Sustainable Agriculture Reviews 61

Shah Fahad · Subhan Danish
Rahul Datta · Shah Saud
Eric Lichtfouse *Editors*

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Biochar to Improve Crop Production and Decrease Plant Stress under a Changing Climate

Springer

Sustainable Agriculture Reviews

Volume 61

Sustainable agriculture is a rapidly growing field aiming at producing food and energy in a sustainable way for humans and their children. Sustainable agriculture is a discipline that addresses current issues such as climate change, increasing food and fuel prices, poor-nation starvation, rich-nation obesity, water pollution, soil erosion, fertility loss, pest control, and biodiversity depletion.

Novel, environmentally-friendly solutions are proposed based on integrated knowledge from sciences as diverse as agronomy, soil science, molecular biology, chemistry, toxicology, ecology, economy, and social sciences. Indeed, sustainable agriculture decipher mechanisms of processes that occur from the molecular level to the farming system to the global level at time scales ranging from seconds to centuries. For that, scientists use the system approach that involves studying components and interactions of a whole system to address scientific, economic and social issues. In that respect, sustainable agriculture is not a classical, narrow science. Instead of solving problems using the classical painkiller approach that treats only negative impacts, sustainable agriculture treats problem sources.

Because most actual society issues are now intertwined, global, and fast-developing, sustainable agriculture will bring solutions to build a safer world. This book series gathers review articles that analyze current agricultural issues and knowledge, then propose alternative solutions. It will therefore help all scientists, decision-makers, professors, farmers and politicians who wish to build a safe agriculture, energy and food system for future generations.

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Preface

The predicted increase in the frequency of extreme climate events such as drought and floods is threatening agricultural production and food security worldwide. Extreme climate events are degrading soil health and properties, and increasing plant stress from heat and pests. These issues can be partly alleviated by application of biochar to soils. Biochar is a carbon-neutral, porous carbonaceous material produced by pyrolysis of modern biomass and organic waste. Application of biochar to soils has several benefits such as improving crop productivity and soil structure, and storing nutrients and water (Fig. 1). Biochar also decreases plant stress from heat, drought, diseases and pollution. Biochar provides habitat for soil microbial communities. Adding biochar to soils is also indirectly offsetting the negative effects of climate change by sequestrating stable carbon in the long run. This book reviews the major benefits of biochar amendment to soils, with emphasis on climate extremes and arid land. The 16 chapters are sorted into 4 parts: improvement of crop yield, alleviation of plant stress, improvement of soil health and microbial interactions.

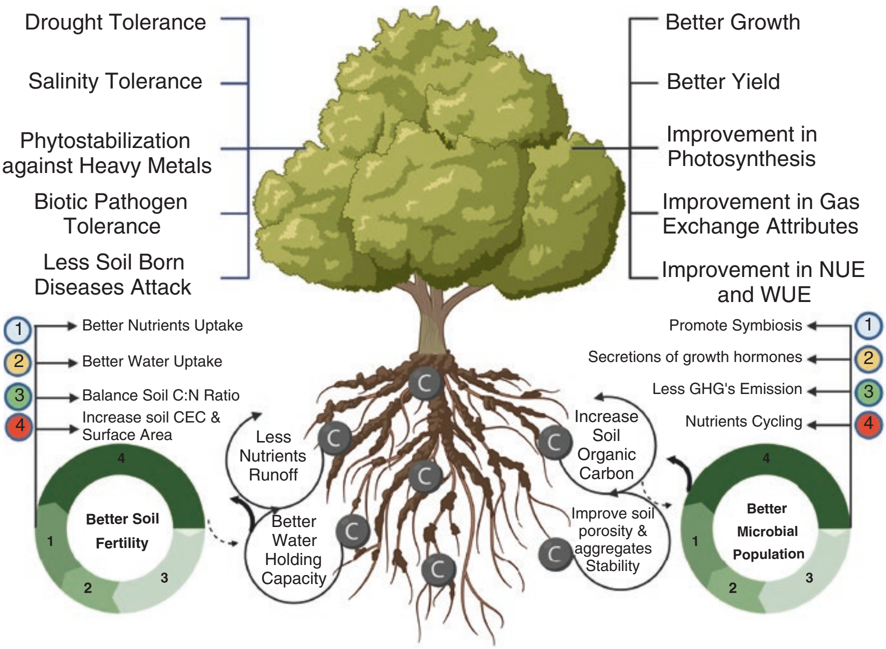

Fig. 1 Major benefits of adding biochar to soils. Biochar is symbolized as a 'C' for carbon. *CEC* cation exchange capacity, *NUE* nitrogen use efficiency, *WUE* water use efficiency, *GHG* greenhouse gas

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Contents

Part II Alleviation of Plant Stress

Part III Improvement of Soil Health

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Subhan Danish has completed a PhD in Agriculture Soil Science from the Bahauddin Zakariya University in Pakistan. He has expertise in soil microbiology, phytoremediation of heavy metals, biochar use as an amendment and plant nutrition. He has published 72 research articles. He is guest editor of the journal *Sustainability*. He got a Gold Medal in MSc Hons and was awarded Role of Honor for Best Debater at provincial level and interdepartmental university level.

Rahul Datta is a soil microbiologist and enzymologist holding an MSc and PhD from the Department of Geology and Pedology at Mendel University in Brno, Czech Republic, where he is currently a researcher. He has acquired global experience in soil science research by working at the Ohio State University, USA, and at the University of Florence, Italy. He has published numerous research articles and a book. He is editorial board member of the *Journal of Open Agriculture*.

Shah Saud received his PhD and post doctorate in turf grasses, horticulture, from the Northeast Agricultural University, Harbin, China. He is currently working as Assistant Professor in the College of Life Science, Linyi University, China. He has published over 200 articles, edited 8 books and written 60 book chapters on plant physiology, plant stress responses and environmental problems in relation to agricultural plants.

Eric Lichtfouse is Professor at Xi'an Jiaotong University, China, and Chief Editor founder of the journal *Environmental Chemistry Letters* and the series Sustainable Agriculture Reviews. He has invented carbon-13 dating, a method allowing to measure the relative age of organic molecules in complex media, and has discovered temporal pools of individual substances in soils. He has written about 400 publications and has awards in analytical chemistry and scientific editing. He is teaching scientific writing and communication, and has written the book *Scientific Writing for Impact Factor Journals*. He is XTerra Vice-Champion in his age category.

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Part I
Improvement of Crop Yield

Chapter 1
Biochar Application for Improving the Yield and Quality of Crops Under Climate Change

Debjyoti Majumder, Salil Saha, Bishal Mukherjee, Suddhasuchi Das, F. H. Rahman, and Akbar Hossain

Abstract Global climate change, which is mainly caused by industrialized nations, has a negative impact on the agricultural production of poor and emerging countries, calling for mitigating strategies to reduce fertiliser inputs and greenhous gas emissions. Increasing carbon sequestration in soils can be done by reduced tillage and application of biochar and straw. Here we review the use of biochar application to soil with focus on biochar synthesis, bioenergy, carbon sequestration, soil quality, greenhouse gases, nutrient retention, pesticide decontamination, water management, crop yield, and economy. We also discuss drawbacks of biochar application.

