



Cite this: *Environ. Sci.: Adv.*, 2023, 2, 1042

## Biochar implications in cleaner agricultural production and environmental sustainability

Subhash Babu,<sup>a</sup> Raghavendra Singh,<sup>b</sup> Sanjeev Kumar,<sup>c</sup> Sanjay Singh Rathore,<sup>\*a</sup> Devideen Yadav,<sup>d</sup> Sanjay Kumar Yadav,<sup>e</sup> Vivek Yadav,<sup>f</sup> Meraj Alam Ansari,<sup>g</sup> Anup Das,<sup>h</sup> Gandhamanagenahalli Adireddy Rajanna,<sup>i</sup> Owais Ali Wani,<sup>j</sup> Rishi Raj,<sup>a</sup> Dinesh Kumar Yadav<sup>k</sup> and Vinod Kumar Singh<sup>l</sup>

Achieving food security while mitigating climate change is the foremost challenge for researchers and policy planners globally. Thus, dual objective approaches/techniques need to be developed, which can potentially increase food production with zero/negative greenhouse gas (GHG) emissions. The global agricultural production system generates a huge amount of bio-waste, which threatens agricultural and environmental sustainability. However, conversion of agricultural waste into biochar can potentially address the food insecurity and climate change challenges concurrently. Biochar production and utilization is proposed as an innovative solution for achieving the Sustainable Development Goals (SDGs), such as zero hunger, poverty, and climate change mitigation, by enhancing farm productivity and reducing/offsetting anthropogenic CO<sub>2</sub> emission. Globally, biochar has the potential to increase crop productivity by 11% and reduces 12% human-induced GHG emissions annually. Biochar can potentially sequester ~0.7–1.8 Gt CO<sub>2</sub> (C eq.) y<sup>-1</sup> in the soil system. Furthermore, biochar application improves soil health, which facilitates the plant growth and crop productivity. Biochar application can alter the plant physiology and makes the plant system more tolerant against biotic and abiotic stresses. Biochar is also an excellent *in situ*-sorber for soil contaminants. However, some inconsistent reports about the utility of biochar are also available. Hence, an in-depth understanding about the uses and impact of biochar on the food production, soil health, and climate change mitigation is highly warranted, for framing the research priorities and policies for developing cleaner and sustainable agricultural production systems.

Received 21st December 2022  
Accepted 1st June 2023

DOI: 10.1039/d2va00324d

rsc.li/esadvances

### Environmental significance

Biochar production and utilization is proposed as an innovative solution for climate change mitigation by reducing/offsetting anthropogenic CO<sub>2</sub> emissions. Biochar is an excellent carbon neutral material; one tonne biochar production can permanently remove ~2.68 Mg CO<sub>2</sub>eq. from the atmosphere. Biochar curtails CO<sub>2</sub> emissions through fossil fuel replacement by the production of syngas and bio-oil, in addition to its application and long-term C storage in the soil. Furthermore, biochar application decreases soil bulk density ( $\rho_b$ ) and improves soil productive capacity. Carbon sequestration *via* biochar production is technically feasible and can be economically viable, approach to address the climate change, and land degradation issues especially with the current development of the carbon sink economy.

## 1. Introduction

The United Nations has setup 17 Sustainable Development Goals (SDGs) and 269 targets for 2030, out of which 10 SDGs are

directly linked with agriculture. SDGs 1 and 2 are related to “no poverty” and “zero hunger” as crucial for sustainable agriculture. Globally, ~811 million people suffer from hunger, and one in ten people suffers from chronic hunger.<sup>1</sup> This indicates that

<sup>a</sup>Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, 110012, India. E-mail: subhiari@gmail.com; Tel: +91-8900527308

<sup>b</sup>ICAR-Indian Institute of Pulses Research, Kanpur, Uttar Pradesh, 208017, India

<sup>c</sup>Sardar Vallabhbhai Patel University of Agriculture Meerut, Uttar Pradesh 250110, India

<sup>d</sup>ICAR-Indian Institute of Soil & Water Conservation, Dehradun, UK, 248195, India

<sup>e</sup>ICAR-Indian Institute of Sugarcane Research, Lucknow, Uttar Pradesh, 226002, India

<sup>f</sup>State Key Laboratory of Crop Stress Biology in Arid Areas, College of Horticulture, Northwest A & F University, Yangling 712100, China

<sup>g</sup>ICAR-Indian Institute of Farming Systems Research Modipuram, UP, 250110, India

<sup>h</sup>ICAR Research Complex for NEH Region, Tripura Centre, Tripura, 799210, India

<sup>i</sup>ICAR-Directorate of Groundnut Research, Regional Station, Anantapur, Andhra Pradesh, 51500, India

<sup>j</sup>Department of Soil Science & Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences & Technology, Kashmir, 190025, India

<sup>k</sup>ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh 462038, India

<sup>l</sup>ICAR-Central Research Institute for Dryland Agriculture, Hyderabad, Telangana, 500059, India



the world population is at a critical juncture, and needs technological attention and legislative support to ensure food security. Hence, to meet global food security while harmonizing the dwindling resources and fluctuating climate, agricultural production systems must be more productive and adaptable.<sup>2</sup>

Globally, anthropogenic activities added ~16 Pg C (1 Pg = 1 billion metric tonnes) to the environment annually, which corresponds to 24% net primary productivity.<sup>3,4</sup> Human-induced CO<sub>2</sub> emission increases by >3% per annum, which puts Earth on an irreversible climate change track.<sup>5</sup> Agricultural production systems contribute about 10–14% of the total GHG emissions,<sup>6</sup> which is likely to be increased to 50% by 2030.<sup>7</sup> Hence, the implementation of an ambitious climate mitigation program is highly desirable to achieve environmental sustainability. To control the rising temperature and total GHG emission, future agricultural production systems must be carbon neutral or negative.<sup>8</sup> The initiative of “4 per 1000” was launched by the United Nations Framework Convention on Climate Change<sup>9</sup> with the focus on soils for food security and the environment to combat the global GHG emission issues (<https://www.4p1000.org>). It aims to increase the annual soil organic carbon (SOC) sequestration of global agricultural lands to 2–3 Gt (Giga tonnes) carbon (C) in the upper 100 cm soil, which can effectively offset 20–35% of the global C emission. Hence, carbon negative high food-producing technologies must be adopted to address the multiple challenges.

Agricultural-derived biomass is a readily available renewable energy and nutrient source. However, transportation cost increases the price of biomass energy. Hence, for energy generation from biomass, cost effective and robust technologies are highly warranted.<sup>10</sup> Unscientific biomass management practices like field burning and open dumping causes environmental and human health issues.<sup>11</sup> Field fire impairs the air quality, posing health hazards, like skin/eyes irritation, asthma, bronchitis, emphysema, and cancer.<sup>12</sup> Modern technology-lead biomass valorization can potentially increase the farmer's income, energy security and environmental and soil quality.<sup>13,14</sup> Biomass energy can be cost-effective energy sources in rural areas. Hence, adequate incentive facilities are warranted to encourage the use of low-cost biomass energy.<sup>15,16</sup> Biochar applications in agricultural production systems are attaining immense importance due to its economic and environmental benefits.<sup>17</sup> Biochar can potentially be considered an innovative tool to address the food insecurity and environmental issues by improving soil health,<sup>18</sup> crop productivity,<sup>19</sup> curtailing GHG emissions<sup>20</sup> and water pollution.<sup>21</sup> The biochar production by thermal decomposition at elevated temperature in the absence of oxygen (pyrolysis) has proved to be an alternative strategy for agri-waste management.<sup>22,23</sup> Additionally, modern technology-lead agri-waste-pyrolysis yielded syngas, bio-oil, and biochar.<sup>24</sup> Traditional biochar production methods emit more methane (CH<sub>4</sub>), N<sub>2</sub>O, soot, or volatile organic compounds, which causes excess C payback time and is also hazardous to health.<sup>25,26</sup> Utilizing biomasses as biochar *via* pyrolysis and hydrothermal carbonation reported superiority in terms of GHG reduction over traditional methods.<sup>21</sup> Biochar is a solid C-rich pyrolyzed (250 and 900 °C) biomass material produced under oxygen-free

condition.<sup>17</sup> It is a superior C carbon source and has better nutrient retention capacity over other C sources.<sup>27</sup>

Biochar helps in two ways to reduce the atmospheric CO<sub>2</sub>: (1) by its production and (2) by sequestering atmospheric CO<sub>2</sub> in soil.<sup>28–30</sup> It is possible to offset up to 1.8 Pg CO<sub>2</sub>eq. (Penta gram carbon dioxide equivalent) per annum through biochar, compared to 15.4 Pg CO<sub>2</sub>eq. emitted annually.<sup>4</sup> However, inconsistent reports are also available on the GHG emission mitigation potential of biochar. For instance, biochar-amended soil had higher CO<sub>2</sub> and N<sub>2</sub>O emissions due to the carbonaceous nature and quality of biochar feedstock.<sup>31</sup> Another study suggested that biochar application did not have any significant effect on CO<sub>2</sub> emission from paddy and chestnut soils in China. This was mainly due to the soil and feed stock attributes.<sup>32</sup> However, biochar application at the rate of 30 Mg ha<sup>-1</sup> reduces CO<sub>2</sub> emission by 31.5% and 7.2% in forest and agricultural soils, respectively.<sup>33</sup> Long-term biochar application decreases CH<sub>4</sub> emission.<sup>34</sup> However, short-term applications induced CH<sub>4</sub>.<sup>35</sup> Biochar application induced CO<sub>2</sub> emission by 22.14% and decreased N<sub>2</sub>O emission by 30–38%, and did not influence the CH<sub>4</sub> emission.<sup>36,37</sup> The variable effect of biochar on GHG emission from the soil might be attributed to variations in the soil, feedstock, climate types, and measurement methods of GHG emission, application rate, and pyrolysis temperature.<sup>38,39</sup> Overall, soil-applied biochar improves agricultural and environmental sustainability.<sup>40</sup>

Biochar application decreases soil bulk density ( $\rho_b$ ), and enhances soil productive capacity and plant growth.<sup>41,42</sup> Biochar application modulates the soil health, resulting in higher crop yields.<sup>43–46</sup> Liu *et al.* (2013)<sup>47</sup> screened the 116 published studies from 21 countries, and summarized that biochar application increased crop productivity by 11%. But biochar application rate must be optimized as at higher doses of biochar application had the detrimental effect on plant growth.<sup>48</sup> Abukari *et al.* (2021) showed that application of biochar at the rate of 30 Mg ha<sup>-1</sup> enhanced legume productivity by 30%, vegetable yield by 29%, and cereal yield by 7–8% over no biochar.<sup>49</sup> The addition of recalcitrant C in the soil enhances the soil-water-nutrient holding capacity, which promotes crop growth.<sup>50</sup> An increased level of non-labile C in the total SOC is important to mitigate climate change and restore the fertility of the degraded soil.<sup>50–52</sup> Continuous biochar application with the rate of 11.25 Mg ha<sup>-1</sup> in both crops under a maize-wheat system for five years fixes 182.3 Mg ha<sup>-1</sup> CO<sub>2</sub> over the control plot.<sup>53</sup> Short-term biochar application at the rate of 7.5 Mg ha<sup>-1</sup> also improves SOC by 39% in maize-wheat systems after two cropping cycles. Owing to the priming effect, short-term biochar application increases the labile C pool. However, long-term biochar application suppressed the SOC mineralization.<sup>54,55</sup> Still, the biochar interaction with SOC changes over time, and the negative priming effect is nullified after 3–5 years of application.<sup>28,53</sup> One tonne SOC increment in cropland increases crop productivity by 50% and curtails atmospheric CO<sub>2</sub> by 5–15%.<sup>28,53</sup> Besides that, biochar also has the potential to suppress the plant pathogen by altering the soil microbiome structure.<sup>46,56</sup> Biochar reduces runoff losses, nutrients erosion, and soil pollutant loads,<sup>52</sup> and improves carbon sequestration. Overall, biochar is a potential



solution to address the global food, energy, and environmental challenges.<sup>57–59</sup> However, this information needs to be brought together in a comprehensive and analytical way, which may be more useful to the researchers and policy planners. The present review is an effort to provide a comprehensive assessment and insight of the different mechanisms involved in biochar production, its application and effect on food production, and environmental sustainability, which may be helpful to formulate the biochar-based policy for sustainable and clean agricultural production.

