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REVIEW ARTICLE

Biochar from biomass waste as a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions—a review

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Abstract

Biomass waste generation is increasing enormously and biomass burning emits greenhouse gas emissions causing severe effects on the environment and health of the population. It contains high organic and carbon content which can be reused/diverted for useful products (like Biochar) that facilitate climate change mitigation. Biochar, a renewable carbon, is gaining importance and it opens up an area of research to explore on the properties and stability of biochar, its wide applications, impacts on soil characteristics, techno-economic details, carbon and nitrogen interactions of biochar-soil matrix, and emission control. This review addresses opportunities of biomass wastes for biochar production, various thermo-chemical reactions for preparation and its basics/mechanisms, properties of biochar and hydrochar, and gaps/operational challenges, and summarizes wide applications of biochar in soil improvement, climate change mitigation, energy production, waste management, and environmental remediation. The effect of physico-chemical parameters (temperature, heating rate, chemical composition, etc.) on the biochar production will help in valorizing this industry. The optimized process conditions involved in low temperature (torrefaction, microwave-assisted pyrolysis, hydrothermal carbonization), pyrolysis (Fast, Slow, Flash), gasification, and combustion processes for biochar, syngas, and bio-oil production are to be explored. The critical review on the biochar addition influence on CO_2, CH_4, and N_2O emissions in various soil types and carbon sequestration is done here. The modification and activation of biochar are recently attractive due to their role in improving biochar quality and for expanding its applications. Limitations and future status of biochar production from biomass waste are highlighted. Biochar will be a promising solution as an alternative to fossil fuels, waste management, bioenergy, and combat climate change.

Keywords Biochar · Biomass waste · Carbon · Climate change mitigation · Pyrolysis · Soil amendment

1 Introduction

A major environmental issue affecting the globe presently at an alarming rate is "Global Warming." The challenges and impacts of global warming are well documented by several scientists [1–3]. The Intergovernmental Panel on Climate Change has shown that global warming is increasing drastically in the consecutive three decades and total temperature is elevated by about 0.78 [0.72 to 0.85] °C, which has been recently enforced for limiting to 1.5 °C to prevent adverse global warming impacts [4, 5]. This effect is predominantly due to greenhouse gasses (GHGs) emissions that composed of carbon dioxide (CO_2–72%), methane (CH_4–18%), nitrous oxide (NO_x- 9%), and other gaseous emissions (1%) in atmosphere. Especially, atmospheric CO_2 concentrations contribute to ~60% of gaseous radiative forcing liable for human-induced climate change impact and its CO_2 emission levels have peaked from 1.1% (in 1990–1999) to greater than 3% (in 2000–2004). In turn, it contributes to the rise of mean global atmospheric CO_2 concentrations from 280 (in 1700s) to 380 ppm (in 2005s) and reaching up to a maximum of 405 ppm (in 2017s) primarily attributable to anthropogenic activities and is exceptionally highest concentration in comparison to last 800,000 years [6, 7]. It is evident that carbon

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emissions are the major contributors to climate change, in which burning of biomass plays a bigger role [8, 9].

The major emissions from biomass burning are particulate matter, carbon monoxide, hydrocarbons, oxides of nitrogen (NO_x), oxides of sulfur (SO_x), volatile organic compounds and polycyclic aromatic hydrocarbons, and their effects are severe [8–12]. Jacobson [13] showed impacts of biomass burning that may cause net global warming of ~ 0.4 K (by cloud absorption effects—CAE I (~ 32%), CAE II, semidirect effects, anthropogenic heat (~ 7%) and moisture fluxes, aerosol absorption greater than cooling and indirect effects) and calculated that 5 to 10% of worldwide air pollution mortalities causes premature deaths of about 2, 50,000 people each year are frightening facts in a transient 20-year simulation study. If this biomass waste containing high organic content is reused/diverted properly for waste to energy options rather than burning, then certainly, the biomass facilitates to mitigate climate change by reducing the amount of greenhouse gas emissions. In recent years, conversion of biomass waste to "Biochar" is gaining significant emphasis due to its use in climate change mitigation strategies which offers potential for disposal of organic waste thus facilitating to achieve food security through its use as soil amendment. An in-depth knowledge about biochar production from different biomass wastes; thermochemical reaction fundamentals; biochar properties; wide-ranging biochar applications; effects of different types of biochar amendment on various soils; greenhouse gas reduction mechanism; nitrogen transformation between biochar and soil matrix are to be well understood and applied to our daily lives are addressed in this review.

2 Biochar production from biomass waste

2.1 Biomass feedstock materials

Biomass waste can be defined as an organic material or bio-residue originating from living matter or complexes of organic/inorganic materials from different sources (such as water-based vegetation, forest or organic waste, by-product of crop production and agro or food industries waste) which contains both living organisms (plants and animals) and wastes (from animals, sludge, waste wood, etc.) [14, 15]. The world biomass production is around 105 billion metric tons or 104.9 petagrams of carbon/year that comprises 53.8% of terrestrial (56.4 Pg of C) and 46.2% of oceanic (48.5 Pg of C) [16]. The biomass classification depends upon the source and its waste composition, which is summarized in Table 1 along with their examples. Many authors have explored the various biomass types and their characteristics [14, 17–19]. Among them, agricultural residues can further be classified based on their source as primary residue (yield are field-based) and secondary residue (assembled during processing). The biomass waste feed stock availability globally is projected as in Woolf et al. [19]. This projection scenario showed the total maximum sustainable technical potential of biomass is

Table 1 Biomass waste classification with its waste composition

S. no	Biomass waste source	Waste composition	Examples
1.	Forestry plantations, wood processing wastes and logging residues	Natural forests, woodlands, woods from forests and residues from wood industries	Logs, wastewood, leaves, wood shavings, forest industry based waste products, sawdust, wood chips, barks, slabs and splinters, black liquor. Off-cuts generated during wood processing
3.	Agricultural residues	By-product from processing, harvesting of agricultural crops and others	Straws/stalks of cereals, pulses and fiber crops (wheat, rice, corn, coffee, cocoa pod, sorghum, and millet), crop wastes (like sugarcane trash, rice husk, coconut shell, etc), seed coats of oil seed. Green agricultural wastes; Others like elephant grass, guinea, grass, switch grass, macroalgae and microalgae
4.	Agro-industrial wastes	Agro-industrial based wastes	Wastes from paper mills, pulp wastes from food processing units, textile fiber waste, molasses from sugar refineries, cob/husk of corn, wheat, rice, cocoa, coconut, sugarcane bagasse, oil seed cake, oil palm empty fruit bunch, etc.
5.	Animal wastes	Animal manure	Cow manure, livestock or poultry wastes like goat, cattle, pig, sheep and poultry litter
6.	Industrial wastes	Industrial wastewater and by-product of biofuel processes	By-products such as biodiesel, bioethanol and biomethanation; black liquor from paper manufacturing
7.	Municipal solid wastes (MSW) and sewage	Biodegradable wastes and sewage sludge	food waste, kitchen waste, fabrics, clothes, green waste, compost, paper and inert wastes such as demolition debris
8.	Food processing wastes	Hotel, restaurants and community kitchens waste; Wastes from confectionary industry	Vegetable peel waste, stale food, uneaten bread, rice, dish washer rejects, fruit and vegetable rejects, etc.

Source: Adapted from Kumar et al. [14]; Murali et al. [17]; Brosowski et al.[18]

2.27 Pg C per year. In which, 0.14 Pg C per year are from forestry residues (44% of difference reported between fellings and extraction), 0.62 Pg C per year from agroforestry residues (170 Mha of tropical grass pasture changed to silvopasture), 0.14 Pg C per year from Green/wood waste (75% of low-end estimation of yard trimmings production and wood-milling residues, food waste, including 80% of sawn wood waste), 0.28 Pg C per year from rice residues (rice husks and 90% of paddy rice straw unused for animal feed), 0.18 Pg C per year from cereal residues (20% of total straw and stover—45% extraction rate minus animal feed), 0.13 Pg C per year from sugar cane residues (bagasse waste plus 75% of field trash), 0.60 Pg C per year from crop residues (100% of potential production of abandoned, degraded cropland which is not in other use), and 0.19 Pg C per year from animal waste, i.e., manures (25% of cattle manure plus 90% of pig and poultry manure).

