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Biochar implications in cleaner agricultural production and environmental sustainability

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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_2 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_2 (C eq.) y^{-1} in the soil system. Furthermore, biochar application improves soil health, which facilitates the plant growth and crop productivity. Biochar application can alters the plant physiology and makes the plant system more tolerant against biotic and abiotic stresses. Biochar is also an excellent *in situ*-sorbent 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.

Environmental significance

Biochar production and utilization is proposed as an innovative solution for climate change mitigation by reducing/offsetting anthropogenic CO_2 emissions. Biochar is an excellent carbon neutral material; one tonne biochar production can permanently remove ~2.68 Mg CO_2eq. from the atmosphere. Biochar curtails 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. Furthermore, biochar application decreases soil bulk density (ρ_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 degredation 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.[1] This indicates that

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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.[2]

Globally, anthropogenic activities added ∼16 Pg C (1 Pg = 1 billion metric tonnes) to the environment annually, which corresponds to 24% net primary productivity.[3,4] Human-induced CO_2 emission increases by >3% per annum, which puts Earth on an irreversible climate change track.[5] Agricultural production systems contribute about 10–14% of the total GHG emissions,[6] which is likely to be increased to 50% by 2030.[7] 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.[8] The initiative of "4 per 1000" was launched by the United Nations Framework Convention on Climate Change[9] 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.[10] Unscientific biomass management practices like field burning and open dumping causes environmental and human health issues.[11] Field fire impairs the air quality, posing health hazards, like skin/eyes irritation, asthma, bronchitis, emphysema, and cancer.[12] Modern technology-lead biomass valorization can potentially increase the farmer's income, energy security and environmental and soil quality.[13,14] 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.[15,16] Biochar applications in agricultural production systems are attaining immense importance due to its economic and environmental benefits.[17] Biochar can potentially be considered an innovative tool to address the food insecurity and environmental issues by improving soil health,[18] crop productivity,[19] curtailing GHG emissions[20] and water pollution.[21] 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.[22,23] Additionally, modern technology-lead agri-waste-pyrolysis yielded syngas, bio-oil, and biochar.[24] Traditional biochar production methods emit more methane (CH_4), N_2O, soot, or volatile organic compounds, which causes excess C payback time and is also hazardous to health.[25,26] Utilizing biomasses as biochar *via* pyrolysis and hydrothermal carbonation reported superiority in terms of GHG reduction over traditional methods.[21] Biochar is a solid C-rich pyrolyzed (250 and 900 °C) biomass material produced under oxygen-free condition.[17] It is a superior C carbon source and has better nutrient retention capacity over other C sources.[27]

Biochar helps in two ways to reduce the atmospheric CO_2: (1) by its production and (2) by sequestering atmospheric CO_2 in soil.[28–30] It is possible to offset up to 1.8 Pg CO_2eq. (Penta gram carbon dioxide equivalent) per annum through biochar, compared to 15.4 Pg CO_2eq. emitted annually.[4] However, inconsistent reports are also available on the GHG emission mitigation potential of biochar. For instance, biochar-amended soil had higher CO_2 and N_2O emissions due to the carbonaceous nature and quality of biochar feedstock.[31] Another study suggested that biochar application did not have any significant effect on CO_2 emission from paddy and chestnut soils in China. This was mainly due to the soil and feed stock attributes.[32] However, biochar application at the rate of 30 Mg ha^{-1} reduces CO_2 emission by 31.5% and 7.2% in forest and agricultural soils, respectively.[33] Long-term biochar application decreases CH_4 emission.[34] However, short-term applications induced CH_4.[35] Biochar application induced CO_2 emission by 22.14% and decreased N_2O emission by 30–38%, and did not influence the CH_4 emission.[36,37] 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.[38,39] Overall, soil-applied biochar improves agricultural and environmental sustainability.[40]

