and chemical properties of the resulting biochar and eventually deciding its end application. Thus, the present review emphasizes on feedstocks for biochar production, biochar production techniques with their modernization and application of biochar with special focus on soil amendment, soil fertility, crop productivity, and nutrient availability. The systematic review was intended to evaluate the recent advancement in the field of biochar production along with its applications. In order to obtain all relevant data, multiple engines (Web-of-Science and Scopus) were employed in a systematic search. Considering the recent reports published in the last decade, state-of-art examples were primarily

considered while approaching a systematic review of the same. Though numerous examples are considered and included from distinct regions of the world, special attention was given to the reports from India to get an insight into the current scenario in the country.

2 Feedstock availability for biochar

Feedstock availability and its composition are some of the most important factors for the efficient and economical production of biochar. Though there is a huge availability of feedstocks, their proper classification and characterizations are essential for its appropriate utilization. Thus, the present section emphasizes on the feedstock resources, compositions, and their availability. A wide variety of feedstocks being used for biochar production comprising agricultural residues, urban waste, paper waste, woody biomass, aquatic biomass, animal and human excreta, industrial waste, food and kitchen waste, dairy and paper mill waste, poultry waste, etc.

2.1 Agricultural biomass

Huge quantities of agro-wastes are being generated through agricultural operations all over the world and developing countries in particular. As per the report of the Imperial College Centre for Energy Policy and Technology, the total land area across the world is about 13 Gha, of which 1.5 Gha accounts for agricultural operation [19]. Total land occupied by India is 0.297 Gha, of which 10.57% (0.0314 Gha) constitutes for agricultural operations, where the total agricultural waste generation in India is about 600 MT [20]. The agro-waste is primarily composed of cellulose, hemicellulose, and lignin [21]. Cellulose is the most abundant organic material on the earth, and approximately 4×10^{10} t of cellulose is produced annually by plants [22]. Cellulose is insoluble in water. It has high tensile strength, and much higher tolerance to degradation compared to glucose and starch. In its natural form, cellulose is a linear polymer containing thousands of glucose units linked together by β -1,4 glycosidic linkage. Cellulose is highly resistant to microbial and chemical degradation. Cellulose binds with lignin and hemicelluloses by ether and hydrogen bond, respectively [23, 24]. Hemicellulose is a complex, branched, and heterogeneous polymeric network and structurally similar to cellulose. Glycosidic linkage (β -1,4) connects pyrosyl units. Hemicellulose is a polymer of a pentose sugar, especially xylose unit; however, other pentoses (arabinose, mannose, galactose, etc.) are also present. The composition of hemicellulose in softwood (grasses, agricultural waste, and coniferous tree) and hardwood (forest waste and woody biomass) are

different. Though the hemicelluloses in softwood are composed of galactan (arabino) and glucans (xylo), the major portion is comprised of glucomannan along with arabinoglucuronoxylan, and galacto-glucomannan [25]. Nevertheless, softwood contains glucomannan, a primary form of hemicellulose. The presence of a profoundly branched structured polymer chain connected via acetyl groups brings a lack of crystallinity to the hemicellulose structure. Typically, hemicellulose can facilitate hydrolysis at a lower temperature than cellulose, which allows it to be water-soluble in the presence of acids at elevated temperatures. After cellulose and hemicellulose, lignin is found in lignocellulosic biomass with an abundance. Lignin is an integral part of plant cells and mainly found in grasses, soft/hardwood, algae, etc. It is a highly complex arrangement than cellulose/hemicellulose conferring overall rigidity to the plant structure. Typically, the lignin polymer incorporates aromatic alcohols (i.e., coniferyl, sinnapyl, and *p*-coumaryl) in its structure. Despite its strengthening role in plants, lignin plays several biological as well as ecological functions. Lignin fills spaces in the cell wall between cellulose, hemicelluloses, and pectin components, especially in tracheid, sclereid, and xylem cells. It is covalently linked to hemicelluloses and, therefore, crosslinks different plant polysaccharides, conferring mechanical strength to the cell wall and by extension, the plant as a whole. It is particularly abundant in compression wood but scarce in tension wood. Lignin plays a crucial part in conducting water in plant stems. Polysaccharide components of plant cell walls are highly hydrophilic and thus, permeable to water, whereas, lignin is more hydrophobic [26]. Compositional analysis of selected agro-wastes is depicted in Table 1. It was estimated that the cellulose (35–50%), hemicelluloses (15–40%), and lignin components (15–25%) makes the composition of agro-waste [1, 24]. Most commonly used

agricultural waste for biochar production is cotton stalk [28], rice and wheat straw [26, 27], maize stover [31, 32], corn straw [33], sugarcane bagasse [30], below-ground peanut biomass and switchgrass [34], etc.

Biochar from agricultural wastes, which are mostly rich in cellulose fiber, shows a significant influence on nitrogen and nutrient uptake from the soil and also provides a home to various kinds of soil biota, which increases soil fertility [29, 31]. Coconut shell and Palmyra nutshell are generally used for biochar production by anaerobically burning at 400 °C [35]. Similarly, hazelnut shells, grape seed, and chestnut shells have also been employed for biochar production [36].

2.2 Urban waste

Due to rapid urbanization and uncontrolled population growth, urban waste/municipal solid waste (MSW) has become a big challenge not only for India but also for most of the developing and developed countries. Urban waste is composed of organic and inorganic fractions (Fig. 1). Organic fraction is classified into biodegradable and non-biodegradable fractions. Biodegradable organic fraction is a collection of food remnants, kitchen, fruits and garden wastes, cloths, papers, leather materials, etc. [37]. A non-biodegradable organic fraction consists of plastic bags, bottles, and electronic waste, while inorganic fraction contains glassware, electric waste, metals, sandstone, etc. [38]. Most of the non-degradable organic and inorganic fractions are recyclable, while biodegradable fractions decompose biologically. The rapid industrial growth increases the urban population, which in turn increases urban waste generation. Such a huge generation of waste gives a burden to Municipal Corporations for their proper management. As per the report [39], nearly 90 million

Table 1 Compositional analysis of different types of agro-waste attributed to the cellulose, hemicellulose, and lignin