The biomass waste material composition for their percentage of cellulose, hemicellulose and lignin content is described elsewhere [13, 20, 21]. The growing step of biomass is considered as the efficient method recently existing for carbon dioxide extraction from atmosphere. However, carbon in biomass is easily degraded by microorganisms and releasing it to the atmosphere as greenhouse gasses. If biomass is pyrolyzed, then the organic carbon content is converted into solid (biochar), liquid (bio-oil), and gaseous (syngas) carbonaceous products [22]. Biomass waste conversion is dependent on biomass feedstock source, quantity, moisture content, particle size, operating conditions (temperature, time, heating rate, carrier gas type, flow rate, catalyst, reactor type, etc.), economic conditions, etc. Biochar is produced both from lignocellulosic and non-lignocellulosic biomasses. Biochar can be produced from biomass feedstock like organic materials such as crop residues, wood residues, animal manures, industrial wastes (paper sludge; biosolids) [23–25], agricultural and forest residues (rice husk, corn straw, switch grass, sugar beet tailings, soybean stalk, flax shive, olive pomace, orange waste, hard/pine/oak wood, pine/oak bark, paper, pulp, green waste, etc.) industrial by-products and wastes, municipal solid waste materials, (sewage sludge, anaerobically digested sugarcane bagasse, distillers grain, bagasse, poultry litter, etc.) and non- conventional materials, such as waste tires, papers, and even bones [26, 27]. A study by Ahmed et al. [28] explored the extent of biochar research globally by a bibliometric analysis for a time period of 15 years (2000–2015). It revealed that the biochar research trend is widely growing and new avenues on future biochar research are upcoming. In developing country like India, biochar is commonly produced from agricultural residues and food processing residues (crop residues, cassia stems, rice husk, palm leaves, saw dust, wheat straw, baggase, walnut shell, corn cobs, palm oil press cake waste, soyabean stover, etc.) [29–31], which are also expanding in other areas. Biochar is a rich carbonaceous material produced when heating the biomass waste with little or no air/oxygen condition in a closed-vessel. The biochar production, properties and its application in climate change mitigation aspects are much needed.

The three main biomass conversion technologies are (a) thermo-chemical, (b) bio-chemical/biological, and (c) mechanical extraction (with esterification). When compared to other processes, thermo-chemical conversion process is advantageous, such as complete conversion of lignin content, breaking down of bonds in organic matter using high temperature, time-saving, etc. [32]. Hence, thermo-chemical process is commonly used for biomass utilization as biochar [33].

2.2 Thermo-chemical conversion processes for biochar production

In thermo-chemical conversion processes, the biomass is converted to solid, liquid and gaseous products and its various conversion processes are low-temperature processes (torrefaction, microwave hydrothermal process and hydrothermal liquefaction), pyrolysis (slow, intermediate, fast and flash), gasification, and combustion processes. The operational details of different thermo-chemical conversion processes are summarized in Table 2. The above processes are mainly differentiated based on their equivalence ratio (i.e., ratio of actual air fuel ratio/air ratio to stoichiometric fuel/air ratio). Biomass materials through thermo-chemical decomposition processes are converted to syngas, bio-oil, and biochar [15, 34]. Biochar is a solid carbon material acquired in an oxygen-limited environment from thermo-chemical conversion of biomass waste [35]. Longer residence time with lower pyrolysis temperature yields solid substance 'biochar' and with higher temperature produces gas "syngas." Moderate temperature with short residence time produces liquid 'bio-oil' as presented in Table 2. Production of biochar from biomass waste does not have any remarkable life cycle–based GHGs emissions [36]. Biochar can be produced from biomass waste by pyrolysis process or gasification process and also be a co-product of biofuel/bio-oil production [30]. The principles and reaction mechanisms involved in various thermo-chemical conversion processes of biochar production are as follows.

2.2.1 Torrefaction

Torrefaction is operated in absence of oxygen condition at lower temperature range of 200 to 300 °C and an atmospheric pressure is maintained in the process. The fundamental step in torrefaction process is volatiles removal through different decomposition reactions and its common biomass torrefaction reactions are (a) devolatilization and carbonization of hemicelluloses, and (b) depolymerization and devolatilization of lignin and cellulose. Deng et al. [37] has shown torrefied agricultural biomass residues at 200, 250 and 300 °C for 30 min

Table 2 Different thermo-chemical conversion processes and its conditions for biochar production

S.No	Parameter	Low temperature processes (50 to 300 °C)		Pyrolysis (300 to 700 °C)				Gasification	Combustion
		Torrefaction	Hydrothermal carbonization	Fast	Intermediate	Slow	Flash		
1.	Condition	No oxygen		No oxygen				Partial oxidation	Burning in air
2.	Desired Products	Stabilized friable biomass	Hydrochar	Bio-oil, solids, gas	Bio-oil, biochar, syngas	Biochar, gas (steam water), tar (bio-oil, volatiles)	Bio-oil, gas, Solids	Syngas/producer gas Gaseous products like CO, CO_2, H, N_2, and moisture (H_2O)	Heat, ashes and solids (incomplete combustion) (CO_2, watervapour and hot flue gas)
3.	Solid (wt%)	80	50–80	10	25	35	–	10	Most of carbon to CO_2
4.	Liquid (wt%)	0	5–20	70	50	30	–	5	–
5.	Gas (wt%)	20	2–5	20	25	35	–	85	–
6.	Temperature (°C)	200–300	< 200	Moderate (425–600)	Low–moderate (450–550)	Low–moderate (300–700)	750–1000	> 800	700–1400
7.	Residence time	10–60 min (< 2 h)	1–16 h	Short hot vapor < 2 s	Moderate hot vapor 0.5–20 s	Long minutes/h to days	< 0.5	Long vapor	–
8.	Heating rate °C/s	< 1	< 1	10–1000	1–10	0.1–1	> 1000	–	–
9.	Carbon content of the solid product (mass%) (Biochar production)	51–55	< 70	74	–	95	–	–	–
10.	Carbon yield ($mass_{carbon, product}/mass_{carbon, feedstock}$)	0.67–0.85	~ 0.88	0.20–0.26	–	~ 0.58	–	–	–
11.	Pressure (MPa)	–	–	0.1	0.1	0.1	0.1	–	–
12.	Particle size (mm)	–	–	< 1	1–5	5–50	< 0.2	–	–
13.	Biochar properties	Highly functionalized with high O/C ratio and easily degradable		High porosity, specific surface area and, low H/C and O/C ratios	–	Functionalized with medium O/C ratio and stability depends on time on pyrolysis final temperature	High porosity, specific surface area and, low H/C and O/C ratios	High porosity, specific surface area and, low H/C ratio and adsorption capacity	Low carbon content in an ash-rich material, resulting a with high nutrient content

Source: Adapted from Tripathi et al. [15]; Mohan et al. [34]

in a vertical reactor which produces higher heating value than that of raw material at 17 and 15% for rice straw and rape stalk, respectively.

Torrefaction increases the biomass calorific value and, its proximate/ultimate composition characteristics are enriched. It also enhanced torrefied biomass mechanical strength, particle size/shape/distribution, grindability and pelletability properties [38, 39]. Prins et al. [40] studied wood biomass torrefaction at 270 °C for 15 min which reduced volatile content and elevated energy density with 20.7 MJ/kg than untreated willow with 17.7 MJ/kg, respectively. Usually, torrefaction process is used as a pre-treatment of biomass for downstream applications by chemical methods and/or combustion process.

2.2.2 Pyrolysis

Pyrolysis is a thermochemical decomposition of biomass process operated at higher temperatures usually at 300 to 700 °C to produce solid biochar, liquid bio-oil, and syngas in an inert atmosphere. The pyrolysis conditions varies with respect to temperature, residence time, heating rate and pressure as shown in Table 2. Based on the different conditions, varying quantities of products are obtained as mainly biochar, bio-oil (less quantities of condensable liquid), and syngas (non-condensable gasses). Pyrolysis is reversible reaction and its scale-up is flexible than incineration units. The basic reactions in pyrolysis of biomass containing cellulose, hemicellulose and lignin contents are cross-linking/char formation, depolymerization and fragmentation, and other secondary reactions are usually occurred [41]. In the initial process, moisture and volatile loss occurs following formation of biochar and finally, chemical rearrangement of biochar, where it decomposes slowly and carbon-rich residual solid formation results [21]. Slow and fast pyrolysis are the primary methods for biochar production. Various pyrolysis reactors were used for biochar production namely (i) fixed bed, (ii) fluidized bed, (iii) circulating fluidized bed, (iv) ablative, (v) rotating cone, (vi) vacuum pyrolysis, and (vii) auger/screw reactors. The biochar and bio-oil production by pyrolysis in auger reactors were studied in detail by Brassard et al. [42].

2.2.3 Fast pyrolysis

The fast pyrolysis of biomass without oxygen condition produce bio-oils as their main product with biochar and pyrolysis gas as co-products. Fast pyrolysis requires quicker heating rates and much shorter residence times usually in seconds when compared to slow pyrolysis process. The intermediate pyrolysis also mainly produce bio-oil in less than 30 s. For high yield in fast pyrolysis, the biomass waste samples have to be properly homogenized, moisture content less than 10% and sample size around 2 mm [43]. Zhang et al. [44] studied fast pyrolysis of corncobs biomass on liquid bio-oil yield and its composition under different pyrolysis gas atmospheres in a fluidized bed reactor. The study showed maximum liquid yield (58.7%) was obtained with CH_4 and minimum yield (49.6%) with CO gas atmosphere. The greater heating value of bio-oil was acquired under H_2 at 24.4 MJ/kg, followed by CO and N_2 gas atmosphere at 23.7 and 17.8 MJ/kg, respectively.

