Biochar
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REVIEW

Biochar amendments and its impact on soil biota for sustainable agriculture

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Abstract
Beneficial microbes in soil biota are known to enhance plant growth by stimulating the nutrient supply and by devising certain mechanisms to cope up with the biotic (diseases) or abiotic (salinity, drought, and pollution) stresses. Owing to their effectiveness and sustainability concerns, the application of microbes in the agricultural sector has seen a positive surge recently. Biochar has been commended as an exemplary carrier material for beneficial microbes in the soil ecosystem. Biochar is generally produced from the waste biomasses, which not only resolve the management crisis of agricultural wastes but also render many benefits such as enhancement of soil properties, alteration of nutritional dynamics, removal of pollutants, and in the stimulation of beneficial microbial diversity in soil. The strategic application of biochar in agricultural land could help provide agronomic, economic, and environmental benefits. Since certain risks are associated with the application of biochar, attention needs to be paid while preferring for soil amendments. This present review focused on highlighting the role of microbes in plant growth. The influence of biochar on soil biota along with its detailed mechanisms was discussed further to delineate the scope of biochar in soil amendments. Further, the risks associated with the biochar amendments and the future perspectives in this research arena were highlighted.

Keywords Biochar · Sustainable agriculture · Soil biota · Microbes · Plant growth · Microbial interaction

1 Introduction

The main challenge with the current agriculture practice is to increase productivity in a more sustainable and environment friendly manner (Patel et al. 2015; Hamilton et al. 2016). Postgreen revolution agricultural practices increased their reliance on chemical fertilizer for ensuring higher productivity. Chemical fertilizers do increase productivity, but at the same time, jeopardize the sustainability of the environment by engendering major ecological imbalances such as loss of biodiversity, global warming, incorporation of heavy metals in living organisms, etc. (Srivastav et al. 2020; Ye et al. 2020). Consequences of the dramatic change in global climate, rapid urbanization, and extensive use of agrochemicals have collectively affected crop production worldwide and created an odious situation for food security (Glick 2014; Rashid et al. 2016). The decrease in fertile agricultural lands is further endangering the global food security. The generation of a significant amount of agricultural wastes piles up the additional burden to the agricultural sector. One of the possible ways to tackle the multidimensional challenges faced by the agricultural sector is to increase productivity without compromising environmental sustainability.

The role of microorganisms in improving nutrient availability to plants is an important strategy and related to climate-smart agricultural practices (Sammauria et al. 2020; Pereg and McMillan 2015). Many researchers documented the distinctive properties of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi in enhancing the plant growth with the appropriate precautionary response towards the diseases causing pathogens and different stressful environments (Singh et al. 2011; Bach et al. 2016; Moreira et al. 2020; Bhatt and Maheshwari 2020; Rincón-Molina et al. 2020; Santana et al. 2020). Exploration of a diverse range of stress-tolerant microbes and their effects on host plant species with appropriate management of agricultural habitats in a stressed environment is urgently needed

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(Goswami and Suresh 2020). Thus, adopting a more natural way of farming will reduce the dependency on chemical fertilizers and provide a more promising way to maintain the sustainability of agricultural practice. A large number of articles have been published in the literature advocating the use of biochar in promoting the biodiversity of plant growth-promoting microbes.

Biochar is the product of the thermochemical conversion of organic material under limited supply of air (pyrolysis). It is a carbon-rich solid product having a high porous structure and large surface area (Lehmann and Joseph 2009). Conversion of biomass into biochar is a carbon-negative process and has been reported to sequester up to 87% of carbon (Yu et al. 2018). This not only addresses the issue of waste management of agricultural residues but also provides a sustainable and economical method of converting waste into value-added products. Owing to its unique surface properties, biochar displays exceptional efficiency in removing pollutants like herbicides, dyes, pesticides, antibiotics, and heavy metals and plays an important role in mitigating global climate change (Oliveira et al. 2017). Biochar can also act as a supercapacitor (Rui et al. 2020), reinforcement in rubber, and asphalt flow modifier in the removal of phosphate, as well as help in enzyme immobilization (Pandey et al. 2020).

Biochar can store carbon (C) in the soil for a much longer period compared to that of unpyrolysed biomass (Gupta et al. 2020). Application of biochar in soil has been reported to enhance several characteristics of soil such as electrical conductivity (EC), pH, cation exchange capacity (CEC), nutrient level, porosity, bulk density, and microbial community structures (Dai et al. 2020; Zeeshan et al. 2020; El-Naggar et al. 2018; Sheng and Zhu 2018). Biochar has been noticed to effectuate significant modification in the abundance and composition of soil ecology (Liu et al. 2020a, b; Briones et al. 2020; Zrim et al. 2018; Liang et al. 2010). Due to its porous structure, biochar provides additional habitat to microorganisms, thus transforming the available nutrients in the soil to be utilized by plants (Sheng and Zhu 2018). Changes brought by biochar and microbes to soil properties could enhance soil fertility, improve water holding capacity and nutrients level, and decrease the leaching of elements essential for plant growth, and thus enhances agricultural productivity (Liu et al. 2017; Wang et al. 2017).

The exact mechanism of biochar affecting the microbial population is not yet known properly, but several possible ways had been suggested in recent years regarding the interaction of biochar with soil biota. Although biochar has a net positive effect on soil quality, product yield, nutrient cycling, and removing herbicides, the outcomes may vary depending upon biochar characteristics, dosage, and soil properties. The study of biochar effect on soil biota is fascinating the researchers due to its effect on soil structure and its stability, nutrient recycling, aeration, disease resistance, water use efficiency, and C storage capacity (Wang et al. 2018).

The present review is an attempt to disclose the key solutions for some of the pressing challenges faced in the agricultural sector such as loss of soil fertility and consequent agricultural productivity. Emphasis was given on how to utilize the current microbiological techniques in the soil to enhance plant growth under both biotic and abiotic stress environments. The overall objective of this review is to provide an outline of the impact of biochar amendment on soil biota along with its detailed possible mechanisms. The future challenges and scope of the research-based upon the biochar and microbial interactions were also reviewed.

2 Biochar properties

The safe disposal of the huge amount of generated wastes is a big concern for an agricultural-based country like India. The decreasing nutritional property of agricultural land is creating distress among the practitioners. The burning of the crop residues leads to the emission of several greenhouse gases, further damaging the environment and decreasing the sustainability of the agricultural practices.

Biochar could end the prolonged search of long-term carbon sequestration specifically in the soil (Schiermeier 2006). Many researchers have recommended biochar as a potential soil additive that could promote carbon storage (Lehmann et al. 2006), further it could add value to agricultural products and promote plant growth (Oguntunde et al. 2004). Lehmann et al. (2006) estimated that by the year 2100, approximately 9.5 billion tons of carbon could potentially be stored in the soil with the implementation of various biochar initiatives. For sequestering the carbon in the soil, biochar produced at higher temperatures is recommended, as it has a more stable carbon structure and high *C/N* ratio (Table 1). This enhances biochar stability by making their degradation intractable by the microbes (Zhu et al. 2018). So the better comprehension of biochar interaction and soil microbiota could assist in the attainment of carbon sequestration and potentially contribute to climate change mitigation.

Further, the burning of crop residues poses a huge risk of biodiversity loss and causes soil erosion. Thus, management of agricultural waste needs a more appropriate approach, burning the waste in a controlled environment (pyrolysis) converts the waste into valuable products like biochar and bio-oil. It was observed that lower-to-moderate temperature during the pyrolysis process favours the formation of more biochar (Abhijeet et al. 2019). Biochar retains the nutrients in it, and its further application in soil enhances fertility and at the same time addresses the problems like air pollution caused by open burning of agricultural wastes.