Sr. No.	Crop residue	Hexose sugar (Cellulose component)			Pentose sugar (hemicellulose component)		Lignin (%)
		Glucan (%)	Mannan (%)	Galactan (%)	Xylan (%)	Arabinan (%)	
1	Wheat	37.73	0.86	1.42	28.79	2.46	17.85
2	Rice	34.85	1.82	0.63	26.33	2.25	14.7
3	Sugarcane	42.7	1.38	0.88	30.23	1.66	21
4	Cotton	37.99	1.45	1.84	12.11	1.33	19.32
5	Soyabean	33.87	1.67	1.25	14.83	1.23	16.7
6	Groundnut	33.38	2.11	2.33	13.22	3.23	16.12
7	Food grain	28.12	1.19	2.11	13.16	4.11	18.32
8	Oilseed	41.31	0.89	1.16	21.22	2.22	16.3
9	Sorghum	36.42	1.22	1.36	13.24	1.56	15.2
10	Maize	36.0	1.56	2.03	24.9	2.43	18.93
11	Pulses	36.5	0.88	2.25	17.28	3.23	16.15
12	Banana	44.78	2.11	3.16	8.02	11.11	15.98

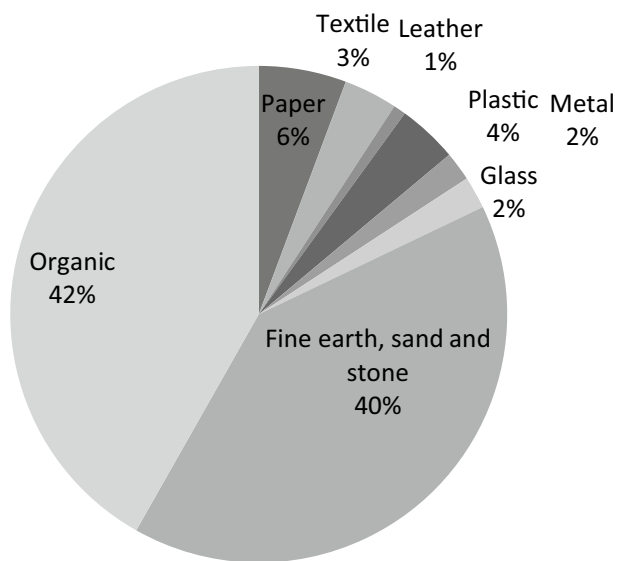


Fig. 1 Showing characterization of Municipal Solid waste [20, 39, 40]

tons of MSW has generated annually in India, with 0.337 t per generation capita rate [20, 40]. The organic fraction of urban waste, which is nearly 30–45%, has the potential to produce energy, soil conditioner, nutrient-rich manure or compost, and biochar. The segregated organic fraction is useful for biogas generation in various dumpsites. A lot of municipalities have started composting of organic waste all over the world. Urban wastes are one of the most potent feedstocks for biochar production and can be categorized into MSW, industrial wastewater, sewage sludge, livestock, and poultry wastes. MSW is used for biochar preparation, which is further used as an adsorbent for the removal of dyes, minerals, pollutants, toxicants, etc. Several researchers have used MSW to produce biochar [41–47]. A group [41] prepared biochar from MSW by using pyrolysis in a custom-designed packed bed reactor at 400–800 °C, which was further used to remove the azo dye. In another report [48], researchers used MSW biochar for the prevention of pollution from landfill leachate. Similarly, the effect of MSW biochar on the removal of aqueous arsenic (V) from wastewater was studied [42].

2.3 Paper waste

The waste paper constitutes a considerable share of municipal and industrial wastes even though recycling efforts have been strengthened in recent years. According to a study [49] and Food and Agricultural Organization report (FAO) [50], the paper production in India is 10.5×10^9 kg y^{-1} . It was further estimated that almost 5.7×10^9 kg y^{-1} out of the total paper and cardboard production in India, is collected and disposed of in the form of

mixed MSW. In another study, MSW constitutes 7–12% of paper waste, which contributes 6–9 MT per year in India, which also matched with the estimates [49]. As per FAO data, 1.9×10^9 kg of paper reused per year; however, the remaining portion (nearly 4.8×10^9 kg) dumped into landfill sites. When paper waste is recycled repeatedly, it loses its quality. The waste paper could be used as an excellent source of lignocellulosic biomass for ethanol production as it contains a significant and underutilized source of cellulose. Similarly, it should be a good resource for biochar production concerning high cellulose content.

2.4 Forest/woody biomass

Russian Federation, Brazil, Canada, the United States of America, China, the Democratic Republic of the Congo, Australia, Indonesia, Sudan, and India are forest megabiodiversity regions of the world, which constitute more than 67% of the total forest [50]. The 2013 forest survey of India documents its forest cover of 69.8 million ha. As per the report issued by FAO [51], India produces 3000 metric tons of paper annually, consuming nearly 10,000 metric tons of wood. Nearly 3000–3500 million cubic tones wood is used as raw material for furniture and craft industry, fuelwood, fodder, and value-added products. Wood is also an important feedstock for biochar production concerning the quality. Biochar from wood source shows more calorific value due to the presence of lignin, resin, pectin, and volatile materials. Several researchers have worked on the effective production of biochar from a wood source, e.g., Lai et al. [52] used hardwood, whereas Dong et al. [53], and Hu et al. [54] used Douglas fir wood chips and woody shavings for biochar production, respectively. Though wood residues are a good feedstock for biochar production, it must be used with care as it may provoke deforestation.

2.5 Aquatic biomass

Aquatic biomass includes algae, giant kelp, other seaweeds, and marine microflora with phytoplankton and zooplankton. The dry floor of rivers, lakes, and ponds is the richest source of such aquatic waste. Similarly, a significant amount of waste generates after fishing and other activities. Among the aquatic wastes, algae are a prominent and diverse group of primarily aquatic organisms, often fast-growing and able to grow in freshwater, seawater, or damped oils. They may be unicellular or microscopic and multicellular or macroscopic. According to Bird et al. [55], algal biochar is more nutritionally rich than lignocellulosic biochar. The concentration of macronutrients (N, P, K, Ca, and Mg) and micronutrients (Mo) is higher in algal biochar than lignocellulosic biochar. However, the applicability of algal biochar is limited due to the high cultivation

and collection cost of algae. Also, cultivated algae have established markets as food, alginate, agar, and carrageenan, which renders more commercial value. Hence, algal biochar for bioremediation does not compete with these existing markets [56]. However, there are several algal species that have been studied for biochar production [55–58] (Table 2).

3 Methods of biochar production

Charcoal forms either naturally as a result of vegetation fire or intentionally induced fire by humans employing burns pits and hand-made structures. A biochar production occurs under anaerobic (limited supply of oxygen) condition. Though a lot of biochar production methods are available in the literature, the proper classification is not available. Thus, in the present section, different approaches for biochar production are highlighted. The biochar production methods are mainly classified into traditional and modern approaches on the basis of their advancements and modernization (Table 3).