2.2.4 Slow pyrolysis

The residence time is longer in slow pyrolysis from minutes to hours, sometimes even days whereas, fast pyrolysis is very short, usually in seconds. Slow pyrolysis is favored than fast pyrolysis for their maximum biochar yield over production of bioenergy, economy and greater nutrient retention [24, 32]. Marculescu et al. [45] studied comparison of three thermochemical processes, viz., direct combustion, pyrolysis, and gasification for their waste to energy conversion efficiencies. Heterogenous wastes such as cellulose-based waste, plastic waste, food industry residue and agriculture residues were used, which operated with low-temperature pyrolysis process at 350–550 °C and high-temperature steam gasification at 850–1050 °C. The results showed that short pyrolysis period is only required for achieving the complete waste carbonization within 30 to 45 min. The slow pyrolysis process is widely used for biochar production. Li and Jiang [27] explored the detailed review on different non-lignocellulosic biomass (sewage sludge, sugar, manure, algae, human/animal hair, bones, feather, and meat) for biochar production using pyrolysis and hydrothermal processes. Recently, microwave-assisted pyrolysis is compared with conventional pyrolysis [46]. The biochar production from different waste biomass in various reactor conditions is summarized in Table 3. Higher yield of biochar is produced at low temperatures and lower residence times produce a highly functional biochar [47–51].

2.2.5 Microwave-assisted pyrolysis (MAP)

Microwave-assisted pyrolysis is an efficient selective heating process of biomass by microwave dielectric heating effects in the presence or absence of catalysts. When compared to conventional pyrolysis, MAP gives higher energy efficiency, fast, easy control, less operating cost, and better end quality product [33, 46]. The main limitations of MAP are capital cost for microwave equipment and scaling up, usually requires pre-treatments of biomass. The two main mechanisms in MAP are dipolar polarization and ionic conduction [46]. It produces potential gaseous hydrocarbons and hydrocarbon oils which are useful as chemicals or fuels. Solid product obtained in MAP provide heat and function as a microwave absorber and gas product is used for feedstock pretreatment (drying). Puligundla et al. [20] have summarized in detail about the different microwave-assisted pre-treatment technologies for

Table 3 Biochar production by pyrolysis using different biomass

S. no	Waste components	Initial properties of biomass			Reactor type	Temperature	Heating rate	Yield with optimum conditions (%)	Reference
		Ash %	Volatile matter %	Fixed carbon %					
1.	a) Olive husk, b) Corncob and c) Tea waste (Turkey)	4.1 1.1 1.5	72.5 84.6 83.8	27.5 15.4 16.2	Cylindrical batch reactor	450–1250 K (177–977 °C)	10 K/s	a) 450 K- 44.5; 1250 K -19.4 b) 450 K- 30.6; 1250 K - 5.7 c) 450 K < 40; 1250 K - ~ 15	Demirbas [21]
2.	a) Bagasse b) Cocopeat c) Paddy straw d) Palm kernel shell e) Wood stem f) Wood bark	2.1 4.6 20.9 3.4 0.4 4.9	71 49.1 56.4 66.8 80.1 68.9	13.7 25.3 15.4 17.9 10.7 16.2	Bench-scale fixed bed reactor (kept in electrically heated furnace)	500 °C	10 °C/min	a) 24.5 b) 38.7 c) 41 d) 32.2 e) 22.3 f) 31.9	Lee et al. [47]
3.	Sewage Sludge (Spain)	32.4	59.2	8.4	Quartz reactor	350–950 °C	30 K/min	350 °C – 52 950 °C – 39	Sanchez et al. [48]
4.	a) Dairy manure b) Feedlot manure c) Poultry litter d) Swine solids e) Turkey litter (USA)	14.8 15.4 16.9 20.9 20.3	80.7 76.7 74.3 73.6 74	4.5 7.9 8.8 5.6 5.7	Furnace equipped with a gas tight retort	350 °C 700 °C	2.5 °C/min 8.33 °C/min	a) 350 °C – 54.9; 700 °C – 35 b) 350 °C – 51.1; 700 °C –32.2 c) 350 °C – 54.3; 700 °C –36.7 d) 350 °C – 62.3; 700 °C –36.4 e) 350 °C – 58.1; 700 °C –39.9	Cantrell et al. [49]
5.	Pine needle (Korea)	1.99 ± 0.08	5.19 ± 0.56	–	Muffle furnace	300 500 700	7 °C/min	300 °C - 57.57 ± 2.19 500 °C - 31.82 ± 0.59 700 °C - 24.95 ± 1.31	Ahmad et al. [50]
6.	Simulated MSW composition was food waste (68%), plastic (20%), paper (8%) and textile (4%) (Thailand)	7.6	77.8	14.6	Vertical-type pyrolyzer having Proportional Integral Derivative (PID) controller	300, 350, 400, and 450	5, 10, 15, 20 and 25 °C/min	300 °C (25 °C/min): ~ 9 350 °C (25 °C/min): ~ 13 400 °C (25 °C/min): 20.9 450 °C (25 °C/min): ~ 17 400 °C (5 °C/min): 50.6 400 °C (10, 15, 20 °C/min): ~ 38–40	Areeprasert et al. [51]

biomass conversion to biofuels. Microwave heating pyrolysis was explored for the conversion of various biomasses, such as macro- and micro-algae, agriculture residue, forestry residue such as wood, pine/fir sawdust, corn stover, wheat/rice straw and sewage sludge into biofuels [33, 46, 52]. MAP of cotton stalk was assessed by Wang et al. [33] in various microwave powers (800 to 1200 W) and additives (sodium hydroxide, sodium carbonate and phosphoric acid). 1000 W microwave power yielded optimum bio-oil production of 26.7% with main components of acetol, furfural, 2-methoxy-phenol and 4-methyl-2-methoxy-phenol. The additives amplified the yield of solid residue/gas and reduced the bio-oil yield. When compared to different production processes, pyrolysis process increase energy recovery and produce less pollutants [53]. Other new pyrolysis processes are laser and plasma cracking technologies for biochar production [54].

2.2.6 Flash pyrolysis

For the flash pyrolysis process, the main desired product is bio-oil and it operates at shorter residence time than the fast pyrolysis with only few seconds and higher heating rates. The main pathway of flash pyrolysis of biomass at higher temperature (700–1000 °C) is depolymerization and biomass cracking to produce bio-oil similar to the viscosity of the diesel oil. Some of the flash pyrolysis are flash hydro-pyrolysis and vacuum flash pyrolysis (negative pressure to remove condensable products) [43]. The flash hydro-pyrolysis operating at 350–600 °C at a heating rate of 10–300 °C/s with residence time > 15 s in a pressure of 5–20 MPa to remove condensable products. The vacuum flash pyrolysis operated at 300–600 °C with heating rate of 0.1 to 1.0 °C/s having low residence time of 0.001–1.0 s in a hydrogen atmosphere of 0.01–0.02 MPa [15].

2.2.7 Gasification

Gasification process is the conversion of a biomass material at atmospheric elevated temperatures above 800 °C with fast heating rate in a gaseous medium like oxygen, air, nitrogen, carbon dioxide and steam that results in a gaseous mixture fuel generally known as synthesis gas (syngas) [24, 55]. It is mainly used for the generation of heat and electricity [56]. Gasification process yields hydrogen, carbon monoxide, carbon dioxide, and water by partial combustion and at low temperatures also yields hydrocarbons. Gasification process generates minimal quantities of biochar in an air containing direct-heated reaction vessel condition. It requires a low oxygen-to-carbon ratio. Lapuerta et al. [57] studied the gasification of biomass wastes such as forest waste (*Pinus pinaster* pruning), agricultural waste (grapevine and olive tree pruning), and industrial wastes (sawdust and marc of grape). The study showed agricultural wastes could produce high gas efficiency and gas yield for fuel production to form producer gas which can be used in combustion engines/turbine, whereas sawdust could produce fuel to generate hydrogen rich gas.

2.2.8 Combustion

In combustion, primarily air is used as an oxidizing agent in the process giving the flue gas having CO_2 and H_2O with more than 50% of N_2 in it. Even though combustion is a clean energy production, its specific investment and global energy efficiency (high air excess) play as a disadvantage [22, 45]. If biomass waste generation is discontinuous, then combustion process can be applied. Most of the cases, the direct combustion of the biomass (like woody biomass) is not efficient and it requires pretreatment such as drying or chipping. Sometimes due to the length of woody biomass (i.e., 12 to 24 ft. long), pretreatment is necessitated. Whereas, in some newer systems, minimal or no pretreatment is practised. Marculescu et al. [45] conducted combustion process for heterogeneous solid waste such as packaging waste, agriculture waste and food industry waste in a tubular electrically heated reactor operating at 900–1200 °C with the excess air of 1.3–1.7. The agricultural waste with less than 45% moisture content can recover maximum power from 2.2 to 3.7 MWe. Pyro-combustion generates power capacity of 1.4 MWe up to 2.35 MWe. Additionally, wood boilers that provide heat and power are being retrofitted to offer and off take of biochar. This biochar production can be seen as a way to off-set some of the cost of biomass haul to the power generation site.