Table 1 Chemical and physical properties of different biochars at various operational temperatures

Biomass	Temperature (°C)	C (%)	Fixed C (%)	Aromatic C (%)	*C/N* ratio	Ash (%)	Volatiles (%)	pH	CEC (kg^{-1})	SSA (m^2/g)	Reference
Corn stover	60	42.6	6.0	2.0	83	8.8	85.2	6.70	269.4	–	Lehmann et al. (2011)
	350	60.4	39.8	76.9	51	11.4	48.8	9.39	419.3	293	
	600	70.6	59.8	88.2	66	16.7	23.5	9.42	252.1	527	
Oak wood	60	47.1	11.1	–	444	0.3	88.6	3.73	182.1	–	Lehmann et al. (2011)
	350	74.9	38.1	82.8	455	1.1	60.8	4.80	294.2	450	
	600	87.5	71.2	86.6	489	1.3	27.5	6.38	75.7	642	
Poultry litter	60	24.6	3.1	–	13	36.4	60.5	7.53	363.0	–	Lehmann et al. (2011)
	350	29.3	1.6	–	15	51.2	47.2	9.65	121.3	47	
	600	23.6	0.1	–	25	55.8	44.1	10.33	58.7	94	
Cow manure	600	43.7	–	–	–	67.5	17.2	10.20	149	21.9	Zhao et al. (2013)
Pig manure	500	42.7	–	–	–	48.4	11.0	10.50	82.2	47.4	Zhao et al. (2013)
Wheat straw	500	62.9	–	–	–	18.0	17.6	10.20	33.2	95.5	Zhao et al. (2013)
Walnut shell	900	55.3	–	–	117.6	40.4	–	9.70	33.4	227.1	Mukome et al. (2013)
Bamboo	600	80.9	–	–	539	–	–	7.9	–	470.4	Zhou et al. (2013)
Domestic sewage	400	42.1	–	–	5.1	37.1	34.5	7.3	–	–	Kameyama et al. (2016)
Grass (*Festuca arundinacea*)	400	77.3	–	–	62.3	16.3	26.8	-	–	8.7	Keiluweit et al. (2010)
Japanese cedar	400	72.0	–	–	45	0.1	57.7	7.7	–	–	Kameyama et al. (2016)
Municipal sludge	500	17.5	–	–	11.36	74.2	-	8.8	76.8	-	Chen et al. (2014)
Pine wood	450	81.4	–	–	271.3	4.6	8.2	-	–	166	Mohanty et al. (2013)
Poultry manure	400	34.3	–	–	6.7	48.4	28.3	10.8	–	–	Kameyama et al. (2016)
Rice	400	37.3	–	–	28.6	47.9	38.2	6.7	–	–	Kameyama et al. (2016)
Turkey litter	700–800	15.6	–	–	20	64	-	10.9	24.9	21.8	Mukome et al. (2013)
Wood (*Pinus ponderosa*)	400	74.1	–	–	123.5	1.4	36.4	-	-	28.7	Keiluweit et al. (2010)
Oak	350	71	37		165.1	1.5	58	7.2			Zhang et al. (2017)
	400	73	32		187.2	2	64	7.7			
	450	75	35		174.4	2.4	59	8.9			
	500	80	38		173.9	2.7	57	8.8			
	550	79	36		171.7	3.2	58	9.1			
	600	80	45		222.2	2.3	50	9.0			
	650	81	48		213.2	2.9	46	9.2			
	700	78	50		210.8	3	44	9.2			
	750	85	49		257.6	2.5	45	9.1			

Table 1 (continued)

Biomass	Temperature (°C)	C (%)	Fixed C (%)	Aromatic C (%)	*C/N* ratio	Ash (%)	Volatiles (%)	pH	CEC (kg^{-1})	SSA (m^2/g)	Reference
Pine	350	72	31		171.4	1.7	65	5.3			Zhang et al. (2017)
	400	74	36		172.1	2.4	59	5.8			
	450	78	38		190.2	2.5	57	7.4			
	500	81	44		184.1	2.8	50	8.0			
	550	78	46		205.3	2.7	49	8.1			
	600	81	49		213.2	3	46	8.1			
	650	81	53		225.0	2.8	42	8.2			
	700	81	53		261.3	2.5	42	8.3			
	750	84	59		254.5	3	36	8.3			
Sugarcane	350	75	35		202.7	3.5	60	8.2			Zhang et al. (2017)
	400	77	34		240.6	4.4	60	9.0			
	450	79	39		263.3	3.7	57	9.2			
	500	82	40		227.8	4.5	54	9.4			
	550	85	42		257.6	4.2	52	9.3			
	600	85	43		265.6	5.1	49	9.1			
	650	79	45		254.8	5.5	47	9.1			
	700	85	56		283.3	3.8	36	9.1			
	750	86	49		238.9	4.6	42	9.5			
Peanut shell	350	69	28		32.9	7.2	63	7.6			Zhang et al. (2017)
	400	72	29		36.0	7.8	61	8.4			
	450	75	31		35.7	7.8	58	8.7			
	500	76	30		36.2	9.7	57	9.3			
	550	77	36		40.5	7.7	53	9.3			
	600	75	37		44.1	9.5	50	9.2			
	650	79	33		43.9	10.1	54	9.2			
	700	78	34		52.0	9.7	54	9.3			
	750	80	42		57.1	9.8	46	9.4			
Willow wood	400	65			29.5	7.1				1.6	Rechberger et al. (2017)
	525	76			31.7	8.7				4.4	
Wheat husk	525	57.5			18.0	20.7				1.8	Rechberger et al. (2017)
Sewage sludge	300	23			7	59		5.8		20.2	Figueiredo et al. (2018)
	400	21			7.5	69		6.5		29.4	
	500	19			8	79		6.5		52.5	

Table 1 (continued)

Biomass	Temperature (°C)	C (%)	Fixed C (%)	Aromatic C (%)	*C/N* ratio	Ash (%)	Volatiles (%)	pH	CEC (kg^{-1})	SSA (m^2/g)	Reference
Wheat straw	300	61.4			43.9	14.39		7.98			Zhang et al. (2020)
	400	64.1			47.1	18.28		9.06			
	500	67.3			48.8	22.39		10.37			
	600	65.3			59.4	21.82		10.83			
Corn straw	300	61.2			20.9	14.26		8.28			Zhang et al. (2020)
	400	63.3			25.1	18.19		9.83			
	500	65.0			26.7	19.97		10.22			
	600	67.4			31.8	21.0		10.26			
Rape straw	300	61.8			60.6	15.1		7.75			Zhang et al. (2020)
	400	63.7			65.0	19.21		9.18			
	500	66.9			76.0	21.19		9.95			
	600	67.8			75.3	22.54		10.28			
Rice straw	300	56.4			26.2	20.2		8.29			Zhang et al. (2020)
	400	56.4			28.3	26.1		9.33			
	500	59.6			31.4	29.4		10.23			
	600	61.3			30.5	30.5		10.75			
Softwood	350	79.9	60		7990.0	3.1	32.1			14.44	Wallace et al. (2019)
	430	79.8	61.3		7980.0	4.8	29.2			28.65	
	660	77.4	69.1		774.0	2	25			9.96	
Hemp	400	78.2	66.8		113.3	2.8	27.6			11.72	Wallace et al. (2019)
	530	76.9	68.1		103.9	1	26.1			12.26	
	600	78.5	71.3		133.1	1	25			12.18	

C carbon, *CEC* cation exchange capacity, *SSA* specific surface area

The physical and chemical properties of a material are the major considerations while selecting a suitable carrier for microbes. Biochar's unique physical and chemical properties make it highly stable, enhance water holding capacity and provide better-buffering capacity that allows the addition of bacterial nutrients, hence, supporting the growth of huge microbial populations as well as providing pesticidal effect. Production from wastes and cost-effective production strategies have given the economic feasibility and practical viability of biochar compared to the other carrier materials. The chemical and physical properties along with their advantages as well as the repercussion on soil properties have been discussed underneath.