3.1 Traditional approaches

Archaeological evidence suggests the production and utilization of biochar by humans started over 2500 years ago. The first evidence was found in the Amazon Basin of South America [72], which was referred as Terra Preta conferring three times higher soil organic matter content and nutrient levels [73]. The ancient people used to pile the wood covered in the soil pits and to burn it slowly with limited or absence of air [74, 75]. In another mode, people used to burn the biomass in open space and immediately cover the half-burned biomass with soil [76, 77]. In ancient times, the soil amendment was not the only application of the production of biochar. The liquid product was also produced from the burning of wood and was used for various purposes such as preservation of dead bodies and meat, house painting, caulking for sealing wood barrels, shipbuilding, and to attach arrowheads to spear shaft [76, 77]. With the continuous evolution of humans and the advancement of science, several traditional biochar production approaches were replaced by modern approaches (Table 3). Handmade reactors such as firebrick pits, clay burners, brick kilns, and iron retorts were employed in the production of biochar. In every method, the common thing was a pit that is surrounded by clay (Clay burner), bricks (Firebrick pits and Brick kilns), and metal (Iron retorts). Such modified methods of biochar preparation are useful in recovering and utilization of volatile compounds produced from pyrolysis [77]. These methods were frequently used until the end of the 19th century and up

to the development of labor and time-saving steel ovens [76, 77]. The application of steel oven in biochar production does increase the production rate while improving the standard of biochar quality. Further, it is also useful in the recovery of volatile compounds and bio-oil.

3.1.1 Pyrolysis

Pyrolysis is a thermal degradation process where biomass is heated under anaerobic conditions or a limited supply of oxygen to produce various gaseous and aqueous products as well as char residues (biochar) [78]. Agricultural biomass is composed of lignin, cellulose, hemicelluloses, and silica. Generally, the pyrolysis point of cellulose is 350 °C, whereas lignin melts above 350 °C [79]. Thus, the effective temperature range for pyrolysis was found to be 300–700 °C [80]. Though pyrolysis is an anaerobic heating process, it needs other means of heating, such as hot gases, hot solids, liquid heat transfer media, oxidation, and partial oxidation reactions [81, 82]. Pyrolysis processes have been evolving for decades. Depending upon the process parameters such as temperature, heating rate, and residential time, it is further divided into various modes such as slow and fast pyrolysis. Slow and fast pyrolysis regards to traditional techniques. However, flash pyrolysis, vacuum pyrolysis, and microwave pyrolysis are modern techniques that were modified using modern technologies. Therefore, slow pyrolysis and fast pyrolysis have been classified and added in the section comprising “traditional approaches”. In contrast, flash pyrolysis, vacuum pyrolysis, and microwave pyrolysis have been added in the section containing “modern approaches” (Table 3).

3.1.1.1 Slow pyrolysis As the name indicates, slow pyrolysis takes several hours to complete the process and produces biochar as a major product. Slow pyrolysis, also known as conventional pyrolysis, where biomass is heated at the temperature in the range of 300–600 °C with a heating rate of 5–7 °C min⁻¹ [52]. Slow pyrolysis yields biochar as a major product (35–45%) along with other products as bio-oil (25–35%), and syngas (20–30%) [52, 67, 83]. A continuous auger/screw pyrolyzer reactor is generally used in the slow pyrolysis [83]. Lai et al. [52] used wood chips to produce biochar by slow pyrolysis, keeping temperature range between 290 to 700 °C with a heating rate of 3 °C min⁻¹ for 2 h. Similarly, Mendez et al. [67] used deinking sludge for the production of biochar by slow pyrolysis process in covered steel cup by employing an electric furnace at a heating rate of 10 °C min⁻¹ for 2 h. Different types of feedstocks have been used to produce biochar by slow pyrolysis such as *Conocarpus* wood wastes [66], cotton stalks [59], coconut shell, palmyra nutshell, and rice husks [35]. Another

Table 2 Feedstocks used in biochar production employing varying experimental conditions

No.	Feedstock	Pyrolyser/reactor	Temperature range (°C)	Resident time (min)	References
<i>I. Agricultural waste</i>					
1	Cotton stalk	Fixed bed reactor Muffle oven	450–600 400–700	60 180	[59] [28]
2	Rice straw	Slow pyrolysis	400–700	120	[29, 30]
3	Wheat straw	Vertical kiln	350–500	60	[60]
4	Maize stover	Fixed bed reactor	400	30	[31, 32]
5	Maize cob, husk	Fixed bed reactor	400	30	[32]
6	Corn straw	Ceramic pots	300–600	250	[33]
7	Sugarcane bagasse, leaves	Electrical muffle furnace and a pyrolysis canister	450–700	60	[30]
8	Below-ground peanut biomass	Slow pyrolysis	600–700	60	[34]
9	Coconut shell, Palmyra nutshell	Slow pyrolysis	400	10	[35]
10	Hazelnut shell, grape seed, chestnut shell, apricot stone	Cylindrical stainless-steel fixed bed reactor	477–550	30	[36]
11	Hornbeam shell residues	Fixed bed reactor	400	30	[61]
12	Orange peel	In ceramic pot	150–700	3600	[62]
13	Green waste	Programmable pyrolysis batch reactor	450	60	[63]
14	Paunch grass,	Steam gasification with slow pyrolysis	680	8–10	[34]
15	Pistachio hull waste	Oven	500	120	[64]
<i>II. Municipal waste</i>					
1	Papermill sludge	Slow pyrolysis unit	550	–	[8]
2	Papermill sludge Poultry litter	With steam activation; Without steam activation	550–400	40	[65]
3	Sewage sludge,	Horizontal quartz reactor; Hot air oven	300–700 650	180 120	[66]
4	Sewage sludge, wastewater sludge, broiler litter, dewatered pond sludge, dissolved air-floatation sludge	Steam gasification with slow pyrolysis	680	8–10	[34]
5	Deinking sludge	Steel cup reactor with an inside electric furnace	300	120	[67]
6	Lyophilized manure	Vacuum tube furnace	400	250	[68]
<i>III. Woody biomass</i>					
1	Pine sawdust	Fluidized bed reactor	600–700	60	[34]
2	Hardwood, Waste wood chips	Slow pyrolysis	290–700	160	[52]
3	Pinewood Coconut fiber	Fixed-bed quartz reactor	200–300	20	[69]
4	Douglas fir wood chips	Auger pyrolysis reactor	600	1	[53]
5	Woody shavings	Fixed-bed tubular reactor with a moving silica sample-carrier	250–600	–	[54]
6	Residues from Eucalypt plantations	HTT (highest temperature treatment)	480	180	[70]
<i>III. Algae biomass</i>					
1	<i>Spirulina platensis</i> and <i>Spirulina</i> sp.	Fixed bed pyrolysis	450–600	60	[55, 58]
2	<i>Macroalgae Oedogonium</i>	Muffle furnace	300–900	–	[6]
3	Seaweed	Stainless steel retort inside a muffle furnace	300–700	60	[6]
4	Parthenium weed	Stainless steel boxes with muffle furnace,	200–500	60	[71]
5	<i>Polytrichum commune</i> , <i>Dicranum scoparium</i> , <i>Thuidium tamarascinum</i> , <i>Sphagnum palustre</i> , <i>Drepanocladus revolvens</i> , <i>Cladophora fracta</i> , and <i>Chlorella protothecoides</i>	Slow pyrolysis and gasification	302–652	–	[55]
6	<i>Cladophora vagabundac</i> , <i>Caulerpa taxifoliac</i> , <i>Cladophorus sp.</i> , <i>Chaetomorpha linum</i> , <i>Chaetomorpha indica</i> , <i>Cladophora patentiramea</i> , <i>Cladophora coelothrix</i>	Stainless steel inside a muffle furnace	307–517	30–40	[55]

