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Review article

A comprehensive review on biochar against plant pathogens: Current state-of-the-art and future research perspectives

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ABSTRACT

Plant pathogens cause a serious menace to food production. The diseases caused by pathogens are estimated to cause a yield loss of about 14.1 %, whereas, in India, up to 26 %. Several plant pathogens like *Pythium, Phytophthora, Rhizoctonia, Sclerotinia, Fusarium,* and *Verticillium* can cause 50–75 % yield losses in cereals, cotton, and horticultural crops (fruits, vegetables, and flowers) 10–100 % in pulses, 30–60 % loses in oilseed crops and 40–50 % in plantation crops. Biochar as soil amendment is emerging as an effective environment friendly substitute for fungicides to counter plant pathogens. It has also been reported to induce resistance in plants to combat plant pathogens by activating the two important defense pathways such as salicylic acid, jasmonate/ethylene defense, and triggering the plant's antioxidant enzymatic activities. Biochar promotes soil health and consequently improves the plant health, resulting in reduced incidence of disease. This novel amendment also helps in the priming of expression of genes against foliar fungal pathogen infection. This review paper will summarize the effect of biochar incorporation in the plant disease management as well as on their growth parameters.

1. Introduction

Biochar, an organic residue formed by the pyrolysis of biomass is utilized in several fields including industrial utilization, bioremediation and as substrate to promote the soil health and plant growth. International Biochar Initiative (IBI) describes biochar as "the solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment". Biochar is a stable product and can survive in soil for thousands of years and contains ample amount of pyrogenic carbon. The word "biochar" was originated from the Greek word, "bios" (life) and "char" (production of charcoal by biomass carbonisation). Application of biochar, as an amendment in soil is gaining popularity now-a-days as its a source of carbon sequestration, and is an efficient method of utilising waste (industrial and agricultural waste). Biochar is mainly produced from agricultural wastes, animal manures, paper products and its production from agricultural waste is an eco-efficient way of utilising the waste materials (Fig. 1) [1–3]. Biochar incorporation in soil alters the fertility of soil by changing soil properties [4]. It enriches the soil and thus enhances plant growth leading to high crop yield. The impact of

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biochar on crop yield rely on a number of factors like sources of biochar, processes involved in its production, types of soil in which biochar has to be added and also the types of crop to be planted.

The use of biochar dates back to an old era when pre-Columbian Amazonians used agricultural waste materials to produce biochar by smoldering (covering burning biomass with soil) in trenches or pits [5–7].Though their intention was not clear whether they used biochar to enhance soil fertility or productivity or for other purposes. The word *terra preta de Indio was* used by Europeans for biochar [8,9].The main area of interest in biochar research is its half-life period (100–1000s of years) in the soil after application, thus helping in the sequestration of carbon [6,10]. The first report of the optimistic influence of biochar in minimizing disease incidences such as wheat rust and mildew in other agricultural crops had been discussed, dated back to about 170 years ago [11] and has gained a lot of attention since last decades when researchers have studied the effects of biochar in several patho-systems worldwide [12,13].

Addition of biochar in soil not only helps in the amelioration of pollutants but the porosity of biochar also facilitates sufficient surface area for harbouring microbes such as bacteria and mycorrhizae and enhance their metabolic activities [14]. During the pyrolysis process of organic (lignocellulosic) materials, usually, complex chemical reactions take place involving depolymerization, decarboxylation, aromatization and decarboxylation of O-alkyl carbons, lignin, hemicellulose and cellulose. Besides these, several other volatile organic compounds (furan, terpenes, benzaldehyde, 2,3-butadione, phenol, acetonitrile, pyrazine) are also produced during pyrolysis, and are found to inhibit the action of *Fusarium oxysporum* and *Rhizoctonia solani* in solanaceous crops [15,16]. Hui [17] and Liu et al. [3] have found colonization of bacterial populations such as *Bacillus pumilus*, *Streptomyces pseudovenezuelae* and *Pseudomonas chlororaphis*, in the porous structure of animal bone biochar and they have used it to control the seedling disease of tomato caused by *Pythium aphanidermatum* and *Fusarium oxysporum f.sp. lycopersici*.

Biochar interacts with various soil microbes and helps in the plant growth by the suppression of plant pathogens. Biochar is an eco-friendly alternative for the management of plant diseases. Biochar incorporation in soil alters the nutrient availability/cycling, root exudates, and soil properties which directly or indirectly affects the plant pathogenic populations in the soil [13,18]. Also, biochar incorporation in soil induces systemic resistance, leads to the activation of active oxygen species, and stress hormone response consequently leads to the resistance of host plants against pathogens [2,19]. Alterations in microbial communities, root exudates, and induction of defense response in host plants also affect the plant parasitic nematode population in the soil. Most of the reviews highlighted the positive sides of biochar application in agri-horticultural operation such as stabilization of soil organic carbon, increased biomass and yield of plants with reduced greenhouse gas emissions. There is only a handful of literature on how biochar application can have multiple effects on the crop. It can contribute in improving, soil health, and plant health. Also, it contributes in protecting the plants from fungal, bacterial and viral diseases [7,20].

Among various cultural practices, soil amendments have been found effective in the suppression of various soil-borne diseases which are otherwise often difficult to manage [1,21].Though soil amendments have many positive effects in the majority of host-pathogen systems but due to the above-mentioned side effects and non-availability of the guidelines regarding the effect of organic amendments on soils and patho-systems, further research is required for their application in particular host-pathogen systems. Keeping this in view, biochar appears to be a recently available tool to combat various soil-borne diseases. Therefore, the main purpose of this review is to a) deal with the plant disease management aspects of biochar, prepared from different feedstocks; b) discuss most probable mechanisms involved in the management; c) highlight the direct influence of biochar in promoting the plant growth and d)