## 2. Agricultural waste and biochar production

Conversion of forest land to biomass producing crops or forest felling for feedstock is not a sustainable practice as land-use changes lose  $\sim 22 \text{ Mg C ha}^{-1}$ , and will result in a carbon payback time of  $\sim 10$  years. Hence, forest trees must not be cut for the cultivation of biomass-producing crops. Furthermore, productive land should not be brought under the cultivation of biomass crops, as it will compromise food security. On the other hand, crop residue management is challenging to farmers as it is a labor-consuming and costly affair. The absence of site-specific residue management technologies further makes it tedious.<sup>11</sup> Crop residue, poultry litter, dairy manure, sugarcane trash, cotton trash green wastage of various crops, animal manures, and other forests' unused wood material are potential substrates for biochar production.<sup>60,61</sup> Weed biomass can be pyrolyzed in an oxygen-free condition to produce biochar. Lignin-rich agro-waste is more efficient for biochar production, as it yielded more char as compared to cellulose and hemicellulose-rich materials. Pyrolysis temperature also plays a key role in biochar production. Lignin-rich biomass pyrolyzed at a wider temperature range (160–900 °C) while hemicellulose and cellulose-rich residues were pyrolyzed at a temperature of 220–315 °C and 315–400 °C, respectively. Low-temperature/high-pressure (hydrothermal carbonization) and slow pyrolysis are two effective methods of biochar production from different feedstock. Biochar properties mainly depend on the type of feedstock and pyrolysis temperatures. Biochar produced at a higher temperature ( $>550$  °C) has more surface area and sorption capacity, as compared to those produced at a lower temperature. Pyrolysis completely avoided the immediate decay of residue inputs, and halted the  $\text{CO}_2$  and  $\text{CH}_4$  emissions.

Pyrolysis converts cellulosic carbons into more stable aromatic carbons, which can subsequently be customized for diverse agricultural uses.<sup>62</sup> Biochar production from crop biomass is performed by the dry pyrolysis process in the absence of oxygen at high temperatures.<sup>41</sup> Thermochemical conversion techniques, including gasification, pyrolysis, hydrothermal carbonization, and torrefaction, are the most commonly used practices for biochar production.<sup>47,63</sup> Pyrolysis is the most commonly used technique for biochar production.<sup>64</sup> The process of conversion of crop residue into final biochar production depends on the nature of the crop, stage of crop residue, size, shape, and composition concerning organic

material, *viz.*, cellulose, hemicellulose, lignin, *etc.*<sup>65,66</sup> Biochar production at higher temperatures is reported to have a higher surface area and pore volume than those produced at a lower temperature.<sup>67</sup> The wet pyrolysis process of biochar production is associated with the hydrothermal carbonization (HTC) process, in which biochar is produced at low temperature and pressure in an aqueous solution. This process is more useful in residues containing more lignin, cellulose, and hemicellulose.<sup>68,69</sup> The temperature requirement in this process for converting biomass into biochar is comparatively lower than pyrolysis.<sup>70</sup> Biochar produced through HTC has less surface area and is not ideal for agricultural use as compared to biochar produced by pyrolysis.<sup>71</sup> However, the HTC is an energy-efficient process and operates at lower temperatures with higher biochar recovery.<sup>72</sup> Biochar produced through pyrolysis has higher surface areas than that produced through hydrothermal carbonation. Liquid biofuels and syngas, such as  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ ,  $\text{CO}$ ,  $\text{CH}_4$ , and  $\text{H}_2$ , are the co-biochar products resulting from pyrolysis and hydrothermal carbonation.<sup>71,73–75</sup>

## 3. Effect of biochar on crop productivity

Biochar application in agriculture improves crop yield by altering soil properties and enhancing the SOC content.<sup>76,77</sup> Improvement in soil quality and tolerance in plants against biotic and abiotic stresses due to biochar application is responsible for improvements in agricultural production.<sup>78</sup> The increased crop yields from biochar application are linked to improved soil quality.<sup>79</sup> Biochar improves carbon sequestration, soil quality, and crop growth significantly.<sup>80</sup> Biochar application in nutrient-deficient and degraded soils increases agricultural productivity.<sup>81</sup> Application of eucalyptus-based biochar at the rate of  $50 \text{ Mg ha}^{-1}$  increases maize productivity by 48–50% in acidic soils of humid tropical condition.<sup>82</sup> Yield improvements in different crops due to biochar application under various ecologies were reported by several researchers (Table 1). Biochar improves soil structure and carbon content, as well as nutrient availability, and microbial population, which improve crop yields.<sup>83</sup> The delayed production of an organic layer on the biochar surface during aging helps to retain nutrients, and may account for the higher yield.<sup>84,85</sup> Biochar increases soil structure, fertility, nutrients use efficiency (NUE), and crop yields.<sup>86,87</sup> Biochar application enhances agricultural productivity *via* improvement soil health, decrease in crop biotic and abiotic stresses, and modulation of plant physiological processes.

## 4. Effect of biochar on stress tolerance in crops

Biochar has various benefits in agriculture, including the alleviation of various kinds of abiotic stress, such as salt and drought.<sup>88,89</sup> Biochar application at a rate of  $20 \text{ Mg ha}^{-1}$  increased nutrient uptake and chlorophyll concentrations in pumpkin plants.<sup>90</sup> Biochar improved tomato leaf water usage efficiency, stomatal conductance, chlorophyll concentration,





Table 1 Effect of biochar on the productivity of different crops under various ecologies

Location	Crop	The material used and dose	Yield enhancement	Reference
<b>Cereals</b>				
Hunan province, China	Rice	Rice husk biochar (20 t ha <sup>-1</sup> )	6% economic yield enhancement over control	167
São Paulo, Brazil	Wheat	Sugarcane straw biochar (1.9%)	27% and 16%, improvement in grain and total biomass yields, respectively over control	168
Nanjing, China	Maize	Straw biochar (20 Mg ha <sup>-1</sup> )	The grain yield was 2.91–19.4% higher over urea application at 200 kg ha <sup>-1</sup>	33
Sumatra, Indonesia	Maize	Cacao shell biochar (15 Mg ha <sup>-1</sup> )	Cacao shell biochar recorded 8.6 times higher grain yield compared to the same dose of rice husk biochar	169
Northern and Upper East Ghana		Rice husk and sorghum (2 Mg ha <sup>-1</sup> )	27% and 16%, increment in grain and shoot biomass yield over control, respectively	170
<b>Pulses</b>				
Kumasi, Ghana	Cowpea	Corn cob feedstock (5 Mg ha <sup>-1</sup> )	Increased seed yield by 36% over control	78
Lake Victoria basin, Kenya	Soybean	<i>Accasia</i> spp. wood biochar (100 Mg ha <sup>-1</sup> )	Increased seed yield by 0.43 t ha <sup>-1</sup> over control	171
Bule wereda, Southern Ethiopia	Garden pea	<i>Lantana camara</i> biochar (12 Mg ha <sup>-1</sup> )	54% higher yield compared to corn cob biochar of the same rate of application	172
Montes Claros, Brazil	French bean	Biochar from sawdust filter (7.12%)	448% higher per plant seed yield (18.6 g) compared to control (3.39 g)	173
Karnal, India	Green gram	Sugarcane bagasse biochar (SBB) (4.5 g kg <sup>-1</sup> soil)	Enhanced pod yield by 15% over 50% RDF alone	116
<b>Oilseeds</b>				
Rasuwa, Nepal	Mustard	<i>Eupatorium adenophorum</i> shrub biochar (40 Mg ha <sup>-1</sup> )	Increased grain yield by 134% compared to control	174
Riyadh, Saudi Arabia	Sunflower	Rice straw biochar + foliar silicon	Increased seed yield by 27% over control	175
North Queensland, Australia	Groundnut	Willow wood biochar (10 Mg ha <sup>-1</sup> )	Increased seed yield by 21% over fertilizer alone	94
Dhaka, Bangladesh	Sesamum	Biochar (6 Mg ha <sup>-1</sup> )	18.8% higher yield over control	176
<b>Vegetables</b>				
Geraldton, Western Australia	Cucumber	Poultry litter biochar (PLB) (13 Mg ha <sup>-1</sup> )	Application of PLB + poultry manure (9 Mg ha <sup>-1</sup> ) + nitrophos (5 Mg ha <sup>-1</sup> ) increased cucumber yield by 300% over PLB (1 Mg ha <sup>-1</sup> ) + poultry manure (2 Mg ha <sup>-1</sup> ) + nitrophos (13 Mg ha <sup>-1</sup> )	177
Dhading, Nepal	Pumpkin	<i>Eupatorium adenophorum</i> biomass loaded with urine	300% higher pumpkin yield over urine application alone	178
Hohai, China	Tomato	Wheat straw biochar (8%)	Increased ~50% fruit yield over control	179
Ondo State, Nigeria	Cocoyam	Hardwood biochar (20 t ha <sup>-1</sup> )	Increased economic yield by 9% over hardwood biochar (10 Mg ha <sup>-1</sup> )	180

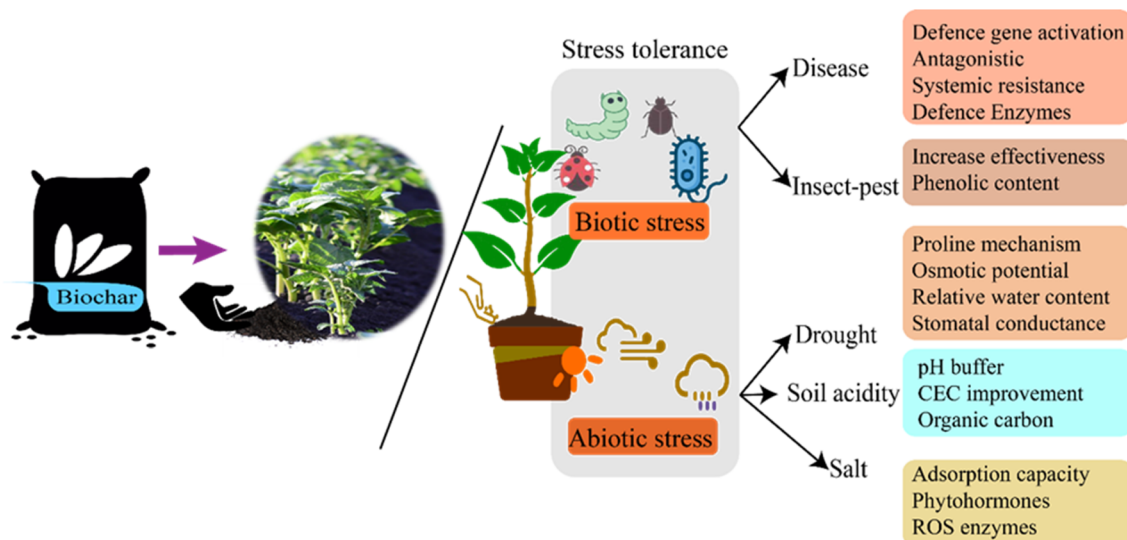


Fig. 1 Biochar modulates soil condition and plant physiology.

photosynthesis, and relative water content in dry conditions.<sup>91</sup> The high adsorption capacity of salt makes biochar an excellent ameliorant for the reclamation of the degraded salt-affected region.<sup>92</sup> Biochar has a high salt adsorption capability due to its vast surface area and cation exchange capacity. As a result, biochar can be used to reduce plant sodium intake, and thereby mitigate the negative effects of salt stress. Biochar application increases agricultural output in acidic soils by allowing plants to tolerate salt.<sup>82</sup> Biochar facilitates the absorption of an array of soil contaminants owing to its high surface area, porosity, and adsorption ability.<sup>93</sup> The plants' physiological and biochemical properties were altered due to biochar application, which helps to combat the multiple stresses.<sup>94</sup> Biochar modulates the different plant physiological and soil properties, which helps the plants develop the resistance mechanism against biotic and abiotic stresses (Fig. 1). Biochar application increases plant photosynthesis, chlorophyll content, and transpiration rate in different crops under various growing media.<sup>87,94</sup> It also enhances the gas exchange ability of crop leaves and reduces oxidative stress.<sup>95</sup> Differential crop responses to various kinds of biochar are reported by various research across the eco-regions of the world (Table 2). Biochar has been shown to boost plant performance, and lessen the severity of both air and soil-borne pathogen when used as a soil amendment. Biochar has the potential to have both direct and indirect antagonistic effects on pathogens, such as generating systemic resistance in plants, as pathogens and biochar both reside in the soil.<sup>96</sup> The biochar application geared the acquired and induced systemic resistance pathways, giving the soil a broad-spectrum disease-controlling potential.<sup>97</sup> Biochar generated from green waste and wood waste was used to reduce early blight growth in tomatoes.<sup>91</sup> Biochar has a positive impact on favorable microorganisms that actively defend against diseases causing soil pathogens by producing complex chemicals. Some plant-based products with insecticidal qualities, such as neem cake, can be used to make biochar, and their effect on insect-pest tolerance in plants can be studied. The nature of raw

material and the application rate of biochar influence the management of insect pests and nematodes.<sup>98</sup> Moreover, plant tolerance to biotic and abiotic stresses due to biochar is linked with improvements in beneficial soil microorganisms in the soil, soil amelioration, modulation in plant biochemical constituents, and morpho-physiological characteristics.