Table 3 Biochar production using different traditional and modern approaches

Sr. No.	Biochar production techniques	Biochar production conditions	Applications	References
<i>Traditional approaches</i>				
1	Early approach	Burning of biomass in a pit covered by soil to prevent oxygen supply. Burning of biomass in open space and covering half-burned biomass immediately with soil. Handmade reactors such as firebrick pits, clay burners, brick kilns, and iron retorts.	Soil amendment, Liquid product as preservation for dead bodies and meat, house painting, caulking of sealing wood barrels, ship-building and to attach arrowheads to spear shaft, etc.	[74–77]
2	Slow pyrolysis	Temperature: 300–600 °C; heating rate: 5 to 7 °C min ⁻¹	Soil amendment, Bio-oil, Syngas as an energy fuel	[52, 83]
3	Fast pyrolysis	Temperature: > 500 °C; heating rate: 300 °C min ⁻¹	Adsorbent, Soil amendment, Bio-Oil, Syngas	[29, 85, 89, 95]
<i>Modern approaches</i>				
4	Gasification	Temperature: > 700 °C with gasifying agents (steam)	Dye Removal, Adsorbent, Carbon Sequestration Soil Amendments, Syngas	[91, 92]
5	Torrefaction	Temperature: 230–300 °C	Regarded as a pre-treatment step to improve the physical, chemical, and biochemical characteristics of raw biomass	[98, 99]
6	Flash pyrolysis	Temperature: 900–1200 °C; heating rate: 800–1000 °C sec ⁻¹	Soil amendment, Bio-Oil, Syngas	[106, 107]
7	Vacuum pyrolysis	Pressure: 0.05–0.20 MPa; temperature: 450–600 °C; heating rate: 300 min ⁻¹	High porosity biochar, Adsorption of mineral, Soil amendment	[108–112]
8	Hydrothermal carbonization	Pressure: 2 to 10 MPa and temperature: 220 to 240 °C	Retention of nutrients High calorific value, Better grindability, Improved hydrophobicity	[113, 115–117]
9	Microwave pyrolysis	Temperature: 450–800 °C; microwave power: 400–600 W and microwave frequency: 2450 MHz	Soil amendment, Bio-Oil, Syngas	[103, 127, 128]
10	Electro-modified biochar	Current supply: 0–100 V and 0–12 A for 5 min; pyrolysis temperature: 400–500 °C; heating rate: 5 °C min ⁻¹ in the absence of oxygen	Adsorbent of pollutant, Adsorption of nutrient	[130–134]
11	Magnetic biochar	Temperature: 450–1000 °C; material soaked with a solution of Fe ₂ O ₃ , FeSO ₄ ·7H ₂ O, or FeCl ₃ ·6H ₂ O before pyrolysis	Adsorbent of pollutant, Adsorption of nutrient	[74, 136–138]

report [84] conducted slow pyrolysis with sawdust, bull manure, pinewood, oak wood, dairy manure with rice hulls, hazelnut shells, corn, food waste, and white paper mill sludge in a Daisy Reactor at Best Energies Inc. USA and concluded that the type of pyrolysis and composition of feedstock play an important role in the chemical composition of biochar. A similar experiment was also carried out by Roberts et al. [6] with four different feedstocks using slow pyrolysis in a sealed stainless-steel retort inside a muffle furnace with the inert condition for 60 min and reported that the pyrolysis temperature and biomass rinsing pre-treatment affect the yield of biochar. The yield of biochar decreased with increasing temperature, and the most effective biochar was produced from un-rinsed *Ulva* processed as flake at a pyrolysis temperature of 300 °C. As per a report [61], a slow heating rate was found to be more effective than a fast heating rate for biochar production.

3.1.1.2 Fast pyrolysis Fast pyrolysis is nothing but a high-efficiency thermochemical process to produce biomass-derived biofuels [85]. The advantages of fast pyrolysis include short retention time and high product recovery. However, the major products are bio-oil and syngas rather than biochar when subjected to the upgrading process for the production of liquid transportation fuels or fuel additives [86]. The operation of fast pyrolysis is carried out at a temperature above 500 °C with a heating rate of more than 300 °C min⁻¹ in the absence of oxygen. Fast pyrolysis is a rapid process of biochar production and takes seconds to complete. The product yield of fast pyrolysis is reported as 60% bio-oil, 20% biochar, and 20% syngas [85, 86]. It is mostly applied for large scale biochar production. Liu et al. [87] prepared biochar by fast pyrolysis of biomass in a fixed-bed quartz reactor equipped with a temperature controller and a furnace. The furnace was heated to the desired temperature (200–330 °C) with a heating rate of 15 °C min⁻¹ and kept at the desired temperature for less than 20 min. Due to the low temperature [87], more biochar yield was obtained when compared to bio-oil and syngas. A group [88] used the biochar for removal of 4-nitroaniline, salicylic acid, benzoic acid, and phthalic acid from water, and concluded that the biochar from fast pyrolysis has more advantageous for adsorptive actions. According to another report [89], adsorptive removal of salicylic acid and ibuprofen from aqueous solution by employing pinewood pyrolysis biochar was studied, which was prepared by fast pyrolysis at a temperature of 425 °C and residence time of 20–30 min. Moreover, a group [53] prepared a low-cost catalyst from pyrolysis-derived biochar using fast pyrolysis in an Auger pyrolysis reactor at 600 °C for 1 min, which was used for pre-esterification in biodiesel production. Another group

[90] prepared biochar by fast pyrolysis from hardwood, which showed a positive impact on soil quality and yield of crop biomass.

3.2 Modern approaches

At the end of the twentieth century, several modifications and changes in biochar production methods were surfaced. Eventually, various approaches have been developed for biochar production, such as modern pyrolysis (flash-, vacuum-, and microwave-pyrolysis), gasification, torrefactions, hydrothermal carbonization, electro-modified techniques, etc. (Table 3).