Keywords Biochar · Climate change · Sustainable agriculture · Greenhouse gas · Carbon sequestration

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Abbreviations

AMF	Arbuscular mycorrhizal fungi
BNF	Biological N fixation
FYM	Farm yard manure
GWP	Global warming potential
IPCC	Inter governmental panel on climate change
IWUE	Irrigation water use efficiency
NUE	Nutrient use efficiency
PUE	Phosphorus use efficiency
RUE	Relative water contents
SAR	Sodium adsorption ratio
USEPA	United States Environmental protection Agency
WHC	Water holding capacity
WUE	Water use efficiency

1.1 Introduction

Climate change is defined as deviations from the average atmospheric state produced by both natural and anthropogenic forces such as the orbit of the earth's revolution, volcanic activity, and crustal motions (Arunanondchai et al. 2018; Yang et al. 2022; Ahmad et al. 2022; Shah et al. 2022; Muhammad et al. 2022; Wiqar et al. 2022; Farhat et al. 2022; Niaz et al. 2022). Climate change by global warming, or the average increase in global temperature, has become a major issue, a megatrend that will result in significant future world developments. Devastating environmental changes have harmed natural systems, human health, and agricultural production (Ihsan et al. 2022; Chao et al. 2022; Qin et al. 2022; Xue et al. 2022; Ali et al. 2022; Mehmood et al. 2022; El Sabagh et al. 2022; Ibad et al. 2022).

Warming of weather and climate systems can lead to significant changes in the occurrence of severe events, such as temperature increases and irregular rainfall patterns (Ahmad et al. 2018; Al-Zahrani et al. 2022; Rajesh et al. 2022; Anam et al. 2021; Deepranjan et al. 2021; Haider et al. 2021; Amjad et al. 2021; Sajjad et al. 2021a, b). The number of stress episodes, their influence on daily living, and damage to crops are used to evaluate the effects of climate change and environmental variation (FAO 2018; Reckling et al. 2018; Deepranjan et al. 2021; Haider et al. 2021; Huang et al. 2021; Ikram et al. 2021; Jabborova et al. 2021; Khadim et al. 2021a, b; Muzammal et al. 2021). The two major challenges of the twenty-first century are climate change and food insecurity (Fakhre et al. 2021; Khatun et al. 2021; Ibrar et al. 2021; Bukhari et al. 2021; Haoliang et al. 2022; Sana et al. 2022; Abid et al. 2021; Zaman et al. 2021; Sajjad et al. 2021a, b; Rehana et al. 2021). Malnutrition affects approximately 815 million people, making it difficult for sustainable development projects to fulfil the universal objective of ending hunger by

2030 (Hafeez et al. 2021; Khan et al. 2021; Kamaran et al. 2017; Safi et al. 2021; Sajjad et al. 2019; Saud et al. 2013, 2014, 2016, 2017; 2020, 2022a, b; Shah et al. 2013). In 2050, the world's population is predicted to reach around 9 billion people, resulting in an 85% increase in food demand (FAOSTAT 2017; Richardson et al. 2018; Aziz et al. 2017a, b; Chang et al. 2021; Chen et al. 2021; Emre et al. 2021; Habib Ur et al. 2017; Hafiz et al. 2016; Hafiz et al. 2019; Ghulam et al. 2021; Guofu et al. 2021). Current cropping systems with little variety and high input concentrations, as well as unstable production due to environmental changes in crops, exacerbate climatic influences (Saboor et al. 2021a, b; Ashfaq et al. 2021; Amjad et al. 2021; Atif et al. 2021; Athar et al. 2021; Adnan et al. 2018a, b; Adnan et al. 2019; Akram et al. 2018a, b).

Agricultural yields in underdeveloped nations are primarily harmed by adverse environmental circumstances, therefore high temperatures and CO_2 accumulation forced scientists to find new techniques to deal with fewer predictable difficulties (Zafar-ul-Hye et al. 2021; Adnan et al. 2020; Ilyas et al. 2020; Saleem et al. 2020a, b, c; Rehman et al. 2020; Farhat et al. 2020; Wu et al. 2020; Mubeen et al. 2020; Farhana et al. 2020; Jan et al. 2019; Wu et al. 2019; Ahmad et al. 2019; Baseer et al. 2019; Hafiz et al. 2018; Tariq et al. 2018). Evidence suggests that high temperatures and variable rainfall distribution have a negative impact on crop output over the world (Lobell and Field 2011; Fahad and Bano 2012; Fahad et al. 2017). Agriculture is one of the most sensitive water sectors to climate change, as it is a major water consumer in both developing and developed countries (Farah et al. 2020; Sadam et al. 2020; Unsar et al. 2020; Fazli et al. 2020; Md. Enamul et al. 2020; Gopakumar et al. 2020; Zia-ur-Rehman 2020; EL Sabagh et al. 2020; Al-Wabel et al. 2020a, b). As per Inter governmental panel on climate change (IPCC 2013) temperature affects the rate of plant growth and development. The temperature ranges surrounding the plant and each species are represented by a minimum, maximum, and optimal (Chen et al. 2015; Adhikari et al. 2016).

Temperatures are expected to rise by 2–3 °C during the next 30–50 years. In a recent analysis of the effect of temperature extremes, frost and heat, on wheat (*Triticum aestivum* L.) (Amanullah et al. 2021; Rashid et al. 2020; Arif et al. 2020; Amir et al. 2020; Saman et al. 2020; Muhammad et al. 2019; Md Jakir and Allah 2020; Mahmood Ul et al. 2021; Barlow et al. 2015), who found that frost caused sterility and abortion of produced grains, whereas excessive heat reduced grain number and lengthened the grain filling period. According to Majumder et al. (2016), increased water demands under warming scenarios will put more strain on water resources in north-west India thereby challenging crop stand. According to (IPCC 2007; Asseng et al. 2017; Ahmad et al. 2019; Hesham and Fahad 2020. Iqra et al. 2020; Akbar et al. 2020), daily minimum temperatures will rise faster than daily maximum temperatures; resulting in an increase in daily mean temperatures and an increased likelihood of extreme occurrences, which could have a negative impact on grain yield (Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b). Under future warmer and drier conditions, wheat production could be lowered by 3–10% (You et al. 2009; Mahar et al. 2020; Noor et al. 2020; Bayram et al. 2020; Amanullah and Fahad 2017, 2018a, b; Amanullah et al. 2020), winter wheat production could be reduced by 5–35% (Özdoğan 2011; Senol 2020; Amjad et al. 2020; Ibrar et al. 2020; Sajid et al. 2020; Muhammad et al. 2021; Sidra et al. 2021; Zahir et al. 2021; Sahrish et al. 2022), and maize yield could be reduced by 2.4–45.6% due to higher temperatures (Tao and Zhang 2010; Rosenzweig et al. 2014; Qamar-uz et al. 2017; Hamza et al. 2021; Irfan et al. 2021; Wajid et al. 2017; Yang et al. 2017; Zahida et al. 2017; Depeng et al. 2018; Hussain et al. 2020; Hafiz et al. 2020a, b; Shafi et al. 2020; Wahid et al. 2020; Subhan et al. 2020; Zafar-ul-Hye et al. 2020a, b). The current book chapter has unfolded a detailed outlook of global abatement potentials which reveals that biochar, as a "climate-friendly" agricultural solution; can be used to transform agriculture and land use (International biochar Initiatives (IBI 2009; Lehmann et al. 2015). Since, biochar is fine-grained charcoal that is applied to soils, which has been advocated largely by many earlier findings for mitigation of climate change though improvement of soil fertility leads to the betterment of crop health ultimately enhancing crop productivity. Although, there are significant concerns about the global impact, capability, and sustainability of biochar, which are highlighted in the current chapter.