## 5. Effect of biochar on soil health

Most tropical and subtropical soils suffer from severe soil fertility depletion due to excess nutrient mining and soil organic matter reduction, resulting in poor agricultural productivity.<sup>99,100</sup> Hence, the application of an innovative product like biochar is highly warranted to address the complex issue of soil quality and agricultural productivity.<sup>2,101</sup> Biochar addition modulates the soil biology, chemistry, and physical properties.<sup>10</sup> During the last two decades, even though biochar as an amendment has been widely researched, the impact of its application was mixed due to the complex nature of biochar, soils, and crops.<sup>2,102</sup> The effects of the biochar is variable; it works efficiently in acidic, but deteriorated coarse textures soils.<sup>103</sup> The optimum application of biochar has the potential to improve soil conditions and reduce GHG emissions, and also immobilize toxic metals and other organic pollutants.<sup>86,101</sup> However, contrary to these, some adverse effects of biochar at higher doses have also been documented.<sup>104</sup>

### 5.1 Effect of biochar on soil physical properties

Biochar application has shown a differential effect on soil physical properties like bulk density ( $\rho_b$ ), porosity, hydraulic conductivity, and soil color under diverse soil and climate types.<sup>104,105</sup> The  $\rho_b$  is an important physical soil parameter that controls nutrient availability, porosity, and compactness of the soil. Biochar is a porous material having less  $\rho_b$  (0.3 to 0.6 Mg m<sup>-3</sup>) than the common agricultural soils. The temperature during pyrolysis and the nature of the feedstock used for





Table 2 The effects of biochar on crop stress tolerance

Location	Crop	Biochar application	Type of stress tolerance	References
<b>Cereals</b>				
Changsha, China	Rice	Rapeseed stover biochar 40 g kg <sup>-1</sup> soil	Reduced heat stress by altering root zone soil and regulating heat shock protein in roots and leaves	167
Bahawalpur, Pakistan	Wheat	Wheat straw biochar (37.18 g kg <sup>-1</sup> soil)	Drought stress resistance by increasing water use efficiency by 19.30% over control	181
Rawalpindi, Pakistan		Biochar (2%)	Mitigating salt stress by decreasing proline and soluble sugar contents by 51% and 27%, respectively, and increasing leaf water by 16% and osmotic potentials by 10%	182
Matatirha, Nepal	Maize	<i>Eupatorium adenophorum</i> biochar (2%)	Increased nutrient availability in acidic soils in nutrient-stressed condition	174
El-Gharbia, Egypt	Barley	Biochar (20 Mg ha <sup>-1</sup> )	Reduced electrolyte leakage, lipid peroxidation, and proline levels reduce drought stress	183
<b>Pulses</b>				
Henan, China	Soybean	Wheat straw biochar (10 g kg <sup>-1</sup> soil)	Significantly increased water use efficiency by 27.5% over control	41
Gazipur, Bangladesh		Poultry litter biochar (50 Mg ha <sup>-1</sup> )	Enhanced drought resistance due to increase in water content in plants and reduction in chlorophyll breakdown in leaves	184
Gazipur, Bangladesh	Pea	Sawdust and rice husk biochar	Reduces oxidative and osmotic stress	95
Germany	Lupin	Biochar char from maize and wood	Inoculated bacteria <i>Pseudomonas putida</i> and <i>Stenotrophomonas pavanii</i> survived better in the rhizosphere	185
<b>Vegetables</b>				
Rishon Lezion, Israel	Tomato	Pepper plant waste biochar (3%)	Enhanced resistance against <i>Fusarium oxysporum</i> f. sp. <i>radicis lycopersici</i>	96
Guangdong, China		Peanut shell and wheat straw biochar (2%) of each	The bacterial wilt disease index was reduced by 28.6% and 65.7%, respectively	47
Lubbock, United States	Brinjal	Oak and pine biochar (12.5 kg)	Increased stomatal conductance and photosynthetic rate, as well as reduced leaf temperature and electrolyte leakage, to reduce salinity stress in plants	186
New Delhi, India	Spinach	Wood biochar	Increased chlorophyll, carotenoid, and relative water of the leaf	187
<b>Forage</b>				
Yangzhou, China	Forage sorghum	Wheat straw biochar (2.5%)	Mitigate the negative effects of salinity on antioxidant enzymes	188
Amhara Region, Ethiopia	Teff	Eucalyptus biochar (12 Mg ha <sup>-1</sup> )	Lowering exchangeable soil acidity reduced the negative effects of soil acidity on plants	189
<b>Others</b>				
Multan, Pakistan	Mint	Fruit and vegetable waste and compost biochar (1:1)	The leaves' lead uptake was reduced by 13.5% over non-treated plants	190
Merelbeke, Belgium	Strawberry	Biochar (3%)	On both leaves and fruits, there is a decreased sensitivity to the fungal disease <i>Botrytis cinerea</i>	191

biochar production influence the  $\rho_b$  of the biochar. Hence, the reduction in  $\rho_b$  is entirely driven by soil condition, the dose, and the properties of biochar applied. Application of woodchip biochar decreases the  $\rho_b$  of planosol by 5.1% over the control.<sup>2</sup> The response of the biochar on  $\rho_b$  is more effective in light soil than in heavy soils.<sup>106,107</sup> Biochar addition promotes soil fungal growth, as well as microbial activities, resulting in soil agglomeration, along with profuse root development, subsequently reducing  $\rho_b$ .<sup>108</sup> The positive effect of biochar on soil porosity and hydraulic conductivity have also been reported by many researchers.<sup>66,109</sup> The aggregate formation and stability index of silty loam, sandy loam, silty clay, and clay soils had been improved with biochar application,<sup>110</sup> while no change was reported in sandy loam soil.<sup>34</sup> The biochar application can change the size and distribution of soil pores to a relatively smaller pore size, which positively impacts crop growth and development.<sup>111</sup> Biochar application reduces the  $\rho_b$ , which alters soil porosity and nutrient availability, resulting in higher above and below-ground biomass.<sup>112</sup> Hydraulic conductivity of the soil is crucial for available soil water movement within the soil, and also for the water holding capacity. Biochar application had more impact on sandy soil as compared to clay soil.<sup>2,113</sup> The feedstock used for biochar preparations also had a varied response for WHC; woody feedstock had higher WHC than lignocellulosic and herbaceous feedstock due to the greater pore space.<sup>114</sup> In sandy soil, the application of biochar significantly reduced the saturated hydraulic conductivity due to more water retention in a single layer.<sup>115</sup>

## 5.2 Effect of biochar on soil chemical properties

The soil chemical properties are very crucial sustainability indicators of crop production, which is entirely dependent on soil nutrient status and crop acquisition pattern.<sup>116</sup> The post-green revolution era created a multi-nutrient deficiency in soil due to the global continuous overuse of straight fertilizers.<sup>117</sup> A healthy soil environment plays a pivotal role not only in good plant growth, but also in higher productivity.<sup>6</sup> Hence, innovative nutrient management options, *viz.*, application of biochar produced from different feedstocks over a long period to the soil can increase the soil nutrient effectiveness and their use efficiency compared to the control.<sup>105</sup> Over a long term (>5 years), biochar additions enhanced the soil organic matter (46%), which is the basis for the nutrients mineralization process.<sup>118</sup> The necessary mineral nutrients contained in the biochar keep helping the plants by providing continuous flow from soil to the plants.<sup>105</sup> Furthermore, biochar application increases the cation exchange capacity, which resulted in improved K, Ca, Mg, Zn, Mn, and Cu availability. All such positive effects of biochar have been reported to enhance plant growth and crop yield.<sup>119</sup> All these plant nutrients are pH-dependent, which is very much affected by the application of biochar as its nature is alkaline (pH 6–12).<sup>100</sup> Biochar application reduces the concentration of  $Al^{3+}$  and  $H^+$  in the ions in acidic soils.<sup>120</sup>

A large variation in biochar applications ranging from 10 to 150 Mg ha<sup>-1</sup> in soil has been reported in many studies. However, the economic feasibility was mostly observed in the

range between 20 and 30 Mg ha<sup>-1</sup>.<sup>32</sup> In many studies, the biochar application increased the C, N, and P content in the soils, and promoted soil aggregation and stimulation of microorganism activities.<sup>18,121,122</sup> The improvement of soil chemical properties was witnessed with the increase in organic matter. Furthermore, similar positive results of improvement of electrical conductivity and pH were observed in contaminated soil with the application of biochar.<sup>123</sup> The availability of essential plant nutrients is largely dependent on the soil pH. The nutrient supplying ability of biochar applied to the soil is mainly dependent on the feedstock used for its preparation. The increased availability of the nutrient with the addition of biochar is mainly due to changes in circulation, retention, and conversion to plant-available form.<sup>124</sup> The higher CEC of biochar adsorbed  $NH_4^+$  on the surface and was reused. Therefore, N utilization and its loss were minimized by the adsorption of  $NH_3$ .<sup>125</sup> The soil microbial nitrogen content increased with increasing biochar addition into the soil as microorganisms absorbed  $NO_3^-$  N in  $R-NH_2$ , which is easily adsorbed by biochar and soil minerals. Biochar can detoxify heavy metals in contaminated soil,<sup>126</sup> as well as other sources of toxic effluents.<sup>101</sup> The biochar with a large specific surface area and diverse negatively charged anions suitably immobilized the inorganic pollutants in soil.<sup>127</sup> The mobility of heavy metals in soil is reduced due to adsorption, ion exchange, and stabilization with the formation of organometallic compounds.<sup>128</sup> The combined application of biochar along with compost help in the immobilization of toxic materials in heavy metal polluted soils.<sup>123,129</sup> Rodríguez-Vila *et al.* (2016)<sup>124</sup> reported a reduced concentration of Al, Cu, Fe, Mn, Ni, Zn, Co, and Mg in soil water and increased potential immobilization of toxic elements, thereby reducing the contamination risk with oak wood biochar. The combined application of biochar with compost is reported to reduce potentially toxic metals, improve soil fertility, and thus have a synergistic effect on soil remediation, as well as higher crop productivity.<sup>18,130</sup> Maize biochar-based fertilizer can be used as a remedial measure for cadmium (Cd)-polluted soil, as its presence caused rigorous health issues in humans *via* induction into the food chain.<sup>123</sup> Furthermore, due to the nutrients chelating properties, biochar application reduces the nutrient leaching in the soil system.<sup>10</sup>

## 5.3 Effect of biochar on soil biological health

The soil biological properties play a crucial role in nutrients mineralization, which is the basis for plant nutrients availability.<sup>129</sup> Soil microbial diversity is directly related to the soil's physicochemical properties.<sup>33</sup> The biochar itself, having a porous and aromatic structure with stretched surface, becomes a harbor for soil microbial organisms and provides nutrients for their multiplication.<sup>18,131</sup> Biochar is helpful in bacterial decomposition, as it contained decomposed C and N on its surface. The enhanced microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) contents have accompanied the corresponding decrease in dissolved organic C concentration, and have a stronger microbial diversity.<sup>132</sup> The biochar surface adsorbed the bacteria, making them less



susceptible to leaching, and thus increased the population of bacteria in the soil. The biochar application increased the nitrogen fixation capacity by increasing the number of N-fixing bacteria.<sup>133</sup> Biochar application significantly enhanced the soil MBC and MBN.<sup>126</sup> Biochar alters the soil enzymatic reaction; however, the intensity of the soil enzymatic alterations depends upon the feedstock nature from which biochar has been developed.<sup>134</sup> The addition of biochar developed from pine-woods and grass as feedstock has decreased the  $\beta$ -glucosidase and phosphate activities in soil.<sup>135</sup> In contrast, Oladele *et al.* (2019)<sup>19</sup> reported that the activities of alkaline phosphatase, urease, invertase, and catalase have been increased with the addition of rice husk biochar ( $12 \text{ Mg ha}^{-1}$ ).

## 6. Biochar for climate change mitigation

### 6.1 Carbon sequestration potential of biochar

The global carbon cycle is largely linked to climate change and  $\text{CO}_2$  emission from fossil fuel usage and land-use change.<sup>99</sup> Soil carbon sequestration is the trapping of  $\text{CO}_2$  from the atmosphere, and storing it in the soil in more stable forms.<sup>136,137</sup> As a climate change extenuation approach, carbon sequestration is a simple and robust technique to track national carbon accounting.<sup>138,139</sup> Furthermore, carbon sequestration facilitates the conversion of biomass into the recalcitrant soil C pool and lowers the  $\text{CO}_2$  levels in the atmosphere. Thus, the production of biochar from crop residue and its application into the soil have demonstrated a significant potential for carbon sequestration and extenuation of the harmful impacts of climate change.<sup>29,136</sup> Biochar is an excellent carbon neutral material. A total of  $2.879 \text{ Mg CO}_2\text{eq.}$  is embodied in a tonne of biochar (dry basis), and one tonne biochar production can permanently remove  $\sim 2.68 \text{ Mg CO}_2\text{eq.}$  from the atmosphere.<sup>140</sup> However, the carbon removal capacity of the biochar depends on the quality of the raw material and biochar production temperature. Conversion of one tonne agricultural residues into biochar removes  $\sim 0.92 \text{ Mg CO}_2\text{eq.}$  from the atmosphere,<sup>141</sup> while conversion of one tonne forestry residue sequesters  $2.74 \text{ Mg CO}_2\text{eq.}$ <sup>142</sup> Furthermore, it has been estimated that by 2050, the carbon removal potential of biochar will be about  $0.3\text{--}2 \text{ Gt CO}_2 \text{ y}^{-1}$ .<sup>143</sup> It has been predicted that the use of biochar can offset anthropogenic  $\text{CO}_2$  emissions by up to 12%.<sup>4</sup> Some studies reported that biochar can sequester carbon by up to  $2.27 \text{ Pg C y}^{-1}$  in the soil at the global level. Due to the inherently fixed carbon in the biomass materials, which would otherwise break down into GHG and remain buried in the soil for a longer time, biochar has the potential to avert climate change.