2.1 Chemical properties

Biochar is a pyrolytic product with higher aromatic proportion that increases the stability of biochar in the soil, which allows it to remain in the field for a significant amount of time as compared to other organic materials (Nguyen et al. 2010). Percentage of aromatic carbon has been observed to increase with the increase in pyrolytic temperature (Table 1). Biochar's stability reduces its availability of carbon for microbes; however, the microbial abundance and their activity could be stimulated by mineralization caused by a readily leachable fraction of char. This fraction is termed as volatile matter (Steiner et al. 2008). Biochar has a higher portion of ash that is contained with several macro- and micronutrients, which are considered as valuable resources in the soil food web. Ash content of biochar plays an important role in organometallic chemical interactions occurred amid the pyrolysis process, consequently, resulting in the incorporation of metals in biochar (Leinweber et al. 2007). Application of metal-modified biochar could serve as a ready-made source of a specific desired metal element for plants. Biomass with higher ash content is supposed to have greater CEC, pH, and charge density. The high operational temperature during pyrolysis decreases CEC but enhances the surface area of biochar (Nguyen et al. 2010). Biochar produced at higher pyrolytic temperature was observed to increase its alkalinity; however, it could also be affected by the nature of selected biomass (Nguyen and Lehmann 2009). The pH of biochar plays a vital role in adjusting the soil alkalinity on which it has been applied. During the thermal decomposition of feedstock, persistent free radicals (PFRs) are formed and PFRs could activate reactive oxygen species (ROS), which enables the transfer of electrons between biochar and microbial cells, further helping in the degradation of the organic contaminant and heavy metal transformation. Table 1 presents the chemical and physical characteristics of biochar. All the reported carbon content, aromatic content, ash content, pH, CEC, *C*: *N* ratio, and surface area of biochar were observed to follow a similar correlation with temperature. However, apart from the pyrolytic conditions, the consideration of the difference in the biomass characteristics has equal importance in determining the properties of biochar.

2.2 Physical properties

Due to its unique characteristics, the physical properties of biochar play a major role in altering the soil properties. Biochar and soil properties differ a lot, therefore when biochar is mixed with soil, it positively affects certain soil properties such as its tensile strength, soil-hydrodynamics, and transportation of gases. Depending upon the experimental production conditions and biomass characteristics, micro- and macrostructural changes are expected to take place, which could have major impacts on the soil characteristics (Downie et al. 2009).

Since the biochar has low tensile strength, the application of biochar to the soil has been majorly observed with the decline in tensile strength of the soil which further facilitates the root penetrability in soil. In this way, the application of biochar could accelerate root growth (Bengough and Mullins 1990). Biochar has macro- and micropores, due to its hollow structure, it has low bulk density, so when it was mixed with soil, the bulk density of the soil got reduced significantly. Downie et al. (2009) found that the reduction in bulk density enhanced the soil water relation, rooting pattern, and soil fauna. The surface charge, pore structure, pore size, and its distribution pattern vary according to the pyrolysis condition and feedstock nature. The porosity of biochar enhances its sorption potential of minerals and organic matter, which consequently affects the energy availability and ensure requisite pore space to soil biota (Kasozi et al. 2010). A large surface area of biochar could be compared to an aggregated soil structure, which serves many purposes such as it protects organic matter, provides habitat for soil biota, and aids in the retention of soil moisture and nutrients within the biochar-amended soil (Tisdall and Oades 1982). Aggregated structure of biochar helps in the preferential oxidation of biochar outer surface compared to the interior of biochar, which results in limited O_2 flux to the interior of biochar. Such differential redox conditions not only influence the organic matter but also enhance metallic element transformation (Cheng et al. 2006).

Biochar has the potential to improve the soil properties and sustainably increase agricultural productivity. Biochar production conditions could be varied according to the demands of the soil and the targeted crop. The following are a few general recommendations that could be implemented to increase productivity while performing the biochar amendments.

Biochar with higher water holding capacity could be used to grow crops under drylands conditions. Biochar could be applied to improve the alkalinity of acidic soil, and biochar produced at higher temperatures is observed to have more alkalinity. The use of biochar in alkaline soil is not recommended; however, it could be used along with the acidic chemical fertilizer. The biochar application rate has not been optimized for a large-scale application, so it is not recommended for the farmers to apply biochar at a higher rate. However, several pots and greenhouse studies have been performed and hence biochar could be a cost-effective option for nursery and small-scale farmers. Particular type of biochar could not resolve all soil issues, so biochar could be modified or engineered as per the specific soil defects. For example, soil with reduced organic matter content could be treated with the biochar-compost mixture to overcome the deficiency and increase productivity. Biochar could contain certain toxic chemical compounds, so the toxicity analysis of biochar needs to be done before its application in the soil.

The above recommendations are general and could be modified with special needs. Further, there should be more research on the above suggestions to strengthen the points and increase their reliability. Due to the desired characteristics, biochar can be used as an efficient carrier for PGPR and microbes. The detailed analysis of biochar application on soil properties and its effect on agricultural productivity could be found in Al-Wabel et al. (2018). Owing to its unique properties, biochar could be used to enhance the soil biota. Before advocating the application of biochar in soil and its effect on soil microbiota, it is essential to understand the role of microbes in plant growth and the underlying mechanism behind it. Figure 1 summarizes the properties of biochar and its potential impact on soil biota.

3 Soil biota

3.1 Importance of soil biota in agriculture

The green revolution witnessed a big boom in the agricultural industry by significantly increasing land productivity in the initial years. Although the use of chemical fertilizers has addressed the immediate challenge of productivity and ensures food security, it doesn't fully solve the challenge of nutritional security (Hamilton et al. 2016). Chemical fertilizers are not economically affordable for the majority of farmers from developing countries and prolonged application further decreases soil fertility. Therefore, the application of chemical fertilizers possesses an acute and complex challenge. Intensifying environmental concerns and global hunger attract attention towards environment-friendly, sustainable, and climate-smart agricultural practices (Singh et al. 2011; Rashid et al. 2016).