1.2 Biochar Synthesis

Biochar is a product that is enriched with high carbon content which is prepared generally by burning fossils and remnants bio products under air tight conditions (Lehmann et al. 2009). Biochar is a "solid material that is manufactured from biomass decomposition under oxygen-depleted conditions" (Fig. 1.1, IBF 2009).

The production of biochar, in combination with its storage in soils, has been proposed as one method of lowering CO_2 levels in the atmosphere (Fowles et al. 2007; Laird 2008; Lehmann et al. 2007). Carbon compounds make up the majority of biochar. Hydrogen, oxygen, ash, nitrogen, and sulphur are also present (Ahmad et al. 2016). The type of biomass used, the design of the reactor, and the conditions under which it is created all influence the content and features of biochar (Ahmad et al. 2016). At the very least, biochar has been used since 2000 years ago (Hunt et al. 2010). Biochar can be made at several scales, from huge industrial facilities to small farms and even homes, making it suitable for a wide range of socioeconomic situations (Lehmann et al. 2015). Commercially accessible pyrolysis systems produce varying quantities of biochar and bioenergy products such as bio-oil and syngas. The gaseous bioenergy products are commonly utilised to generate power; the bio-oil, on the other hand, can be used directly for low-grade heating purposes and, after appropriate treatment, as a diesel alternative (Elliott et al. 2007). The first depiction of the word "biochar" was in Western agriculture in the mid-nineteenth century, although its precise application dates back even longer (Abiven et al. 2014). Following the first meeting of the International Biochar Advocacy Organization in Australia in 2007, various nations founded National Biochar Societies to launch biochar research and demonstration conferences, and the amount of biochar research

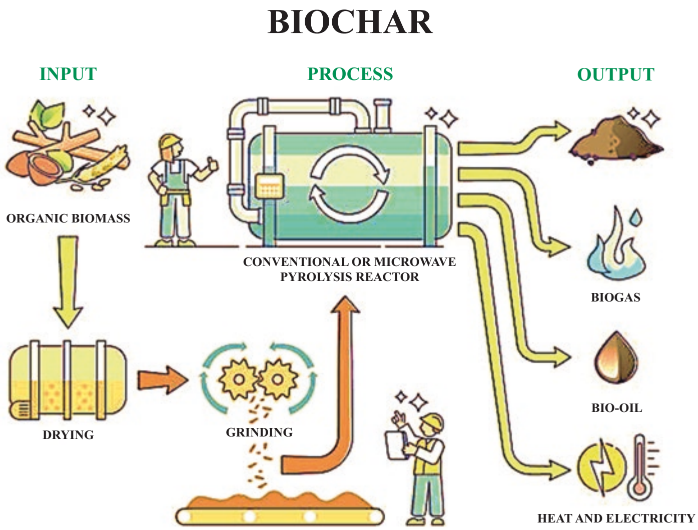

Fig. 1.1 Biochar production: industrial process for manufacturing of biochar productions from raw products conversion into end products

has steadily expanded since then (Han et al. 2020). Recent improvements in our understanding of biochars necessitate a thorough scientific assessment of the relationship between their qualities and their impact on soil parameters, plant growth, yield, and biotic and abiotic stress resistance.

1.3 Biochar for Sustainable Agriculture

The term "sustainable agriculture" is described as the full integration of biological, chemical, physical, ecological, economic, and social disciplines to produce new farming practises that are both safe and environmentally friendly (Lichtfouse et al. 2009). Agriculture is the primary source of greenhouse gases, accounting for slightly less than 25% of total global anthropogenic greenhouse gases in 2014 (Smith et al. 2007), and for 52 and 84% of total global anthropogenic methane and nitrous oxide emissions, respectively, owing to land use change and forestry (Smith et al. 2008). Furthermore, the world's rapidly growing population (expected to reach 9.6 billion by 2050) would unavoidably lead to increased demand for food production from a shrinking amount of arable land (Cleland 2013).

Biochar has been utilised in agriculture for a long time in various parts of Asia, particularly in Japan and Korea. In the mid-1990s, scientists discovered that biochar had a potential future in absorbing carbon dioxide and reducing carbon emissions, as part of the process of attempting to effectively reduce atmospheric carbon dioxide emissions and concentrations to cope with climate change today (Han et al.

2020). Many contaminants with low concentrations but considerable environmental harm are gradually receiving attention as our demand for the environment grows (Cheng et al. 2021). Sewage released into the environment by industrial activities may be carcinogenic, poisonous, mutagenic, and teratogenic to people (Goltz et al. 2005). Biochar has been shown to be effective at removing organic debris, surfactants, and nitrogen (N) from wastewater in previous trials (Dalahmeh 2016; Berger 2012).

Biochar is effective as a phosphorus (P) sorbent in wastewater treatment (Kopecký et al. 2020). The sorbent then used the recycling method to create various products (phosphorous fertilisers), which are highly acknowledged for their potential to improve soil conditions. Biochar applications could be a major input for sustaining output while lowering pollution and fertiliser dependency, according to the developing research (Beesley et al. 2011; Lehmann et al. 2015; Sohi et al. 2009; Stavi et al. 2013). The climate-mitigation potential of biochar originates principally from its abrasive nature, which delays the rate at which photosynthetically fixed carbon (C) is returned to the atmosphere. Biochar also has many potential side effects (Cheng et al. 2008). Under present conditions of high greenhous gas emission worldwide, biochar had proven itself to be good soil greenhous gases reclaiming substance by changing the soil porosity and chemical properties (Kammann et al. 2011; Schmidt et al. 2014; Mukherjee et al. 2011). Several studies have recently shown that adding biochar to soils can boost crop yields and reduce plant stress caused by drought (Akhtar et al. 2014; Liang et al. 2014), salinity (Akhtar et al. 2015a, b; Dugdug et al. 2018), and heavy metals (Fiaz et al. 2014; Karunanayake et al. 2018). Despite the rising number of demonstrated benefits of biochar applications, there are numerous barriers to biochar adoption in sustainable agriculture (Fig. 1.2).

1.4 Role of Biochar in Climate Change Mitigation

1.4.1 Carbon Sequestration

The cycles of carbon stabilization have not been completely uncovered, and it is impacted by many elements (Wiesmeier et al. 2019; Yang et al. 2022). Mechanisms to balance out carbon stock embrace physical interactions, for example, the response of soil mineral framework with carbon compounds shaping a secure bond, difficult to reach for decomposers; inflexible chemical structure of some carbon substances, for example, biochar, a few humic acids or lipids or by biological protection given by arrangement of micro-aggregates bound by hyphae or by certain progressions to deposits inside creatures digestive system (Goh 2004). Knowing carbon stabilization is crucial to work on agricultural management to store soil organic matter, and soil structure, or to moderate the greenhouse gas effect (Singh et al. 2018).