3.2.1 Gasification

Gasification is a common technique for producing syngas from different solid fuel resources. In comparison with other conventional methods, *i.e.*, pyrolysis, combustion, and fermentation, gasification provides larger syngas volume and lower Levelized emissions. Hydrogen is a major product of gasification. However, a considerable amount of biochar can also get generated during the gasification process. Moreover, biochar generated during gasification is considered as a waste and has several important applications such as dye removal from wastewater, adsorption of chemicals, carbon sequestration, and as a soil amendment agent [91, 92]. Gasification is an effective thermochemical conversion process for biomass into energy fuel while producing biochar as a byproduct [9]. Typically, carbonaceous materials derived from organic fossil fuels can be converted into hydrogen, carbon monoxide, and carbon dioxide employing gasification. In this process, at high temperatures (> 700 °C), the reaction of materials is carried out under a controlled supply of steam and oxygen [10]. As per the requirement of the desired gas composition, varying gasifying agents can be employed in the process [93]. A gas holding a higher content of hydrogen can be obtained via supplying steam that helps to elevate the heating value of syngas [94]. During the gasification process, heat transfer within a particle that increases the localized temperature of biomass leads to the removal of water and follows by the progressive release of pyrolytic volatiles. The precursors of primary volatiles are cellulose, hemicellulose, lignin, and extractives comprising permanent gas species (e.g., CO₂, CO, and CH₄). Though biomass component decomposes at different temperatures, the overall decomposition ends nearly in the range of 400–500 °C, where biochar is a prime product. Biochar is further converted into fuel at a higher temperature, where secondary decomposition occurs with a variety of secondary reactions to form syngas composed of hydrogen and methane [95]. Another group [96] used sewage

sludge for the production of hydrogen and biochar by gasification with the introduction of steam at 800 °C and reported 35–45 vol % hydrogen with a significant amount of char. Coal and petroleum coke are used as the primary feedstock for many large gasification plants worldwide. Municipal solid waste, agricultural and industrial waste, sewage sludge, etc. are also being used as a feedstock while performing gasification operation. The same group [96] also has studied the production of biochar employing gasification where wood pellets, sewage sludge, rapeseed, and miscanthus were utilized in a quartz tubular reactor using steam. Similarly, some other group [97] used steam gasification for pine sawdust and reported an increase in hydrogen volume fraction with increasing temperature as a result of further cracking at 850 °C.

3.2.2 Torrefaction

Burning of the biomass at relatively low temperatures (230 and 300 °C) improves the properties of biomass and widely termed as torrefaction [98, 99]. Alternatively, torrefaction, which can be regarded as a pretreatment step to improve the physical, chemical, and biochemical characteristics of raw biomass, makes the biomass perform better for combustion, gasification, and co-firing purposes [100, 101]. In this process, the hemicellulose fraction of the wood decomposes so that torrefied wood and volatiles are formed, which are more stable and carbon-rich solid products [102]. Torrefaction is the thermochemical treatment of biomass, which is carried out in the absence of oxygen under atmospheric pressure. A fixed bed reactor is generally used for the torrefaction process. Several researchers demonstrated that torrefaction and densification technology was an effective method to form torrefied wood pellets of superior quality, compared to the raw controlled pellets. There are several studies focused on torrefaction of agricultural and forest residues [102–104] investigated torrefaction of three agricultural wastes, *i.e.*, coffee residue, sawdust, and rice husk followed by examining the influence of torrefaction on properties and structure of biomass through proximate, elemental, fiber, calorific, thermogravimetric, SEM, and FTIR analysis [105]. It was concluded that the hemicellulose decomposition was more in coffee residue, while all biomass became more hygroscopic compared to raw biomass. The effect of temperature during the torrefaction process on biomass was also investigated by a group [105] using four different varieties of biomass, including bamboo, willow, coconut shell, and wood while focusing on compositional changes. The group concluded that hemicellulose decomposition was observed prominently at temperature 240 °C while cellulose decomposition occurred at severe torrefaction (above 280 °C).

3.2.3 Flash pyrolysis

Flash pyrolysis is an improved and modified form of fast pyrolysis. In flash pyrolysis, biomass decomposes at high temperatures, *i.e.*, more than 1000 °C within a short period, mostly less than a minute. The heating rate sometimes is more than 1000 °C sec⁻¹. Flash pyrolysis is operated at temperatures ranging from 900 to 1200 °C, which can be attained within a second [106, 107]. Such a rapid heating rate with high temperature and low vapor residence time lead to a high bio-oil yield. However, it reduces the biochar yield in the process [108]. Though flash pyrolysis is carried out in a fluidized bed reactor and twin-screw mixing reactor, its industrial applicability is very limited due to the construction of the reactor to operate at high temperature with extremely high heating rate.

3.2.4 Vacuum pyrolysis

Vacuum pyrolysis is a thermal degradation of biomass under vacuum or low pressure in the absence of oxygen. Pressure and temperature range during the vacuum pyrolysis are controlled between 0.05 and 0.20 MPa and 450–600 °C, respectively [19, 109, 110]. Similar to pyrolysis, the heating rate in vacuum pyrolysis is low. Though the heating condition and heating rate are similar to slow pyrolysis, end products are significantly different from each other. This is due to the effective removal of vapor during vacuum pyrolysis. In the vacuum pyrolysis, only vacuum or low pressure is used to remove the vapor generated during pyrolysis that shows a significantly good impact on product quality and yield due to the prevention of devolatilized inorganic [110, 111]. Another group [111] demonstrated that different chemical reactions, *i.e.*, cracking and volatiles-char interactions, are evident to produce bio-oil containing high water content with biochar during vacuum pyrolysis. Vacuum pyrolysis is highly used to produce high-quality biochar, which shows high porosity and, thus, highly useful in adsorption of mineral and nitrogen while applying as soil amendment [112].