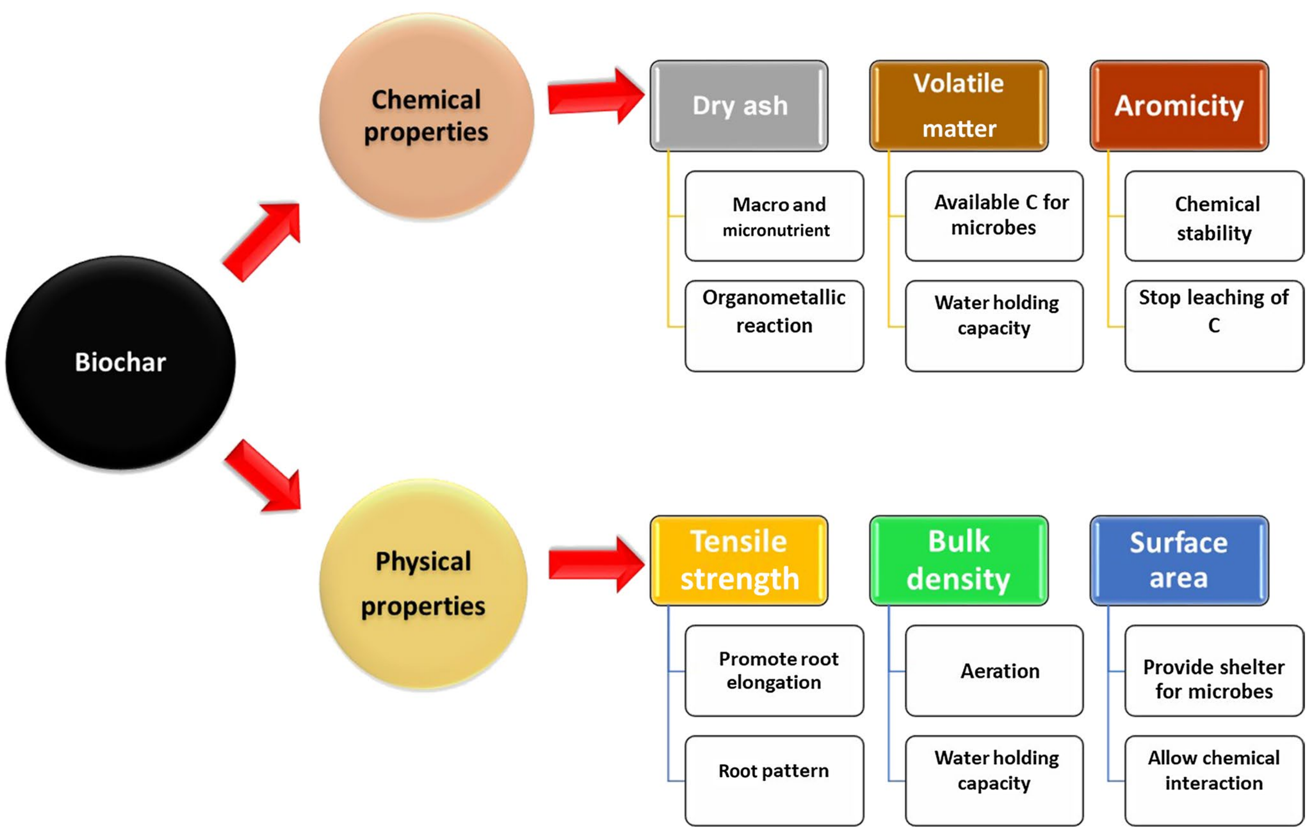

Fig. 1 Physical and chemical properties of biochar and their relevance in soil ecology and plant growth

Figure 2 depicts the various challenges in agriculture from the social, economical, and environmental viewpoint. Although all the challenges demand equal attention for healthy agricultural practices, this review is confined to focus on the challenges related to the environmental sector and in specific about soil fertility. It is also crucial to understand that problems in agriculture are interlinked and need a sustainable approach for their mitigation.

The application of microbes in soil biota and their role in improving the accessibility of nutrients to plants is a key strategy related to climate-smart agricultural technologies (Pereg and McMillan 2015; Hamilton et al. 2016). Many strains of bacteria and fungi contribute to plant growth through several mechanisms. One of the prominent class of these types of microbes is the plant growth-promoting rhizobacteria (PGPR) which are naturally occurring soil (rhizosphere) bacteria capable of benefitting agriculture by improving the plant's productivity and immunity.

3.2 Soil biota benefiting plant growth

There are several mechanisms reported in different works of the literature on the adoption of PGPR/fungi for promoting plant growth. However, these mechanisms could be broadly summarized into the following four different categories: (1) by synthesizing the substances that could be assimilated by the plants; (2) by inducing the resistance in plants against the environmental stresses; (3) by mobilizing nutrients; and (4) by preventing diseases in plants.

PGPR produces a range of substances in the rhizosphere niche that helps in stimulating plant growth by promoting beneficial microbial communities (Etesami et al. 2020). In general, PGPR/fungi can directly enhances plant growth by synthesizing the nutrients (nitrogen, phosphorus, potassium, and essential minerals) which can be directly assimilated by the plants. Also, microbes have been reported to have the ability to synthesize the phytohormones (auxin, cytokinins, gibberellins, and ethylene) which are vital for plant growth (Costacurta and Vanderleyden 1995). The second way in which microbes facilitate plant growth is to help them either by accommodating the plants with the biotic/abiotic stress or by devising certain mechanisms to fight with the environmental stresses. For instance, *Pseudomonas* strains enhance the *asparagus* seedling growth as well as seed germination under salt and water-stress conditions (Yao et al. 2010). The third way in which microbes facilitate plant growth is carried out by mobilizing the insoluble major nutrients such as phosphorous (P) and potassium (K) into a soluble form so that it could be easily uptaken by the plants. *Micrococcus, Pseudomonas, Bacillus,* and *Flavobacterium* have been reported to act as an efficient P and K solubilizers (Dastager et al. 2010; Pindi and Satyanarayan 2012; Sheng et al. 2006). Fe(III) primarily chelated from the environment by an organic compound was named siderophores (Crowley 2006). *Streptomyces* form siderophores that promote *Azadirachta indica* plant growth by increasing the availability of the required amount of iron. And the fourth way, in which microbes facilitate plant growth is to protect the plants from various pathogens by acting as a biocontrol agent, root colonizers, and environmental protectors (Qu et al. 2020). PGPR competes with pathogens for the limited nutrient available in the rhizosphere and rhizoplane by

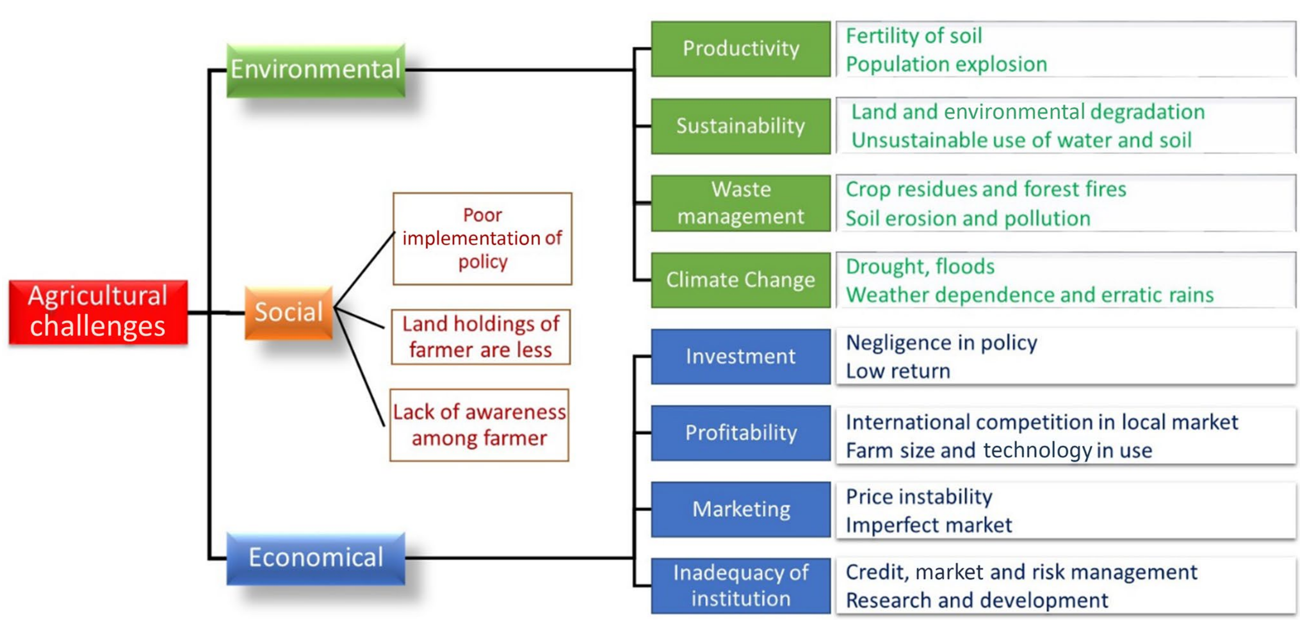

Fig. 2 Social, economical, and environmental challenges in the agricultural sector

reducing the contact surface between pathogen and plant roots or by interfering with the mechanisms leading to plant disease (Jayaprakashvel et al. 2019). The more detailed analysis of the mechanisms involved microbial influence on plant growth can be found in Singh et al. (2018).