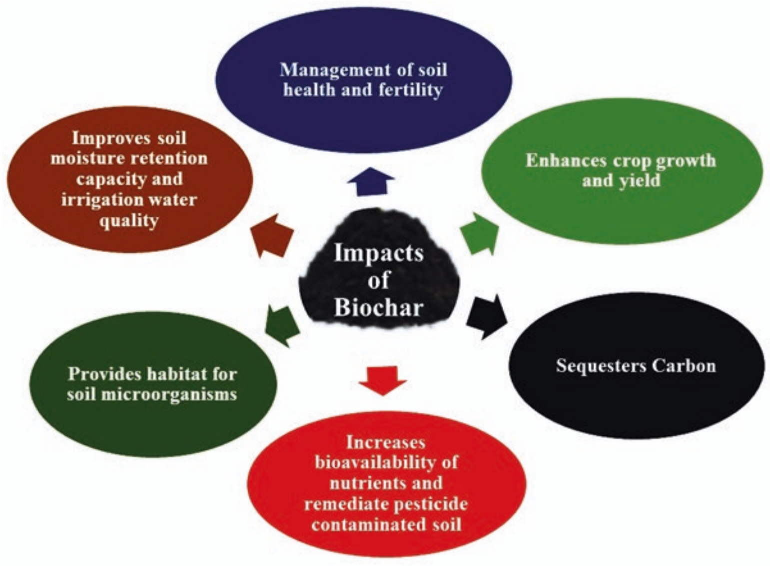

Fig. 1.2 Effect of biochar addition to soil in agricultural activities. This figure depicts the importance of biochar in minimising soil nutrient leaching losses, storing atmospheric carbon in the soil, enhancing agricultural production, reducing the bioavailability of environmental pollutants, and eventually providing a value-added product in sustainable agriculture

Carbon stabilization is firmly connected with carbon sequestration, which is the change of air carbon dioxide into soil carbon (Liao et al. 2020). Increased stabilization of sequestered carbon might assist with moderating the greenhouse impact (Goh 2004; Singh et al. 2018). Biochar content can be coarsely shared into leachable carbon, ash, and recalcitrant carbon. Carbon stabilization in the soil is engaged with the worldwide carbon cycle (Singh et al. 2018). However, not all the carbon inputs into soil repel to processes of mineralization, leaching, or erosion losses. Thus, soil carbon is considered as labile (with a short half-life of 1–20 years) or stable (20–100 years) (Goh 2004). Stable carbon stock is pivotal for evaluating the susceptibleness of soil organic carbon or facilities of environments (Buytaert et al. 2011; Rolando et al. 2017; Yang et al. 2022).

Biochar application is one of the ways of expanding carbon sequestration and stabilization in soil, as it contains 20–80% of stable carbon which isn't delivered into the climate in that frame of carbon dioxide within 2 or 3 years (Llorach-Massana et al. 2017; Masek et al. 2011; McBeath et al. 2015). Contrasted with other natural matter opposing fast mineralization and containing aromatic carbon compounds (like lignin), biochar is principally made out of fused aromatic carbon, hydrocarbons comprising polycyclic aromatic compounds. It has been accounted for that biochar application upturns a humic-like fluorescent element in soil and diminishes co-localization of aromatic-C: polysaccharides-C.

These changes, combined with diminished C metabolism (decreased respiration), appear to be as significant highlights of C stabilization in biochar-revised soils (Hernandez-Soriano et al. 2016). There are two types of labile carbon, firm as dissolved organic carbon and fraction of unstable organic carbon (Al-Wabel et al. 2013). Biochar is by all accounts a material made out of microspores essentially comprising aromatic carbon and less carboxyl and phenolic carbon (Braida et al. 2003). The labile piece of biochar can be shown as unstable matter, and ash content which incorporates crucial nutrients addressing important hotspots for soil biota.

1.4.2 Evaluation of Biochar System

Since pyrolysis is a more carbon-effective method for catching bioenergy than other bioenergy frameworks (in terms of CO_2 MJ^{-1}), the production and capacity of storage of biochar would add critical advantages for climate change mitigation alone. According to this point of view, stockpiling of biochar needn't bother to be in the soil, and it had been recommended that whole valleys could be utilized as storerooms for biochar (Seifritz 1993). However, presently application of biochar to agricultural soils is the most broadly proposed way since it is bound to conquer the opportunity cost in energy production (the recoverable energy sworn off in the biochar). If biochar can give dependable agronomic advantage it may command a value in crop production in addition to a potential carbon credit.

In any case, while the potential for management of the terrestrial carbon cycle is the justification for the ongoing interest in biochar, to be useful a biochar-based situation must: (1) evaluate the financial worth of direct and indirect emission reserve funds emerging from the utilization of biochar against the opportunity cost of biochar ignition or elective use, (2) give assurance, confirmation and potentially proof for carbon-equivalent savings and (3) consider the indirect expenses and advantages to land users and upstream food processors from the utilization of biochar in soil. The last option could incorporate the expense of biochar application, weighed against the marketing benefits acquired through carbon-neutral food items. So, a full life-cycle examination of alternative situations is required.

However, more prominent sureness is expected on the following to completely survey biochar-based soil management for explicit applications: (a) the stability of biochar carbon in the soil, (b) the backhanded effects of biochar on carbon-equivalent emanations, and (c) the security, dependability, and steadiness of cost for pyrolysis feedstocks. The potential for technological advancements in pyrolysis to improve adaptability and overall efficiency is a different subject and will be worked with by its extension and forums such as International Biochar initiatives (IBI), and national organizations like the Network of Australian and New Zealand Biochar Researchers, and the United Kingdom biochar research centre. It should be featured, not withstanding, that according to the viewpoint of the economics of energy catch, the worth of biochar and the general result of the examination is touchy to the cost of heat and power generated from other fuels. Any subsidy likewise impacts renewable energy, which may have the effect of inflating the monetary value of the energy in biochar (Woolf 2008).

1.4.3 Biochar and Bioenergy Production

Biochar can be made in an assortment of ways. Pyrolysis, or the heat degradation of biomass in an oxygen-depleted environment, produces biochar. The nature of the feedstocks, or materials burned, straightforwardly affects a definitive biochar item's quality. Clean feedstocks with 10–20% dampness and high lignin content are great, and agricultural waste and woody biomass are best. Utilizing polluted feedstocks, like those from rail line dikes or sullied ground, can carry poisons into the soil, raise soil pH decisively, and/or potentially keep plants from getting minerals. Heavy metals, like cadmium, copper, chromium, lead, zinc, mercury, nickel, arsenic, and Polycyclic Aromatic Hydrocarbons, are the most well-known toxins. Biochar can be made in two ways: low-cost, small-scale production with adapted stoves or kilns, or large-scale, high-cost production with larger pyrolysis machines and higher feedstock volumes. Pyrolysis with a top-lit updraft biochar machine is one of the most frequent techniques to generate biochar for on-farm applications (Fig. 1.3).