Biochar application decreases soil bulk density (ρ_b), and enhances soil productive capacity and plant growth.[41,42] Biochar application modulates the soil health, resulting in higher crop yields.[43–46] Liu *et al.* (2013)[47] 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 deterimental effect on plant growth.[48] Abukari *et al.* (2021) showed that application of biochar at the rate of 30 Mg ha^{-1} enhanced legume productivity by 30%, vegetable yield by 29%, and cereal yield by 7–8% over no biochar.[49] The addition of recalcitrant C in the soil enhances the soil-water-nutrient holding capacity, which promotes crop growth.[50] 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.[50–52] Continuous biochar application with the rate of 11.25 Mg ha^{-1} in both crops under a maize-wheat system for five years fixes 182.3 Mg ha^{-1} CO_2 over the control plot.[53] Short-term biochar application at the rate of 7.5 Mg ha^{-1} 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.[54,55] Still, the biochar interaction with SOC changes over time, and the negative priming effect is nullified after 3–5 years of application.[28,53] One tonne SOC increment in cropland increases crop productivity by 50% and curtails atmospheric CO_2 by 5–15%.[28,53] Besides that, biochar also has the potential to suppress the plant pathogen by altering the soil microbiome structure.[46,56] Biochar reduces runoff losses, nutrients erosion, and soil pollutant loads,[52] and improves carbon sequestration. Overall, biochar is a potential solution to address the global food, energy, and environmental challenges.[57–59] 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 ∼22 Mg C ha^{-1}, and will result in a carbon payback time of ∼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.[11] 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.[60,61] 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 CO_2 and CH_4 emissions.

Pyrolysis converts cellulosic carbons into more stable aromatic carbons, which can subsequently be customized for diverse agricultural uses.[62] Biochar production from crop biomass is performed by the dry pyrolysis process in the absence of oxygen at high temperatures.[41] Thermochemical conversion techniques, including gasification, pyrolysis, hydrothermal carbonization, and torrefaction, are the most commonly used practices for biochar production.[47,63] Pyrolysis is the most commonly used technique for biochar production.[64] 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.*[65,66] Biochar production at higher temperatures is reported to have a higher surface area and pore volume than those produced at a lower temperature.[67] 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.[68,69] The temperature requirement in this process for converting biomass into biochar is comparatively lower than pyrolysis.[70] Biochar produced through HTC has less surface area and is not ideal for agricultural use as compared to biochar produced by pyrolysis.[71] However, the HTC is an energy-efficient process and operates at lower temperatures with higher biochar recovery.[72] Biochar produced through pyrolysis has higher surface areas than that produced through hydrothermal carbonation. Liquid biofuels and syngas, such as CH_4, C_2H_6, CO, CH_4, and H_2, are the co-biochar products resulting from pyrolysis and hydrothermal carbonation.[71,73–75]