Biochar has been recognized as an important approach for climate change mitigation by sequestering  $\text{CO}_2$  in soils, and thereby reducing excess  $\text{CO}_2$  from the atmosphere.<sup>27</sup> As a result, it may be a viable alternative strategy for sequestering more  $\text{CO}_2$  from crop wastes than traditional agricultural practices, which result in rapid carbon mineralization and increased  $\text{CO}_2$  release into the atmosphere.<sup>144</sup> The carbon sequestration potential of biochar lies between  $0.7$  and  $1.8 \text{ Gt CO}_2\text{eq. y}^{-1}$ .<sup>51,145</sup> The

environmental stability of biochar-C is extremely high as compared to other C sources, which facilitate the changes of the short-term atmospheric C cycle to the long-term geological C cycle when applied to soil.<sup>146</sup> However, the C content of biochar mainly depends on the types of processing (heating temperature of pyrolysis) and types of feedstock used.<sup>145,147</sup> The C content of biochar tends to rise as the production temperature rises. However, the biochar produced at  $500 \text{ }^\circ\text{C}$  had maximum C sequestration ability, even though the biochar produced at higher temperature contains more C in the recalcitrant form than the biochar produced at a lower temperature.<sup>148</sup> Biochar made from wheat straw at  $500 \text{ }^\circ\text{C}$  had a higher carbon content ( $662 \text{ g kg}^{-1}$ ) than biochar made at  $300$  and  $400 \text{ }^\circ\text{C}$ .<sup>149</sup> With an increase in product temperature from  $350$  to  $500 \text{ }^\circ\text{C}$ , there was a greater organic C content of  $13.98\%$  to  $20.57\%$  and  $16.45\%$  to  $26.91\%$  in coffee husk biochar and corn cob biochar, respectively.<sup>150</sup> Biochar's carbon sequestration capacity can be potentially increased by increasing the proportion of stable carbon content. This is usually performed by the pyrolysis process, which reduces the solids production, while increasing the C release as a gas, leading to the increased  $\text{CO}_2$  emissions when burned.<sup>146,151</sup>

The carbon sequestration mechanism through biochar in soil is complicated and not thoroughly understood. However, the C sequestration mechanism of biochar mainly depends on feedstock types, pyrolysis temperature, and soil texture. Biochar put into the soil interacts with the environment's precipitation and temperature to determine how long biochar carbon is kept in the soil. The trapping of the labile pool in biochar pores and the protection of soil C in organo-mineral fractions physically might lead to a negative priming effect.<sup>150</sup> However, the organo-mineral complex formation is the main mechanism of C stabilization in the soil after biochar application.<sup>53</sup> The size of the biochar particles, stability, and interaction with soil particles and environments determine the C residence time in the soil.<sup>8,151</sup> Biochar adds more carbon to the passive pool of stable or inert carbon, which is less prone to degradation.<sup>152</sup> The  $\text{CO}_2$  collected by biochar may bond due to interactions between clay minerals and functional groups on the surface (Fig. 2). As a result of its interactions with soil particles, biochar becomes stable in the soil. Owing to the larger surface area, clay particles stabilize biochar more effectively than the sand particles.<sup>99</sup> Biochar sequester more carbon in C-starved soil than in soils with higher carbon content. The C content in the soil and rate of soil organic carbon (SOC) breakdown are inversely related; thus, biochar application reduces the C degradation and hence improves the SOC status. Biochar additions in soil restricted the gasses' losses of nitrogen by arresting/reducing the nitrification and denitrification processes, in addition to increasing the soil  $\text{CH}_4$  uptake.<sup>133,153</sup> Irrespective of the feedstock types used in biochar preparation, biochar loses the C content over the period due to the aging effect. Biochar prepared from maize stover had less carbon mineralization ability as compared to the biochar prepared from pulses and other cereal residue.<sup>154,155</sup> Likewise, *Eucalyptus saligna* pyrolysis at  $550 \text{ }^\circ\text{C}$  resulted in lower SOC mineralization by  $5.5\%$  over the control.<sup>156</sup> Application of biochar at the rate of  $4.2 \text{ Mg ha}^{-1} \text{ y}^{-1}$  increases the soil C storage of







Fig. 2 Possible mechanism of carbon sequestration by biochar inside the soil.

$2.35 \pm 0.4 \text{ Mg C ha}^{-1} \text{ y}^{-1}$  in sugarcane fields across the different regions of Brazil.<sup>157</sup> In maize crops, biochar produced from corn residue increased the SOC sequestration by 12–37% in the furrow slice (15 cm soil depth).<sup>158</sup>

## 7. Biochar and GHG emission mitigation

Crop residue burning generates a huge amount of greenhouse gases (GHG), especially  $\text{CO}_2$ ,  $\text{CO}$ , and  $\text{CH}_4$ . The burning of one tonne rice straw produces  $\sim 3$  kg of particulate organic matter (POM), 1460 kg of  $\text{CO}_2$ , 60 kg of  $\text{CO}$ , 199 kg of ash, and 2 kg of  $\text{SO}_2$ .<sup>152</sup> The composition of the atmosphere is altered due to crop residue burning, resulting in an imbalance of radiation. Due to increased GHG emissions, the stratospheric ozone layer has been depleted. The long-term application of recalcitrant C-rich biochar has been shown to be an effective technique for mitigating climate change,<sup>159</sup> but the effect of biochar on GHG emission mitigation is variable (Table 3). Priyadarshani and Prabhune (2009)<sup>160</sup> suggested that biochar could help to reduce greenhouse gas emissions by 2–4% out of the 1900 million tonnes of  $\text{CO}_2$  in India. Biochar curtails  $\text{CO}_2$  emissions through fossil fuel replacement by the production of syngas and bio-oil, in addition to its application and long-term C storage in the soil.<sup>161</sup> The beneficial impacts of biochar application in terms of

GHG emission reduction were previously reported by several researchers.<sup>137,152</sup> In contrast, He *et al.* (2018)<sup>36</sup> found that incorporation of biochar enhanced soil  $\text{CO}_2$  fluxes by 22.14%, but lowered  $\text{N}_2\text{O}$  fluxes by 30.92% and had no effect on  $\text{CH}_4$  fluxes. Biochar reduces the capacity of the soil to produce  $\text{N}_2\text{O}$  by causing microbial immobilization of the available nitrogen in the soil.<sup>162</sup> Biochar reduced the cumulative  $\text{N}_2\text{O}$  by 52–84% and  $\text{NO}$  by 47–67% emissions, as compared to those of chemical fertilization.<sup>163</sup> Biochar can thus be used in conjunction with mineral fertilizers to reduce  $\text{N}_2\text{O}$  emissions, while not interfering with mineralization or nitrification processes. Furthermore, at high pyrolysis temperatures,  $\text{N}_2\text{O}$  emissions were shown to be lower than at low pyrolysis temperatures. Under the controlled condition, the conjoint application of *Miscanthus* biochar at the rate of  $30 \text{ Mg ha}^{-1}$  (pyrolyzed at  $600^\circ\text{C}$ ) and nitrogen-rich litter reduces  $\text{N}_2\text{O}$  emissions by 42% over the control.<sup>164</sup> Biochar application increases soil pH, restrains nitrate reductase activity, and reduces  $\text{N}_2\text{O}$  emission.<sup>32</sup> According to Yanai *et al.* (2007),<sup>165</sup> biochar application reduces  $\text{N}_2\text{O}$  emissions by 85% over the control. Application of biochar at the rate of 20 and  $40 \text{ Mg ha}^{-1}$  in rice-wheat systems reduced  $\text{N}_2\text{O}$  emissions by 19.55% and 26.35%, respectively, over the control.<sup>166</sup> However, a lower dose of biochar with the rate of  $20 \text{ Mg ha}^{-1}$  resulted in an 8.89% higher  $\text{N}_2\text{O}$  emission than the control, whereas increasing the biochar dose from  $20 \text{ Mg ha}^{-1}$



Table 3 Impact of biochar application on greenhouse gases emission<sup>a</sup>

Biochar material	Tested crops	Pyrolysis temperature (°C)	Rate of biochar application (Mg ha <sup>-1</sup> )	Impact on greenhouse gases (percent) reduction (-) or increase (+) over control			Reference
				N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	
Wheat straw	Maize	450	20	+5.60	-2.43	+21.67	115
			40	+4.76	-12.57	+23.33	
Maize straw	Maize	450-500	15	+58.15	+22.08	-87.27	158
			30	+79.15	+21.53	-103	
			45	+76.49	+30.97	-74.54	
Wheat straw	Wheat	500	20	+19.55	—	+11.19	126
			40	+26.35	—	+17.45	
Wheat straw	Wheat	—	3.75	+0.99	—	+32.65	21
			7.50	+6.40	—	+25.85	
Rice straw	Rice	600	20	-8.89	—	+23.83	158
			40	+26.06	—	+12.54	
Rice straw	Rice	500	AWD* + 6.65	+30.93	—	+56.19	192
			CF** + 6.65	+38.64	—	+60.34	

<sup>a</sup> \*AWD-alternate wetting and drying; \*\*CF-continuous flooding.

to 40 Mg ha<sup>-1</sup> led to 26.06% lower N<sub>2</sub>O emission.<sup>158</sup> The amount of biochar incorporated also has a tenacious impact on soil N<sub>2</sub>O emissions. Biochar promotes N<sub>2</sub>O emission at lower rates of application, while it lowers N<sub>2</sub>O emission at larger dosage.<sup>158</sup> Soil supplemented with biochar as an organic amendment is reported to reduce CH<sub>4</sub> emissions.<sup>115,158</sup> Biochar improves soil aeration, reduces denitrification, and increases CH<sub>4</sub> sink capacity,<sup>152</sup> thereby retarding the CH<sub>4</sub> emission. The near-complete suppression of CH<sub>4</sub> emissions was noticed in soybean crops supplemented with biochar in acidic soil of Eastern Colombian Plains.<sup>166</sup> Biochar application at the rate of 20 and 40 Mg ha<sup>-1</sup> in rice-wheat systems reduced the CH<sub>4</sub> emission in rice by 11.19–17.45% over the control.<sup>126</sup> Moreover, biochar can potentially reduce the GHG emissions. However, the GHG emission mitigation potential of biochar is controlled by several factors like the biochar substrate, application dose, preparation methods, soil and crop management techniques, and the reaction of biochar with soil constituents and other applied inputs, like manure and fertilizers, *etc.*<sup>158</sup>

## 8. Biochar certification for marketability

In general, carbon sequestration *via* biochar production is technically feasible and can be economically viable, especially with the current development of the carbon sink economy. Carbon removal services *via* biochar offered through marketplaces require appropriate certification and monitoring for building the credential and authenticity. Biochar eligibility is highly dependent on the type of feedstock utilized and processing conditions employed. Biochar includes technical feasibility, scalability potential, costs, carbon permanence, verification and monitoring, as well as application benefits concerning various potential carbon reservoirs.<sup>140</sup> Process optimization is imperative to produce an end product that

meets the basic requirement for achieving the stability in carbon sequestration. Certification is envisioned for sustainable biochar production. Presently, the European Biochar Certificate (EBC) is a well-recognized voluntary industry standard in Europe. In Switzerland, the EBC certificate is mandatory for selling biochar. Based on the uses, the EBC promoted four types of biochar, *viz.*, EBC-Feed, EBC-AgroBio, EBC-Agro and EBC-Material.<sup>143</sup> The EBC certification encompasses a complete assessment of feedstocks and production process eligibilities, health and safety norms, sampling procedures, labeling and quality management protocols, and biochar properties. EBC has given the standard analytic procedures for the estimation of biochar properties. Hence, properties must meet the threshold criteria of the prescribed classes. Fawzy *et al.* (2021)<sup>143</sup> summarized a declaration requirement and threshold of specified biochar properties for the particular classes. The EBC is the first system to provide the methodology for biochar carbon sink potential certification. Hence, the biochar incorporated in the feedstock, manures, slurry, or any other substrate in the carbon sink potential may be converted into the carbon sink certificates. The carbon sink potential is the summation of all form of emission arising from the production of biochar (factory gate to production site). Carbon sink potential certificates enable the produce to sell the carbon sink potential on the online market place. Only carbon-neutral feedstocks like residual biomass and crops that do not reduce the total C stock are allowed to be used for the certification of biochar-based carbon sinks. Biomass obtained *via* the destruction of forests and other natural carbon sinks are not permitted. International biochar initiative (IBI) is also a volunteer biochar certification agency in the USA. Like EBC, the IBI also set its standard for biochar certification, but IBI does not prescribe the biochar production process for certification. Hence, EBC is the only organization that provides the biochar production certifications.<sup>143</sup> Currently, puro and carbon future are two marketplaces that provide carbon removal through biochar. Production process certification from



the EBC or any other similar organization is mandatory for trading the biochar *via* these marketplaces. However, each marketplace has its own C removal quantification process based on the certain parameters.<sup>143</sup>

## 9. Conclusions and future perspectives

The available literature indicates that biochar production and application in cropland not only reduces GHG emission, but also improves soil health, crop productivity, and economic returns. Hence, it can be summarized that the sustainable production and utilization of biochar can help in achieving several SDGs. Although a lot of literature is available on biochar production and application in agriculture, there are major issues that remain unsolved, like biomass characterization for biochar production and its interaction with soil environments. Hence, a comprehensive understanding of the carbon dynamic controlling and GHG regulating mechanism of biochar under different ecosystems need to be properly examined. Furthermore, there is a need of a robust study about the impact assessment of biochar on the microbial structure in soil systems. Furthermore, the biochar impact on the non-targeted organism and its interaction with other components of ecosystems must be evaluated for a proper understanding about the biochar interaction with the soil-plant-human-animal health continuum. Despite the various claimed benefits of biochar in the agricultural and environmental sustainability, its field level uses are very low. Hence, the availability of feedstock, permanency of biochar application, economic feasibility, and demand and supply of biochar need to be evaluated for large-scale adoption. The farm-level economic and social feasibility of the production and application of biochar must be systematically studied, which may give a clear-cut idea in the future propagation of biochar technology. Field level extension functionaries need to be trained about the biochar production. Similarly, there must be awareness among the ultimate clients. In this regard, the government can play a crucial role by providing financial assistance and subsidies to the farmers for the development of community-level low energy requiring preferably renewable energy-based biochar production units, especially in south Asia and other resource-poor countries.