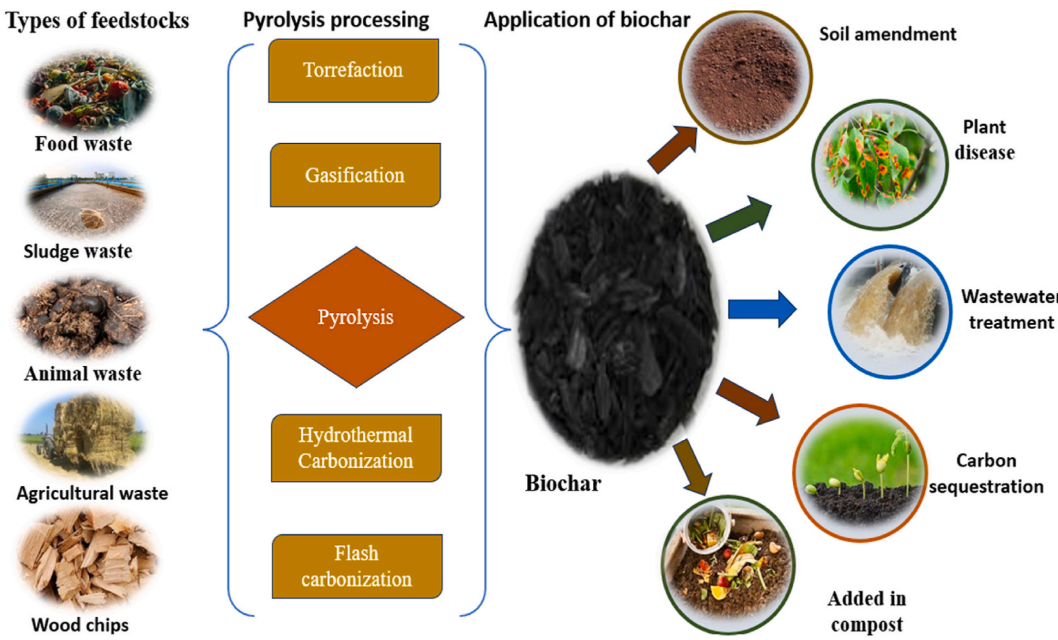


Fig. 1. Sources, processes and applications of biochar.

elucidate the indirect effect of biochar in inducing the disease resistance in plants.

2. Biochar impacted ecosystem and microbial community dynamics

The use of biochar has been greatly emphasized now-a-days in various sectors due to the several advantages it adds to the environment as discussed elsewhere in the present review and the most significant advantage is that it can reduce the burden of waste materials on the environment. Biochar has been reported to show diverse effects on plant pathogenic microbes [22], although no exact mechanisms were found to discuss these effects [23]. The surface of the biochar has labile soil organic matter which promotes the growth of certain beneficial microbes [13,18].

Biochar alters the microbial diversity in the root zone, and promotes plant growth. Biochar based amendment in soil alters the soil properties and consequently changes the microbial dynamics of soil (Fig. 2). Ren et al. [24] and Chen et al. [25] discussed that biochar modified the fungal community and the change of biodiversity from Ascomycota and Basidiomycota divisions of fungi (which majorly includes plant pathogenic fungi) in biochar untreated soils to Zygomycota, Neocallimastigomycota and Glomeromycota (includes plant growth promoting fungi, which can suppress the disease incidence) as the composition of metabolites in soils treated with biochar were different from that with no biochar, which promoted a certain group of microbes and suppressed the other. Yan et al. [26], conducted a study for 3-years by adding biochar at the rate of 10, 20, and 40 t ha m^{-2} and observed that significant alteration in the fungal population Zygomycota, Ascomycota, and Basidiomycota phyla were found in majority which was about more than 90 % of the total sequences. In another study application of biochar enhanced the Ascomycota and Basidiomycota populations i.e. *Aspergillus* (might show antagonistic effect on plant pathogens), *Conocybe*, and *Alternaria* spp., but the abundances of Zygomycota i.e. *Gibberella* and *Actinomucor* were reduced. Bai et al. [27], conducted a study to see the effects of biochar application in soil for longer durations. They have reported that continuous applications of straw and then straw derived biochar to the field for a period of about 6 years in rice-wheat crop rotation system had resulted in the decreased fungal diversity and change in the soil aggregation capacity. Application of straw with biochar and fertilizer reduced the adverse effect of fertilizer and gave better results in the crop yield.

Increased populations of *Sphingomosnas* and *Pseudomonas* (beneficial microbes) was seen in cotton soils which was amended with biochar, but during continuous cropping of 11 years in that soil resulted in the decreased abundances of such bacterial populations [28]. The increase of bacterial population might be due to the increase in soil pH by incorporation of biochar, as pH plays an important role in shifting microbial community in soil while a decrease with continuous cropping might be the result of reduced pH over time. Nguyen et al. [29] observed the differences in the abundances of Cyanobacteria, in freshly incorporated (1 year) and old biochar (9 year) soil. There was a significant increase in the bacterial alpha diversity, Bacillota and Pseudomonadota (non plant pathogenic and may compete with the pathogenic microbes to suppress their growth), while a decrease in the diversity was also observed in the case of Acidobacteria (plant pathogenic bacteria) which might be attributed to the changes in soil properties such as electrical conductivity, pH, extractable organic carbon and extractable nitrogen.

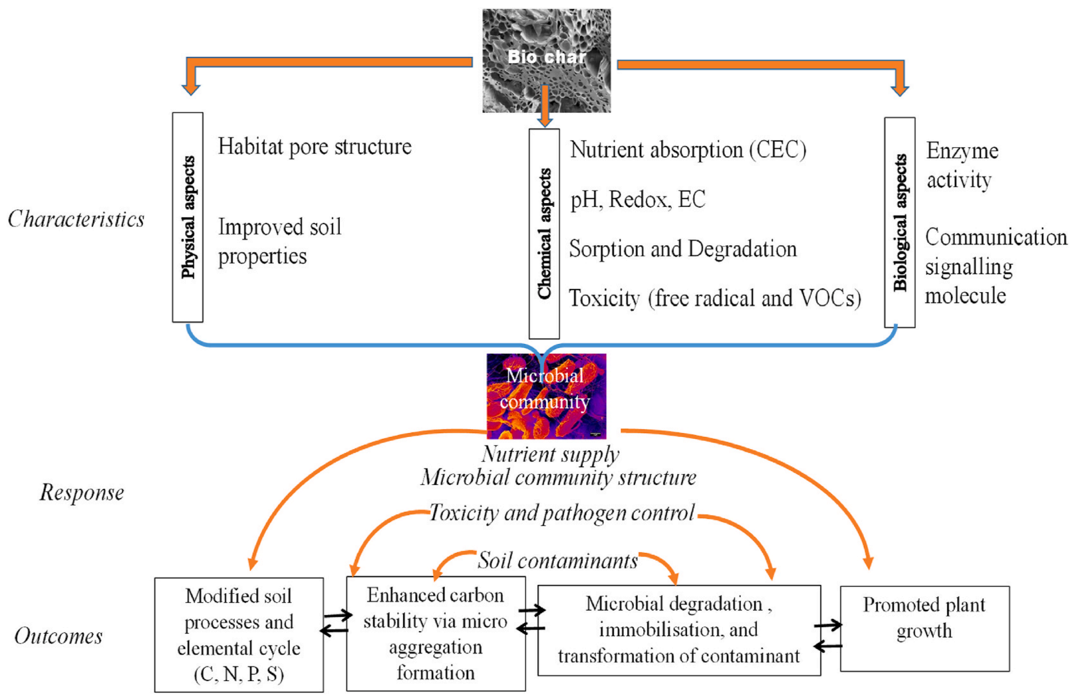


Fig. 2. Biochar interaction with soil microbial communities and associated microbial responses.