2.2.9 Hydrothermal carbonization (HTC)

Hydrothermal Carbonization is a low-temperature thermochemical pretreatment process of biomass mainly operated at 200 to 300 °C. HTC uses water as solvent medium in the reaction to produce the end product, hydrochar [58]. HTC homogenizes the different biomass wastes, produce better fuel efficiency and energetically energy efficient than pyrolysis process for carbonizing the wet biomass. Biomass containing smaller particle size is better in HTC than pyrolysis due to its low char yields [59]. The starting step of HTC is hydrolysis process, followed by dehydration and decarboxylation processed products thereby undergoing condensation, polymerization, and aromatization processes. In hydrolysis of biomass, it reacts with water and produces vast products like oligosaccharides, after breakdown of ether/ester bonds especially β-(1–4) glycosidic bonds. The intermediate products of dehydration and decarboxylation such as 5-HMF, anhydroglucose, furfural, erythrose, and 5-methyl furfural are formed. These intermediate compounds are converted to bio-crude by condensation, polymerization and aromatization processes. This bio-crude with or without auto-nucleation is converted into hydrochar [58]. HTC is decomposed incompletely, produces hydrochar, a gas (mainly CO_2), water, and water-soluble compounds [59]. Hydrochar formed from any reaction medium of liquid-liquid, liquid-solid or solid-solid reaction accordingly results in liquid biocrude or/and solid lignin residue. Liu and Balasubramanian [60] studied the HTC of coconut fiber and eucalyptus leaves biomass at 150 to 375 °C for 30 min. The activation energy of coconut fiber and eucalyptus leaves at 150–300 °C gave 67.41 and 59.18 kJ/mol, respectively. At 300–375 °C, the activation energy increased for coconut fiber and eucalyptus leaves, which was about 179.54 and 173.70 kJ/mol, respectively. Stemann et al. [61] showed HTC of empty palm oil fruit bunches at 220 °C gave a HTC coal having higher heating value (HHV) of 28 MJ/kg. HTC for non-lignocellulosic wastes such as sea food waste (fish and shrimp wastes) was studied by Kannan et al. [62, 63]. The hydrochar yield for fish and shrimp waste was about 35% at 180 °C for 120 min and 29% at 186 °C for 120 min, respectively.

3 Properties of biochar

Biochar has highly porous structure, carbon-rich, negative surface functional groups, aromatic rings, adsorption ability, large specific area, micro-scale crystalline, macro-scale amorphous structure and resistant to biological decomposition. Biochar is a highly heterogeneous substance with their chemical composition largely depends on biomass characteristics and pyrolysis conditions [13, 50, 64–66]. Its properties also depend upon the reactor design, gas flow rate, and post-pyrolysis treatments [67]. Biochar is primarily composed of carbon (C), oxygen (O), hydrogen (H) and nitrogen (N), other compounds such as sulfur (S), calcium (Ca), and potassium (K) are also present depending on biomass properties [68–72]. The selection of appropriate pyrolysis technology is also important for high biochar yield and properties [73]. Lignocellulosic biomass converted into biochar through thermo-chemical processes have a 3-dimensional interconnected structure similar to its original physical morphology, resulting in a high surface area (> 300 $m^2\ g^{-1}$) and large pore size (macro-, meso-, and nanopores) distribution [74]. Biochar's surface area range from 0.5 to 450 $m^2\ g^{-1}$ [67]. Porosity, economical cost and its high nutrient recovery capacity makes the biochar potentially as a best carbon-based material. Biochar has high chemical and biological stability, high cation exchange capacity, and highly functionalized with high O/C ratio depending on pyrolysis conditions (residence time and final temperature) [25, 75]. It can improve soil physical properties, enlarge soil carbon storage capacity and stabilize soil organic carbon pools [76]. Different particle sizes of biochar have various influences on the physical, mechanical and chemical properties of soils [77].

3.1 Property dependence on temperature

The biochar characteristics are strongly determined by pyrolysis temperature and residence time for their proximate and ultimate compositions of carbon, volatile matter, ash, and moisture content. Several studies have been conducted for investigating the effect of temperatures on biochar characteristics, which is as summarized in Table 4. Most of the studies showed as temperature increases, biochar carbon, and nitrogen content increases, whereas hydrogen and oxygen content decreases. The temperature ranges for cellulose, hemicellulose, and lignin degradation are at 300–400, 200–300, and 200–700 °C, respectively [67].

Angin [53] demonstrated that safflower seed-based biochar produced at higher temperature (600 °C) gave a higher total carbon content than biochars formed at lower temperatures (400, 450, 500, and 550 °C). In steam gasification, biochar generated at higher temperatures by rapid pyrolysis is more reactive than those produced at lower temperatures [21]. Al-Wabel et al. [78] studied the effect of pyrolysis temperature (200–800 °C) on biochar characteristics. The biochar yield decreases at increasing temperatures of 200, 400, 600, and 800 °C as 51.33 ± 2.38%, 31.86 ± 1.19%, 27.22 ± 0.57%, and 23.19 ± 0.65%, respectively. It has been shown that biochar produced at higher temperatures (600–700 °C) have higher content of aromatic C and porosity, lower content of H and O functional groups, and hence lower cation exchange capacity. Conversely, biochar produced at lower temperatures (300–400 °C) have higher content of C-O and C-H functional groups and surface area, leading to higher cation exchange capacity and lower porosity [70, 79–81]. Such, a biochar characteristics is suitable for agricultural applications for soil improvements.

3.2 Property dependence on other parameters and biochar yield

Biomass waste containing high lignin content yields maximum biochar [41]. The other biomass properties having influence on higher biochar yield are large biomass particle size, high ash, and nitrogen content. The pyrolysis process parameters also play a major role for higher yield was lower pyrolysis temperature generally less than 400 °C, lower heating rate, higher pressure and residence time and long vapor/solid interaction. A study by Demirbas [21] exhibited a difference in particle size of olive husk and corncob resulted in varying biochar yield even when performed under same pyrolysis conditions. The higher lignin content in olive husk produced maximum biochar yield in comparison to corncob. A high temperature and smaller particles increase heating rate resulting in a decreased bio-char yield. Similar to biochar yield, other characteristics affected by raising temperature were oxygen, hydrogen, sulfur, acidic functional group, water sorption

Table 4 Physico-chemical characteristics of biochar from biomass wastes at varying pyrolysis temperature

S. no	Biomass waste	Temperature (°C)	C %	H %	O %	N %	Ash %	Volatile content %	pH	Reference
1.	Peanut hull	a) Hull: 400;500	75; 82	4.5; 3	10; 3	2.7; 2.7	8.2; 9.3	38.4; 18.1	7.9; 8.6	Novak et al. [70]
	Pecan shell	b) Shell: 350;700	65; 91	5; 1.5	28; 2	0.3; 0.5	2.4; 5.2	61.6; 9.7	5.9; 7.2	
	Switch grass	c) Grass:250;500	55; 84	6; 2.4	36; 4	0.4; 1.1	2.6; 7.8	74.4; 13.4	5.4; 8	
	Poultry Litter	d) Poul: 350/700	46; 44	4; 0.3	9; 0	4.9; 2.8	36; 52	36.7; 14.1	8.7; 10	
2.	Willow	a) Willow-450	78.4 ± 0.5	2.03 ± 0.03	-	0.82 ± 0.01	4.3 ± 0.1	11.2 ± 0.4	7.3 ± 0.1	Nelissen et al. [71]
	Pine	b) Willow-650	84.8 ± 0.5	1.14 ± 0.01		1.00 ± 0.01	4.9 ± 0.1	6.0 ± 0.3	8.1 ± 0.2	
	Maize	c) Pine –450	86.8 ± 0.7	2.80 ± 0.06		0.19 ± 0.04	0.9 ± 0.1	12.1 ± 1.1	6.7 ± 0.0	
	Wood mixture	d) Pine - 650	92.6 ± 0.1	1.68 ± 0.01		0.15 ± 0.00	1.1 ± 0.1	6.0 ± 1.2	7.7 ± 0.1	
	(Spruce, Silver fir, Scots pine, Beech, Oak)	e) Maize – 350	67.3 ± 0.4	4.25 ± 0.04		1.47 ± 0.04	7.7 ± 0.4	32.6 ± 0.6	8.3 ± 0.1	
		f) Maize - 550	72.1 ± 0.3	2.21 ± 0.00		1.52 ± 0.01	10.9 ± 0.3	12.1 ± 0.5	9.8 ± 0.0	
		g) Wood – 480	68.1 ± 2.5	1.50 ± 0.00		0.40 ± 0.00	8.3 0	12.0 ± 0	8.6 ± 0.1	
3.	Conocarpus wastes	a) 200	a) 64.19 b) 76.83 c) 82.93 d) 84.97	3.96	26.61	0.69	4.53 ± 0.07	–	6.69 ± 0.01	Cha et al. [68]
		b) 400		2.83	14.16	0.87	5.27 ± 0.04		9.51 ± 0.02	
		c) 600		1.28	6.55	0.71	8.56 ± 0.02		12.52 ± 0.01	
		d) 800		0.62	4.87	0.90	8.64 ± 0.01		12.70 ± 0.01	
4.	Orange Peel and Water treatment sludge	a) Orange: 0; 400	41.9; 68.4	6.4; 4.8	47.9;19.8	1.0; 2.0	2.9; 5.0	–	4.1;11.6	Oh et al. [72]
		b) Orange: 600;700	74.7; 74.8	2.1; 1.6	13.4;13.4	1.7; 1.7	8.1;8.5		12.2;12.3	
		c) Sludge:0; 400	6.6; 8.5	1.8;1.0	15.3;6.4	0.3;0.3	76.0;83.7		5.7;6.4	
		d) Sludge: 600; 700	8.4; 8.1	0.6; 0.5	2.0;0.6	0.2;0.2	88.8;90.7		6.6;6.8	
5.	Municipal Solid waste	a) 400	48.6 ± 2.0	12.2 ± 0.5	31.7 ± 2.5	1.3 ± 0.3	6.1 ± 1.6	22.3 ± 4.1	8.0 ± 0.02	Jin et al. [69]
		b) 500	59.5 ± 5.5	9.1 ± 0.3	20.8 ± 4.9	1.4 ± 0.3	9.2 ± 3.3	26.4 ± 5.1	8.5 ± 0.05	
		c) 600	70.1 ± 0.6	8.4 ± 0.1	13.7 ± 2.4	1.3 ± 0.1	6.2 ± 0.6	15.1 ± 1.3	9.0 ± 0.02	