## Data availability

All the data supported the statements given in the manuscript.

## Author contributions

Subhash Babu: conceptualization; methodology; writing original draft; Raghavendra Singh: formal analysis; writing – original draft; Sanjeev Kumar: writing – review & editing; Sanjay Singh Rathore: resources; supervision; writing – review & editing; Deviden Yadav: writing – review & editing; Sanjay Kumar Yadav: writing – review & editing; Vivek Yadav: writing – review & editing; Meraj Alam Ansari: writing reviewing & editing; Anup

Das: software; writing – review & editing; Gandhamanagenahalli Adireddy Rajanna: resources; writing – review & editing; Owais Ali Wani: software; writing – review & editing; Rishi Raj: writing – original draft; Dinesh Kumar Yadav: writing – original draft; Vinod Kumar Singh: writing – review & editing.

## Conflicts of 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.

## Acknowledgements

The authors greatly acknowledge the immense contribution of Dr Gulab Singh Yadav (Research Team Member), who conceptualized the idea and reviewed the first draft. Unfortunately, he is no longer with us, as he succumbed to COVID-19 on 19.05.2021.

## References

- 1 Food and Agriculture Organization (FAO) of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme, and World Health Organization, *The State of Food Security and Nutrition in the World 2017: Building Resilience for Peace and Food Security*, 2017.
- 2 L. D. Burrell, F. Zehetner, N. Rampazzo, B. Wimmer and G. Soja, Long-term effects of biochar on soil physical properties, *Geoderma*, 2016, **282**, 96–102.
- 3 H. Haberl, K. H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzer, S. Gingrich, W. Lucht and M. Fischer-Kowalski, Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 12942–12947.
- 4 D. Woolf, J. E. Amonette, F. A. Street-Perrott, J. Lehmann and S. Joseph, Sustainable biochar to mitigate global climate change, *Nat. Commun.*, 2010, **1**, 1–9.
- 5 S. Solomon, G. K. Plattner, R. Knutti and P. Friedlingstein, Irreversible climate change due to carbon dioxide emissions, *Proc. Natl. Acad. Sci. U. S. A.*, 2009, **106**, 1704–1709.
- 6 S. Babu, R. Singh, R. Avasthe, G. S. Yadav, K. Mohapatra, T. Selvan, A. Das, V. K. Singh, D. Valente and I. Petrosillo, Soil carbon dynamics in Indian Himalayan intensified organic rice-based cropping sequences, *Ecol. Indic.*, 2020, **114**, 106292.
- 7 M. Boko, I. Niang, A. Nyong, A. Vogel, A. Githeko, M. Medany, B. Osman-Elasha, R. Tabo and P. Z. Yanda, *Africa Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007.
- 8 A. N. Yadav, Beneficial plant-microbe interactions for agricultural sustainability, *J. Appl. Biol. Biotechnol.*, 2021, **9**, 1–4.



- 9 D. Roberts, A global roadmap for climate change action: From COP17 in Durban to COP21 in Paris, *S. Afr. J. Sci.*, 2016, **112**, 1–3.
- 10 A. I. Osman, S. Fawzy, M. Farghali, M. El-Azazy, A. M. Elgarah, R. A. Fahim, M. A. Maksoud, A. A. Ajlan, M. Yousry, Y. Saleem and D. W. Rooney, Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review, *Environ. Chem. Lett.*, 2022, **20**, 2385–2485.
- 11 P. Chawala and H. Sandhu, Stubble burn area estimation and its impact on ambient air quality of Patiala & Ludhiana district, Punjab, India, *Heliyon*, 2020, **6**, e03095.
- 12 M. I. Abdurrahman, S. Chaki and G. Saini, Stubble burning: Effects on health & environment, regulations and management practices, *Environ. Adv.*, 2020, **2**, 100011.
- 13 S. Babu, S. S. Rathore, R. Singh, S. Kumar, V. K. Singh, S. K. Yadav, V. Yadav, R. Raj, D. D. Yadav, K. Shekhawat and O. A. Wani, Exploring agricultural waste biomass for energy, food and feed production and pollution mitigation: A review, *Bioresour. Technol.*, 2022, **360**, 127566.
- 14 G. S. Yadav, M. Datta, S. Babu, C. Debnath and P. K. Sarkar, Growth and productivity of lowland rice (*Oryza sativa*) as influenced by substitution of nitrogen fertilizer by organic sources, *Indian J. Agric. Sci.*, 2013, **83**, 1–038.
- 15 S. Babu, A. Das, R. Singh, K. P. Mohapatra, S. Kumar, S. S. Rathore, S. K. Yadav, P. Yadav, M. A. Ansari, A. S. Panwar and O. A. Wani, Designing an energy efficient, economically feasible, and environmentally robust integrated farming system model for sustainable food production in the Indian Himalayas, *Sustain, Food Technol.*, 2023, **1**, 126–142.
- 16 A. I. Osman, L. Chen, M. Yang, G. Msigwa, M. Farghali, S. Fawzy, D. W. Rooney and P. S. Yap, Cost, environmental impact, and resilience of renewable energy under a changing climate: a review, *Environ. Chem. Lett.*, 2023, **21**, 741–764.
- 17 S. Khan, C. Chao, M. Waqas, H. P. H. Arp and Y.-G. Zhu, Sewage sludge biochar influence upon rice (*Oryza sativa* L) yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil, *Environ. Sci. Technol.*, 2013, **47**, 8624–8632.
- 18 S. Ye, G. Zeng, H. Wu, J. Liang, C. Zhang, J. Dai, W. Xiong, B. Song, S. Wu and J. Yu, The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil, *Resour., Conserv. Recycl.*, 2019, **140**, 278–285.
- 19 S. Oladele, A. Adeyemo and M. Awodun, Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils, *Geoderma*, 2019, **336**, 1–11.
- 20 C. M. Roberts, *The Dissertation Journey: A Practical and Comprehensive Guide to Planning, Writing, and Defending Your Dissertation*, Corwin. Press., 2010.
- 21 L. Xiang-Hong, H. Feng-Peng and Z. Xing-Chang, Effect of biochar on soil aggregates in the Loess Plateau: results from incubation experiments, *Int. J. Agric. Biol.*, 2012, **14**.
- 22 S. Das, P. Ngene, P. Norby, T. Vegge, P. E. De Jongh and D. Blanchard, All-solid-state lithium-sulfur battery based on a nanoconfined LiBH<sub>4</sub> electrolyte, *J. Electrochem. Soc.*, 2016, **163**, A2029.
- 23 K. Zazai, O. Wani, A. Ali and M. Devi, Phytoremediation and carbon sequestration potential of agroforestry systems: A review, *Int. J. Curr. Microbiol. Appl. Sci.*, 2018, **7**, 2447–2457.
- 24 S. Mau, I. Pletikosa and J. Wagner, Forecasting the next likely purchase events of insurance customers: A case study on the value of data-rich multichannel environments, *Int. J. Bank Mark.*, 2018, **36**, 1125–1144.
- 25 L. Dunnigan, B. J. Morton, P. J. Ashman, X. Zhang and C. W. Kwong, Emission characteristics of a pyrolysis-combustion system for the co-production of biochar and bioenergy from agricultural wastes, *Waste Manage.*, 2018, **77**, 59–66.
- 26 Q. Yang, O. Masek, L. Zhao, H. Nan, S. Yu, J. Yin, Z. Li and X. Cao, Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation, *Appl. Energy*, 2021, **282**, 116275.
- 27 J. Lehmann, M. C. Rillig, J. Thies, C. A. Masiello, W. C. Hockaday and D. Crowley, Biochar effects on soil biota—a review, *Soil Biol. Biochem.*, 2011, **43**, 1812–1836.
- 28 R. Lal, Soil carbon sequestration impacts on global climate change and food security, *Sci*, 2004, **304**, 1623–1627.
- 29 R. Lal, Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security, *Bio. Sci.*, 2010, **60**, 708–721.
- 30 J. Lehmann, A handful of carbon, *Nature*, 2007, **447**, 143–144.
- 31 I. Hawthorne, M. S. Johnson, R. S. Jassal, T. A. Black, N. J. Grant and S. M. Smukler, Application of biochar and nitrogen influences fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O in a forest soil, *J. Environ. Manage.*, 2017, **192**, 203–214.
- 32 Z. Wang, Y. Li, S. X. Chang, J. Zhang, P. Jiang, G. Zhou and Z. Shen, Contrasting effects of bamboo leaf and its biochar on soil CO<sub>2</sub> efflux and labile organic carbon in an intensively managed Chinese chestnut plantation, *Biol. Fertil. Soils*, 2014, **50**, 1109–1119.
- 33 H. Sun, W. Shi, M. Zhou, X. Ma and H. Zhang, Effect of biochar on nitrogen use efficiency, grain yield and amino acid content of wheat cultivated on saline soil, *Plant, Soil Environ.*, 2019, **65**, 83–89.
- 34 Y. Liu, M. Yang, Y. Wu, H. Wang, Y. Chen and W. Wu, Reducing CH<sub>4</sub> and CO<sub>2</sub> emissions from waterlogged paddy soil with biochar, *J. Soils Sediments*, 2011, **11**, 930–939.
- 35 K. Karhu, T. Mattila, I. Bergström and K. Regina, Biochar addition to agricultural soil increased CH<sub>4</sub> uptake and water holding capacity—Results from a short-term pilot field study, *Agric., Ecosyst. Environ.*, 2011, **140**, 309–313.
- 36 S. He, L. Ding, X. Wang, Y. Pan, H. Hu, K. Li and H. Ren, Biochar carrier application for nitrogen removal of domestic WWTPs in winter: challenges and opportunities, *Appl. Microbiol. Biotechnol.*, 2018, **102**, 9411–9418.
- 37 N. Borchard, M. Schirrmann, M. L. Cayuela, C. Kammann, N. Wrage-Mönnig, J. M. Estavillo, T. Fuertes-Mendizábal,