Microbes could either act as biofertilizers by directly contributing to plant growth or they could enhance the plant by protecting them from pathogenic bacteria with their bactericidal effect. The mode of mechanisms used by microbes for the growth of plants has been summarized in Fig. 3.

These PGPR or other beneficial microbes are inoculated in soil with a carrier material, which acts as vehicles for the bacteria in the formulation of biofertilizer. There are different materials available that could be used as carriers such as talc, peat, vermiculite, perlite, bentonite, zeolite, diatomaceous earth, rice or wheat bran, rock phosphate pellets, soil, sawdust or compost and biochar. The selection of carrier material generally depends on the mode of application (liquid, powder, granulated, or as a seed coating) or the basis of viability of the bacteria transported. Biochar could be an effective carrier material for bacterial transportation and growth in the soil. The rationale behind choosing biochar as a carrier material, its influence on soil microbiota, and the possible mechanism for the effects have been described in the following section.

4 Influence of biochar on soil biota

Biochar's ability in sequestering carbon, enhancing soil fertility, and its ability in remediating contaminants have increased its applicability in soil amendments. The presence of free radicals, volatile organic compounds (VOCs), and minerals in biochar could enhance the microbial niches, soil enzyme activity, catalysis of biogeochemical processes and have the potential of reshaping the microbial diversity that exists in the soil (Ahmad et al. 2016; Mackie et al. 2015). Due to the beneficial effects of biochar on soil and microbial communities, it could be considered as an effective agent in increasing agricultural productivity by retaining the soil biodiversity. The results of the soil amendment are not specific and could vary based upon the type of biochar, mode of application, and soil properties; thus, several mechanisms were reported in the literature for describing biochar interaction with the soil microbiota and its effect on soil properties. The majority of the documented results highlighted the positive effect of biochar application on soil microbiota; however, few works of the literature reported the negative effect of biochar on the microbiota ecosystem and raised question-related to the risk associated with the application of biochar for soil amendments. In the following section, both advantages and risks associated with the application of

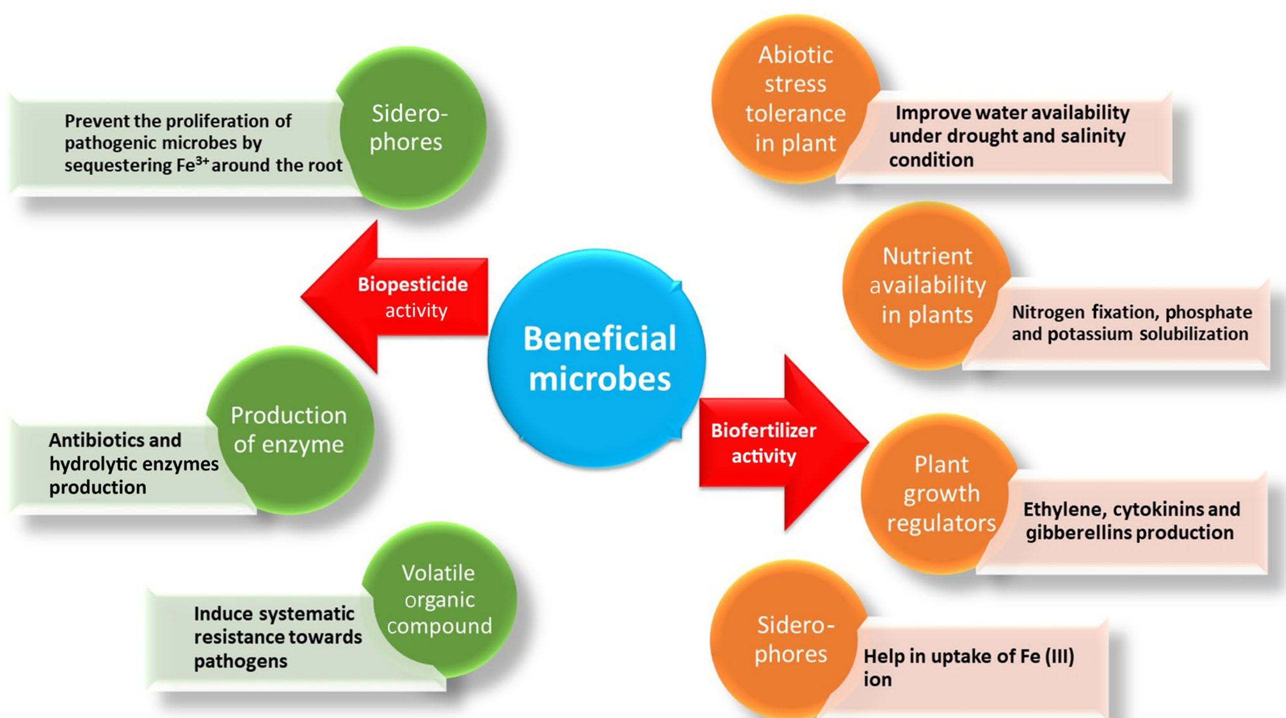

Fig. 3 Microbial biofertilizer and biopesticide activities in soil biota

biochar towards the soil microbiota have been outlined with possible mechanisms resulting in the corresponding effect.

4.1 Positive effect of adding biochar on soil biota

Biochar has a porous structure that provides shelter to microbes which further allows them to attach on its surface and helps in thriving against predators (Bamminger et al. 2016). *Geobacter metallireducens* and *Methanosarcina barkeri* were taken from bacterial co-culture. When they were applied to the biochar amended soil, it was observed that they were attached on the surface of biochar within the 20 days of their application on soil (Chen et al. 2014). Pores enable the sorption and desorption of a diverse range of molecules such as organic compounds, ammonia, nitrates, minerals, and other nutrients, thus play a vital role in enhancing microbial activity. Biochar helps in reducing soil acidity that favors the growth of the microbial population significantly. Application of char increases organic C and Ca content, which helps in reducing the toxic effect of metals like aluminium (Bashir et al. 2018). Biochar has been observed to increase the water holding capacity and thus plays a crucial role in microbial growth. The application of biochar shows a significant improvement in fungal activity and microbial community structure. Biochar application enhances the growth of *Arbuscular mycorrhizal* (AM) and *ectomycorrhizal* (EM) fungi which further helps plants in assimilating nutrition (Holste et al. 2017; Toju and Sato 2018). Biochar properties such as its morphology, elemental composition, redox capacity, conductivity, pH, CEC, VOCs, and porosity are primarily influenced by the experimental condition during the pyrolysis process and on the feedstock nature (Zhu et al. 2017). Autotrophic ammonia-oxidizing bacteria (AOB) are microbes mediating nitrification. The addition of biochar to soil could alter the local microsite pH as biochar increases the alkalinity of the soil, which provides a more favorable habitat for nitrifying organisms, in particular, AOB (Deboer and Kowalchuk 2001). Biochar application to soils has been reported as an enhancing agent for biological nitrogen fixation (BNF) in legume crops (Mia et al. 2018; Scheifele et al. 2017). Among these two parameters, feedstock nature plays a critical role in determining the properties and consequently the application of biochar. Feedstock having high lignin content will have greater C content and thus result in an increased C:N ratio, which further indicates the slower mineralization rates.