capacity, and cation exchange capacity (CEC) [78, 82]. Whereas, parameters such as pH, ash, carbon, electrical conductivity, phosphorus, potassium, calcium, magnesium, basic functional groups, BET surface area, available nutrients, and heavy metal stability have favorable influence on increasing temperatures as shown in Table 4 and other studies [78, 82]. High-pyrolysis temperature biochar may have lower nutrient retention capability. Biochar having high porosity, large specific surface area, low H/C ratio and low carbon content in an ash-rich material yields a material with high nutrient content [43, 68, 83]. Yoder et al. [84] indicated biochar costs around $0.1/kg much lesser than the low-priced activated carbon around $5/kg.

3.3 Hydrochar

Hydrochar is a major stable solid product of hydrothermal carbonization or liquefaction process, sometimes called as HTC biochar. Hydrochar is hydrophobic in nature that has high quantities of stable carbon and nutrient contents, vital for soil amendment [58]. In the comparison of hydrochar and biochar, they are typically different from their production and properties. Hydrochar has lower carbonization degree than biochar by pyrolysis, higher H/C ratios and lower aromaticity [59, 75].

HTC exhibits higher carbon efficiency (i.e., amount of carbon in final product compared to initial carbon content of the feedstock) than other biomass conversion techniques. Hydrochar is a “carbon sink” that stores total carbon present in raw material. This could be used as an energy source directly from hydrochar without any further treatment and which also reduces GHG emissions.

3.4 Modifications and activation of biochar

The modification and activation of biochar are recently becoming important due to their role in improving the quality of biochars and expanding its applications.

3.4.1 Activation

Activation of biochar is a process for optimizing the sorption capacity through enlarging specific area and it can be done in two ways either by one step as direct activation or two steps by an activation after pyrolysis process. There are biological, physical, and chemical activation of biochars. Biological activation of biochar increase the water and nutrient retention in soils that can happen naturally (several months to years) or can be fastened by addition of manure/compost [79]. Physical and chemical activation are carried out by using several physical/chemical activating reagents. The physical activation is also called as thermal activation or gas activation of biomass which is mainly used to increase its porosity. The common physical activating agents used are water, steam, CO_2, air/O_2 [56]. The chemical activation of biochar changes its porous structure, functional groups on biochar surface, and its adsorption capacity [69]. Some of the chemical activating agents used are KOH, H_3PO_4, K_2CO_3, NaOH, $ZnCl_2$, $FeCl_3$, H_2SO4, HCl, HNO_3, Urea, etc.

Both physical and chemical activation have advantages and disadvantages. The physical activation takes place at high temperatures and produces low yields, whereas, chemical activation takes place at low temperatures with higher yields depending upon the activating agent used. Even, chemical activation sometimes has demerits like causing corrosion problems based on acidic/basic nature of chemical activating agents involved [59]. The extent of activation depends upon chemical used, mixing intensity, temperature, and duration. Study by Jin et al. [69] chemically activated surface of MSW biochar for enhanced As (V) adsorption capacity by 2 M KOH solution. The study results showed that chemically activated MSW biochar have greater adsorption capacity than non-activated biochar with 30.98 and 24.49 mg/g, respectively. In some cases, chemical activation of biochar surfaces may cause hazardous/unwanted by-products generation in application to soil due to exposure to chemicals [85]. The extent of physical activation depends upon biomass type, oxidant (or physical activating agent), temperature and duration [56]. Borchard et al. [85], physically activated wood biochar by steam activation for improvement in soil amendment. The biochar activation was conducted at 900 °C for 30 min, where hot water steam (ambient air - N_2/O_2 gas mixture) was introduced into the reactor at every 30 s/min. The results showed that the physical activation of biochar has increased soil nutrient retention, availability and uptake by plants by a factor of 2, when compared to non-activated biochar.

3.4.2 Modification

Modification of biochar is a process for increasing sorption capacity for the specific sorbates. It is generally done by introduction of non-carbon moieties to the biochar surface. Modification can be done after or instead of activation [56]. Some of the recent modifications methods of biochar are metal impregnation, low-temperature plasma, organic matter grafting and ozone oxidation [54]. Oxidative modification can be done by hydrogen peroxide (H_2O_2) or nitric acid (HNO_3) at low temperatures to create oxidized functional groups and sometimes ammonia/sulfur is also used. Biochar-based composites are produced by impregnation or coating the surface of the biochar with metal oxides, clay minerals, carbonaceous structures (graphene oxide or carbon nanotubes), complex organic compounds (chitosan) or amino acids, or inoculation with microorganisms [86]. The common metal ions used for impregnation are iron, magnesium, silver, zinc, etc. Akgul et al. [87] conducted a modification process in tea biochar using metal salts for elimination of pollutants such as PO_4^{3-} and Cd^{2+}. The metal impregnation on biochar was carried out using metal oxides (of Mg, Fe, Mn, and Al) which improved the adsorption capacity. The study results showed that both biochar and metal-impregnated composites are good and inexpensive compounds for phosphate and cadmium removal, especially due to their more surface functional groups rather than porosity. Among the different metal impregnated biochars prepared, Mg-impregnated tea biochar is most effective composite for Cd^{2+} and PO_4^{3-}removal. The possible applications of biochar are detailed below.

4 Applications of biochar

Biochar is a sustainable alternative to other carbon materials. A schematic diagram of potential biochar applications in various fields is depicted in Fig. 1. Many authors have studied the applications of biochar [26, 34, 88–92]. Biochar application on soils has wide advantages for soil fertility improvement. Biochar produced from large-scale industrial purposes to small-scale domestic purposes [32].

4.1 Soil improvement

Several author's have reported benefits of biochar addition to soils [36, 91, 93–98]. The direct benefits are soil fertility enhancement, remediation of polluted soils and increase of soil carbon storage [25, 93]. The soil properties (pH, bulk density, water holding capacity, or cation exchange capacity), plant growth and carbon uptake are improved on addition of biochar to it. It also causes native soil organic matter decomposition and non-CO_2 greenhouse gas emissions to occur due to variations in soil moisture and/or nutrient availability [65]. Biochar on to soil is a 'carbon negative' as the carbon sink is converted as a carbon storage and it is present in soil for hundreds of years [24, 99]. Carbon mineralization studies of biochar addition to soils are done [98, 100, 101]. Biochar's diverse ability to influence nitrogen cycling processes are explained in detail elsewhere [102]. A study by Novak et al. [70] demonstrated a sandy Ultasol soil amended with switchgrass (`Panicum virgatum` L.) biochar increased water holding capacity by 6.7 to 15.9%. Non-irrigated soil field can be used for crop production using biochar amendment as it retains more water from rainfall than un-amended soil [93]. An indirect benefit can be improved infiltration, leading to less field run-off (i.e., erosion potential).