- G. Sigua, K. Spokas and J. A. Ippolito, Biochar, soil and land-use interactions that reduce nitrate leaching and N<sub>2</sub>O emissions: a meta-analysis, *Sci. Total Environ.*, 2019, **651**, 2354–2364.
- 38 G. Zhou, X. Zhou, T. Zhang, Z. Du, Y. He, X. Wang, J. Shao, Y. Cao, S. Xue and H. Wang, Biochar increased soil respiration in temperate forests but had no effects in subtropical forests, *For. Ecol. Manage.*, 2017, **405**, 339–349.
- 39 C. Ji, Y. Jin, C. Li, J. Chen, D. Kong, K. Yu, S. Liu and J. Zou, Variation in soil methane release or uptake responses to biochar amendment: a separate meta-analysis, *Ecosystems*, 2018, **21**, 1692–1705.
- 40 B. Hu, Y. Ai, J. Jin, T. Hayat, A. Alsaedi, L. Zhuang and X. Wang, Efficient elimination of organic and inorganic pollutants by biochar and biochar-based materials, *Biochar*, 2020, **2**, 47–64.
- 41 Y. Zhang, J. Ding, H. Wang, L. Su and C. Zhao, Biochar addition alleviate the negative effects of drought and salinity stress on soybean productivity and water use efficiency, *BMC Plant Biol.*, 2020, **20**, 1–11.
- 42 H. Liao, C. Zheng, J. Long and I. Guzmán, Effects of biochar amendment on tomato rhizosphere bacterial communities and their utilization of plant-derived carbon in a calcareous soil, *Geoderma*, 2021, **396**, 115082.
- 43 S.-H. Jien and C.-S. Wang, Effects of biochar on soil properties and erosion potential in a highly weathered soil, *Catena*, 2013, **110**, 225–233.
- 44 T. Purakayastha, S. Kumari and H. Pathak, Characterisation, stability, and microbial effects of four biochars produced from crop residues, *Geoderma*, 2015, **239**, 293–303.
- 45 B. Dume, D. Ayele, A. Regassa and G. Barecha, Interactive effects of biochar in soil related to feedstock and pyrolysis temperature, American-Eurasian, *J. Agric. Environ. Sci.*, 2016, **16**, 442–448.
- 46 M. Zhang, G. Cheng, H. Feng, B. Sun, Y. Zhao, H. Chen, J. Chen, M. Dyck, X. Wang and J. Zhang, Effects of straw and biochar amendments on aggregate stability, soil organic carbon, and enzyme activities in the Loess Plateau, China, *Environ. Sci. Pollut. Res.*, 2017, **24**, 10108–10120.
- 47 X. Liu, A. Zhang, C. Ji, S. Joseph, R. Bian, L. Li, G. Pan and J. Paz-Ferreiro, Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data, *Plant and Soil*, 2013, **373**(1/2), 583–594.
- 48 L. A. Biederman and W. S. Harpole, Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis, *GCB Bioenergy*, 2013, **5**, 202–214.
- 49 A. Abukari, Z. A. Imoro, A. Z. Imoro and A. B. Duwiejuah, *Sustainable use of biochar in environmental management*, ed. T. Otsuki, IntechOpen, 2021, vol. 8, DOI: [10.5772/intechopen.96510](https://doi.org/10.5772/intechopen.96510).
- 50 J. Lehmann, J. Gaunt and M. Rondon, Biochar sequestration in terrestrial ecosystems—a review, *Mitig. Adapt. Strateg. Glob. Chang.*, 2006, **11**, 403–427.
- 51 K. Paustian, J. Lehmann, S. Ogle, D. Reay, G. P. Robertson and P. Smith, Climate-smart soils, *Nature*, 2016, **532**, 49–57.
- 52 A. Saini, N. K. Aggarwal, A. Sharma, M. Kaur and A. Yadav, Utility potential of Parthenium hysterophorus for its strategic management, *Adv. Agric.*, 2014, **2014**, 381859.
- 53 Y. Liu, Y. Bi, Y. Xie, X. Zhao, D. He, S. Wang, C. Wang, T. Guo and G. Xing, Successive straw biochar amendments reduce nitrous oxide emissions but do not improve the net ecosystem economic benefit in an alkaline sandy loam under a wheat–maize cropping system, *Land Degrad. Dev.*, 2020, **31**, 868–883.
- 54 Y. Luo, Q. Lin, M. Durenkamp, A. Dungait and P. Brookes, Soil priming effects following substrates addition to biochar-treated soils after 431 days of pre-incubation, *Biol. Fertil. Soils*, 2017, **53**, 315–326.
- 55 M. Ventura, G. Alberti, P. Panzacchi, G. Delle Vedove, F. Miglietta and G. Tonon, Biochar mineralization and priming effect in a poplar short rotation coppice from a 3-year field experiment, *Biol. Fertil. Soils*, 2019, **55**, 67–78.
- 56 M. Kolton, E. R. Graber, L. Tsehansky, Y. Elad and E. Cytryn, Biochar-stimulated plant performance is strongly linked to microbial diversity and metabolic potential in the rhizosphere, *New Phytol.*, 2017, **213**, 1393–1404.
- 57 M. K. Awasthi, Y. Duan, S. K. Awasthi, T. Liu, H. Chen, A. Pandey, Z. Zhang and M. J. Taherzadeh, Emerging applications of biochar: Improving pig manure composting and attenuation of heavy metal mobility in mature compost, *J. Hazard. Mater.*, 2020, **389**, 122116.
- 58 S. Shao, Y. Zhao, W. Zhang, G. Hu, H. Xie, J. Yan, S. Han, H. He and X. Zhang, Linkage of microbial residue dynamics with soil organic carbon accumulation during subtropical forest succession, *Soil Biol. Biochem.*, 2017, **114**, 114–120.
- 59 D. A. Laird, The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality, *Agron. J.*, 2008, **100**, 178–181.
- 60 S. Varjani, G. Kumar and E. R. Rene, Developments in biochar application for pesticide remediation: current knowledge and future research directions, *J. Environ. Manage.*, 2019, **232**, 505–513.
- 61 D. Datta and S. Saxena, Efficient Recycling of Crop Residue through biochar for better agriculture and environment, *Indian Farming*, 2017, **67**(4), 17–19.
- 62 R. Gurav, S. K. Bhatia, T.-R. Choi, Y. L. Park, J. Y. Park, Y. H. Han, G. Vyavahare, J. Jadhav, H. S. Song and P. Yang, Treatment of furazolidone contaminated water using banana pseudostem biochar engineered with facile synthesized magnetic nanocomposites, *Bioresour. Technol.*, 2020, **297**, 122472.
- 63 S. Pang, Advances in thermochemical conversion of woody biomass to energy, fuels and chemicals, *Biotechnol. Adv.*, 2019, **37**, 589–597.
- 64 J. I. Osayi, S. Iyuke and S. E. Ogbeide, Biocrude production through pyrolysis of used tyres, *J. Catal.*, 2014, **2014**, 386371.
- 65 J. A. Libra, K. S. Ro, C. Kammann, A. Funke, N. D. Berge, Y. Neubauer, M. M. Titirici, C. Fühner, O. Bens and J. Kern, Hydrothermal carbonization of biomass residuals:



- a comparative review of the chemistry, processes and applications of wet and dry pyrolysis, *Biofuels*, 2011, **2**, 71–106.
- 66 S. Joseph, C. Peacocke, J. Lehmann and P. Munroe, Developing a biochar classification and test methods, Biochar for environmental management, *Sci. Technol.*, 2009, **1**, 107–126.
- 67 M. Ahmad, S. S. Lee, X. Dou, D. Mohan, J.-K. Sung, J. E. Yang and Y. S. Ok, Effects of pyrolysis temperature on soybean stover-and peanut shell-derived biochar properties and TCE adsorption in water, *Bioresour. Technol.*, 2012, **118**, 536–544.
- 68 J. Mumme, L. Eckervogt, J. Pielert, M. Diakité, F. Rupp and J. Kern, Hydrothermal carbonization of anaerobically digested maize silage, *Bioresour. Technol.*, 2011, **102**, 9255–9260.
- 69 M. Buttmann, Climate friendly coal from hydrothermal carbonization of biomass, *Chem. Ing. Tech.*, 2011, **83**, 1890–1896.
- 70 J. Lee, K. Lee, D. Sohn, Y. M. Kim and K. Y. Park, Hydrothermal carbonization of lipid extracted algae for hydrochar production and feasibility of using hydrochar as a solid fuel, *Energy*, 2018, **153**, 913–920.
- 71 G. Gascó, J. Paz-Ferreiro, M. L. Álvarez, A. Saa and A. Méndez, Biochars and hydrochars prepared by pyrolysis and hydrothermal carbonisation of pig manure, *Waste Manage.*, 2018, **79**, 395–403.
- 72 B. M. Ghanim, D. S. Pandey, W. Kwapinski and J. J. Leahy, Hydrothermal carbonisation of poultry litter: effects of treatment temperature and residence time on yields and chemical properties of hydrochars, *Bioresour. Technol.*, 2016, **216**, 373–380.
- 73 M. Lucian, M. Volpe, L. Gao, G. Piro, J. L. Goldfarb and L. Fiori, Impact of hydrothermal carbonization conditions on the formation of hydrochars and secondary chars from the organic fraction of municipal solid waste, *Fuel*, 2018, **233**, 257–268.
- 74 M. Volpe, J. L. Goldfarb and L. Fiori, Hydrothermal carbonization of *Opuntia ficus-indica* cladodes: Role of process parameters on hydrochar properties, *Bioresour. Technol.*, 2018, **247**, 310–318.
- 75 C. Gopu, L. Gao, M. Volpe, L. Fiori and J. L. Goldfarb, Valorizing municipal solid waste: Waste to energy and activated carbons for water treatment *via* pyrolysis, *J. Anal. Appl. Pyrolysis*, 2018, **133**, 48–58.
- 76 B. A. Oni, O. Oziegbe and O. O. Olawole, Significance of biochar application to the environment and economy, *Ann. Agric. Sci.*, 2019, **64**, 222–236.
- 77 A. Tomczyk, Z. Sokołowska and P. Boguta, Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects, *Rev. Environ. Sci. Biotechnol.*, 2020, **19**, 191–215.
- 78 E. Yeboah, G. Asamoah, P. Ofori, B. Amoah and K. O. A. Agyeman, Method of biochar application affects growth, yield and nutrient uptake of cowpea, *Open Agric.*, 2020, **5**, 352–360.
- 79 S. Jeffery, D. Abalos, M. Prodana, A. C. Bastos, J. W. Van Groenigen, B. A. Hungate and F. Verheijen, Biochar boosts tropical but not temperate crop yields, *Environ. Res. Lett.*, 2017, **12**, 053001.
- 80 S. Sahota, V. K. Vijay, P. Subbarao, R. Chandra, P. Ghosh, G. Shah, R. Kapoor, V. Vijay, V. Koutu and I. S. Thakur, Characterization of leaf waste-based biochar for cost effective hydrogen sulphide removal from biogas, *Bioresour. Technol.*, 2018, **250**, 635–641.
- 81 M. Hussain, M. Farooq, A. Nawaz, A. M. Al-Sadi, Z. M. Solaiman, S. S. Alghamdi, U. Ammara, Y. S. Ok and K. H. Siddique, Biochar for crop production: potential benefits and risks, *J. Soils Sediments*, 2017, **17**, 685–716.
- 82 L.-M. Raboin, A. H. D. Razafimahafaly, M. B. Rabenjarisoa, B. Rabary, J. Dusserre and T. Becquer, Improving the fertility of tropical acid soils: Liming *versus* biochar application? A long term comparison in the highlands of Madagascar, *Field Crops Res.*, 2016, **199**, 99–108.
- 83 V. Vijay, S. Shreedhar, K. Adlak, S. Payyanad, V. Sreedharan, G. Gopi, T. Sophia van der Voort, P. Malarvizhi, S. Yi and J. Gebert, Review of large-scale biochar field-trials for soil amendment and the observed influences on crop yield variations, *Front. Energy Res.*, 2021, 499.
- 84 N. Hagemann, S. Joseph, H.-P. Schmidt, C. I. Kammann, J. Harter, T. Borch, R. B. Young, K. Varga, S. Taherymoosavi and K. W. Elliott, Organic coating on biochar explains its nutrient retention and stimulation of soil fertility, *Nat. Commun.*, 2017, **8**, 1–11.
- 85 G. Bonanomi, F. Ippolito, G. Cesarano, B. Nanni, N. Lombardi, A. Rita, A. Saracino and F. Scala, Biochar as plant growth promoter: better off alone or mixed with organic amendments?, *Front. Plant Sci.*, 2017, **8**, 1570.
- 86 G. Agegnehu, A. M. Bass, P. N. Nelson and M. I. Bird, Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil, *Sci. Total Environ.*, 2016, **543**, 295–306.
- 87 D. Trupiano, C. Coccozza, S. Baronti, C. Amendola, F. P. Vaccari, G. Lustrato, S. Di Lonardo, F. Fantasma, R. Tognetti and G. S. Scippa, The effects of biochar and its combination with compost on lettuce (*Lactuca sativa* L.) growth, soil properties, and soil microbial activity and abundance, *Int. J. Agron.*, 2017, 3158207.
- 88 S. Ali, M. Rizwan, M. F. Qayyum, Y. S. Ok, M. Ibrahim, M. Riaz, M. S. Arif, F. Hafeez, M. I. Al-Wabel and A. N. Shahzad, Biochar soil amendment on alleviation of drought and salt stress in plants: a critical review, *Environ. Sci. Pollut. Res.*, 2017, **24**, 12700–12712.
- 89 S. Mansoor, N. Kour, S. Manhas, S. Zahid, O. A. Wani, V. Sharma, L. Wijaya, M. N. Alyemeni, A. A. Alsahli and H. A. El-Serehy, Biochar as a tool for effective management of drought and heavy metal toxicity, *Chemosphere*, 2020, 129458.
- 90 A. R. S. Langeroodi, E. Campiglia, R. Mancinelli and E. Radicetti, Can biochar improve pumpkin productivity and its physiological characteristics under reduced irrigation regimes?, *Sci. Hortic.*, 2019, **247**, 195–204.