Woody biomass pyrolysed at higher temperature losses most of the acidic functional group so biochar produced from woody biomass can be used to control the alkalinity of the soil. Biochar obtained from feedstock having high ash content such as crop residues and manures could facilitate CEC and increase nutrient content, which facilitates microbial growth. Thus, biochar could be used to improve soil fertility. Apart from having biofertilizer properties, biochar could inhibit the growth of pathogens. For example, biochar obtained at lower temperature has low molecular VOCs, which could have a toxic effect on the microbial population. Hence, these types of biochar could inhibit the microbial population and thus have the potential to be used for limiting the growth of soil-borne pathogens. Application of biochar was reported to induce resistance in pepper and tomato plants against two fungal pathogens such as *Botrytis cinerea* and *Leveillula taurica* (Elad et al. 2010). Biochar produced at moderate temperature has good sorption and electron capacity; thus, it could be considered for soils waste remediation purpose (Zhu et al. 2017). Many researchers have confirmed that biochar enhances the growth of microbial abundance and diversity by providing shelter, nutrition, and a suitable environment for their growth.

Some of the broad and prominent mechanisms that could explain the positive effects of biochar on soil microbes have been discussed underneath and further experimental verification is required for increasing the certainty of biochar amendment in soil. Broadly, the supplementation of biochar to the soil acts as a shelter for microbes. Further, biochar supplies nutrients, resist toxicity, assists in altering the enzyme activity of microbes, and enhances the microbial communications for strengthening the interactions within soil microbial ecology.

4.1.1 Providing shelter for microorganisms

Biochar has a relatively more habitual pore volume per unit volume than soil, which helps in accommodating a large variety of microbes and further increases their abundance on its surface. Microbes take shelter in biochar by attaching themselves to its surface (Li et al. 2018). Microbial colonization on biochar surface depends on the aging process of biochar; as the age increases, the surface area and volume start decreasing. On the contrary, biochar pores have less nutrient accessibility as compared to soil pores, and pores of biochar can be blocked by organic compounds such as humic acids (Zhu et al. 2018). Biochar supplementation leads to the enumeration of beneficial microorganisms (Stella et al. 2019).

4.1.2 Supplying nutrients to microbes

Due to high pore volume, surface area, and negative surface charge, biochar enriches the soil with nutrients. Biochar contains cations like K, Mg, Na, N, and P which are vital for microbial growth (Rodriguez-Vila et al. 2016). Biochar has high CEC and thus retained the cations for a longer period. Biochar minimizes the nutrient losses that facilitate microbial metabolism and ensures their growth. Nutrient content in biochar is largely determined by the operational conditions and nature of the feedstock. Biochar obtained from manure and crop residues were observed to have higher ash content as compared to woody biochar, which could increase nutrient availability for plants (Akhter et al. 2015). Further, biochar slowly releases the nutrients and thus contributes to long-term benefits of soil.

4.1.3 Microbial habitat modification by biochar

The addition of biochar in soil decreases the bulk density of soil and helps in enhancing the soil aeration. The improved bulk density of the soil increases the available water content and facilitates the availability of the essential nutrients to microbes. Biochar improves soil physical properties and provides an ideal environment that could boost the microbial population. Biochar porosity increases its water storing capacity, it stores the excess water that is not available directly to the plants; however, this could be beneficial to the plants grown mainly in sandy or degraded soil. The importance of pyrolysis operational conditions (time, pyrolysis temperature, and heating rate) and biomass (elementary and biochemical composition) needs special attention as these parameters play an important role in determining the porosity, stable carbon content, biochar stability, and thus indirectly influence the adsorptive capacity of nutrients (Abit et al. 2012; Cantrell et al. 2012; Chen et al. 2008). Biochar could be utilized as an effective liming agent to neutralize the soil pH (Yuan et al. 2011). Pyrosequencing analysis of the soil bacterial community showed a strong correlation between soil pH and microbial colony composition. Microbes like *Acidobacteria*, *Actinobacteria*, and *Bacteroidetes* have shown a strong positive correlation with the pH increment from 3.5 to 9 (Lauber et al. 2009). Carbonate and an alkaline ash content of biochar were reported to alter the microbial diversity abundance, and composition of nitrifying bacteria in the soil. Thus biochar has the significant potential to enhance and alter the microbial populations.

4.1.4 Enzyme activity alteration by biochar

Enzyme response towards biochar may vary depending upon its type, application rate, and soil properties (Luo and Gu 2016). Biochar could affect the enzyme activity by allowing the enzyme and substrate to interact on its surface. The enzyme activity could be affected with the alteration of soil's physicochemical properties, or with the release of small molecules (aromatic hydrocarbons, heterocyclic compounds, polycyclic, and benzofurans) that could act as allosteric regulators or inhibitors for specific enzymes (Bailey et al. 2011; Zimmerman et al. 2010). Biochar could reduce the activation energy of an enzyme-catalysed reaction thus making the process more spontaneous. Bandick and Dick (1999) found that the response of soil enzyme towards organic matter amendments is quick; hence, changes in soil properties with biochar application can reasonably influence soil enzyme activities. These are some of the most generally reported mechanisms to explain the influence of biochar on enzymatic activities; however, there could be several other mechanisms that could also influence the enzymatic activity. So, further study needs to be performed to investigate and evaluate the other possible mechanisms of biochar.

4.1.5 Biochar effect on intra- and interspecific communication of organisms

Biochar adsorbed signaling molecules like *N*-acyl-homoserine lactone (AHL), which have the potential to modify microbial cell-to-cell interaction. Masiello et al. (2013) found that sorption is the main mechanism that enables biochar in capturing signaling molecules. Sorption capacity generally depends on the physical properties of biochar and is mainly influenced by properties such as on the surface area and total pore volume of biochar. However, recent studies accounted for the role of the functional group present on the surface for effective adsorption. Gram-negative soil bacteria like nitrogen-fixing plant symbionts use *N*-3-oxo-dodecanoyl-L-homoserine lactone (AHL) as their signaling molecule for regulating gene expression and enhance intraspecific communication (Masiello et al. 2013). With the adjustment of soil pH, biochar can promote and inhabit signaling compounds that are responsible for enhancing the interaction between microbes and their activities. While bacterial signals are pH-sensitive, the fungal signaling molecule is less sensitive towards pH. Consequently, the application of biochar could shift the ratio between the fungal and bacterial populations of soil (Gao et al. 2016). The application of biochar could induce the microbe's communication with plants by enhancing their activity in the niche of the rhizosphere (Akhter et al. 2015; Elad et al. 2011). For a better understanding of the interaction mechanism between biochar and soil microbiota, identification and quantification need to be performed for the compounds that are released from biochar and they could have a potential effect on the microbial activity.

Biochar could interact with soil biota and facilitate their growth in several ways as represented in Fig. 4. The operational conditions and biomass nature predominantly affect the physicochemical characteristics of biochar and, consequently, influence the soil microbiota directly or indirectly.