A clay loam soil amended with wood-derived biochar increased the soil workability (at dosages of 6 or 10%), fertility,

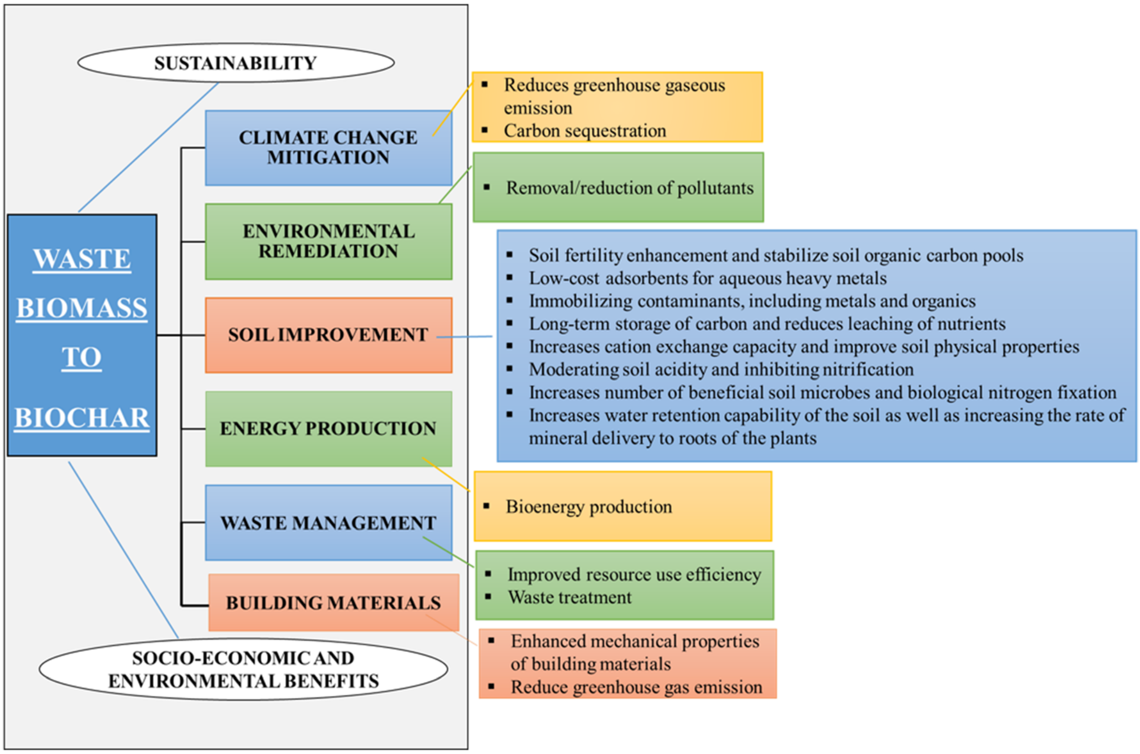

Fig. 1 Applications of biochar. Source: Adapted from Novotny et al. [43]

texture, plasticity index, and moisture retention was demonstrated by Ahmed and Raghavan [77]. Wardle et al. [103] described a "priming" effect of biochar, in which biochar amendment catalyzed decomposition of existing soil organic carbon. Biochar amended soil studies by different authors: (i) A meta-analysis of biochar and its effects on plant productivity and nutrient cycling was carried out by Biederman and Harpole [104]. (ii) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils was observed by Zimmerman et al. [105]. (iii) The soil biota and their microbial activity also affected by biochar addition which maintains the soil health [91, 106, 107] and (iv) Biochar commonly used as an agricultural soil amendment can improve crop production in acidic soils [94].

Mukherjee et al. [108] studied oak biochar (at 650 °C) for their effects on silt loam soil properties, greenhouse gaseous emissions, and their global warming potential. The biochar amendment resulted in considerable rise in soil carbon content (7%) and surface area (15%), whereas the soil bulk density dropped (13%) compared to control. A study by Rondon et al. [91] showed biological nitrogen fixation by common beans showed significant improvement when moderate rates of biochar additions were done. The nitrogen fixation increased from 50% for soils without biochar additions to 72% with 90 g kg^{-1} biochar added soils. While total nitrogen derived from atmosphere considerably raised by 49 and 78% with 30 and 60 g kg^{-1} biochar addition to soil, respectively. Ahmed et al. [109] studied the effect of maple wood (*Acer* sp.) biochar (at 500 °C) on silt loam soil. They evaluated the compactibility and strength of biochar amended soil, which resulted in decreased bulk density (18.1%), penetration resistance (66.6%), shear strength (97.4%) and, increased moisture content (26.8%), plastic limit (5.3%), liquid limit (13.7%), plasticity index (8.4%) than non-amended soil.

4.2 Climate change mitigation in soil aspects (reduction of greenhouse gaseous emissions and carbon storage)

Biochar as soil amendment, mitigates climate change by reducing greenhouse gas emissions and sequestrating carbon are being evaluated. It also simultaneously improving the soil properties and its functions [93]. Biochar having properties such as C/N ratio < 30, $O/C_{org} < 0.2$ and $H/C_{org} < 0.7$ are shown to mitigate climate change and sequester carbon in soil [73]. The biogenic carbon is stored in soil by biochar addition and thereby offsetting carbon emissions, which are usually emitted during fossil fuel burning [110–113]. The biochar addition to soil has potential to decrease CO_2 emission release back to atmosphere and substantially reduces greenhouse gaseous emissions (N_2O and CH_4) from soils which has a predominant effect on abatement of greenhouse effect [36]. The climate impacts of biochar are studied in detail by Meyer et al. [114]. Biochar amendment into soil has been recommended as a key to offset the global greenhouse gas emissions by Lucchini et al. [115]. The production processes of biochar also influence GHGs from initial biomass collection, transportation, biochar generation and until its use [65]. Biochar stability decides its appropriateness as a climate mitigation tool.

The soil emission studies with biochar in varying soil types world-wide are summarized in Table 5. Several studies have reported increase/decrease of methane and/or nitrous oxide emissions from soils amended with biochar as shown in Table 5 [71, 101, 116–121]. From the studies, it shows that soil properties such as carbon content, nitrogen content, and C/N ratio played a foremost role in the emission of CH_4 and N_2O. Biochar amended in soil containing higher nitrogen, lower carbon and C/N ratio resulted in elevated N_2O emissions, and also sometimes reduced CH_4 emissions [67].

4.2.1 Influence of biochar on CO_2 and CH_4 emission reduction in soil

The biochar in soil has both positive/negative effects on CO_2 emissions. In some studies, biochar CO_2 emissions elevated with heating temperature and duration [122], few studies reduced CO_2 emissions from soil [123] and some has no significant effect or minor effect on CO_2 flux [97, 120, 124]. During biochar addition to soil, an immediate short-term rise in CO_2 emission was demonstrated by many authors [105, 122, 125] which might be due to biotic consumption or abiotic release of some biochar particles and/or higher mineralization of native soil organic matter [100, 126, 127]. Biochar subjected to microbial incubation were evaluated for carbon dioxide emissions under combustion conditions for a year. It revealed that biochar with abiotic incubations resulted in higher carbon release around 50 to 90% than that of microbially inoculated incubations. Both biochar incubations reduced the amount of emissions with their raising char temperature [122]. The carbon content in soil is almost 3.3-fold higher concentration than the atmosphere and 4.5-fold more than plants/animals, respectively [128].

Several author's explored the effect of biochar on CH_4 and CO_2 emissions in different soil types. A study by Liu et al. [123] showed bamboo chip and rice straw biochar amended in paddy soil reduced the CH_4 and CO_2 emissions, however, rice straw biochar was very efficient. The decrease in CH_4 emissions is observed due to methanogenic activity inhibition and/or methylotrophic activity stimulation. A study by Zhang et al. [129] also showed a significant reduction in indirect CO_2 emission from rice paddy field amended with biochar. In a Mediterranean wheat crop, biochar addition (3 or 6 kg m^{-2}) has no significant increase of CO_2 and CH_4 emissions studied by Castaldi et al. [120]. Biochar addition to boreal agricultural soil had no effect on CO_2 fluxes in short-term pilot field study. Whereas, increased water holding capacity and CH_4 uptake (96% increase avg. cum. CH_4 uptake) rate were observed in biochar amended soil than control plots [124]. The amounts of CH_4 emissions will greatly depend on physico-chemical properties of biochar, soil type, microbiological circumstances, and water/fertilizer management [123]. Yu et al. [130] demonstrated soil moisture levels and microbial communities of different soils in influencing production and consumption of CH_4 emission following biochar amendment. Matovic [131] calculated that biochar production and its amendment in soil revealed that globally 10% of net primary productivity in a year would be offset towards annual increment of CO_2 emission in atmosphere. Biochar reduces global greenhouse gaseous emissions annually by 12% and sequesters 2.2 Gt C/yr by 2050 [19, 65]. Gaunt and Lehmann [132] exhibited abatement of GHG emissions for biochar production from corn stover and switchgrass at 10.7 and 12.6 t CO_2 ha^{-1} yr^{-1}, respectively. Carbon sequestration of 200 million metric tons (0.2 Pg) annually can be achieved by incorporating biochar into soils [110]. Biochar produced at higher temperatures has greater carbon sequestration capacity than produced at lower temperature [78]. Spokas et al. [133] studied the effects of woodchip biochar addition on the greenhouse gas emission. Study by Sheng and Zhu [134] investigated microbial response and CO_2 emissions in biochar amended soil under varying pH (5.19; 7.81) and application rates. The results showed CO_2 emissions elevated in acidic ferralsol soil owing to maximum biochar degradation, whereas CO_2 emissions reduced in alkaline phaeozems soil due to negative priming effect of soil organic carbon. The pH parameter in soil plays an important role for CO_2 emissions by increasing the bioavailability of organic carbon. Lehmann [25] investigated the effect of biochar amendment in arable and forest soils, which showed that it can amplify the carbon storage in soils. Fargione et al. [135] indicate that by 2025, biochar has the potential to sequester 95 million tons of CO_2 annually in the USA at costs of up to \$100 per ton of CO_2. Increased soil carbon sequestration by amending agricultural soils with biochar, which converts non-recalcitrant carbon (residue biomass) to recalcitrant carbon (biochar) through pyrolysis. 79.6% of biochar carbon persists on a time scale of > 100 years.