3. Effect of biochar on crop productivity

Biochar application in agriculture improves crop yield by altering soil properties and enhancing the SOC content.[76,77] Improvement in soil quality and tolerance in plants against biotic and abiotic stresses due to biochar application is responsible for improvements in agricultural production.[78] The increased crop yields from biochar application are linked to improved soil quality.[79] Biochar improves carbon sequestration, soil quality, and crop growth significantly.[80] Biochar application in nutrient-deficient and degraded soils increases agricultural productivity.[81] Application of eucalyptus-based biochar at the rate of 50 Mg ha^{-1} increases maize productivity by 48–50% in acidic soils of humid tropical condition.[82] 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.[83] The delayed production of an organic layer on the biochar surface during aging helps to retain nutrients, and may account for the higher yield.[84,85] Biochar increases soil structure, fertility, nutrients use efficiency (NUE), and crop yields.[86,87] 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.[88,89] Biochar application at a rate of 20 Mg ha^{-1} increased nutrient uptake and chlorophyll concentrations in pumpkin plants.[90] 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
Cereals				
Hunan province, China	Rice	Rice husk biochar (20 t ha^{-1})	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		Straw biochar (20 Mg ha^{-1})	The grain yield was 2.91–19.4% higher over urea application at 200 kg ha^{-1}	33
Sumatra, Indonesia	Maize	Cacao shell biochar (15 Mg ha^{-1})	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^{-1})	27% and 16%, increment in grain and shoot biomass yield over control, respectively	170
Pulses				
Kumasi, Ghana	Cowpea	Corn cob feedstock (5 Mg ha^{-1})	Increased seed yield by 36% over control	78
Lake Victoria basin, Kenya	Soybean	*Accasia* spp. wood biochar (100 Mg ha^{-1})	Increased seed yield by 0.43 t ha^{-1} over control	171
Bule wereda, Southern Ethiopia	Garden pea	*Lantana camara* biochar (12 Mg ha^{-1})	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^{-1} soil)	Enhanced pod yield by 15% over 50% RDF alone	116
Oilseeds				
Rasuwa, Nepal	Mustard	*Eupatorium adenophorum* shrub biochar (40 Mg ha^{-1})	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^{-1})	Increased seed yield by 21% over fertilizer alone	94
Dhaka, Bangladesh	Sesamum	Biochar (6 Mg ha^{-1})	18.8% higher yield over control	176
Vegetables				
Geraldton, Western Australia	Cucumber	Poultry litter biochar (PLB) (13 Mg ha^{-1})	Application of PLB + poultry manure (9 Mg ha^{-1}) + nitrophos (5 Mg ha^{-1}) increased cucumber yield by 300% over PLB (1 Mg ha^{-1}) + poultry manure (2 Mg ha^{-1}) + nitrophos (13 Mg ha^{-1})	177
Dhading, Nepal	Pumpkin	*Eupatorium adenophorum* 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^{-1})	Increased economic yield by 9% over hardwood biochar (10 Mg ha^{-1})	180

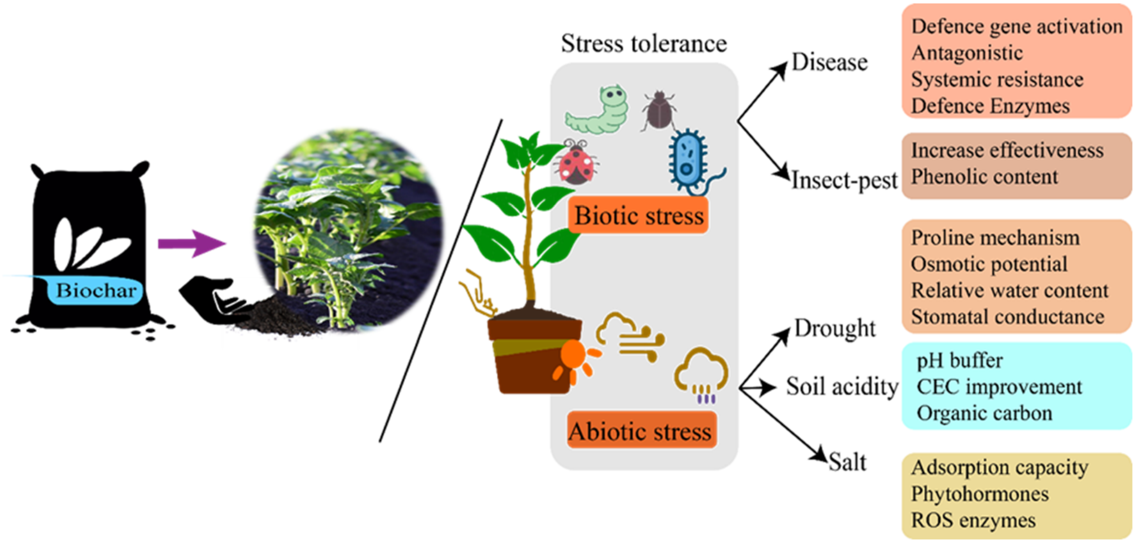

Fig. 1 Biochar modulates soil condition and plant physiology.