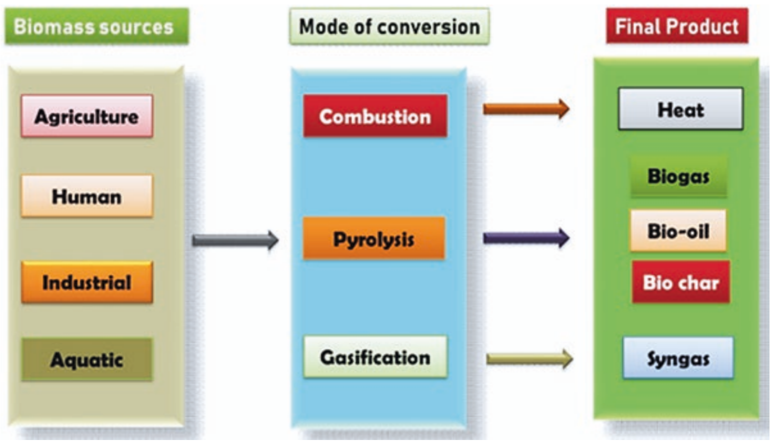

Fig. 1.3 Methods of biochar production. This figure depicts the source from different sectors and how it is being converted to the final product i.e., biochar, bio-oil, biogas by various techniques

1.4.4 Soil Biological Activity and Biochar Stability

Soil harbours complex micro-organisms populations that are uninterruptedly changing in response to the soil properties, climate, and land management practices. Soil microbial populations, their abundance, and their activities are closely interlinked to soil respiration, organic carbon content, soil nutrient cycling, and crop productivity (Dempster et al. 2012; Song et al. 2018). Soil microbial activity is influenced by biochar addition and the effect varies with the type of soil, biochar quality, and application rate (Rousk et al. 2010; Farkas et al. 2020). A meta-analysis reported that biochar amendment considerably increased the ammonia-oxidizing archaea (AOA) abundance and denitrification gene (nirS, nirK, and nosZ) by an average of 25.3, 32.0, 14.6, and 17.0%, respectively, (Xiao et al. 2019). Biochar stimulates soil microbial activity by providing carbon substrate and growth nutrients. In addition, it serves as a suitable habitat for growth and protects them from predators (Chen et al. 2018; Lu et al. 2020). Furthermore, biochar increases the buffering capacity of the soil thereby minimizing pH variations in microhabitats present inside biochar particles.

Improvement in microbial abundance after biochar addition (47 t ha^{-1}) was observed in a 3.5-years field study in Tasmania, Australia (temperate region) (Abujabhah et al. 2016). In another field study (2 years) in Australia, a rise in P-mobilizing mycorrhiza in biochar-added soils was observed owing to the indirect effects of biochar on soil physicochemical properties (Solaiman et al. 2010). An increase in the colonization rate of arbuscular mycorrhizal fungi (AMF) after the application of bark charcoal of *Acacia mangium* was observed in maize in South Sumatra, Indonesia (Yamato et al. 2006). In contrast, studies have also found neutral and negative effects of biochar amendment on soil microbial activity. For a field trial on the wheat crop, biochar addition (3 or 6 kg m^{-2}) did not show any changes in soil microbial biomass either 3 or 14 months after char addition (Castaldi et al. 2011).

However, a field study of mango-wood (*Mangifera indica*) biochar application in Colombia at rates of 23.2 and 116.1 t C ha^{-1} has resulted in a decrease of AMF abundance in soils by 43 and 77%, respectively, (Warnock et al. 2010). The decrease in AMF abundance could be due to the release of ethylene or organic pyrolytic byproducts, including phenolics and polyphenolics from biochar that exert a negative effect on soil microflora (Spokas et al. 2010; Warnock et al. 2010). Further, owing to different mechanisms of action, biochar may elicit variable metabolic responses in microbial populations resulting in specific taxonomic shifts in the composition of the microbial community.

A field study conducted at three European locations (West Sussex, UK; Prato Sesia, Italy; Lusignan, France) using Zea mays-derived biochar (30 t ha^{-1}) showed significant changes in the composition of the microbial community (Jenkins et al. 2017). After a year of biochar application, the UK site showed an increase in Gemmatimonadetes, and Acidobacteria, the Italian site showed an increase in Gemmatimonadetes, and Proteobacteria whereas the French site reported no significant impact on the abundance of individual bacterial taxa. Further, fungal diversity was influenced by biochar treatment in Italy and France but was unaffected in the UK samples. An increase in the abundance of Proteobacteria, Bacteroidetes, and Actinobacteria and a decrease in that of Acidobacteria, Chloroflexi, and Gemmatimonadetes on biochar treatment was earlier reported in a laboratory study in China using Zea mays biochar (Xu et al. 2016). Another field study in Foshan, Southern China (subtropical) using sugarcane bagasse biochar showed an increased bacterial and actinomycetes population and decreased fungal population (Nie et al. 2018). On the contrary, a significant increase in the fungal community diversity and a decrease in the bacterial community diversity was reported on biochar amendment in the soil of a Chinese fir plantation (Cunninghamia lanceolate) (Song et al. 2020). Table 1.1 presents the effects of biochar application on the biological properties of soils.

The steadiness of carbon, and the importance of how long it will stay out of the quicker carbon cycle, is setting subordinate since various applications will incite various degrees of biotic and abiotic stress to the carbon (Wang et al. 2016). This deviation in both biochar and its potential applications represents a test to track down a standardized method for predicting biochar stability. Moreover, the pertinent time viewpoint is really difficult while assessing and foreseeing the biochar stability. To quantify the degradation rate checking the degradation of carbon for many years or more would be essential. But this isn't a choice. Hence, a more reasonable chance is to imitate the normal degradation by simulating and modelling the degradation of biochar to estimate the stability (Leng et al. 2019). Such modelling is likewise an asset and time-taking practise and it is sensible to expect that it isn't possible for each biochar maker and for each bunch of biochar. Therefor a dependable and more assessable method to indicate the stability is needed to connect a biochar property to a modelled degradation behaviour to more easily estimate the carbon sequestration potential.

1.4.5 Effect of Biochar on Tillage

Biochar is used in agriculture to improve soil and compost quality. Soil deterioration is a major problem in agriculture around the world. As a remedy to this expanding problem, researchers proposed utilizing biochar to restore the state of degraded soils. Strengthening soil structure, increasing water retention and aggregation, decreasing acidity, reducing nitrous oxide emissions, improving porosity, regulating nitrogen leaching, and encouraging microbial features are just some of the ways biochar can help improve soil quality. Biochar has also been discovered to be beneficial for composting, as it reduces greenhouse gas emissions while simultaneously limiting nutrient loss. It also promotes microbial activity, which helps the composting process go faster. It also helps with ammonia losses, bulk density, and odour control in the compost.