4.2.2 Influence of biochar on N_2O emission reduction in soil

Many authors' reported effects of biochar application to soil on nitrous oxide emissions [95–97]. Mukherjee et al. [108] measured greenhouse gaseous emissions of a silt loam amended with biochar obtained from the slow pyrolysis of oak at 650 °C, at 0.5% w/w (7.5 t/ha). N_2O emissions were drastically reduced amounting to 92%. Biochar addition produced a net negative Global Warming Potential (GWP) effect. Sun et al. [136] studied combined effect of biochar and nitrogen fertilizer on plant nitrogen uptake and N_2O emissions in a cereal rotation system on a sandy loam soil. Four levels of nitrogen fertilizer, corresponding to 0, 50, 100, and 130% of recommended fertilizer level, were applied in winter wheat

Table 5 Soil emission studies with biochar in varying soil types world-wide

S. no	Soil type	Soil characteristics	Country	Feedstock for biochar	Experiment conditions (biochar)	Biochar characteristics	Effect of biochar application on soil	Emission studies	Reference
1.	Grassland	Sandy clay loam (Eutric Cambisol) pH -6.2	United Kingdom	Hardwood (*Fraxinus excelsior* L., Fagus sylvatica L. and *Quercus robur* L.)	Biochar at 450 °C Application rate-10 t ha^{-1}	pH - 10.42 ± 0.02 C:N ratio - 146 ± 4 DOC (mg C kg^{-1}) - 1646 ± 33	Enhancing nutrient availability (P and K), moisture retention and increasing soil C content	Unlikely to influence rates of N_2O emissions	Reed et al. [116]
2.	Paddy	a) Inceptisol: pH– 7.6; SOC - 7.50 g kg^{-1} Total N – 1.35 g kg^{-1} b) Ultisol: pH– 7.6; SOC - 3.25 g kg^{-1} Total N – 0.66 g kg^{-1}	China	Corn stalk	Biochar reactor heated from 200, 250, 300, 400 and 500 °C for 1.5 h	Biochar (500 °C) pH - 10.12 ± 0.03 C/N ratio - 88.94 ± 5.08 Carbon (total)-48.44 ± 0.77	Retain more carbon in soil, stimulate soil microbes, enhance soil productivity and increase grain yields	CH_4 emissions reduced by 61–63%	Feng et al. [117]
3.	Rice (rainfed upland)	Anthraquic gleysols Soil depth:0–15; 15-30 cm pH – 6.5; 6.6 TOC – 15.3; 11.3 g kg^{-1} Sand (g kg^{-1}) – 210; 260 Silt (g kg^{-1}) – 370; 340 Clay (g kg^{-1}) – 420; 400	Philippines	Rice husk	Carbonization of rice husk -Burning chamber	pH – 8.6 Ash - 45%	Soil organic carbon and crop yield increased for poor soils, whereas, have little effect on fertile soils. High C/N ratio biochar on fertile soil have limited N availability	CH_4 and CO_2 emission relatively stable for thousand years	Haefele et al. [118]
4.	Organic farm - Vegetable crop rotation	Silt loam (Yolo) Silt – 29% Clay – 22% Sand - 49% pH – 7.8 TC% - 1.6 C:N – 13.3	United States of America	Walnut shell	Biochar at 900 °C using a controlled partial air stream in internal combustion engine	pH – 9.7 Ash – 40.4% TC – 55.3% C:N – 117.7	Significant increases in total carbon and exchangeable cations	Neither a significant positive or negative effect on nitrous oxide	Suddick and Six [119]
5.	Wheat crop in silty-loam	Silty-loam pH 5.4 organic C - 21 g kg^{-1} Total N - 1.2 g kg^{-1}	Italy	Coppiced woodlands (beech, hazel, oak and birch)	Pyrolysis at 500 °C	pH – 7.2 Total C - 840 g kg^{-1} Total N - 12 g kg^{-1}	Short-term stimulating effect of biochar on soil microflora	Nitrous oxide emission reduced by 26–76%	Castaldi et al. [120]
6.	Paddy and Forest	a) Paddy soil loam – sand −30%, silt – 46%, and clay −24%; pH – 5.41 SOC (g kg^{-1}) – 19.31 C/N- 12.10;C g kg^{-1} -11.11 b) Forest soil loam sand −32%, silt – 54%, and clay −14%; pH – 3.84 SOC (g kg − 1) – 52.89	South China	Chicken manure	Muffle furnace, 5–10 °C/min, and final temperature at 540 °C for 1 h; Soil moisture (35, 60, 85 and 100%)	pH – 9.63 Volatile matter (g kg^{-1}) - 267.1 C/N - 11.32 C(g kg^{-1}) - 191.6 H(g kg^{-1}) - 11.41 N(g kg^{-1}) - 16.92	Stimulated soil respiration and increased soil pH	Enhanced CH_4 sink effect at low soil moisture (30 & 60%) and CH_4 source effect at high soil moisture levels (85 and 100%)	Yu et al. [121]

Table 5 (continued)

S. no	Soil type	Soil characteristics	Country	Feedstock for biochar	Experiment conditions (biochar)	Biochar characteristics	Effect of biochar application on soil	Emission studies	Reference
		C/N-15.23; C g k-g^{-1}- 22.1							
7.	Sandy soil-Inceptisol Sandy clayey loam (Entisol) Clayey soils (Oxisol and Vertisol)	a) Inceptisol – pH - 5.70, Sand - 97.5%, Silt - 1.2%, Clay - 1.3%, OC - 0.95%, b) Entisol pH – 8.77, Sand – 66.3%, Silt - 12.2%, Clay – 21.5%, OC – 2.53%, In OC – 6.01%, c) Oxisol - pH - 5.65, Sand – 24.3%, Silt - 31.6%, Clay – 44.1%, OC – 4.39%, d) Vertisol pH – 7.89, Sand – 27.3%, Silt – 28.5%, Clay – 44.2%, OC – 2.25%	Australia	Wood (*Eucalyptus saligna* saplings)	Slow pyrolysis using a batch pyrolyser heating rate at 5–10 °C/ min from 20 to 450 °C; 550 °C	Biochar 450 °C pH - 8.64, OC - 67.40% Biochar 550 °C pH - 9.96%, OC - 73.19%	Biochar causes positive priming in clay-poor soil (Inceptisol) and negative priming in clay-rich soils	Sandy soils, mineralization of native SOC was stimulated whereas in clayey soils mineralization of native SOC was generally suppressed in presence of biochar (except at 60 °C in Entisol and Oxisol)	Fang et al. [101]
8.	Silt loam soil or agricultural Luvisol	Sand −16.2% (50-2000 μm) Silt - 66.5% (2–50 μm) Clay - 17.3% (<2 μm)	Belgium	Willow, Pine maize and Wood mixture (Spruce, Silver fir, Scots pine, Beech, Oak) Pyrolysis	Slow pyrolysis Willow and Pine (450 and 650 °C); Maize (350 and 550 °C); Wood mixture (480 °C)	Willow - 450;650 °C pH - 7.3; 8.1 C:N - 96; 85 Pine −450; 650 °C pH - 6.7; 7.7 C:N - 457; 617 Maize – 350; 550 °C pH - 8.3; 9.8 C:N - 46; 47 Wood mixture pH - 8.6 C:N - 164	Nitrate concentrations decreased by 6–16% on biochar addition. Non-electrostatic sorption of NH_4^+ or NO_3^- through biochar's micropores	Decreased both cumulative N_2O (52–84%) and NO (47–67%) emissions compared. N_2O emissions were more decreased at high compared to low pyrolysis temperature	Nelissen et al. [71]

(Triticumaestivum L.) and winter rye (Secale cereal L.) followed by crop oil radish (*Raphanus sativus* L. var. oleiformis). Without applied fertilizer, 39% higher nitrogen uptake was found in the presence of biochar, accompanied by higher soil NH_4^+ content and elevated cumulative CO_2 emissions. Biochar showed no effect on N_2O emissions and nitrogen uptake at recommended nitrogen fertilizer rate. At 130% of fertilizer level, 16% lower nitrogen uptake and lower cumulative N_2O emissions were found in biochar-mediated treatment. Biochar amendment in a boreal agricultural soil (9 t ha^{-1}) showed no significant effect on N_2O fluxes measured between sowing and canopy closure even under highest N_2O emissions capture period [124]. Brassard et al. [137] showed the life cycle approach of switchgrass to biochar as a negative emission technology from cultivation, harvesting, transportation, pyrolysis of biochar, soil amendment till bio-oil/syngas as energy sources.