4.2 Risk of biochar amendments on soil biota

Although the biochar has many positive effects on soil biota, its negative impacts and the risk associated with its application have been reported by a few pieces of literature. For instance, Shaaban et al. (2018) reported that the biochar application enhances the transport of viruses in soil and

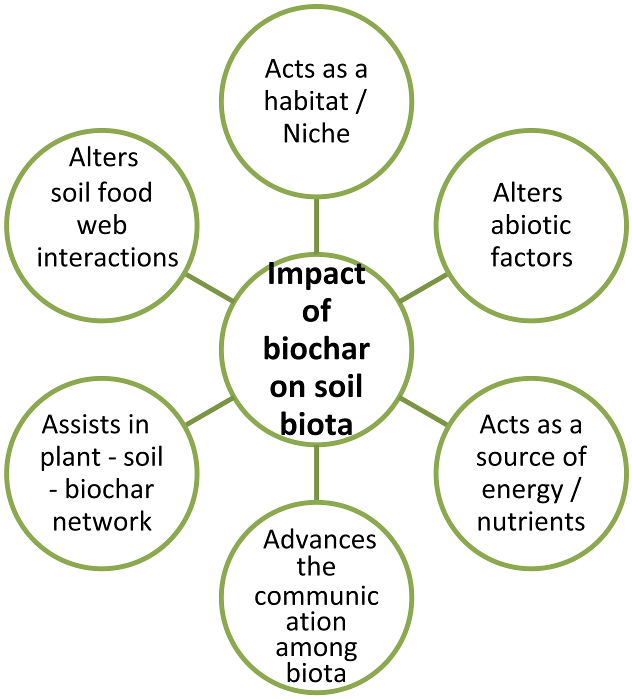

Fig. 4 Various strategies of biochar on influencing the soil biota

its sediments, which further increases the risk of pathogen contamination in soil. Further, the possible leaching of biochar could lead to the contamination of drinking water on nearby wells. Several field trials revealed that oak biochar couldn't alter the surface area when applied for four months at a dose of 7.5 Mg ha^{-1}. Application of oak biochar was reported to increase the difficulty in penetration of water in the soil by 10–18% (Mukherjee and Lal 2014). Murphy et al. (2011) found that biochar addition to soil decreased microbial biomass carbon (MBC), which resulted in a decrease in soil organic matter. These findings revealed that it is equally important to be cautious about the possible negative effect such as a decrease in microbial mass, activity, and structural diversity during the amendment of biochar into the soil. Thus in certain cases, the excessive application of biochar could also kill the beneficial microbes in soil biota. In certain cases, the fatalistic effect on microbial communities was observed to hamper crop production. Similarly, Mierzwa-Hersztek et al. (2016) reported the adverse effect of biochar on soil enzymatic activity, which resulted in a declined yield of grass crops. The long-term effect of the biochar application on dissolved organic carbon in the soil has been investigated by Zhang et al. (2012). The application of biochar has been reported in decreasing the dissolved organic carbon in the soil, which may be due to the fixation of dissolved organic carbon by the added biochar.

When biochar obtained from eucalyptus wood was applied to a sandy loom soil, it reduced the dry root weight by 13% and P in leaves by 26% as compared to the control samples of the tomato (*Solanum lycopersicum*) (Nzanza et al. 2012). Growth of maize shows a reduction in pot experiments when a variety of biochar was amended to loamy soil at different application rates, ranging from 0 to 2.0% w/w (Rajkovich et al. 2012). Biochar produced from green waste at 520℃ increased the N_2O emission by 54% when applied to sandy loam Haplic Calcisol soil (Sánchez-García et al. 2014). From the above-reported cases, it could be concluded that biochar application sometimes inhibits microbial growth and consequently results in reduced crop yield. The mechanism in which biochar could negatively affect the biota has been discussed below.

4.2.1 Toxicity of biochar towards microbial population

Compounds such as benzene, methoxyphenol, phenol, furans, ketones, carboxylic acids, and polycyclic aromatic hydrocarbons (PAHs) are formed during pyrolysis under certain circumstances, and these compounds are known to inhibit the microbial growth. The presence of these compounds could be determined by water or organic solvent extractions of biochar. Biochar produced at moderate temperature (300–400 ℃) is found to contain toxic compounds like PAHs and polychlorinated dioxins and furans. Volatile organic compounds (VOCs) present in fresh biochar are essential for certain microbes; however, their presence in higher concentration (especially for some low molecular weight oxygenated VOCs, including alcohols, carbonyls, and acids) may inhibit microbes (Ghidotti et al. 2017). During pyrolysis, persistent free radicals (PFRs) such as semiquinones, phenoxyl, cyclopentadienyls, and phenols are produced, which are toxic to the microbial cell. Oxidative stress induced from the free radicals could decrease the integrity of the cell membrane with the generation of reactive oxygen species (ROS) such as hydrogen peroxide, the superoxide radical anion (O_2), and hydroxyl radicals (OH) (Liao et al. 2014; Balakrishna et al. 2009). Further, free radicals play a significant role in the degradation of organic matters and thus endanger the microbial populations by extinguishing the *C* and *N* sources.

Different soils have different properties and choosing specific biochar that could fulfill the additional requirements of the soil is an important step that needs careful consideration before applying the biochar for soil amendments. The toxic compounds present in biochar could be both beneficial and harmful depending upon the amount and type of compound. Therefore, before administering the biochar as a soil amendment, the analysis for toxic elements present in biochar should be considered.

Biochar has the potential to affect the soil biota directly or indirectly according to production conditions and the nature of its feedstock. Some of the positive and negative impacts

Table 2 Impact of different biochar on soil biota and crop yield reported in the published literature

Feedstock type	Effect	Mode of impact	Changes	Reference
Acacia arabica	Positive	Biofertilizer	Increased the availability of N, P, K by 75%, 28%, and 17%, respectively. Enhance the tomato yield by 48%	Zeeshan et al. (2020)
Bamboo	Positive	Biopesticidal	Decrease the leaching of organic pollutants	Gomez-Eyles et al. (2011)
Bamboo	Positive	Biofertilizer	Preferentially enhance the fungi population which are promoting the growth of rubber plant	Herrmann et al. (2019)
Black carbon	Positive	Biofertilizer	Maize yield increase by 28% when biochar applied in Oxisol soil at a rate of 20 t ha^{-1}	Major et al. (2010)
C. fistula fruits	Positive	Biofertilizer	Increased rice plant seedlings shoot height by 18% and increased bacterial community	Swagathnath et al. (2019)
Charcoal	Positive	Biofertilizer	Moong yield increase by 22% when biochar applied in Delhi soil at a rate of 0.5 t ha^{-1}	Glaser et al. (2002)
Cow manure	Positive	Biofertilizer	Increase nutrient uptake and yield of maize by 98%	Uzoma et al. (2011)
Date palm fronds	Mixed		Enhance water retention and pH and CEC by (2.5 up to 6.7 meq 100 g^{-1})	Khalifa and Yousef (2015)
Eucalyptus sp. barks	Positive	Biofertilizer	Increased rice plant seedlings shoot height by 12% and increased bacterial community	Swagathnath et al. (2019)
Eucalyptus-wood	Negative	Microbial inhibition	Decrease in tomato dry weight by 13% and phosphorous in leave by 26%	Nzanza et al. (2012)
Green waste	Positive	Biofertilizer	Radish yield increase by 266% when biochar applied in Alfisol soil at a rate of 100 t ha^{-1}	Chan et al. (2008)
Hardwood	Positive	Biofertilizer	Maize yield increase by 10% when biochar applied in Midwestern mullsoils soil at a rate of 68 t ha^{-1}	Rogovska et al. (2014)
Herbaceous plant cutting	Neutral	–	No improvement in soil aggregate stability and hydrological properties	Jeffery et al. (2015)
Mixed crop	Positive	Biofertilizer	Increase water holding capacity when applied in loamy soil at a dose of 16 t ha^{-1}	Liu et al. (2016)
Mixed wood chip	Positive	Biofertilizer	Increase pH by 0.9 and CEC by (+4 up to 8.9 mmol kg^{-1}) when applied to sandy loam clay slit soil	Kloss et al. (2014)
Oak	Negative	–	Penetration resistance of soil decrease by 10–18%	Mukherjee and Lal (2014)
Orchid pruning	Positive	Biofertilizer	Grape yield increase by 20% when biochar applied in sandy clay loam soil at a rate of 22 t ha^{-1}	Genesio et al. (2015)
Palm kernel shell	Neutral	–	Enhance soil chemical properties. However, not effective for microbial population	Igalavithana et al. (2017b)
Peanut husk	Negative	Microbial inhibition	The decrease in organic carbon and total nitrogen content	Qian et al. (2014)
Pecan shell	Positive	Biofertilizer	Reduce nitrate leaching and increase the availability of phosphorous	Novak et al. (2010)
Poultry litter	Positive	Biofertilizer	Radish yield increase by 42% when biochar applied in Alfisol soil at a rate of 51.5 t ha^{-1}	Chan et al. (2008)
Poultry manure	Positive	Biofertilizer	Reduce odor emission, loss of nitrogen, and form mature compost with balanced nutrient composition	Dias et al. (2010)
Rice straw	Positive	Biofertilizer	Increase *C: N* ratio when applied to acidic soil	Xu et al. (2014)
Secondary forest wood	Positive	Biofertilizer	Rice yield increase by 50% when biochar applied in Xanthic ferrosolsoil at a rate of 68 t ha^{-1}	Glaser et al. (2002)
Sewage sludge	Positive	Biofertilizer	Increase pH, nitrogen, and carbon content of acidic soil	Khan et al. (2013)
Vegetable waste	Positive	Biofertilizer	Enhancement of the soil chemical properties and microbial population	Igalavithana et al. (2017a)
Wheat straw	Positive	Biofertilizer	Rice yield increase by 14% when biochar applied in Paddy soil at a rate of 40 t ha^{-1}	Zhang et al. (2010)
Wheat straw	Neutral	–	No improvement in soil properties when added to Sandplain soil	
Wheat straw	Negative	Microbial inhibition	Enhancement in crop growth. However, a huge amount of biochar application (60 t ha^{-1}) reduces plant beneficial fauna population	Liu et al. (2020b)