Table 1.1 Impact of biochar application on biological properties of soils

Property	Impact	% Change	Biochar feedstock, application rate	Soil type, location	References
Total viable count	–	+15	Acacia tree green waste, 47 t ha^{-1}	Kurosol, Australia	Abujabhah et al. (2016)
Actinobacteria	Decreased from 18.71 to 8.69%	−10.02	Peanut shells and wheat straw, 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Acidobacteria	Increased from 4.86 to 5.91%	+1.05	Peanut shells and wheat straw, 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Proteobacteria	–	+3.0	Acacia tree green waste, 47 t ha^{-1}	Kurosol, Australia	Abujabhah et al. (2016)
	Increased from 21.96 to 24.1%	+2.14	Peanut shells and wheat straw, 10% (v/v)	Subtropical landfill cover soil, China	Lu et al. (2020)
Alphaproteobacteria	–	+1.81	Zea mays biochar, 30 t ha^{-1}	Sandy loam, United Kingdom	Jenkins et al. (2017)
	–	+12	Acacia tree green waste, 47 t ha^{-1}	Sandy loam, Tasmania	Abujabhah et al. (2016)
Betaproteobacteria	–	+11	Acacia tree green waste, 47 t ha^{-1}	Sandy loam, Tasmania	Abujabhah et al. (2016)
Gammaproteobacteria	–	+10			
Bacterial 16SRNA gene (*106)	Increased from 600 to 1400	+133.3	15 t ha^{-1}	Tianjin, North China	Wang et al. (2021)
Arbuscular Mycorrhizal fungal abundance (in root)	–	−77	Mango wood, 116.1 t C ha^{-1}	Alluvial sediments, Columbia	Warnock et al. (2010)
Ascomycota	–	+39	Acacia tree green waste, 47 t ha^{-1}	Kurosol, Australia	Abujabhah et al. (2016)
Fungal ITSRNA gene (*106)	Increased from 1 to 6	+500	15 t ha^{-1}	Tianjin, North China	Wang et al. (2021)

1.4.6 Biochar to Improve Soil Quality

Biochar is applied to agricultural soils in a variety of ways, with different application rates and preparation methods. The rate at which biochar is applied and prepared is largely dictated by soil conditions and the materials used to make the biochar. It's customary to mix biochar with compost or other materials to inoculate it with nutrients and helpful organisms. The recommended approach for spreading biochar will vary depending on how healthy or nutrient-depleted your soil is. Consider the state of your soil before beginning to use biochar in your own garden or farm.

1.4.7 Biochar Impact on Greenhouse Gases

Carbon sequestration in biochar enhances carbon's storage time in comparison with other terrestrial sequestration approaches like afforestation or reforestation (Wang et al. 2016). Biochar amendment can thus play a significant role in carbon removal from the atmosphere and the simultaneous reduction of greenhous gas emission. Emissions of radioactively active gases such as CH_4 and N_2O, whose global warming potential (GWP100) for a 100 years time horizon is more than 28 and 265 times stronger than CO_2, respectively, have been reduced from soils with biochar application (Vijay et al. 2021).

Biochar can play a greater role in short-term CH_4 emission reduction to help meet the 2050 greenhous gas targets, as methane's GWP20 (for 20 years time horizon) value of 84 is much higher than its GWP100, due to its short residence time in the atmosphere (Balcombe et al. 2018). The N_2O, having a much longer residence time in the atmosphere, is a significant contributor to greenhous gas. Around 62% of the atmospheric N_2O emissions are attributed to soils (Biernat et al. 2020). High rates of nitrogen-based fertilizer application to the fields also emit N_2O into the environment. Biochar addition to soil effectively mitigates the soil N_2O emissions and the mitigation can be attributed to the inhibition of either stage of nitrification and/or denitrification as reported in both field and lab studies (Rondon et al. 2007; Cayuela et al. 2014; Weldon et al. 2019).

Improved soil aeration from biochar application decreases denitrification due to the inhibition of the activity of anaerobic microorganisms involved in denitrification. Biochar application leads to microbial immobilization of available N in the soil, reducing the N_2O source capacity of the soil. Improved pH from the application of biochar drives the formation of N_2 from N_2O. Furthermore, the enhanced fertility of the soil with biochar application will also assist farmers to adapt to the changing climate, thus reducing the intensity of climate change (Zhang et al. 2016). Application of 5 t ha^{-1} biochar in bamboo plantations in China has shown a reduction in soil N_2O efflux by 28.8% in the first year and 19.7% in the second year (Song et al. 2020). The increasing application rate of biochar to 15 t ha^{-1} led to a 31.3 and 30.1% reduction in N_2O flux over the first and second year, respectively, concerning the control. Biochar application reduced soil N_2O emissions by decreasing the concentrations of soil labile N forms and hindering the activities of N-cycling enzymes (Song et al. 2020). A field study on maize in Switzerland reported that the enhanced soil gas diffusivity in biochar-added soil (and thus improved soil aeration), may lead to reduced N_2O emission (Keller et al. 2019). However, Suddick and Six (2013) found no considerable change in N_2O flux with the application of biochar and compost. The study recommended that certain biochar types may be less suitable for N_2O mitigation in some agricultural soils, at least on shorter temporal scales, or that a minimum biochar quantity is needed for effective reduction (Suddick and Six 2013). Findings are corroborated with another study wherein it was observed that N_2O emissions do not always get reduced, and sometimes biochar application shows neutral or negative effects (Gao et al. 2020). Improved aeration, especially of fine-grained soils, also enhances the sink capacity for CH_4 by increasing the abundance of methanotrophic proteobacteria, enhancing CH_4 oxidation and thereby reducing CH_4 emissions (Al-Wabel et al. 2019).

Biochar application was found to reduce the total CH_4 and N_2O emissions from paddy fields under controlled irrigation in two rice seasons (Yang et al. 2019). Controlled irrigation considerably reduced CH_4 emissions while increasing N_2O emissions in comparison with flood irrigation management. Biochar application (20 t ha^{-1}) in this study did not have any effect on SOC or soil pH, whereas it increased the soil DOC, Total N, NH_4^+ -N significantly and reduced NO_3^- -N concentrations compared to non-amended soil (Yang et al. 2019). Another study reported that the biochar addition reduced the abundance of methanogenic archaea resulting in lower CH_4 emission (Huang et al. 2019). Beyond its application in the agricultural context, biochar has also gained interest in the waste management industry as a media to enhance control of landfill gas emissions. Landfills are one of the largest contributors to global anthropogenic CH4 emissions at approximately 17.4% of the total CH_4 emissions in 2018 in the United States alone (USEPA 2020). One of the options for the long-term reduction of CH_4 fluxes is the microbial oxidation of CH_4 in biofilters, bio-windows, or bio-covers (Huber-Humer et al. 2008; Scheutz et al. 2009). The performance of these engineered methane oxidation systems can be enhanced if the soils in use are amended with biochar. Reddy et al. (2014) showed that both, the abundance of methanotrophs and the CH_4 oxidation capacity, were increased by adding 20% biochar from wood chips to a fine-grained soil (fraction <75 μm = 92%) (Reddy et al. 2014). In a more coarsely-grained, sand-dominated soil, enhanced CH_4 oxidation following a 10% biochar amendment as attributed to the positive effect of biochar on the soil's water retention capacity (Yargicoglu and Reddy 2018).