4.2.3 Soil carbon storage

Biochar application to soils that sequester carbon is currently being considered as one of the promising way for mitigating climate change [93]. Biochar is a way of getting carbon into soils as a carbon sink and it is recommended as long-term soil carbon storage by many authors [25, 110]. Steinbeiss et al. [138] demonstrated that biochar amendments increase the carbon storage in soils. They used biochar produced from hydrothermal pyrolysis of glucose and yeast. The study results showed that the mean residence times of biochar in soils varied between 4 and 29 years, depending on soil type and quality of biochar. The biochar combining fertilizer and carbon storage function in soils would activate the microbial community leading to nutrient release and fertilization and would add to the decadal soil carbon pool. Biochar contributes to refractory soil organic C pool that can decrease atmospheric CO_2 concentrations, thus decreasing effects of global warming [35, 100]. Wang et al. [139] described that biochar can persist in soils on a centennial scale, has a positive effect on soil organic matter dynamics and contributes directly to long-term C sequestration in soils. A recent study by Minamino et al. [140] demonstrated that biochar addition on a leaf litter decomposition in a forest soil ecosystem facilitated efficient C sequestration. The biochar from wood waste will be a good option to increase the soil carbon. The forest soils are shown to contain less carbon due to soil fertility loss caused by unmanaged fertilizer application practises. So, to replenish it with carbon from wood biomass waste or leaf litter from forests can be converted to biochar and utilized. This will sequester carbon in soil and carbon cycle is well maintained. Wood waste into biochar is cheap to produce and also generates revenue through selling it. The biochar addition in degraded forest soils will increase soil carbon content and also mitigate the global climate change.

Biochar proved to be an effective means to mitigating greenhouse gaseous emissions from soils. Developing countries like India can widely use this approach for biochar production from biomass wastes for soil amendment in forest and agricultural soils that has potential for extremely changing global climate scenarios. This soil amendment method will have immense advantages, especially in increasing soil water holding capacity and carbon content which possibly can contribute towards expanding the green cover in India. Implementation of wide awareness about the advantages on the use of biochar for forest conservation such as increment in soil carbon, forest land management, revenue generation from biomass to biochar and its potential role in strategic wildfire risk reduction has to be strongly emphasized world-wide.

4.3 Energy production

Bioenergy produced from biomass pyrolysis can replace non-renewable energy usage [132]. The energy production is most favored in fast pyrolysis of biomass, where its products such as syngas (gas product) and bio-oil (liquid product) are considered as substitutes for fossil fuels. Generally, bio-oil has lower energy content than fossil fuel; however, with subsequent refining processes, it can be used as an alternative energy source. The use of bio-oil for other applications is explored in the literature. Ko et al. [141] studied pyrolysis fuel oil (PFO) molecular structures for its utilization as a raw material for mesophase pitch synthesis. The structural analysis (elemental analysis, matrix-assisted laser desorption/ionization time of flight mass spectrometry, ^{1}H NMR and ^{13}C NMR) data revealed aromaticity of PFO. It had three aromatic rings, one naphthenic ring fused with one pericondensed and two catacondensed aromatic carbons and a short alkyl side chain (with a methyl group) shown as a viable source for mesophase pitch synthesis. PFO is also used for preparation of petroleum-based impregnating pitches using two-step heat treatment without a separation process studied by Choi et al. [142]. Bio-oil can soon be applied in transportation fuels, heating oil, and for extracting some chemicals with treatments by zeolite cracking, hydrodeoxygenation and aqueous phase processing [44]. Electricity production in single-anode/cathode Microbial Fuel Cell (MFC) fed with simulated synthesis gas (syngas) as the sole electron donor has recently been demonstrated by Hussain et al. [143]. To address the growing demand, the pyrolysis of biomass to renewable energy production is a good option and it can help in mitigating global warming.

4.4 Waste management

The different biomass waste materials as shown in Table 1 are widely used for the biochar, syngas and bio-oil production. The pyrolysis of various biomass wastes is summarized in

Tables 3 and 4. The waste materials are converted to useful materials for combating climate change and energy production.

4.5 Environmental remediation

The biochar is commonly used for removal of pollutants by acting as adsorbent [26, 34, 69, 144]. The efficiency of contaminants removal depends on biochar's properties like surface area, pore size distribution and ion-exchange capacity [141]. A study by Huggins et al. [145] showed that biochar is better than activated carbon for high strength wastewater treatment. It has significant adsorption capacity for phosphate, ammonia, and COD at higher concentrations. The macroporosity of biochar supports in unblocking of smaller micropores which could contribute in higher adsorption capacities.

4.6 Building materials

Biochar application in building materials (both concrete and asphalt) is recently being explored. It can sequester carbon, enhance the properties of the building materials and also reduce the embodied energy of such construction materials. Gupta and Kua [146] explored the use of biochar as concrete admixture that reduces the greenhouse gas emissions when used in building constructions. A study by Consentino et al. [147] demonstrated the use of biochar as nanoparticles in cement matrix composites (as filler). This improved the mechanical properties of the composites and sooner has wider opportunity for creating new green building materials from it. Biochar is also explored as a replacement for any product that utilizes carbon black in its manufacture (such as tires, plastic, ink, etc).

4.7 Others

The other applications of biochar, syngas, and bio-oil are fuel cells, super capacitors, catalyst, heat generation, power production, gas purification, water sanitation and metallurgy [148–151]. Study by Yuan et al. [130] used sewage sludge biochar at 900 °C as cathodic oxygen reduction reaction catalyst in a MFC. Maximum power density of 500 mW m^{-2} was obtained from biochar cathode. The results are comparable to Pt cathode, hence biochar can be a potential alternative to Pt in MFCs.

5 Limitations

Biochar has several advantages, however many authors have also highlighted the associated limitations for its production and application. The challenges during different production processes are addressed in detail by Meyer et al. [114]. They have pointed out that extensive exploration on biochar capability produced from gasification processes for soil improvement and data from pilot projects is needed for biochar technology commercialization purposes. In-depth studies on the biochar stability and its carbon perseverance in different soil and climatic conditions [65, 111]. A study by Wardle et al. [103] described a risk to forest (duff), surface organic matter. Similarly, if assumed to apply for a Histisol (soil OM accumulations exceed decomposition; i.e., peat soil) at the wrong loading, the following consequences are expected to occur. It may be possible to alter OM accumulations and change the soil's developmental trajectory. Also given the water holding capacity potential, it may also be possible to alter the angle of repose for wet soils on a slope. Therefore we need to be judicious as to where biochar is placed as a treatment. The locations least likely to have a detrimental effect, are stable slopes with low soil productivity and drought conditions. Biochar's adverse environmental impacts, particularly a reduction in agrochemical effectiveness and introduction of soil contaminants are to be evaluated. Processing difficulties due to variability of biomasses, dust from fine biochar particles and proper degradation mechanism of biochar in soils are not known. Interactions among biochars, soils, microbes and plant roots are not well understood. The impact of biochar on soil nutrient dynamics are still not clear. The degradation rates of biochar in soil to be known [79]. The detailed information for policy makers and industrialists is still required to run pilot-scale studies with biochar for soil improvement and climate change mitigation.

6 Conclusion and future scope

Biomass wastes from different sources are used to produce useful and renewable carbon material called Biochar. The various thermo-chemical methods for biochar production are summarized. The biochar, syngas, and bio-oil products yield are based upon the pyrolysis conditions such as heating rate, temperature, chemical composition, residence time, etc. Biochar application on soil for its impacts on soil properties and greenhouse gaseous emission is to be well understood. The other applications of biochar in various fields such as waste management, soil improvement, energy production, environmental remediation, climate change mitigation is discussed. Some limitations for application of biochar in pilot-scale studies have to be addressed in future studies. The policy-makers, industrialists and general public are to be well informed about full technical details and awareness about biochar production and its benefits.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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