photosynthesis, and relative water content in dry conditions.[91] The high adsorption capacity of salt makes biochar an excellent ameliorant for the reclamation of the degraded salt-affected region.[92] 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.[82] Biochar facilitates the absorption of an array of soil contaminants owing to its high surface area, porosity, and adsorption ability.[93] The plants' physiological and biochemical properties were altered due to biochar application, which helps to combat the multiple stresses.[94] 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.[87,94] It also enhances the gas exchange ability of crop leaves and reduces oxidative stress.[95] 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.[96] The biochar application geared the acquired and induced systemic resistance pathways, giving the soil a broad-spectrum disease-controlling potential.[97] Biochar generated from green waste and wood waste was used to reduce early blight growth in tomatoes.[91] 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.[98] 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.[99,100] Hence, the application of an innovative product like biochar is highly warranted to address the complex issue of soil quality and agricultural productivity.[2,101] Biochar addition modulates the soil biology, chemistry, and physical properties.[10] 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.[2,102] The effects of the biochar is variable; it works efficiently in acidic, but deteriorated coarse textures soils.[103] 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.[86,101] However, contrary to these, some adverse effects of biochar at higher doses have also been documented.[104]

5.1 Effect of biochar on soil physical properties

Biochar application has shown a differential effect on soil physical properties like bulk density (ρ_b), porosity, hydraulic conductivity, and soil color under diverse soil and climate types.[104,105] The ρ_b is an important physical soil parameter that controls nutrient availability, porosity, and compactness of the soil. Biochar is a porous material having less ρ_b (0.3 to 0.6 Mg m^{-3}) 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
Cereals				
Changsha, China	Rice	Rapeseed stover biochar 40 g kg^{-1} 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^{-1} 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
Matatirtha, Nepal	Maize	*Eupatorium adenophorum* biochar (2%)	Increased nutrient availability in acidic soils in nutrient-stressed condition	174
El-Gharbia, Egypt	Barley	Biochar (20 Mg ha^{-1})	Reduced electrolyte leakage, lipid peroxidation, and proline levels reduce drought stress	183
Pulses				
Henan, China	Soybean	Wheat straw biochar (10 g kg^{-1} soil)	Significantly increased water use efficiency by 27.5% over control	41
Gazipur, Bangladesh		Poultry litter biochar (50 Mg ha^{-1})	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 *Pseudomonas putida* and *Stenotrophomonas pavanii* survived better in the rhizosphere	185
Vegetables				
Rishon Lezion, Israel	Tomato	Pepper plant waste biochar (3%)	Enhanced resistance against *Fusarium oxysporum* f. sp. *radicis lycopersici*	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
Forage				
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^{-1})	Lowering exchangeable soil acidity reduced the negative effects of soil acidity on plants	189
Others				
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 *Botrytis cinerea*	191

biochar production influence the ρ_b of the biochar. Hence, the reduction in ρ_b is entirely driven by soil condition, the dose, and the properties of biochar applied. Application of woodchip biochar decreases the ρ_b of planosol by 5.1% over the control.[2] The response of the biochar on ρ_b is more effective in light soil than in heavy soils.[106,107] Biochar addition promotes soil fungal growth, as well as microbial activities, resulting in soil agglomeration, along with profuse root development, subsequently reducing ρ_b.[108] The positive effect of biochar on soil porosity and hydraulic conductivity have also been reported by many researchers.[66,109] The aggregate formation and stability index of silty loam, sandy loam, silty clay, and clay soils had been improved with biochar application,[110] while no change was reported in sandy loam soil.[34] 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.[111] Biochar application reduces the ρ_b, which alters soil porosity and nutrient availability, resulting in higher above and below-ground biomass.[112] 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.[2,113] 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.[114] In sandy soil, the application of biochar significantly reduced the saturated hydraulic conductivity due to more water retention in a single layer.[115]