- 91 M. Rasool, A. Akhter, G. Soja and M. S. Haider, Role of biochar, compost and plant growth promoting rhizobacteria in the management of tomato early blight disease, *Sci. Rep.*, 2021, **11**, 1–16.
- 92 S. C. Thomas, S. Frye, N. Gale, M. Garmon, R. Launchbury, N. Machado, S. Melamed, J. Murray, A. Petroff and C. Winsborough, Biochar mitigates negative effects of salt additions on two herbaceous plant species, *J. Environ. Manage.*, 2013, **129**, 62–68.
- 93 M. Rizwan, S. Ali, M. F. Qayyum, M. Ibrahim, M. Zia-ur-Rehman, T. Abbas and Y. S. Ok, Mechanisms of biochar-mediated alleviation of toxicity of trace elements in plants: a critical review, *Environ. Sci. Pollut. Res.*, 2016, **23**, 2230–2248.
- 94 G. Agegnehu, A. M. Bass, P. N. Nelson, B. Muirhead, G. Wright and M. I. Bird, Biochar and biochar-compost as soil amendments: effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia, *Agric., Ecosyst. Environ.*, 2015, **213**, 72–85.
- 95 M. Z. Alam, L. Carpenter-Boggs, M. A. Hoque and G. J. Ahammed, Effect of soil amendments on antioxidant activity and photosynthetic pigments in pea crops grown in arsenic contaminated soil, *Heliyon*, 2020, **6**, e05475.
- 96 A. K. Jaiswal, Y. Elad, I. Paudel, E. R. Graber, E. Cytryn and O. Frenkel, Linking the belowground microbial composition, diversity and activity to soilborne disease suppression and growth promotion of tomato amended with biochar, *Sci. Rep.*, 2017, **7**, 1–17.
- 97 Y. Elad, E. Cytryn, Y. M. Harel, B. Lew and E. R. Graber, The biochar effect: plant resistance to biotic stresses, *Phytopathol. Mediterr.*, 2011, **50**, 335–349.
- 98 J. Poveda, Á. M. Gómez, C. Fenoll and C. Escobar, The use of biochar for plant-pathogen control, *Phytopathology*, 2021, **111**, 1490–1499.
- 99 R. Lal, Sequestering carbon and increasing productivity by conservation agriculture, *J. Soil Water Conserv.*, 2015, **70**, 55A–62A.
- 100 G. Agegnehu, A. Srivastava and M. I. Bird, The role of biochar and biochar-compost in improving soil quality and crop performance: A review, *Appl. Soil Ecol.*, 2017, **119**, 156–170.
- 101 J. A. Antonangelo, X. Sun and H. Zhang, The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration, *J. Environ. Manage.*, 2021, **277**, 111443.
- 102 T. E. Lychuk, R. C. Izaurralde, R. L. Hill, W. B. McGill and J. R. Williams, Biochar as a global change adaptation: predicting biochar impacts on crop productivity and soil quality for a tropical soil with the Environmental Policy Integrated Climate (EPIC) model, *Mitig. Adapt. Strateg. Glob. Change*, 2015, **20**, 1437–1458.
- 103 A. Crane-Droesch, S. Abiven, S. Jeffery and M. S. Torn, Heterogeneous global crop yield response to biochar: a meta-regression analysis, *Environ. Res. Lett.*, 2013, **8**, 044049.
- 104 M. Brtnicky, R. Datta, J. Holatko, L. Bielska, Z. M. Gusiatin, J. Kucerik, T. Hammerschmidt, S. Danish, M. Radziemska and L. Mravcova, A critical review of the possible adverse effects of biochar in the soil environment, *Sci. Total Environ.*, 2021, 148756.
- 105 Y. Zhang, J. Wang and Y. Feng, The effects of biochar addition on soil physicochemical properties: A review, *Catena*, 2021, **202**, 105284.
- 106 P. R. Quin, A. Cowie, R. Flavel, B. Keen, L. Macdonald, S. Morris, B. P. Singh, I. Young and L. Van Zwieten, Oil mallee biochar improves soil structural properties—A study with x-ray micro-CT, *Agric. Ecosyst. Environ.*, 2014, **191**, 142–149.
- 107 J. Ulyett, R. Sakrabani, M. Kibblewhite and M. Hann, Impact of biochar addition on water retention, nitrification and carbon dioxide evolution from two sandy loam soils, *Eur. J. Soil Sci.*, 2014, **65**, 96–104.
- 108 C. Steiner, W. G. Teixeira, J. Lehmann, T. Nehls, J. L. V. de Macêdo, W. E. Blum and W. Zech, Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil, *Plant Soil*, 2007, **291**, 275–290.
- 109 P. G. Oguntunde, B. J. Abiodun, A. E. Ajayi and N. van de Giesen, Effects of charcoal production on soil physical properties in Ghana, *J. Plant Nutr. Soil Sci.*, 2008, **171**, 591–596.
- 110 L. Ouyang, F. Wang, J. Tang, L. Yu and R. Zhang, Effects of biochar amendment on soil aggregates and hydraulic properties, *J. Soil Sci. Plant Nutr.*, 2013, **13**, 991–1002.
- 111 H. Dokoochaki, F. E. Miguez, D. Laird, R. Horton and A. S. Basso, Assessing the biochar effects on selected physical properties of a sandy soil: an analytical approach, *Soil Sci. Plant Anal.*, 2017, **48**, 1387–1398.
- 112 K. Rasa, J. Heikkinen, M. Hannula, K. Arstila, S. Kulju and J. Hyväluoma, How and why does willow biochar increase a clay soil water retention capacity?, *Biomass Bioenergy*, 2018, **119**, 346–353.
- 113 F. G. Verheijen, A. Zhuravel, F. C. Silva, A. Amaro, M. Ben-Hur and J. J. Keizer, The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs. sandy loam soil in a column experiment, *Geoderma*, 2019, **347**, 194–202.
- 114 C. A. Masiello, B. Dugan, C. E. Brewer, K. A. Spokas, J. M. Novak, Z. Liu and G. Sorrenti, in *Biochar for Environmental Management*, Routledge, 2015, pp. 575–594.
- 115 J. Zhang, C. Qun and Y. Changfu, Biochar effect on water evaporation and hydraulic conductivity in sandy soil, *Pedosphere*, 2016, **26**, 265–272.
- 116 A. Singh, A. Singh and T. Purakayastha, Characterization of biochar and their influence on microbial activities and potassium availability in an acid soil, *Arch. Agron. Soil Sci.*, 2019, **65**, 1302–1315.
- 117 S. Babu, K. Mohapatra, A. Das, G. S. Yadav, M. Tahasildar, R. Singh, A. Panwar, V. Yadav and P. Chandra, Designing energy-efficient, economically sustainable and environmentally safe cropping system for the rainfed



- maize-fallow land of the Eastern Himalayas, *Sci. Total Environ.*, 2020, **722**, 137874.
- 118 K. Zygourakis, Biochar soil amendments for increased crop yields: how to design a “designer” biochar, *AIChE J.*, 2017, **63**, 5425–5437.
- 119 F. Liang, G.-t. LI, Q.-m. LIN and X.-r. ZHAO, Crop yield and soil properties in the first 3 years after biochar application to a calcareous soil, *J. Integr. Agric.*, 2014, **13**, 525–532.
- 120 R. Chintala, T. E. Schumacher, L. M. McDonald, D. E. Clay, D. D. Malo, S. K. Papiernik, S. A. Clay and J. L. Julson, Phosphorus Sorption and Availability from Biochars and Soil/Biochar Mixtures, *Clean: Soil, Air, Water*, 2014, **42**, 626–634.
- 121 J. M. Novak, J. A. Ippolito, D. W. Watts, G. C. Sigua, T. F. Ducey and M. G. Johnson, Biochar compost blends facilitate switchgrass growth in mine soils by reducing Cd and Zn bioavailability, *Biochar*, 2019, **1**, 97–114.
- 122 R. Radin, R. A. Bakar, C. F. Ishak, S. H. Ahmad and L. C. Tsong, Biochar-compost mixture as amendment for improvement of polybag-growing media and oil palm seedlings at main nursery stage, *Int. J. Recycl. Org. Waste Agric.*, 2018, **7**, 11–23.
- 123 H. Chen, S. K. Awasthi, T. Liu, Y. Duan, Z. Zhang and M. K. Awasthi, Compost biochar application to contaminated soil reduces the (im) mobilization and phytoavailability of lead and copper, *J. Chem. Technol. Biotechnol.*, 2020, **95**, 408–417.
- 124 A. Rodríguez-Vila, R. Forján, R. S. Guedes and E. F. Covelo, Changes on the phytoavailability of nutrients in a mine soil reclaimed with compost and biochar, *Water, Air, Soil Pollut.*, 2016, **227**, 1–12.
- 125 A. Taghizadeh-Toosi, T. J. Clough, R. R. Sherlock and L. M. Condon, Biochar adsorbed ammonia is bioavailable, *Plant Soil*, 2012, **350**, 57–69.
- 126 B. Wu, G. Cheng, K. Jiao, W. Shi, C. Wang and H. Xu, Mycoextraction by *Clitocybe maxima* combined with metal immobilization by biochar and activated carbon in an aged soil, *Sci. Total Environ.*, 2016, **562**, 732–739.
- 127 C. Nzediegwu, S. Prasher, E. Elsayed, J. Dhiman, A. Mawof and R. Patel, Effect of biochar on heavy metal accumulation in potatoes from wastewater irrigation, *J. Environ. Manage.*, 2019, **232**, 153–164.
- 128 Z. D. Nejad, M. C. Jung and K.-H. Kim, Remediation of soils contaminated with heavy metals with an emphasis on immobilization technology, *Environ. Geochem. Health*, 2018, **40**, 927–953.
- 129 H. Liu, S. Guo, K. Jiao, J. Hou, H. Xie and H. Xu, Bioremediation of soils co-contaminated with heavy metals and 2, 4, 5-trichlorophenol by fruiting body of *Clitocybe maxima*, *J. Hazard. Mater.*, 2015, **294**, 121–127.
- 130 X. Zhang, H. Wang, L. He, K. Lu, A. Sarmah, J. Li, N. S. Bolan, J. Pei and H. Huang, Using biochar for remediation of soils contaminated with heavy metals and organic pollutants, *Environ. Sci. Pollut. Res.*, 2013, **20**, 8472–8483.
- 131 K. Mackie, S. Marhan, F. Ditterich, H. Schmidt and E. Kandeler, The effects of biochar and compost amendments on copper immobilization and soil microorganisms in a temperate vineyard, *Agric., Ecosyst. Environ.*, 2015, **201**, 58–69.
- 132 X. Song, M. Liu, D. Wu, B. S. Griffiths, J. Jiao, H. Li and F. Hu, Interaction matters: Synergy between vermicompost and PGPR agents improves soil quality, crop quality and crop yield in the field, *Appl. Soil Ecol.*, 2015, **89**, 25–34.
- 133 M. A. Rondon, J. Lehmann, J. Ramírez and M. Hurtado, Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions, *Biol. Fertil. Soils*, 2007, **43**, 699–708.
- 134 C. Amoah-Antwi, J. Kwiatkowska-Malina, S. F. Thornton, O. Fenton, G. Malina and E. Szara, Restoration of soil quality using biochar and brown coal waste: A review, *Sci. Total Environ.*, 2020, **722**, 137852.
- 135 E. J. Foster, N. Hansen, M. Wallenstein and M. F. Cotrufo, Biochar and manure amendments impact soil nutrients and microbial enzymatic activities in a semi-arid irrigated maize cropping system, *Agric., Ecosyst. Environ.*, 2016, **233**, 404–414.
- 136 R. Sedjo and B. Sohngen, Carbon sequestration in forests and soils, *Annu. Rev. Resour. Econ.*, 2012, **4**, 127–144.
- 137 G. Venkatesh, K. Gopinath, K. S. Reddy, B. S. Reddy, J. Prasad, G. R. Rao, G. Pratibha, C. Srinivasarao, G. R. Chary and M. Prabhakar, *Biochar Production and its Use in Rainfed Agriculture: Experiences from CRIDA*, 2018.
- 138 B. Glaser, J. Lehmann and W. Zech, Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—a review, *Biol. Fertil. Soils*, 2002, **35**, 219–230.
- 139 E. Yeboah, P. Ofori, G. Quansah and S. Sohi, Improving soil productivity through biochar amendments to soils, *Afr. J. Environ. Sci.*, 2009, **3**, 34–41.
- 140 S. Fawzy, A. I. Osman, N. Mehta, D. Moran, H. Ala'a and D. W. Rooney, Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study, *J. Cleaner Prod.*, 2022, **371**, 133660.
- 141 Q. Yang, O. Mašek, L. Zhao, H. Nan, S. Yu, J. Yin, Z. Li and X. Cao, Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation, *Appl. Energy*, 2021, **282**, 116275.
- 142 E. Muñoz, G. Curaqueo, M. Cea, L. Vera and R. Navia, Environmental hotspots in the life cycle of a biochar-soil system, *J. Cleaner Prod.*, 2017, **158**, 1–7.
- 143 S. Fawzy, A. I. Osman, H. Yang, J. Doran and D. W. Rooney, Industrial biochar systems for atmospheric carbon removal: a review, *Environ. Chem. Lett.*, 2021, **19**, 3023–3055.
- 144 E. Bruun, D. Müller-Stöver, P. Ambus and H. Hauggaard-Nielsen, Application of biochar to soil and N<sub>2</sub>O emissions: potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry, *Eur. J. Soil Sci.*, 2011, **62**, 581–589.
- 145 O. Mašek, W. Buss, P. Brownsort, M. Rovere, A. Tagliaferro, L. Zhao, X. Cao and G. Xu, Potassium doping increases biochar carbon sequestration potential by 45%,