3. Global scenario of biochar for soil-borne and foliar plant diseases management

Soil borne pathogens are deadliest plant pathogens; being soil borne in nature their management becomes really difficult. They adversely influence the yield, and quality of many economically important crops around the world. The underground plant parts such as the root system (damping off, root rot, vascular wilt etc.) is severely affected, and consequently their effects can also be seen in the upper plant parts (wilting of foliage, tissue discoloration, root decay and sudden death) [30].Soil borne plant pathogens survive along with the vast variety of soil microbes which may be helpful or injurious for the plants and are highly influenced by the living and non-living factors of the soil, the kind of cultivation practices followed i.e. preparation of fields, fertilizers and manures application and irrigation [31]. Though there are several chemical management methods such as soil disinfestations [32], they have their own disadvantages such as ill effects on the beneficial microbes, increased chemical loads in the soil and high costs of application. In addition, in the case of soil application, soil being a dense medium the proper dispersion of the chemical compound is also a serious concern. Thus emphasis is now on promoting the soil health and to improve the soil properties for conquering the pathogens to minimize the losses caused by plant pathogens [7,20]. Biochar, as soil amendment, can be a potential tool to promote soil health and to suppress plant pathogens without keeping the environment at stake [33]. Stimulation of the photosynthetic activities and plant growth hormones regulating genes along with the plant growth promotion are considered as the direct and indirect effect of biochar addition to the soil which also enable quick plant responses to pathogen invasion [34,35]Addition of biochar has a direct influence on the enzymatic activity of plant pathogens such as adsorption of cell wall degrading enzymes and can suppress the disease by the soil borne plant pathogens (Table 1).

Globally a handful of studies have been made utilising biochar from different sources for the management of soil borne and foliar plant pathogens (Tables 1 and 2) [47,34]. Similarly, a study conducted in Israel by Jaiswal et al. [40] showed that biochar incorporation reduced the incidence of *Rhizoctonia solani* in cucumber by promoting plant growth. Suppression of disease incidence of wilt in tomato was observed by Murtaza et al. [48] in Austria utilising wood biochar. Zhang et al. [35] observed the reduced incidence of *Ralstonia solancearum* by the use of rice straw biochar in China, as it increased the beneficial microbes in soil such as *Sphaerodes, Sphingobium, Sphingomonas* and *Caulobacter*. A reduced incidence of *Pythium* or *Phytophthora aphanidermatium* in cucumber *was* observed in a study conducted in Israel, by increasing the population of beneficial microbes in soil [44]. In case of virus plant pathogens, a study conducted by in Italy showed a reduced incidence of Tomato spotted wilt virus by the incorporation of biochar obtained from alfalfa, through alteration of microbiome [49]. Reduced incidence of early blight of tomato was observed by the use of fruits and vegetable waste derived biochar in Pakistan by promoting plant growth through enhanced rhizobacterial activity [2]. A recent study conducted in India by showed the reduced incidence of Sclerotinia stem rot of tomato by the use of rice husk biochar [50] (Fig. 3). Both the studies concluded that biochar induced disease resistance in host plants by enhancing the production of host defense compounds, while in a study conducted against *Sclerotinia sclerotiorum with* rice husk biochar suppressed the carpogenic germination of

Table 1
Biochar used for soil borne plant disease management.

Pathogen/Disease	Host plant	Biochar feedstocks	Mechanism involved	Place of study	Reference
Fusarium oxysporum f.spasparagi Fusarium proliferatum	*Asparagus* sp	Commercial Quest biochar	Enhanced AM colonization	New York, USA	[36]
Phytophthora cinnamomi P. cactorum	*Acer rubrum Quercus rubra*	*Pinus taeda, P. palustris, P. echinata, P. elliotti*	Induced disease resistance in plants	Washington, USA	[37]
Pythium ultimum	*C. annum, Ocimum basilicum*	Spruce bark	Induced host defence	Canada	[38]
Phytophthora infestans	*Solanum tuberosum*		In combination with Stremptomyces strains enriched rhizosphere	China	[39]
Rhizoctonia solani	*C. sativus Phaseolus vulgaris*	Greenhouse wastes	Plant growth promotion	Israel	[40]
Decline disease	*Bayberry*	Plant biochar	Microbial diversity	China	[24]
Fusarium oxysporum f.sp lycopersici	*L. esculatum*	*Wood biochar*	Suppressed mycelial growth	Austria	[41]
Ralstonia solanacearum	*Solanum tuberosum*	Rice straw	Increased microbial richness	China	[35]
Fusarium oxysporum f. sp. radicis lycopersici	*L. esculatum*	*Eucalyptus wood chips and* greenhouse pepper plant wastes	Adsorption of cell wall degrading enzymes and toxins produced by the pathogens	Israel	[42]
Fusarium oxysporum* f. sp. *lycopersici	*L. esculatum*	Stems of *Helianthus tuberosus*	Increased beneficial microbes	China	[43]
P. aphanidermatum	*Cucumis sativus*	*Eucalyptus wood chips*	Increased beneficial microbes	Israel	[44]
Phytophthora capsici	*Capsicum annum*	Corn stalk	Increased abundance of potential biocontrol fungi	China	[16]
Stemphylium vesicarium	*Allium cepa*	Poultry litter biochar	–	Pakistan	[45]
Ralstonia solancearum	*Nicotiana tabacum*	Tobacco stem	Diversity of beneficial microorganisms.	China	[46]

Table 2
Biochar used for foliar plant disease management.

Pathogen	Host plant	Biochar feedstocks	Mechanism involved	Place of study	Reference
Levilula taurica	Tomato	Citrus wood	Systemic induced resistance	Israel	[51]
***Botrytis cinerea, Colletotrichum acutatum* and *Podosphaeraapahanis*,**	Strawberry	Wood biochar	Induced the expression of defense-related gene	Israel	[52]
Botrytis cinerea	*L. esculatum*	Green house waste	Jasmonic acid signaling	Italy	[53]
Tobacco mosaic virus	*L. esculatum*	Salix wood chips	Induce systemic resistance	Egypt	[54]
Tomato leaf curl virus	*L. esculatum*	Maize cobs	Induced plant defence	Pakistan	[55]
Magnaporthe oryzae	Perrenial rye grass	Rice straw biochar based Si source amendment	Increased Silicon content tissue	China	[16]
Tomato spotted wilt virus	*L. esculatum*	Alfa alfa	Altered bacterial and fungal microbiome	Italy	[56]
Alternaria solani	*L. esculatum*	Green waste biochar, and wood biochar	Enhanced rhizobacterial activity to promote plant growth	Pakistan	[2,3]
Gloeocercospora sorghi	*Agrostis stolonifera* L	Biochar compost mixture	–	US	[57]

sclerotia resulting in the reduction of disease incidence.