The amelioration of crop productivity in tropical conditions after biochar application results in higher photosynthesis rates and higher CO_2 reduction in the atmosphere if part of the C fixed by photosynthesis is sequestered in the soil in the long term. Biochar is reported to be 10–100 times more stable than most of the other soil organic matter due to its condensed aromatic content (Jeffery et al. 2011). A meta-analysis (128 studies) on the stability of biochar in soils estimated the mean residence time of biochar labile and recalcitrant fraction, pool size 3% and pool size 97% as 108 days and 556 years, respectively, indicating that the major part of biochar (97%) contributes to long-term carbon sequestration in soil (Wang et al. 2016). A model prediction estimated that biochar production and implementation to soil can potentially offset a maximum of 1.8 Pg CO_2eq emissions (12% of anthropogenic CO_2eq. emissions) every year, and over the century, the total net offset of emissions from biochar would be 130 Pg CO_2eq. (Woolf et al. 2010). Production of biochar from crop waste and its amendment is reported to avoid 4348–4878 kg CO_2 ha^{-1} emissions in a year based on modelling predictions (Gaunt and Lehmann 2008). As biochar contains 60–80% (approx.) of carbon, for every tonne of biochar added to soil 0.6–0.8 tonnes of carbon can be sequestered which is equivalent to the 2.2–2.93 MT of CO_2 (Galinato et al. 2011). Limestone is commonly used to reduce the soil pH for agricultural applications, however, per tonne of limestone usage leads to 0.059 MT C or 0.22 MT CO_2 emission in the atmosphere. These emissions can be avoided by using biochar in place of lime. It is estimated that if 6.48 MT lime usage per hectare of land is replaced by 76.53 MT biochar, it can offset 225.6 MT CO_2 ha^{-1} through avoided emissions and biochar carbon sequestration (West and McBride 2005).

1.4.8 Economic Feasibility

The economic viability of biochar production and utilization is still a significant challenge. In general, the cost associated with the feedstock acquisition and transportation, capital, operations, and transportation of biochar to application sites significantly affects the economic feasibility of biochar. Also, the revenue streams from biochar, including sales, climate offsets, and energy subsidies, are less developed and could impede investments in biochar production. Without policy intervention, it is unlikely, at least in the near future, that biochar systems could out-compete bioenergy systems. Evidently, in the last decade, many biochar producers emerged and failed in the Great Lakes region, challenging the notion of biochar production as a financial opportunity. Feedstock cost is the most critical component of the biochar supply chain and is largely responsible for determining economic feasibility. Feedstock alone can cost 45–75% of the total expenditure in biochar production. In general, studies have suggested that feedstock procurement for agricultural and forestry residues could cost 63–82 US$ per ton. In addition, low-cost production technology is lacking and expensive, if available, challenging biochar systems' profitability. Larger production technology exists and provides some advantages to the economy of scale; however, this is negated by the necessity of a longer feedstock haul. This has limited the procurement of feedstock (less than 50 miles) and product supply extent to regional markets (less than 100 miles). The selling price of biochar varies significantly depending on the type, texture, and quality. The current average market price of biochar is about $9 per cubic foot when negotiated for the bulk price but can cost up to $42 per cubic foot in retail stores such as Lowes and home depot. The biochar market is growing and is expected to reach $3 billion globally by 2025.

1.5 Biochar for Improving Crop Health

1.5.1 Soil Health Management

Soils are the basis for agriculture and the medium in which almost all food-producing plants grow and as such, they need to be kept healthy. In turn, healthy soils produce healthy crops that nourish humans and animals alike. They are the foundation of the profitable and sustainable agricultural system. By the definition of Doran and Zeiss (2000), soil health refers to soil's capacity to function as a vital living system, within the boundaries of ecosystems and land uses, as it sustains plant and animal productivity, enhances water and air quality, and promotes plant, animal, and human health. Soil health is reflected in biotic and abiotic indicators such as soil organic matter, nutrient status, moisture and pH which are influenced largely by management practices (Atkinson et al. 2005; Karlen et al. 2003). Many of the functions of a healthy soil support plant growth, such as nutrient cycling, biological control of pests, and regulating water and air supply. To keep soil healthy, good management practices are very important. Many of these practices are already being practiced as well as new ones are being adopted.

Although agricultural soils contain a relatively small amount of global soil carbon but their contribution to the annual atmospheric flux is significant (Sohi et al. 2010). The addition of organic carbon to agricultural soils improves soil fertility which in turn increases crop production also. The practice can also permanently sequester carbon in order to reduce greenhouse gas emissions. Lehmann et al. (2009) defined biochar as a carbon-rich product obtained by thermally converting biomass (farm wastes, wood waste, manures, etc.) in an oxygen-limited environment (pyrolysis). Biomass is converted to char, combined gas (mixture of H_2, CO, CH_4 and CO_2) and bio-oil with heat energy in the absence of O_2 during pyrolysis. Biochar contains high concentrations of carbon that can be rather recalcitrant to decomposition, so it may stably sequester carbon (Glaser et al. 2002). The addition of biochar can immediately increase nutrient availability primarily by increasing potassium, phosphorus, and zinc availability, and to a lesser extent calcium and copper availability (Lehmann et al. 2003). The contribution of biochar to soil health management is briefly discussed below:

1.5.1.1 Impact of Biochar on Soil Physical Properties

Significant effects of biochar have been found over the years on the physical properties of agricultural soil. Physical properties of the soil influence the productivity of crops by determining water-holding capacity, soil aeration as well as soil strength limitations (Benjamin et al. 2003). After the incorporation of biochar into soils, due to its unique physical properties such as superior concentrations of organic carbon, high porosity and large surface area presence of micropores, improvements in soil properties, such as structure and aggregation, would be expected (Mukherjee et al.

2011; Chintala et al. 2014). Soils amended with biochar show an increase in surface area and porosity (Eastman 2011). Changes in soil properties under compaction can influence the state of the soil (Chen & Weil, 2011). Studies by Novak et al. (2016) and Prober et al. (2014) showed that the infiltration rate increased following the application of biochar (Table 1.2).

1.5.1.2 Impact of Biochar on Soil Chemical Properties

Different soil chemical properties soil pH, cation exchange capacity (CEC), and organic carbon content are influenced by biochar application in soil (Table 1.3). As a result of applying biochar, the chemical properties of soil are improved such as soil pH, cation exchange capacity, base saturation, exchangeable bases, organic carbon content, and reduction of Al saturation in acid soils, thereby reducing fertilizer and lime requirements (Glaser et al. 2002; Van Zwieten et al. 2010). As a result of biochar amendments, soil pH increased particularly in acidic soils, with greater increases observed in sandy and loamy soils than in clayey soils (Yamato et al. 2006; Major et al. 2010).

Table 1.2 Impact of biochar on soil physical properties

Biochar source	Effect on soil physical properties	References
Biochar derived from lignocellulosic biomass e.g. rice husk, cacao shell, wooden chips	Decrease in density, increase in surface area, increase in porosity, decrease in soil penetration resistance, increase in water holding capacity	Abel et al. (2013) and Eastman (2011)
Biochar derived from animal waste e.g. poultry manure, dairy manure	Decrease in soil penetration resistance, increased hydrophobicity, increase in hydraulic conductivity	Liu et al. (2012) and Reddy et al. (2015)
Biochar derived from plant biomass e.g. eucalyptus green waste, olive tree pruning	Increase in surface area and porosity, higher water holding capacity, a moderate increase in hydraulic conductivity	Kinney et al. (2012) and Kameyama et al. (2014)