- facilitating decoupling of carbon sequestration from soil improvement, *Sci. Rep.*, 2019, **9**, 1–8.
- 146 *Biochar for Environmental Management: Science, Technology and Implementation*, ed. J. Lehmann and S. Joseph, Routledge, 2015.
- 147 N. Ameloot, E. R. Graber, F. G. Verheijen and S. De Neve, Interactions between biochar stability and soil organisms: review and research needs, *Eur. J. Soil Sci.*, 2013, **64**, 379–390.
- 148 V. Yadav, T. Karak, S. Singh, A. K. Singh and P. Khare, Benefits of biochar over other organic amendments: Responses for plant productivity (*Pelargonium graveolens* L.) and nitrogen and phosphorus losses, *Ind. Crops Prod.*, 2019, **131**, 96–105.
- 149 M. A. Naeem, M. Khalid, M. Arshad and R. Ahmad, Yield and nutrient composition of biochar produced from different feedstocks at varying pyrolytic temperatures, *Pak. J. Agric. Sci.*, 2014, 51.
- 150 B. Dume, G. Berecha and S. Tulu, Characterization of biochar produced at different temperatures and its effect on acidic nitosol of Jimma, Southwest Ethiopia, *Int. J. Soil Sci.*, 2015, **10**, 63.
- 151 K. Crombie, O. Mašek, S. P. Sohi, P. Brownsort and A. Cross, The effect of pyrolysis conditions on biochar stability as determined by three methods, *GCB Bioenergy*, 2013, **5**, 122–131.
- 152 C. Srinivasarao, K. Gopinath, G. Venkatesh, A. Dubey, H. Wakudkar, T. Purakayastha, H. Pathak, P. Jha, B. Lakaria and D. Rajkhowa, *Use of Biochar for Soil Health Enhancement and Greenhouse Gas Mitigation in India, Potential Constraints*, 2013.
- 153 L. Van Zwieten, S. Kimber, S. Morris, K. Chan, A. Downie, J. Rust, S. Joseph and A. Cowie, Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility, *Plant Soil*, 2010, **327**, 235–246.
- 154 A. Anand, V. Kumar and P. Kaushal, Biochar and its twin benefits: Crop residue management and climate change mitigation in India, *Renewable Sustainable Energy Rev.*, 2022, **156**, 111959.
- 155 D. K. Gupta, C. K. Gupta, R. Dubey, R. K. Fagodiya, G. Sharma, N. Mohamed, R. Dev and A. Shukla, in *Biochar Applications in Agriculture and Environment Management*, Springer, 2020, pp. 141–165.
- 156 Z. H. Weng, L. Van Zwieten, B. P. Singh, E. Tavakkoli, S. Joseph, L. M. Macdonald, T. J. Rose, M. T. Rose, S. W. Kimber and S. Morris, Biochar built soil carbon over a decade by stabilizing rhizodeposits, *Nat. Clim. Change*, 2017, **7**, 371–376.
- 157 D. Lefebvre, A. Williams, J. Meersmans, G. J. Kirk, S. Sohi, P. Goglio and P. Smith, Modelling the potential for soil carbon sequestration using biochar from sugarcane residues in Brazil, *Sci. Rep.*, 2020, **10**, 1–11.
- 158 W. Yang, G. Feng, D. Miles, L. Gao, Y. Jia, C. Li and Z. Qu, Impact of biochar on greenhouse gas emissions and soil carbon sequestration in corn grown under drip irrigation with mulching, *Sci. Total Environ.*, 2020, **729**, 138752.
- 159 J. Layek, R. Narzari, S. Hazarika, A. Das, K. Rangappa, S. Devi, A. Balusamy, S. Saha, S. Mandal, R. G. Idapuganti, S. Babu, B. U. Choudhary and V. K. Mishra, Prospects of biochar for sustainable agriculture and carbon sequestration: an overview for Eastern Himalayas., *Sustainability*, 2022, **14**(11), 6684–1822.
- 160 K. Priyadarshani and R. Prabhune, *Biochar for Carbon Reduction, Sustainable Agriculture and Soil Management (BiocharM), Final Report APN Project. J.*, 2009.
- 161 A. Cross and S. P. Sohi, The priming potential of biochar products in relation to labile carbon contents and soil organic matter status, *Soil Biol. Biochem.*, 2011, **43**, 2127–2134.
- 162 T. DeLuca, M. MacKenzie, M. Gundale and W. Holben, Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests, *Soil Sci. Soc. Am. J.*, 2006, **70**, 448–453.
- 163 V. Nelissen, B. K. Saha, G. Ruyschaert and P. Boeckx, Effect of different biochar and fertilizer types on N<sub>2</sub>O and NO emissions, *Soil Biol. Biochem.*, 2014, **70**, 244–255.
- 164 C. Bamminger, N. Zaiser, P. Zinsser, M. Lamers, C. Kammann and S. Marhan, Effects of biochar, earthworms, and litter addition on soil microbial activity and abundance in a temperate agricultural soil, *Biol. Fertil. Soils*, 2014, **50**, 1189–1200.
- 165 Y. Yanai, K. Toyota and M. Okazaki, Effects of charcoal addition on N<sub>2</sub>O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments, *Soil Sci. Plant Nutr.*, 2007, **53**, 181–188.
- 166 M. Rondon, J. Ramirez and J. Lehmann, Charcoal additions reduce net emissions of greenhouse gases to the atmosphere, *Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration in Agriculture and Forestry*, USDA Baltimore, 2005, pp. 21–24.
- 167 M. Huang, X. Yin, J. Chen and F. Cao, Biochar Application Mitigates the Effect of Heat Stress on Rice (*Oryza sativa* L.) by Regulating the Root-Zone Environment, *Front. Plant Sci.*, 2021, **12**, 711725.
- 168 T. F. Abbruzzini, C. A. Davies, F. H. Toledo and C. E. Cerri, Dynamic biochar effects on nitrogen use efficiency, crop yield and soil nitrous oxide emissions during a tropical wheat-growing season, *J. Environ. Manage.*, 2019, **252**, 109638.
- 169 G. Cornelissen, N. L. Nurida, S. E. Hale, V. Martinsen, L. Silvani and J. Mulder, Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol, *Sci. Total Environ.*, 2018, **634**, 561–568.
- 170 E. Calys-Tagoe, A. Sadick, E. Yeboah and B. Amoah, Biochar effect on maize yield in selected farmers fields in the northern and upper east regions of Ghana, *J. Exp. Agric. Int.*, 2019, **30**, 1–9.
- 171 T. Kätterer, D. Roobroeck, O. Andrén, G. Kimutai, E. Karlton, H. Kirchmann, G. Nyberg, B. Vanlauwe and K. R. de Nowina, Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10



- years in sub-humid regions of Kenya, *Field Crops Res.*, 2019, **235**, 18–26.
- 172 T. Berihun, S. Tolosa, M. Tadele and F. Kebede, Effect of biochar application on growth of garden pea (*Pisum sativum* L.) in acidic soils of Bule Woreda Gedeo Zone Southern Ethiopia, *Int. J. Agron.*, 2017, **2017**, 6827323.
- 173 I. C. Silva, L. A. Fernandes, F. Colen and R. A. Sampaio, Growth and production of common bean fertilized with biochar, *Cienc. Rural*, 2017, **47**(11), DOI: [10.1590/0103-8478cr20170220](https://doi.org/10.1590/0103-8478cr20170220).
- 174 N. R. Pandit, J. Mulder, S. E. Hale, V. Martinsen, H. P. Schmidt and G. Cornelissen, Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil, *Sci. Total Environ.*, 2018, **625**, 1380–1389.
- 175 M. F. Seleiman, Y. Refay, N. Al-Suhaibani, I. Al-Ashkar, S. El-Hendaw and E. M. Hafez, Integrative effects of rice-straw biochar and silicon on oil and seed quality, yield and physiological traits of *Helianthus annuus* L. grown under water deficit stress, *Agron*, 2019, **9**, 637.
- 176 T. S. Roy, M. T. Rahaman, R. Chakraborty, M. Mostofa and M. S. Rahaman, Effect of Biochar Application as a Soil Amendment on Growth and Yield of Sesame (*Sesamum indicum* L.), *Bangladesh Agron. J.*, 2019, **22**, 113–127.
- 177 Z. M. Solaiman, M. I. Shafi, E. Beamont and H. M. Anawar, Poultry litter biochar increases mycorrhizal colonisation, soil fertility and cucumber yield in a fertigation system on sandy soil, *Agriculture*, 2020, **10**, 480.
- 178 H. P. Schmidt, B. H. Pandit, V. Martinsen, G. Cornelissen, P. Conte and C. I. Kammann, Fourfold increase in pumpkin yield in response to low-dosage root zone application of urine-enhanced biochar to a fertile tropical soil, *Agriculture*, 2015, **7**, 723–741.
- 179 D. She, X. Sun, A. H. Gamareldawla, E. A. Nazar, W. Hu, K. Edith and S. E. Yu, Benefits of soil biochar amendments to tomato growth under saline water irrigation, *Sci. Rep.*, 2018, **8**, 14743.
- 180 A. O. Adekiya, T. M. Agbede, A. Olayanju, W. S. Ejue, T. A. Adekanye, T. T. Adenusi and J. F. Ayeni, Effect of biochar on soil properties, soil loss, and cocoyam yield on a tropical sandy loam Alfisol, *Sci. World J.*, 2020, **2020**.
- 181 I. Haider, M. A. Raza, R. Iqbal, M. U. Aslam, M. Habib-ur-Rahman, S. Raja, M. T. Khan, M. M. Aslam, M. Waqas and S. Ahmad, Potential effects of biochar application on mitigating the drought stress implications on wheat (*Triticum aestivum* L.) under various growth stages, *J. Saudi Chem. Soc.*, 2020, **24**, 974–981.
- 182 S. Kanwal, N. Ilyas, S. Shabir, M. Saeed, R. Gul, M. Zahoor, N. Batool and R. Mazhar, Application of biochar in mitigation of negative effects of salinity stress in wheat (*Triticum aestivum* L.), *J. Plant Nutr.*, 2018, **41**, 526–538.
- 183 Y. Hafez, K. Attia, S. Alamery, A. Ghazy, A. Al-Doss, E. Ibrahim, E. Rashwan, L. El-Maghraby, A. Awad and K. Abdelaal, Beneficial effects of biochar and chitosan on antioxidative capacity, osmolytes accumulation, and anatomical characters of water-stressed barley plants, *Agronomy*, 2020, **10**, 630.
- 184 M. A. Mannan, E. Halder, M. A. Karim and J. U. Ahmed, Alleviation of adverse effect of drought stress on soybean (*Glycine max.* L.) by using poultry litter biochar, *Bangladesh Agron. J.*, 2016, **19**, 61–69.
- 185 D. Egamberdieva, V. Shurigin, B. Alaylar, H. Ma, M. E. Müller, S. Wirth, M. Reckling and S. D. Bellingrath-Kimura, The effect of biochars and endophytic bacteria on growth and root rot disease incidence of *Fusarium* infested narrow-leaved lupin (*Lupinus angustifolius* L.), *Microorganisms*, 2020, **8**, 496.
- 186 V. Parkash and S. Singh, Potential of biochar application to mitigate salinity stress in eggplant, *Hortic. Sci.*, 2020, **55**, 1946–1955.
- 187 D. Jabborova, K. Annapurna, S. Paul, S. Kumar, H. A. Saad, S. Desouky, M. F. Ibrahim and A. Elkelish, Beneficial features of biochar and arbuscular mycorrhiza for improving spinach plant growth, root morphological traits, physiological properties, and soil enzymatic activities, *J. Fungi*, 2021, **7**, 571.
- 188 M. E. Hussien Ibrahim, A. Y. Adam Ali, G. Zhou, A. M. Ibrahim Elsidig, G. Zhu, N. E. Ahmed Nimir and I. Ahmad, Biochar application affects forage sorghum under salinity stress, *Chil. J. Agric. Res.*, 2020, **80**, 317–325.
- 189 A. Abewa, B. Yitafaru, Y. G. Selassie and T. Amare, The role of biochar on acid soil reclamation and yield of Teff (*Eragrostis tef* [Zucc] Trotter) in North western Ethiopia, *J. Agric. Sci.*, 2014, **6**, 1.
- 190 M. Zafar-ul-Hye, M. Tahzeeb-ul-Hassan, A. Wahid, S. Danish, M. J. Khan, S. Fahad, M. Brtnicky, G. S. Hussain, M. L. Battaglia and R. Datta, Compost mixed fruits and vegetable waste biochar with ACC deaminase rhizobacteria can minimize lead stress in mint plants, *Sci. Rep.*, 2021, **11**, 1–20.
- 191 A. Caroline, J. Debode, B. Vandecasteele, T. D'Hose, P. Cremelie, A. Haegeman, T. Ruttink T, P. Dawyndt and M. Maes, Biological, physicochemical and plant health responses in lettuce and strawberry in soil or peat amended with biochar, *Appl. Soil Ecol.*, 2016, **107**, 1–2.
- 192 D. Pandey, A. Daverey and K. Arunachalam, Biochar: Production, properties and emerging role as a support for enzyme immobilization, *J. Cleaner Prod.*, 2020, **255**, 120267.