4. Comparison of biochar with other soil amendments in plant disease management aspects

Use of biochar in soilless substrate has been studied for several plants (Table 3). Combinations of biochar produced from different substrates with several other fertilizers, mycorrhiza, and humic acid products had also been reported in the literature [2,33]. Han et al. [8] and Jaiswal et al. [44] have evaluated the positive effects of biochar on the development of plant compared to peat media at lower concentration (30 % (v/v)) [17,58] and it was found that they were not harmful even at high dosages (>40 %) [10]. Biochar substrates with other growth media along with plant biological enhancers significantly promoted the plants growth [31,35]. Several studies which amended the biochar with plant growth promoting bacteria (PGPB), biological agents and arbuscular mycorrhizal fungi combination observed the increase in arbusular mycorrhiza and PGPB levels in soil [26,27]. Very few studies were based on the combination of biochar with biological control agents [32,59]. Also the biochar addition in the potting media may reduce the damage

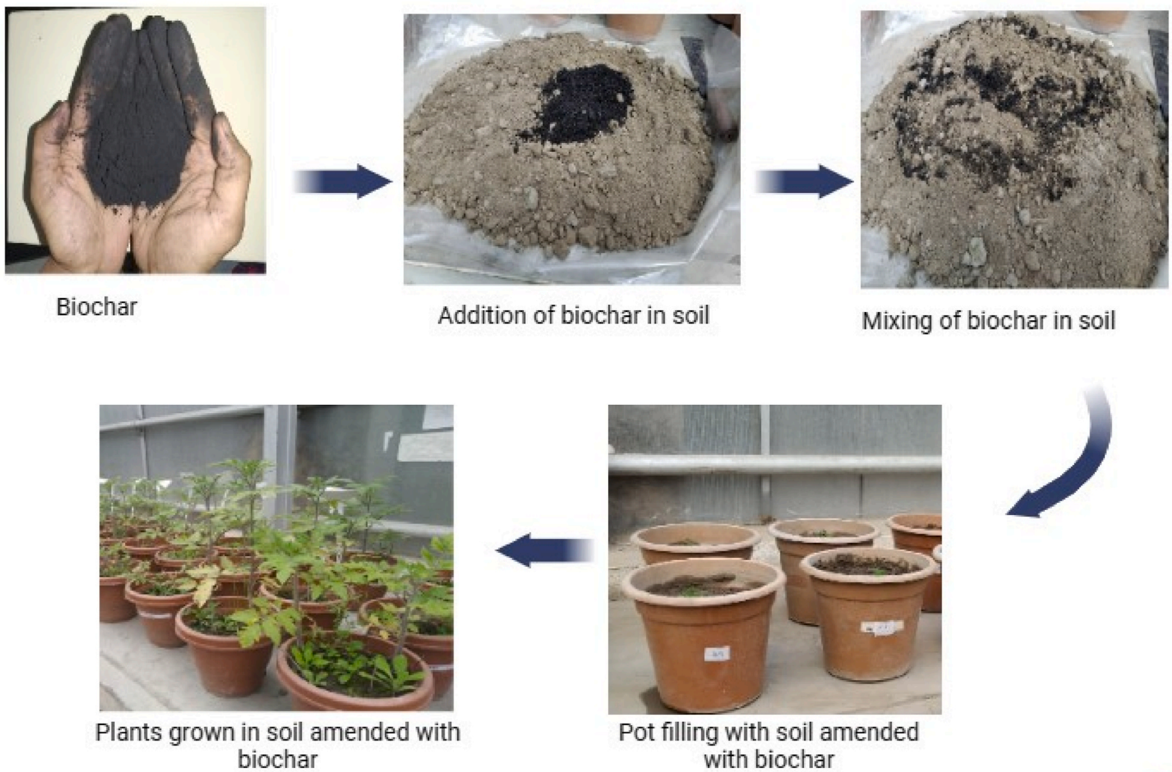


Fig. 3. Picture showing stepwiseapplication of biochar in soil for plant disease management.

Table 3
Summary table showing synergistic and antagonistic effects of biochar on plant growth.

Effect	Biochar (source)	Crop	Mechanism	Place of study	Reference
Synergistic					
Increased biomass and seed yield	Sawdust	Soybean	Decrease in soil pH	Pakistan	[60]
Improvement in growth and physiology of maize	Grapevine twigs	Maize	Enhanced beneficial microbes	Pakistan	[49]
Increased biomass and seed yield	Sawdust	Soybean	Decrease in soil pH	Pakistan	[61]
Improvement in growth and physiology of maize	Grapevine twigs	Maize	Enhanced beneficial microbes	Pakistan	[62]
Increased yield	Biochar	Rice	Synergistic effect with PGPR	Egypt	[63]
Increase in grain yield and biological yield	Cow manure	Maize	Increased Nitrogen availability	Pakistan	[64]
Antagonistic					
Negative yield impacts	Wheat-straw biochar	Rye grass (*Lolium perenne*L)	-		[65]
Increased disease incidence of *Rhizoctonia solani*	Greenhouse waste (GHW)	Cucumber	Toxic effect	Israel	[40]
Reduced asparagus yield	Biochar	Asparagus	Absorbed some nutrients, such as nitrogen,	USA	[66]
Reduced P availability	Wheat	Suaeda salsa	Occurrence of phosphate precipitation/sorption reaction	China	[67]
Reduction in uptake of Ca and Mg in maize	Wheat straw and pine wood biochar	Maize	Access addition of Potassium to soil	Denmark	[68]

by the plant pathogenic nematodes [34]. One of the aspects that can be taken into consideration is that whether the applied biochar can minimize the pesticide's dosages in the nursery plantation?

4.1. Plant growth and disease response

Plant patho-systems involve soil borne and foliar pathogens [47,69]. The data to comprehend the influence of incorporation of biochar on plant diseases was summarised [24] and observed that biochar had a positive influence on 85 % of the investigations based on the minimizing disease severity. Only3% of the reported studies had showed that biochar favoured the occurrences of the plant diseases [10,20]. They had also concluded that the dosages of application of biochar were the determinative factor for enhancing or suppressing the susceptibility of the host plants against diseases (Fig. 4).