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.[116] The post-green revolution era created a multi-nutrient deficiency in soil due to the global continuous overuse of straight fertilizers.[117] A healthy soil environment plays a pivotal role not only in good plant growth, but also in higher productivity.[6] 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.[105] Over a long term (>5 years), biochar additions enhanced the soil organic matter (46%), which is the basis for the nutrients mineralization process.[118] The necessary mineral nutrients contained in the biochar keep helping the plants by providing continuous flow from soil to the plants.[105] 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.[119] 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).[100] Biochar application reduces the concentration of Al^{3+} and H^+ in the ions in acidic soils.[120]

A large variation in biochar applications ranging from 10 to 150 Mg ha^{-1} in soil has been reported in many studies. However, the economic feasibility was mostly observed in the range between 20 and 30 Mg ha^{-1}.[32] 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.[18,121,122] 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.[123] 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.[124] 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.[125] 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,[126] as well as other sources of toxic effluents.[101] The biochar with a large specific surface area and diverse negatively charged anions suitably immobilized the inorganic pollutants in soil.[127] The mobility of heavy metals in soil is reduced due to adsorption, ion exchange, and stabilization with the formation of organometallic compounds.[128] The combined application of biochar along with compost help in the immobilization of toxic materials in heavy metal polluted soils.[123,129] Rodríguez-Vila *et al.* (2016)[124] 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.[18,130] 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.[123] Furthermore, due to the nutrients chelating properties, biochar application reduces the nutrient leaching in the soil system.[10]

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.[129] Soil microbial diversity is directly related to the soil's physicochemical properties.[33] 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.[18,131] 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.[132] 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.[133] Biochar application significantly enhanced the soil MBC and MBN.[126] 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.[134] The addition of biochar developed from pine-woods and grass as feedstock has decreased the β-glucosidase and phosphate activities in soil.[135] In contrast, Oladele *et al.* (2019)[19] reported that the activities of alkaline phosphatase, urease, invertase, and catalase have been increased with the addition of rice husk biochar (12 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 CO_2 emission from fossil fuel usage and land-use change.[99] Soil carbon sequestration is the trapping of CO_2 from the atmosphere, and storing it in the soil in more stable forms.[136,137] As a climate change extenuation approach, carbon sequestration is a simple and robust technique to track national carbon accounting.[138,139] Furthermore, carbon sequestration facilitates the conversion of biomass into the recalcitrant soil C pool and lowers the 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.[29,136] Biochar is an excellent carbon neutral material. A total of 2.879 Mg CO_2eq. is embodied in a tonne of biochar (dry basis), and one tonne biochar production can permanently remove ∼2.68 Mg CO_2eq. from the atmosphere.[140] 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 ∼0.92 Mg CO_2eq. from the atmosphere,[141] while conversion of one tonne forestry residue sequesters 2.74 Mg CO_2eq.[142] Furthermore, it has been estimated that by 2050, the carbon removal potential of biochar will be about 0.3–2 Gt CO_2 y^{-1}.[143] It has been predicted that the use of biochar can offset anthropogenic CO_2 emissions by up to 12%.[4] Some studies reported that biochar can sequester carbon by up to 2.27 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 CO_2 in soils, and thereby reducing excess CO_2 from the atmosphere.[27] As a result, it may be a viable alternative strategy for sequestering more CO_2 from crop wastes than traditional agricultural practices, which result in rapid carbon mineralization and increased CO_2 release into the atmosphere.[144] The carbon sequestration potential of biochar lies between 0.7 and 1.8 Gt CO_2eq. y^{-1}.[51,145] 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.[146] However, the C content of biochar mainly depends on the types of processing (heating temperature of pyrolysis) and types of feedstock used.[145,147] The C content of biochar tends to rise as the production temperature rises. However, the biochar produced at 500 °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.[148] Biochar made from wheat straw at 500 °C had a higher carbon content (662 g kg^{-1}) than biochar made at 300 and 400 °C.[149] With an increase in product temperature from 350 to 500 °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.[150] 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 CO_2 emissions when burned.[146,151]