Table 2 (continued)

Feedstock type	Effect	Mode of impact	Changes	Reference
Wood	Positive	Biopesticidal	Induce systematic resistance in Strawberry	Harel et al. (2012)

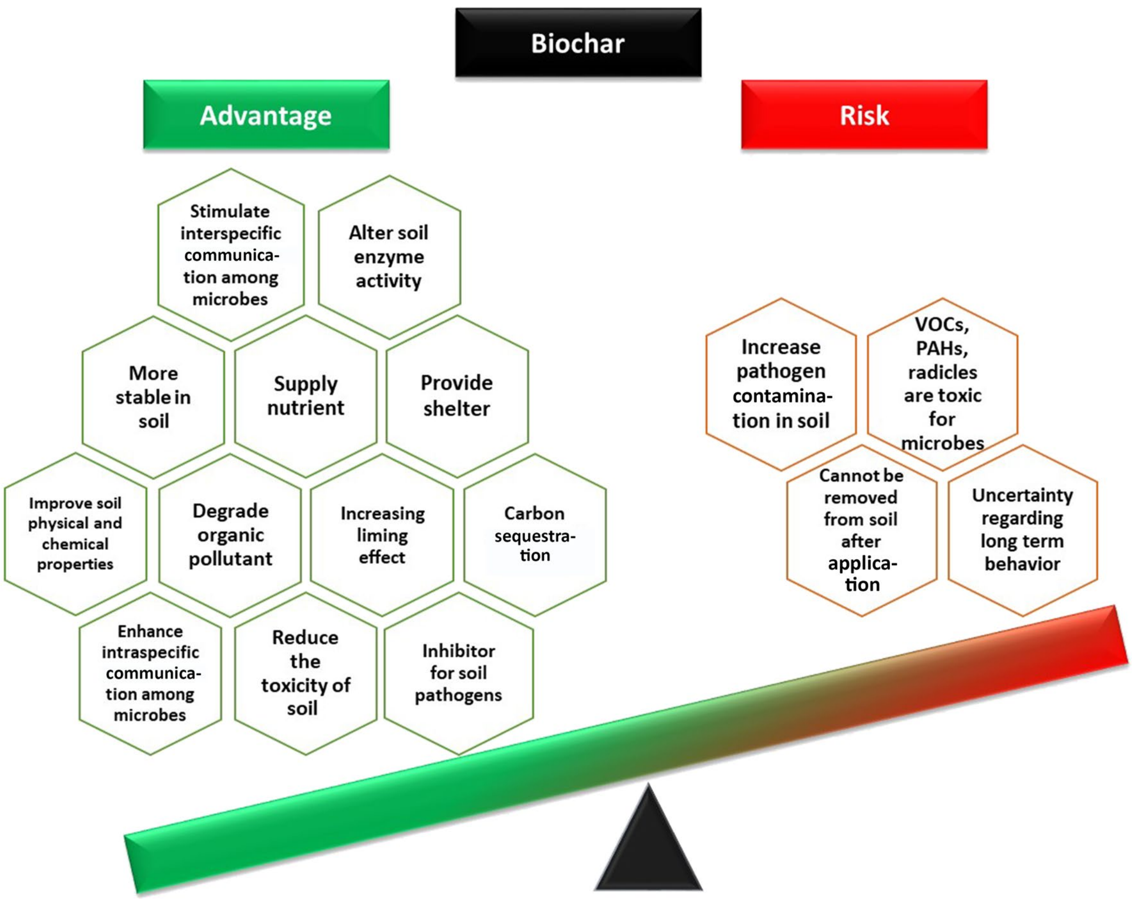

Fig. 5 Positive and negative impact of biochar on soil biota

of biochar produced from a wide array of feedstocks along with its supplementation to the soil are listed in Table 2. And the overall impact of biochar on soil biota can be generalized as illustrated in Fig. 5.

5 Summary and future scope

The agricultural sector in developing and poor countries is currently struggling to cope with the increased demand for food due to population explosion. Although the use of chemical fertilizer has increased productivity, its extensive use has engendered many serious complications such as the degradation of soil ecology, reduced soil fertility, and caused environmental pollution. For increasing the soil fertility and productivity without compromising the sustainability of the agricultural practices, the utilization of beneficial microbe could be implemented as one of the economical and sustainable approaches. The application of microbes was reported to enhance the plant growth and further was observed to strengthen the soil microbial ecology. To enumerate the beneficial microbes in the soil, biochar could be a sustainable and economically viable option. The numerous advantages and few risks associated with the application of biochar have been reported in different studies. Overall, the biochar has been observed to increase the microbial abundance and diversity in the soil, which strengthen the soil ecology and yield numerous benefits for the plant growth.

The mode of biochar effect on microbial population needs further investigation, for new mechanisms and strengthening the existing ones. The physical and chemical characteristics that influence the soil biota primarily depend upon the nature of the feedstock and operational condition (pyrolysis temperature, heating rate, time). Therefore, more research could be performed to investigate the individual or combined effect of biomass characteristics and experimental conditions on biochar properties. As the agricultural productivity has been observed to differ with the application of the different types of biochar, more studies could be performed to underlie the root cause of the varying results, and emphasis could be given to bring the uniformity in the application procedure and yield outputs. Based on the soil requirements, different novel modifications have been undertaken by engineering biochar with various chemical and physical treatments. More research could be performed to compare the efficacy of engineered biochar with the pristine biochar. And the economic feasibility of the modified biochar could be analysed for increasing the applicability. Further, the risk associated with the biochar application on soil microbiota should be investigated in detail to ensure the reliability of the biochar application. It is high time to shift our focus towards material like biochar and its engineering, and more studies need to be performed to investigate its impact on soil biota for economical, sustainable, and eco-friendly agriculture.

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Compliance with ethical standards

Conflict of interests The authors declare no conflict of interest to disclose.

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