Majority of the studies had evaluated biochar at concentrations in the range of 0.5–5 % (w/v), with some of the studies had reported negative to neutral impact on plant diseases of vegetable crops when compared to control and maximum effective biochar

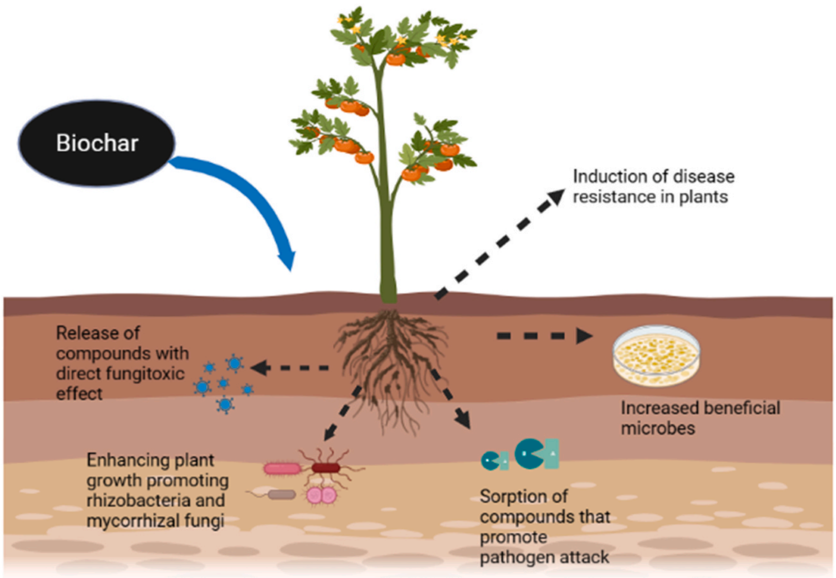


Fig. 4. Schematic representation of the plant disease control mechanism (reduction in survival and germination of dormant structures) in biochar amended soils.

concentrations (3–5%) [24,28,47,70]. In this case, an inverted U-shaped biochar dose curve was observed in most of the studies [1,71]. Several previous studies were conducted to test the effects of biochar in suppressing disease using a growing media showed that the disease was suppressed when biochar was used at low dosages (≤1 %) [13,24], while the use of biochar in high concentrations (3 %) was found to be ineffective in suppressing the disease [2,3]. With the further increase in biochar concentrations probably a reversed U-shaped dose response curve was obtained though the less effect was observed in the foliar disease causing pathogens [48,70] but the effect was prominent in soil-borne pathogens.

4.2. U shape effect for biochar (in soilless culture/media)

Biochar can be successfully utilized as an amendment at low concentration for a soilless media, whereas complete replacement of soil by biochar needs some thorough study as it promotes plant growth against pathogens but at high concentrations it may have some adverse effect either in the plant growth or may promote the disease incidence by pathogens (Table 4).The use of biochar as a major portion of soil media is still under question due to its mixed response. Though in plant nurseries, strict measures are taken for sanitation to reduce the disease risk from several fungal and bacterial plant pathogens such as *Corynebacterium michiganesis*, *Xanthomonas campestris* and *Pythium aphanidermatum* [69,72]. *Arabidopsis thaliana* plants when applied with high concentration (>3 %) of biochar resulted in the increased leaf area and root length, and the molecular assessment of genes showed the up-regulation of genes responsible for auxin and brassinosteroids pathways which are growth stimulators. But the down regulation of defense genes responsible for salicylic acid, jasmonic acid, and ethylene pathways, was also observed [20,39]. Depending on the substrates used for biochar preparation, it may reduce availability of nutrients to plants rendering them susceptible to disease [73]. Biochar may consist of

Table 4
Effects of biochar on plant-pathogenic fungi, arthropods, bacteria, nematodes, and oomycetes.

	Host plant	Source of biochar	Mechanism involved	Place of study	Reference
Fungi					
Fusarium oxysporum* f. *spasparagi* *Fusarium proliferatum	*Asparagus* sp	Commercial Quest biochar	Enhanced AM colonization	USA	[42]
Botrytis cinerea	*L. esculatum*	Green house waste	Jasmonic acid signaling	Italy	[53]
Botrytis cinerea	*L. esculatum*	Green house waste	Jasmonic acid signaling	Italy	[70]
Fusarium oxysporum f. sp. lycopersici	*L. esculatum*	*Eucalyptus urophylla and E. saligna*	Reduced micrconidial germination	Brazil	[15]
Levilulataurica	*L. esculatum*	Citrus wood	Systemic induced resistance	Israel	[44]
Arthropods					
Nilaparvatalugens	Paddy	Wheat straw	Reduced egg hatching rate	China	[19]
Laodelphaxstriatellusas	Paddy	Corn	Decreased fecundity	China	[84]
Cnaphalocrocismedinalis	Paddy	Wheat straw	Mortality of larvar, reduced body weight of Mature larval, lowered consumption of rice leaves	China	[12]
Sitobion avenae	Wheat	Wheat, corn or rice straw	Decrease the duration of stylet penetrations	China	[9]
Douglas-Fir Tussock Moth	Douglas-fir	Douglas-fir	Reduced survival and weight gain	Moscow, USA	[85]
Bacteria					
Ralstonia solanacearum	Tomato	Peanut shell and wheat straw	Enhanced soil microbial diversity	China	[5]
Ralstonia solanacearum	Tomato	Pine wood biochar	Supress pathogen swarming ability	China	[86]
Ralstonia solancearum	Tobacco	Rice hull	Increased beneficial bacterial count	China	[9]
Ralstonia solancearum	Tomato	Wheat straw	Increased microbial diversity	China	[87]
Ralstonia solancearum	Tobacco	Tobacco stem	Diversity of beneficial microorganisms.	China	[46]
Nematode					
Meloidogyne graminicola	Rice	Wood biochar	Transcriptional enhancement of genes involved in the ethylene (ET) signaling pathway.	China	[88]
Pratylenchus penetrans	Carrot	*Pinus sylvestris* spelt husk biochar	Induced host defence	Germany	[34]
Meloidogyne incognita	Tomato	Rice husk	Reduced number of galls, egg and females	Pakistan	[89]
Meloidogyne incognita	Lentil	*Prosopis juliflora*	Reduced nematode population	India	[90]
Meloidogyne javanica	Tomato	Grape pomace-derived biochars	Reduced egg masses and eggs per plant	Spain	[91]
Oomycetes					
Phytophthora cinnamomi P. cactorum	*Acer rubrum Quercus rubra*	*Pinus taeda, P. palustris, P. echinata, P. elliotti*	Induced disease resistance in plants	USA	[37]
Pythium ultimum	*C. annum, Ocimum Basilicum*	Spruce bark	Induced host defence	Canada	[38]
P.aphanidermatum	*Cucumis sativus*	*Eucalyptus wood chips*	Increased beneficial microbes	Israel	[44]
Phytophthora capsici	Pepper	Corn stalk	Increased abundance of potential biocontrol fungi	China	[92]

a number of organic compounds which may have some phytotoxic effects. Some biochars showed emission of ethylene, which has a role in plant growth as well as in plant defense but it showed negative impacts at high concentrations (>20 ppm) [24,74]. Incomplete pyrolysis of biochar results in production of polycyclic aromatic hydrocarbons (PAHs), which are organic pollutants of the environment [75]. Biochar application may reduce the availability of pesticides [76,77], which would require application of higher doses of pesticides for managing pest [78]. Biochar contains volatile organic compounds (VOCs) [79] which are toxic. Some microbes produce VOCs signaling molecules [80] and can elicit plant growth by promoting rhizobacteria [81]. VOCs produced biochar may interfere with them and inhibit the fungal growth [82] and can inhibit nitrification [83].