3.2.5 Hydrothermal carbonization (HTC)

The high moisture containing feedstocks such as sewage sludge, animal waste, and compost are converted into biochar with the help of hydrothermal carbonization (HTC) method [113]. In the HTC method, there is no need to dry the biomass before processing, where the wet biomass mixture is heated up to temperatures ranging 220–240 °C under high pressure (2–10 MPa) reactor for several hours. HTC process is operated in rotary drums, kilns, and stoves. Most organics HTC processes remain either in dissolved form or transformed into brown coal [114]. HTC process

is useful to generate various carbonaceous materials with different sizes, shapes, surfaces, and functional groups. However, most of the initial carbon remains in the soluble form [115]. Important characteristics of HTC produced biochar is the retention of nutrients such as N and P, which is useful in soil fertility. The advantages of HTC process over torrefaction or pyrolysis process for biochar production include a significant reduction in O/C ratio, increased calorific value, better grind ability, and improved hydrophobicity [116]. Various studies on the HTC process for biochar production and their application as soil amendment was conducted by the various researcher [116, 117]. A group [117] prepared loblolly pine hydrochar at the temperature ranging from 200 to 260 °C and observed a 30% increase in calorific value. A similar observation was noted by Yang et al. [118] with biochar produced from nut husk as a feedstock. Reza et al. [119, 120] used pelletized hydrothermal carbonized loblolly pine char to study the effects of biochar on hydrophobicity, abrasion resistance, and density. The group observed a significant increase in these properties of biochar. According to another group [121], hydrothermal carbonized pellets showed considerably superior physicochemical properties when compared to the raw and torrefied pellets. Thus, they concluded HTC is a more promising technology for biochar production compared to torrefaction and hydrothermal.

3.2.6 Microwave pyrolysis

Biochar production through microwave heating is a prominent advanced technique. Microwave heating is advantageous over conventional heating as microwave generates thermal energy through dielectric heating, and the energy is introduced into the reactor remotely without making any contact between the energy source and the reaction mixture [122–124]. It is a more rapid and material-selective heating technique than the conventional one [125, 126]. Microwave technology has drawn attention in academic and industrial fields for outstanding thermal characteristics due to rapid, selective, and uniform heating while offering decreased sintering temperature that enhances steam gasification. Biochar produced through microwave heating has more advantages over conventional pyrolysis technique as it reduces temperature requirement by 200 °C while achieving similar results [86]. Several researchers have focused their attention on microwave processing for biochar production. A group [127] investigated experimental conditions for maximum biochar and hydrogen production and reported 450 °C temperature, 400 W microwave power, and 4–6 min resident time as the best conditions for microwave pyrolysis for biochar production. However, maximum hydrogen production was obtained at 700 °C temperature, 400 W microwave

power, and 4–6 min retention time. They further studied biochar quality and reported biochar produced through microwave pyrolysis shows more calorific value than conventional biochar. A similar observation was reported by Menedez et al. [128], where they prepared biochar from four types of wet sewage collected from different wastewater treatment plants. A group [128] pyrolyzed the material at 2450 MHz microwave frequency, and 800 °C for 4 min residence time. In another experiment, Huang et al. produced biochar from rice straw through microwave pyrolysis at a frequency of 2450 MHz by using a single-mode microwave device. Moreover, the biochar produced by microwave pyrolysis could potentially be used for CO₂ adsorption [129].

3.2.7 Electro-modified biochar

The adsorption capacity of biochar is useful to remove pollutants from soil, water, and air. Also, it is useful in the adsorption of nutrients. The medication of biochar should be done in such a way that it adsorbs a particular group of compounds while easily removing undesired moiety from a particular environment. Such modification of biochar carried out by chemical treatment, and the resultant biochar is termed as modified biochar. The chemical treatment includes mixing of biochar in Fe, Mg, or Al for 2–12 h in the presence of electric current that might alter functional groups on the surface of pores and ultimately improves specific adsorption [130–135]. Modern, simple, and time-saving approaches for preparing modified biochar involve the application of an electric field. By this method, *i.e.*, electro-modification, enhancement of the biochar surface area along with impregnation of chemicals on the biochar surface occurs. For such an electrochemical process, strong oxidant, *e.g.*, hypochlorous acid/hypochlorite ions (HOCl/OCl), aluminum ion (Al³⁺) can be produced by chemical reaction or aluminum electrodes at acidic pH [130]. Jung et al. [130] produced electro-modified biochar by an aluminum electrode-based electrochemical process where a dried brown marine microalga, *Laminaria japonica*, was used as a feedstock. Macro-alga was dipped in 200 mL of deionized distilled water, stirred for 150 rpm, and supplied current with a density of 0–100 V and 0–12 A for 5 min. After treatment, the macro-algae were separated using filtration followed by pyrolysis at 450 °C at a rate of 5 °C min⁻¹ under an inert atmosphere. The resultant biochar showed improved surface area and nano-sized crystalline beohemite on the biochar surface, which enabled higher adsorption capability for phosphate from aqueous solution. In another parallel experiment, Jung et al. [130] used MgCl₂ to improve texture properties of biochar where Mg–Al assembled nano-composites (MgO, spinel MgAl₂O₄, AlOOH, and Al₂O₃) were successfully dispersed

on the biochar surface with a highly crystalline structure to enhance the phosphate adsorption capability up to several folds.

3.2.8 Magnetic biochar

The enhanced adsorption capacity with complete recovery of adsorbent material has attracted many researchers worldwide, which can intensify research towards novel adsorbents. The magnetic biochar shows tremendous adsorption capacity with complete separation and recovery from water or pollutant site. Magnetic biochar, which is derived from various types of biomass, exhibits a good magnetic property with high surface area and significant morphology through various production methods. Magnetic biochar has been prepared from the addition of Fe ions on the surface of biochar with the help of a binding agent from the chestnut shell at temperature 450 °C under microwave heating. A group [136] prepared magnetic biochar by the addition of gelatine and iron. Another group [74] prepared magnetic biochar using the biomass in a programmable muffle furnace model Wise Therm, at 1000 °C, under vacuum condition with the addition of iron (III) oxide (Fe_2O_3), iron (II) sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) and iron (III) chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$). Magnetic biochar is useful in adsorption of various pollutants such as arsenic from wastewater [136], Pb^{+2} , and Cu^{+2} from industrial wastewater [137], and Zn^{+2} from another source of wastewater [138]. A group [136] demonstrated magnetic biochar as an environment-friendly and low-cost arsenic removal candidate. The adsorption capacity with the application of magnetic biochar increases up to 3–4 folds when compared to conventional biochar. Similar observations were reported by several researchers [74, 133, 137, 138]. Magnetic biochar/c- Fe_2O_3 was prepared by immersing biomass into the prepared FeCl_3 solution for 2 h. The mixture was then dried at 80 °C for 2 h under atmospheric air. The pretreated biomass was pyrolyzed in a furnace at a temperature of 600 °C in N_2 supplied environment for 1 h. Biochar/c- Fe_2O_3 composite produced from the pyrolysis was gently crushed, sieved, and further analyzed.