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.[150] However, the organo-mineral complex formation is the main mechanism of C stabilization in the soil after biochar application.[53] The size of the biochar particles, stability, and interaction with soil particles and environments determine the C residence time in the soil.[8,151] Biochar adds more carbon to the passive pool of stable or inert carbon, which is less prone to degradation.[152] The 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.[99] 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 CH_4 uptake.[133,153] 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.[154,155] Likewise, *Eucalyptus saligna* pyrolysis at 550 °C resulted in lower SOC mineralization by 5.5% over the control.[156] Application of biochar at the rate of 4.2 Mg ha^{-1} y^{-1} increases the soil C storage of

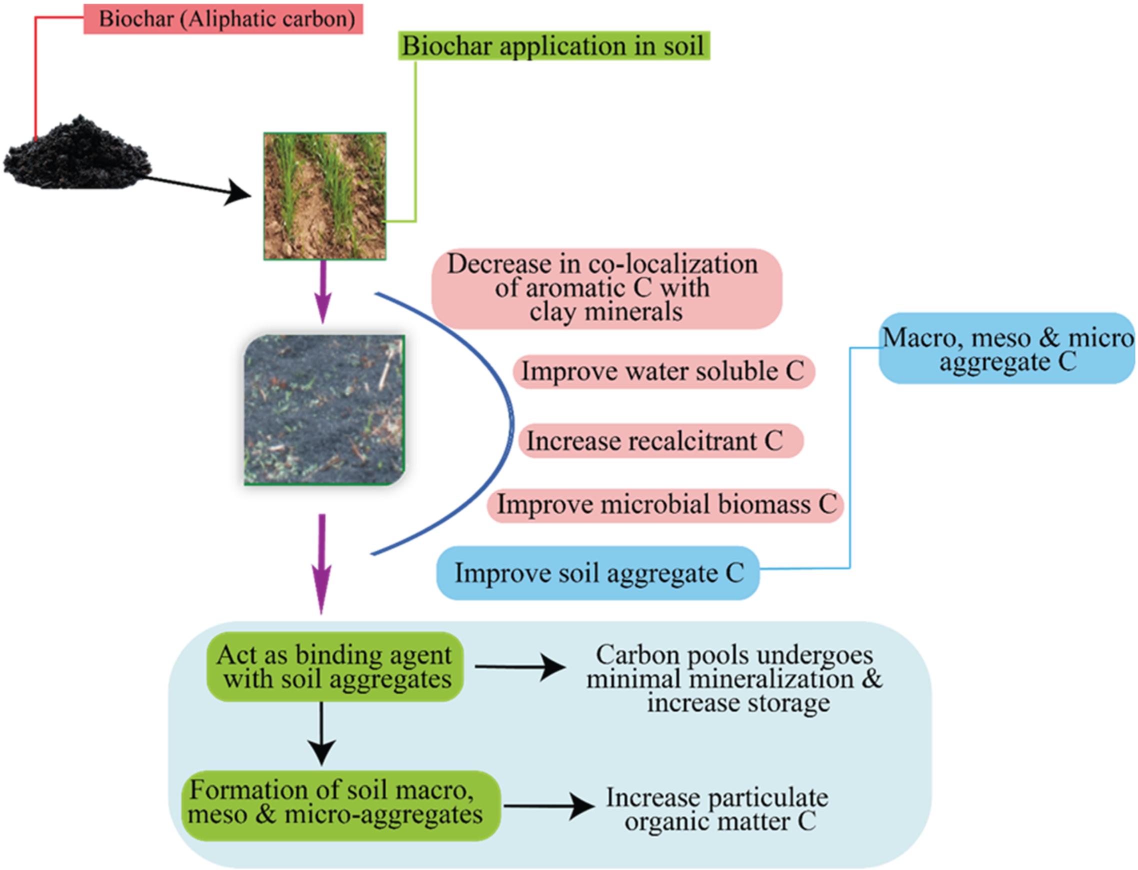

Fig. 2 Possible mechanism of carbon sequestration by biochar inside the soil.