Therefore, researchers have justified that there is no specific concentration on which the efficiency of biochar can be determined as different factors might define the effectiveness of the biochar starting from its sources to the sink (soil) [17]. For disease suppression the use of different concentrations of biochar might depend on the various mechanisms involved in that particular patho-system. Some of the probable mechanisms researchers have discussed in recent decades include the alteration of microbial communities in soil and enhanced population of beneficial microbes, supply of the nutrient contents to plants, and the hormesis effect of phytohormones [69,72,56]. The growth of most pathogens is often favoured by acidic soils (pH <6.5), but it has been reported that biochar addition enhanced soil pH which makes the nutrients unavailable to the pathogens and increases the beneficial microbial biomass to protect the plant from pathogen attacks [22,28].

4.3. Molecular assessment of biochar interaction with pathogenic fungal community

Plants have innate mechanism of defense (Induced systemic resistance), which protect plants against pathogenic fungi, bacteria, viruses, nematodes, and insect pests [70,60]. Biochar also induces resistance in host plants. Chen et al. [25] and Poveda et al. [7] described the mechanisms of inducing disease resistance in plant pathogen *Botrytis cinerea*a and *Colletotrichum acutatum* in pepper and *Leveillula taurica* in tomato. Increased expression of genes linked with the defense induction was observed in strawberry cultivated in potting media incorporated with biochar [20,48]. Biochar leads to the production of the phytotoxic molecules and phenols influencing the plants and also the associated microbes [49,93].Green waste biochar incorporated at concentrations of 1 % and 3 % was effective against *Fusarium oxysporum* f.sp. *Radicis lycopersici* (causal organism of crown rot in tomato), and mortality caused by disease up to 43

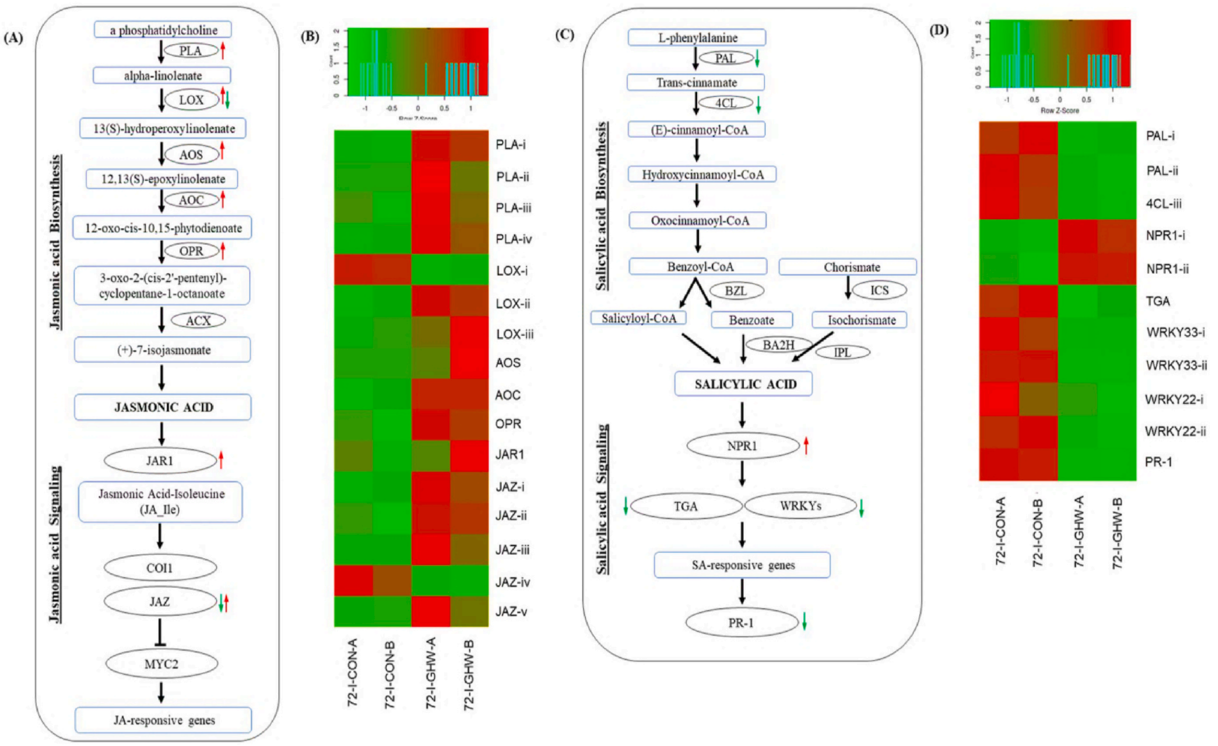


Fig. 5. Heat map diagram showing molecular transcripts expression of genes induced by biochar (adapted from Jaiswal et al. [19]). (A) Plant signaling pathway and JA biosynthesis induction. Significant up- and down-regulation is present in the transcripts indicated by the green and red arrows, respectively; (B) Expression heatmap of genes involved in signaling and JA biosynthesis in treatments with and without modified biochar at 72 h post-immunization. Rescaled transcripts per kilobase per million (TPM) values are represented by Z-scores; (C) Plant induction of SA biosynthesis and signaling pathway; (D) Transcript expression heatmap associated with to signaling and SA production in treatments with and without modified biochar at 72 h post-irradiation. Systemically induced signaling pathways for jasmonic acid (JA) and salicylic acid (SA) in response to the biochar and pathogen at 72 hpi. This image copyright belongs to the respective publisher and/or authors.

% and 57 %, respectively, indicating efficacy of 1 % over 3 %. Transcriptomic analysis (RNA-seq) of tomato was carried out in that study and differences were observed in the expression of genes in biochar treated plants indicating the priming effect of biochar on genes expression. Up-regulation of Jasmonic acid, lignin, flavonoid, phenylalanine and phenylpropanoid biosynthesis pathways was observed, which, were the key indicators of defense responses in plants (Fig. 5(A–D)) [19]. Rasool et al. [3] conducted study using wood and green waste biochar (at 3 % and 6 % rate of application for both) against early blight of tomato caused by *Alternaria solani* and observed the reduced disease incidence in the soil that was incorporated with wood biochar and 6 % green waste biochar treatment. They have observed expression of defense related genes such as Pti4 responsive to ethylene, PI2 and Tomlox D, related to jasmonic acid and PR1a, PR2 related to salicylic acid in that study. Expression of PI2, Tomlox D, PR2 and PR1a was more in the case of green waste biochar (6 %) and it was found that production of catalase, phenolics, and peroxidase reduced the infection by pathogens. Chen et al. [25] have observed that plants showed high resistance in biochar-amended soil against *Fusarium oxysporum* and *Rhizoctonia solani* due to the increased phenolic compounds and high activities of key enzymes of phenylpropanoid pathway i.e. phenyl ammonia-lyase and peroxidases, which might be associated with the enhanced lignification process.