4 Applications of biochar

4.1 Effects of biochar amendment on adsorption of inorganic nitrogen and phosphate

Nitrogen present in the soil is the most vital element for plant growth, which is present in two forms, *i.e.*, organic and inorganic nitrogen. Most of the organic nitrogen gets converted into inorganic ammonium and nitrate form, which is absorbed by plants [139]. Soluble inorganic

nitrogen gets adsorbed on the soil surface, which is utilized by plants. However, various microbial activities cause degradation and removal of nitrogen. Thus, biochar acts as a soil additive and reduces nitrogen loss and ultimately improves soil fertility [140]. Though there are contradictory reports regarding nitrogen adsorption when biochar is applied, most of the report supports a positive impact on the adsorption of soluble nitrogen on soil [141–145]. Several reports suggested that the chemical groups present on the surface of biochar are responsible for the adsorption of nitrogen [146, 147]. Acid functional groups include carboxylic, hydroxyl, lactone, and lactol, which are negatively charged groups, are effectively bind to NH_4^+ by electrostatic attraction [63, 148]. Similarly, the existence of base functional groups, including chromenes, ketones, and pyrones on biochar, can facilitate NO_3^- adsorption on biochar [148, 149]. The efficacy of nitrogen adsorption on biochar is also dependent on the time of process and temperature. Old biochar adsorbs more NH_4^+ than the newer form as hydrophilicity increases during aging [150]. Biochar prepared at high temperature (≥ 600 °C) shows decreased cation exchange capacity (CEC) as acidic functional groups (mainly carboxyl) are converted to neutral or basic fused aromatic groups [151–153]. Thus, biochar prepared at moderate temperature was found to be best for the sorption of soluble nitrogen. Moreover, the biomass type also influences the nitrogen adsorption capacity of biochar. Biochar from grassy biomass shows more adsorption than woody biomass due to the presence of more carboxylic groups [152, 154].

Phosphorus is the second most important plant nutrient and essential element in DNA metabolism. It is present in phosphate form in soil or rock. To make it available for plants, a solubilized form of phosphate is crucial. Phosphate solubilizing microorganisms solubilize phosphate that gets adsorbed on biochar and makes it available to plants for a longer duration. One of the most important properties of biochar is the ability to absorb various chemicals, nutrients, and heavy metals on their surface and make them available for plants for a longer period due to its large surface area, porous structure, large cation exchange capacity, and abundant functional group [155–157]. Several studies state that biochar could prevent leaching of nitrogen, phosphate, and other nutrients from the compost and make them available for plants [158, 159]. These findings also supported by several other groups [160, 161]. They have reported that the amendment of hardwood biochar to soil would decrease the leaching of nitrogen and phosphate. Moreover, a group [162] demonstrated nutrient conservation of soil by using spent mushroom substrate derived biochar, and both nitrogen and phosphate could get adsorbed on the surface while preventing it from leaching through composting. Zhang et al. reported

the concentration of alkaline nitrogen (29%), available phosphorus (77%), and available potassium (100%) significantly increased in the biochar amendment [134]. The group further compared the sorption capacity of biochar against activated carbon and found that the sorption capacity of the biochar for NH_4^+ was much higher than that on the activated carbon.

4.2 Effects of biochar on soil structure

Incorporation of biochar may improve the physical structure of the soil, especially increased porosity, surface area, water adsorption and holding capacity, oxygen uptake, etc. [163–165]. Increased surface area and pore structure are essential to colonize the soil bacteria and fungi, which are useful in the absorption of nutrients from soil [165]. Increased porosity of soil could help it to maintain moisture and aeration, which is essential to microbial life and thus stimulates nitrifier activities [133, 166]. Several other groups demonstrated the stimulation of nitrification due to enhanced porosity of soil by absorbing nitrifier inhibitor (e.g., phenolics) [166–168]. However, it is a very slow process and takes several months for biochar to provide habitat for nitrifiers to colonize [143]. Employing the biochar in the soil changes its property that helps nitrogen-fixing bacteria to make habitat inside the biochar pore. Both symbiotic and free-living bacteria show a positive impact of biochar application. Free-living *Azotobacter* sp. and *Azospirillum* colonized and multiplied in biochar treated soil due to surplus habitat and required oxygen supply. Similarly, symbiont (e.g., Rhizobia) in biochar treatment also gets activated [169], which results in increased nodulation and nitrogenase activity [142, 170].

4.3 Biochar as a source of nutrients

Biochar can also be a source of micronutrients, for example, boron, molybdenum, K, P, Ca, etc. [171], which are necessary elements for nodulation of Rhizobia. Biochar, in a combination of compost, significantly increases the availability of nutrients and enhances crop productivity as a result [172]. Another group [13] reported 25% enhancement in crop productivity compared to chemical fertilizers and noted the increased soil organic carbon (SOC) from 0.93% (by fertilizer) to 1.25% (Biochar amended), soil water content (SWC) from 18% (by fertilizer) to over 23% (biochar amended) and CEC from 8.9 $\text{cmol}(+)\text{kg}^{-1}$ (by fertilizer) to over 10.3 $\text{cmol}(+)\text{kg}^{-1}$ (biochar amended) with significant increase in leaf chlorophyll content, nodulation number (NN), leaf nutrient concentration, etc. A chemical fertilizer, when applied to the soil, gets rapidly depleted either by leaching or degrading to another form. Similarly, manure or compost can also get depleted from soil resulting in

an increased financial burden to the farmers. Leaching of major plant nutrients such as P, K, and nitrate-nitrogen ($\text{NO}_3^- \text{N}$), potentially lead to environmental pollution [75]. In such conditions, the application of fertilizers or compost in combination with biochar could be more beneficial. A similar observation was reported by a group [172] where they stated increased peanut yield along with an increase in soil pH, available nitrogen/phosphorus, and CEC. Moreover, several studies support the positive influence of biochar on soil fertility and the productivity of a wide range of crops [13, 172–174].

4.4 Effects of biochar on microbial diversity and soil enzyme

Effects of biochar on microbial growth, diversity, and soil enzyme are studied by the various researcher and observed stimulatory effects. Several researchers [29, 175] observed an increase in bacterial and fungal growth in biochar added to soil at relatively low concentration (1%) followed by an increasing concentration of more than 5% of biochar resulted in a decrease in microbial biomass. Another group [29] reported an increase in 16S rRNA gene copies by biochar addition in the bacterial dominated microbial community, which was further supported by studies carried out by some others [176]. However, both the studies reported a decrease in bacterial and fungal gene copies by 74 and 25%, respectively, when 5% of biochar was added compared to the control. The possible explanation provided by a group [177] states that the pH value could have played a major role. Slightly alkaline or neutral soil favored bacterial and fungal growth compared to acidic soil [178]. When biochar was applied in the range of 1–2% in soil, pH was in the range of 7–7.5; however, at 5% biochar addition, pH increased up to 8.5 which are again found to be unfavorable to microbial growth and ultimately inhibited bacterial and fungal coding gene copies. A positive effect of biochar on soil fungi (*Arbuscular mycorrhizal*(AM) and *Ectomycorrhizal*) was documented by other groups [179, 180]. For such an abundance of microbial and fungal biomass by the addition of biochar, a group [181] hypothesized that biochar might have provided a habitat where bacteria and fungi could sustain themselves from predators and mitigated their diverse requirements of carbon, energy, and mineral nutrients. Not all the bacteria show stimulatory effects with biochar amendments [182]. Denitrifying bacteria could get reduced with biochar amendments [183, 184]. Denitrifying bacteria could also increase N_2O emission and reduce soil nitrogen availability. Thus, the biochar amendment again helps in the enrichment of soil N_2 by decreasing the population of denitrifying bacteria. Biochar amendment has a positive effect on iron-reducing bacteria