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

7. Biochar and GHG emission mitigation

Crop residue burning generates a huge amount of greenhouse gases (GHG), especially CO_2, CO, and CH_4. The burning of one tonne rice straw produces ~3 kg of particulate organic matter (POM), 1460 kg of CO_2, 60 kg of CO, 199 kg of ash, and 2 kg of SO_2.[152] 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,[159] but the effect of biochar on GHG emission mitigation is variable (Table 3). Priyadarshani and Prabhune (2009)[160] suggested that biochar could help to reduce greenhouse gas emissions by 2–4% out of the 1900 million tonnes of CO_2 in India. Biochar curtails 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.[161] The beneficial impacts of biochar application in terms of GHG emission reduction were previously reported by several researchers.[137,152] In contrast, He *et al.* (2018)[36] found that incorporation of biochar enhanced soil CO_2 fluxes by 22.14%, but lowered N_2O fluxes by 30.92% and had no effect on CH_4 fluxes. Biochar reduces the capacity of the soil to produce N_2O by causing microbial immobilization of the available nitrogen in the soil.[162] Biochar reduced the cumulative N_2O by 52–84% and NO by 47–67% emissions, as compared to those of chemical fertilization.[163] Biochar can thus be used in conjunction with mineral fertilizers to reduce N_2O emissions, while not interfering with mineralization or nitrification processes. Furthermore, at high pyrolysis temperatures, N_2O 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 Mg ha^{-1} (pyrolyzed at 600 °C) and nitrogen-rich litter reduces N_2O emissions by 42% over the control.[164] Biochar application increases soil pH, restrains nitrate reductase activity, and reduces N_2O emission.[32] According to Yanai *et al.* (2007),[165] biochar application reduces N_2O emissions by 85% over the control. Application of biochar at the rate of 20 and 40 Mg ha^{-1} in rice-wheat systems reduced N_2O emissions by 19.55% and 26.35%, respectively, over the control.[126] However, a lower dose of biochar with the rate of 20 Mg ha^{-1} resulted in an 8.89% higher N_2O emission than the control, whereas increasing the biochar dose from 20 Mg ha^{-1}

Table 3 Impact of biochar application on greenhouse gases emission[a]

				Impact on greenhouse gases (percent) reduction (−) or increase (+) over control			
Biochar material	Tested crops	Pyrolysis temperature (°C)	Rate of biochar application (Mg ha^{-1})	N_2O	CO_2	CH_4	Reference
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	

[a] *AWD-alternate wetting and drying; **CF-continuous flooding.

to 40 Mg ha^{-1} led to 26.06% lower N_2O emission.[158] The amount of biochar incorporated also has a tenacious impact on soil N_2O emissions. Biochar promotes N_2O emission at lower rates of application, while it lowers N_2O emission at larger dosage.[158] Soil supplemented with biochar as an organic amendment is reported to reduce CH_4 emissions.[115,158] Biochar improves soil aeration, reduces denitrification, and increases CH_4 sink capacity,[152] thereby retarding the CH_4 emission. The near-complete suppression of CH_4 emissions was noticed in soybean crops supplemented with biochar in acidic soil of Eastern Colombian Plains.[166] Biochar application at the rate of 20 and 40 Mg ha^{-1} in rice-wheat systems reduced the CH_4 emission in rice by 11.19–17.45% over the control.[126] 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 constitutes and other applied inputs, like manure and fertilizers, *etc.*[158]

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.[140] 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.[143] 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)[143] 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.[143] 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.[143]

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; Devideen 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.

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