4.4. Effect of biochar on the survival of dormant structures of pathogens

Resting structures such as melanized mycelium, oospores, chlamydospores, and sclerotia acts as a primary source of inoculum for several plant pathogens and are responsible for the initiation of infection in the host plant. Reducing the viability and interrupting the germination of these resting structures can prevent the occurrence of disease. Soil pathogens mainly survive in the low ranges of Eh–pH [72], biochar alters the pH in the rhizosphere consequently affect in the viability of pathogens [26]. Biochar incorporation in the soil also alters the composition of root exudates of plants and thus simultaneously affects the germination of resting structures of plant pathogens. Some of the compounds which directly hamper the survival of pathogens are propylene glycol, hydroxy propionic, ethylene glycol, benzoic acid, hydroxybutyric acids, o-cresol, 2-phenoxyethanol, and quinines [47].

Jaiswal et al. [44] observed the reduced survival of *Rhizoctonia solani* by the use of Greenhouse pepper plant waste biochar at the rate of 3 % concentration (w/w) in pot experiments. Akhter et al. [41] observed the positive effects of the green waste biochar in controlling the wilt disease of tomato caused by the *Fusarium oxysporum*f. sp. *lycopersici* by reducing the germination of chlamydospores. Were et al. [94] used the extract of sugarcane bagasse biochar along with vermicompost to observe the suppression in the germination of sporangia and conidia of root rot pathogens. Bhatt and Sharma [50] observed suppression of carpogenic germination of sclerotia by the application of rice husk biochar under *in-vitro* conditions.

5. Strategy and mechanisms of plant disease control

There are varied phenomenon by which biochar protects plants against diseases such as enhancing plant growth by improving the nutrient availability, adsorption of toxic compounds produced by pathogens, alterations in the chemical composition of root exudates, inducing disease resistance [6,95] in plants. In addition, increasing the beneficial microbes count in the soil, stimulation of the specific antibacterial and antifungal compounds also contributed to the disease resistance [24,70] Several studies based on biochar against soil borne and foliar plant pathogens have demonstrated the effectiveness of biochar in minimizing disease incidence [2,3,6,8]. They have hypothesized that the suppression of the soil borne pathogens might take place through the following mechanisms such as by induction of systemic resistance in plants, Jasmonic acid signaling and by enhancing rhizobacterial activity to promote the plant growth.

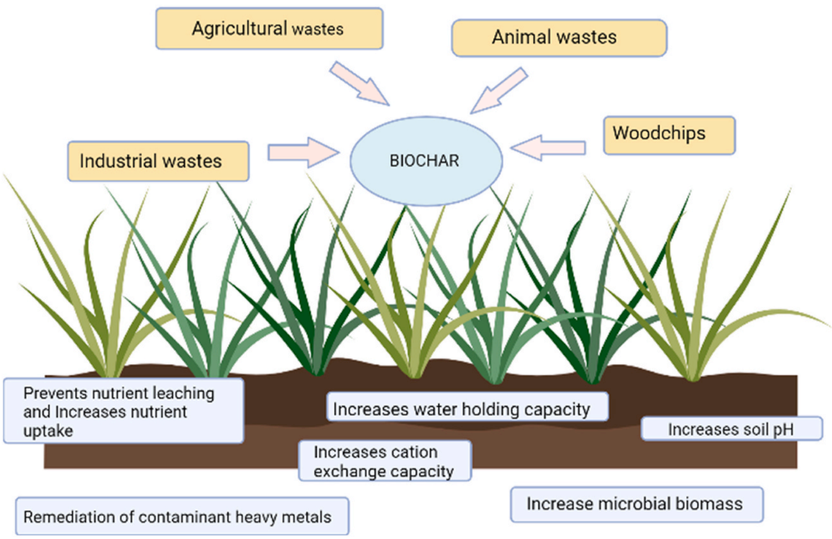
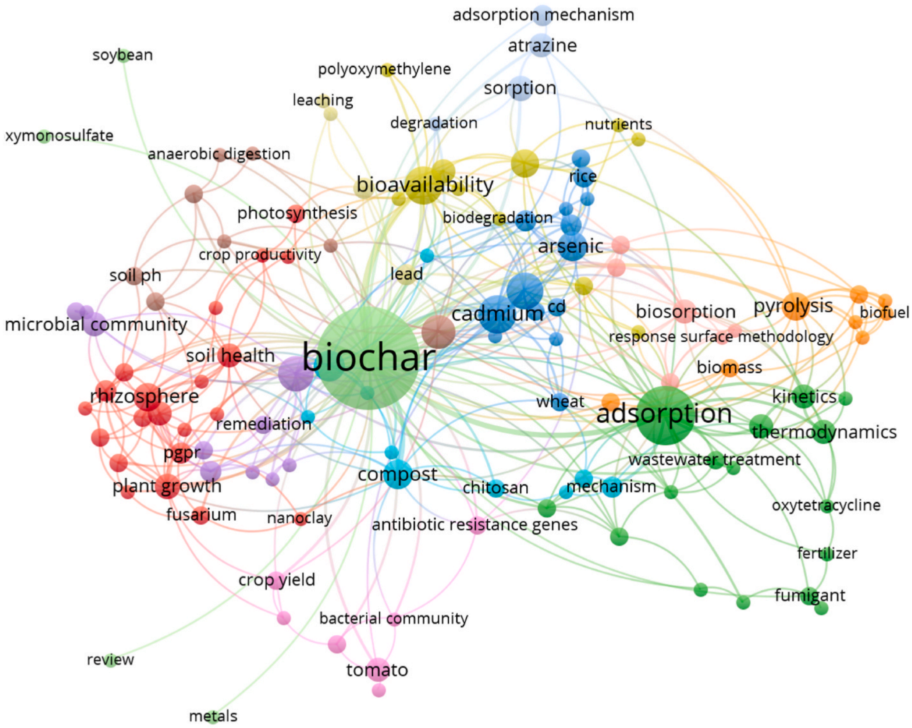


Fig. 6. Effect of biochar application on soil, plants and microbes.