(e.g., *Clostridia*) which increase CH₄ emission [185, 186]. Fe reducing bacteria might play an important role in N and C cycling, especially in paddy soil with biochar amendments as biochar provides a stable platform for biofilm formation and supports electron shuttling between microbes and insoluble electron acceptors such as Fe oxides [187, 188]. A similar influence of biochar on iron-reducing bacteria was studied by several groups [150, 170, 189, 190], where they documented that the biochar could potentially serve as a habitat for microorganisms, and thus, improve the soil properties such as water-holding capacity, nutrient availability, and pH buffering capacity altogether.

Soil microbes are responsible for the breakdown of large organic molecules into simple monomers, which can be utilized by plants. For such metabolism, microbes secrete specific extracellular enzymes such as cellulase, urease, invertase, phosphatase, laccase, glucosidase, galactosidase, etc. that have a crucial role in the recycling of C, N, and P [191, 192]. The addition of biochar, manure/compost increases nutrients availability, which in turn increases microbial biomass [193] and ultimately enhances the production and activity of extracellular enzymes [194]. A group [29] studied the effects of biochar on extracellular enzymes such as invertase, urease, alkaline phosphatase, and reported increased enzyme activity by adding biochar up to 1–2%. A further increase in biochar concentration reduced the enzyme activities. A few researchers [68, 195] observed an increase in alkaline phosphatase and alkaline phosphomonoesterase activities with a low concentration (2.5%) of biochar and demonstrated the activity of enzymes related to P cycling. A group [196] reported a positive effect of biochar amendment on other extracellular enzymes, for example, α -1,4- glucosidase, β -D-cellobiohydrolase, and β -1,4-N acetylglucosaminidase and negative effects on β -1,4-glucosidase and phosphatase activities. Few others [179, 197] also supported a decrease in invertase and alkaline phosphatase activities on the addition of biochar. According to these studies, a possible reason for such decrease could be as follows: (i) strong adsorption property of biochar adversely binds the enzyme which limits its catalytic activity [197]; (ii) biochar addition might have detrimental effects on microbial growth and enzyme production [198]; and (iii) high pH might have influenced the metabolic activities due to biochar addition [199].

4.5 Biochar amendment suppresses plant diseases

Biochar in addition to carbon sequestration, nutrient enrichment, improvement in soil quality, and stimulatory effects on microbial diversity and extracellular enzymes, can also measurably reduce disease severity of different pathogen types and even induce system-wide defense

responses in host plants [29, 182, 195, 200–202]. Another group [203] studied the effect of biochar on lettuce and strawberry plants and reported 3% biochar amendment significantly reduced the susceptibility for the fungal pathogen *Botrytis cinerea* on both leaves and fruits of strawberry; however, the effect was limited on lettuce plant. In another similar work carried out by a group [201] where strawberry plants were grown in a biochar-amended soil, showed an upregulated salicylic acid-induced (SAR) and jasmonic acid/ethylene-induced (ISR) gene expressions and were primed for gene expression upon infection by *Botrytis cinerea* and by *Podosphaeraaphanis*. A group [200] reported pepper and tomato plants were more resistant to *Botrytis cinerea* and *Oidiopsisissicula* when they were cultivated on biochar-amended soil. Similar observations were also noted by a research group [204] where biochar helped to prevent root rot in asparagus caused by *Fusarium oxysporum* f. sp. asparagi. A few others [205, 206] documented suppression abilities of biochar for cucumber damping-off caused by *Rhizoctonia solani* and carrot root-lesion nematode *Pratylenchuspenetrans*. The disease suppression mechanism for biochar amendment soil can be similar to other organic soil amendments such as composts [207]. However, various researchers [169, 208] have discussed main defense-enhancing mechanisms of biochar amendment soil could be due to following reasons such as (i) better availability of nutrients for host plant; (ii) stimulation of microbial biomass; (iii) removal or neutralization of toxins produced by a pathogen or other infection-relevant substances; and (iv) induced system-wide defense responses in the host plant. Moreover, several others suggested that biochar can also affect the plant-wide systemic response, which can further induce disease-related genes linked to induced systemic resistance (ISR) [201, 205, 209].

5 Future prospects

Low soil fertility is a common problem in many regions around the world, which can be overcome by the use of biochar in the future. Biochar can efficiently improve the water holding capacity of the soil, which is extremely helpful in order to develop healthy plantation in the arid area. Also, biochar can be more beneficial in combination with compost where biochar can adsorb nutrients from the compost and keep deposited inside the holes while slowly releasing and making them available for plants and thus can eliminate the dependency on chemical fertilizers. In the future, many agro-industries may formulate such commercial products and make them available to farmers. Further, the adsorptive capacity of biochar could be proven as a milestone for water purifiers. Biochar not only

adsorbs microorganisms but also removes suspended and dissolved solids. The use of biochar filters instead of a carbon filter could be advantageous with respect to cost and work efficiency. Also, due to selective adsorptive properties, it could also be highly useful in dye industries. Further, biochar shows more potential in mitigating climate change, especially in terms of carbon capture or its storage or carbon sequestration. Moreover, it can also be employed in pharmaceutical industries where it can efficiently remove toxicants. In the future, it could immerge as a highly potential commodity for several industries such as food, fertilizer, agriculture, and pharmaceuticals.

6 Conclusion

The recent trends in biochar production methods and their applications have been systematically reviewed. Biochar is being used in an increasing number of fields and has been widely employed in a variety of applications, such as an adsorbent, a source of nutrients, and soil amendment agent where the biochar amendment could further suppress plant diseases as well. Properties of biochar and its applications are highly influenced by the mode of preparation and type of feedstock used. Moreover, the quality and efficiency of biochar to affect soil quality and plant growth vary greatly depending upon the experimental conditions such as pyrolysis temperature, feedstock material, age of produced biochar, etc. Evaluation of field efficiency and economic feasibility of biochar applications should be considered while providing a measure of certainty to the many possible benefits, which is a key challenge to be addressed by further research.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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