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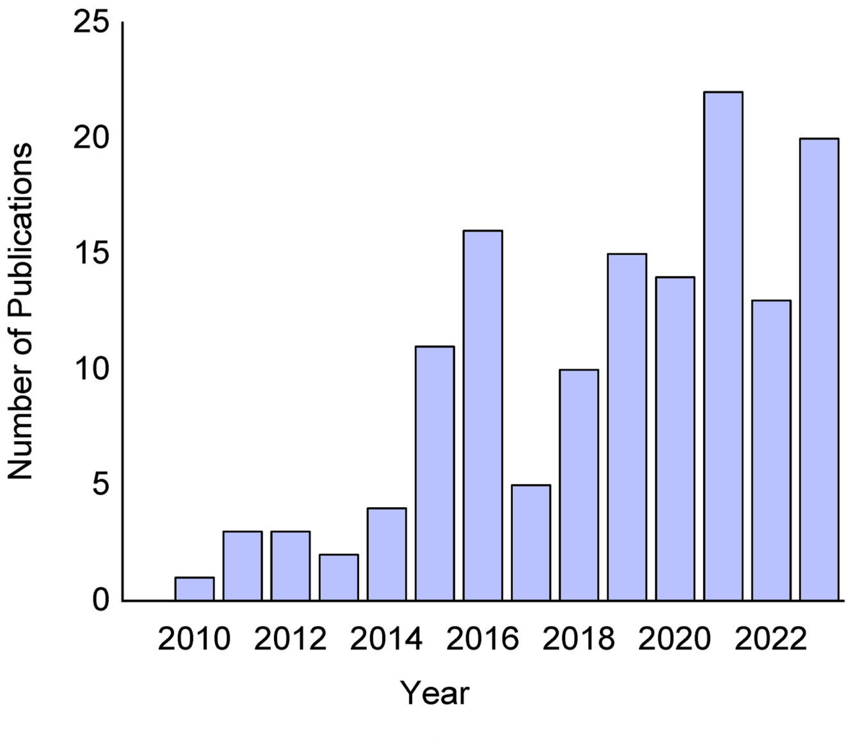

b

(caption on next page)

Fig. 7. a. keyword co-occurrence map showing the most frequently investigated topics using VOS viewer; b. The number of publications covering the role of biochar in the plant disease management.

Fusarium is a common plant pathogen and also known to produce mycotoxin in stored plant products [25]. Elmer [66] observed that incorporation of hardwood biochar led to the increased antagonist (*Pseudomonas* or arbuscular mycorrhizal fungi) population against *F. proliferatum* and *F. oxysporum* f. sp. *asparagi* inciting crown rot and root rot of asparagus. Biochar also induced resistance against foliar plant pathogens such as *Botrytis cinerea,* which is a fungal plant pathogen with broad host ranges by the activation of systemic defenses [6,8]. Alterations in microbial community in rhizosphere in addition with rice husk biochar reduced *F. solani* and *Ilyonectria destructans* infection in *Panax ginseng* plants [96].

In case of the bacterial pathogens of plants, the majority of the studies have focused on Ralstonia solanacearum, causing bacterial wilt and is one of the serious pathogens affecting vegetable production [97]. They have used biochar from different sources thus some differences were observed in case of the disease suppression. The main underlying mechanism was increased bacterial and actinomycetes populations resulted from the improved physicochemical properties of soil and reduced root colonization and swarming motility of the pathogens [86,35]. Burned log wood biochar have been found effective against coffee nematode, *Pratylenchus coffeae,* by reducing its population in soil [98,99]. Incorporation of oak wood at the rate of 1.2 % (w/v) controlled the *Meloidogyne graminicola*, (endoparasitic root-knot nematode) in rice agrosystems, this resulted from the activation of plant defense genes by the accumulation of hydrogen peroxide (H_2O_2) [7,100]. Foliar accumulation of jasmonic acid by using biochar at 10 % concentration (w/w) from dolomite, deciduous trees and molasses increased rice resistance against *Sojatella furcifera* [101]. Likewise, biochar produced from citrus wood was found effective against *Polyphagotarsonemus latus* (Acari: Tarsonemidae), a pest of economic importance by inducing of systemic resistance in pepper plants [69,102]. Thus biochar from different substrates proved their efficiency against the plant pathogens and pests (Fig. 6, Table 4).

6. Future research directions and conclusions

With the negative impacts of chemical pesticides on the management of plant diseases as well as environment and emphasis on the minimizing the use of chemicals for managing plant diseases, biochar application gives a ray of hope as a sustainable disease management strategy. At the same time, the central aspect relating to the use of biochar for the disease control was addressed in a superficial manner in the past reviews (Fig. 7(a and b)). Therefore, the results from the literature reflect the need for further studies on the utilization of biochar in plant disease management with great scopes in the future.

a) Biochar from different substrates may have different mechanisms and insights into these mechanisms which can be very helpful in better utilization of different substrate biochars in different pathosystems.
b) Efforts should be made to comprehend the interaction of biochar with the host plants in promoting plant growth and inducing disease resistance. Very few studies are there based on molecular interactions, therefore further research needs to be carried out in terms of the activation of plant defense genes against pathogens in different host pathosystems.
c) Increased populations of some specific beneficial groups of microbes and inhibition of pathogenic microbes by biochar also need our attention.
d) There is a need for standardization of the doses of biochar as some of the dosages might have a negative impact on plant growth and disease suppression. Also, factors such as the types of substrate used, pyrolysis temperatures, and pH of biochar must be considered to obtain the benefits from its use. Knowledge about the compatibility of biochar with biocontrol agents and its synergistic and antagonistic effects will help us in better management of plant diseases.

Biochar utilization in plant disease management does not require much extra effort as its incorporation can be an additional cultural practice in crop production. It also provides socio-economic benefits as it can be easily produced from locally available agricultural wastes. Biochar incorporation has been found to be beneficial in minimizing the disease incidence for soil-borne and foliar plant pathogens. Studies have shown its effectiveness against nematodes [103] and insect pests using different mechanisms, indicating its further use in plant disease management. More studies need to be carried out to explore the exact mechanisms involved and dose standardization, which will help to understand the negative impacts of biochar incorporation. Very few studies have focused on the molecular mechanisms involved in the induction of disease resistance in plants by the use of biochar, thus more emphasis should be given to exploring the molecular aspect of biochar interaction with plant and soil microbes.

Consent for publication

All the authors read and agreed to publish this article.

Data availability statement

No data was used for the research described in the article.

Ethical compliance

We have meticulously followed the Guide for Authors to prepare this manuscript, ensuring compliance with the Ethics in Publishing Policy outlined in the Guide for Authors.

CRediT authorship contribution statement

Bhagyashree Bhatt: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Satish Kumar Gupta:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Data curation. **Santanu Mukherjee:** Writing – original draft, Supervision, Funding acquisition, Data curation, Conceptualization. **Ravinder Kumar:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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