Table 1.3 Salient impacts of biochar on soil chemical properties

Biochar source	Effect on soil chemical properties	References
Biochar derived from lignocellulosic biomass e.g. rice husk, cacao shell, wooden chips	Increase in pH, increase in cations (K^+, Ca^{2+}, and Mg^{2+}), increase in cation exchange capacity, increase in C content of soil.	Butnan et al. (2015) and Kameyama et al. (2016)
Biochar derived from animal waste e.g. poultry manure, dairy manure	Increase in cations (K^+, Ca^{2+}, and Mg^{2+}), increase in cation exchange capacity, increase in C, N, and P contents, increase in C and N bioavailability	Chathurika et al. (2016) and Gul et al. (2016)
Biochar derived from plant biomass e.g. eucalyptus green waste, olive tree pruning	Increase in pH, increase in cations (K^+, Ca^{2+}, and Mg^{2+}), increase in cation exchange capacity, increase in C and N content of soil, increase in C and N bioavailability	Zhang et al. (2016)

According to Nelissen et al. (2012), the incorporation of biochar into soil improves NH_4^+ immobilization, which in turn reduces nitrification, which in turn reduces H^+ leaching from the soil. In addition, research has shown that the incorporation of biochar increased organic carbon and decreased nitrogenous fertilizer requirements (Glaser et al. 2002; Widowati et al. 2012); this is due to the high levels of carbon in biochar that can be difficult to decompose, so it may steadily sequester carbon. Major et al. (2010) reported that nutrient uptake by plants was increased in biochar-amended soil, with an increase in plant yield and greater availability of Ca and Mg in soil. Biochar was found effective in adsorbing dissolved soluble nutrients such as ammonium (Lehmann et al. 2002), nitrate (Mizuta et al. 2004), phosphate (Beaton et al. 1960) and other ionic solutes (Radovic et al. 2001). Biochar was also found to improve biological N fixation (BNF) of biochar-amended soils (Krishnakumar et al. 2014).

1.5.1.3 Impact of Biochar on Soil Biological Properties

Significant changes in soil biological properties can be brought about by applying biochar amendments in soil which can modify soil microbial and faunal diversity and activities (Gul et al. 2015; Zhang et al. 2017). The biochar-affected changes in soil biological properties appeared to be a function of biochar characteristics and soil texture such as surface area, pH, and porosity (Gul et al. 2015). Consequently, biochar-induced changes in soil properties have different impacts on ecosystem functioning in soil and the rhizosphere (Hussain et al. 2017; Kolton et al. 2016). As per Graber (2009), with an increasing rate of biochar application maximum number of culturable colonies of general bacteria, Bacillus spp., yeasts and Trichoderma spp. were found.

Biochar-amended soil has a more suitable pH which may be beneficial for the growth of microbes, especially for fungal hyphae (Wuddivira et al. 2009). Joseph et al. (2010) showed that most biochar has a higher % of macropores and minerals, and small organic particles might accumulate in these pores. Dehydrogenase activity and microbial biomass carbon are enhanced due to biochar application in soils (Das and Mukherjee 2012). Some other positive impacts of biochar in maintaining soil health are in Table 1.4.

Table 1.4 Impacts of biochar on soil biological properties

Biochar effects on soil biology	References
Enhancement of biological N fixation	Rondon et al. (2007)
Improve colonization of mycorrhizal fungi, earthworms present in soil	Van Zwieten et al. (2010)
Act as potential catalyst in reducing nitrous oxide to nitrogen	Van Zwieten et al. (2009)
Decrease in fungi/bacteria ratio	Zhang et al. (2017) and Gul et al. (2015)
Increase in beneficial microbes and suppression of pathogens	Anderson et al. (2011) and Warnock et al. (2010)

1.5.2 Nutrient Retention, Use Efficiency and Leaching

As a sink, biochar can retain nutrients and reduces its losses through leaching and gaseous emission. Various kinds of soil amendments such as biochar, lime, and organic materials, are known to have a significant impact on the dynamics of soil nutrients (Baligar and Fageria 2007). Nutrient use efficiency (NUE) is the benchmark to increase crop cultivation efficiency and select appropriate methods to prevent nutrient loss from the soil. The effects of biochar-amended soil on different nutrients retention, cycling and maintenance of efficiency of nutrients NUE has been seen over the years by many researchers which are briefly pointed out below:

1.5.2.1 Nutrient Retention

Due to its large surface area, porosity and presence of both nonpolar and polar surface sites, biochar can help to improve the nutrient retention capacity of soil (Ahmad et al. 2014; Mukherjee et al. 2011). Biochar with a high cation exchange capacity (CEC) can retain much amount of nutrients in soil by reducing leaching oriented nutrient loss (Tomczyk et al. 2020). Biochar application also improves nutrient retention by increasing the soil pH and soil organic matter (Mendez et al. 2012). Gao et al. (2016) concluded that the addition of biochar increased NO_3^--N and NH_4^+-N retention in soil by 33 and 53%, respectively. The high cation and anion exchange capacities of biochar and its ability to retain ions and molecules within its pores are further attributed to biochar's enhanced nutrient retention capacity (Schofield et al. 2019). Zhang et al. (2017) reported that water and nutrient transfer facilities can be provided by the pore space of biochar at the initial stage of biochar application. The hydrophobic nature of biochar can inhibit water transport and thus limit N diffusion also (Dong et al. 2020). Several studies also reported that biochar can be used as a slow-release fertilizer. For instance, Sashidhar et al. (2020) reported that biochar-based slow-release fertilizer (BSRF) releases N slowly by 69.8% over a period of 30 days. In addition, modified biochar (calcium alginate pervaded) also increased N and K retention in soil as reported by Wang et al. (2018). Further, the combined application of biochar and farm yard manure (FYM) improved N and P retention in soil (Arif et al. 2017). Many studies on biochar addition in soil also indicated that soil amended with biochar improves P bioavailability and plant growth (Arif et al. 2017; Beheshti et al. 2017; Biederman et al. 2017). Thus the availability of P is increased in the soil after biochar application like the availability of N. Several previous researches (Glaser et al. 2002; Atkinson et al. 2010; Major et al. 2010) reported that the application of alkaline biochar to acidic soils increased K content in soils. The addition of biochar @ 10 t ha^{-1} increased the Mg content of loamy sand soil (Lusiba et al. 2017). Thus, the impacts of biochar application in soil are mostly positive in nature. For instance, Abujabhah et al. (2016) found that woody biochar had a significant influence on exchangeable Ca, Na, and Mg in red loam, black clay loam and brown sandy loam soils.

1.5.2.2 Nutrient Use Efficiency

Nutrient use efficiency (NUE) is evaluated by figuring out how plant nutrients are absorbed from the soil, transported, stored, mobilized, and utilized within the plant but it decreases with increasing soil nutrient levels (Fageria et al. 2005). Increasing nutrient uptake and decreasing leaching and gaseous emission through biochar can raise plant nutrient use efficiency, both directly and indirectly. Several studies (Cao et al. 2019; Coelho et al. 2018) reported that the application of biochar increases N uptake, thereby increasing N use efficiency in crops. Woody biochar (10 t ha^{-1}) in alkaline soil improved the P use efficiency (PUE) of both wheat and maize (Arif et al. 2017). Prapagdee et al. (2017) also found that the application of woody biochar (20%) increased the NUE of green bean crops. Applications of biochar have significantly shown a reduction in leaching losses which are evident from studies mentioned in Table 1.5.

1.5.3 Water Retention and Irrigation Management

Biochar has a significant role in the water retention of soil as well as irrigation management of different field crops. Studies have indicated that biochar addition enhances soil's ability to hold water (Streubel et al. 2011). Accordingly, soil amendment with biochar could benefit crop productivity by retaining more rainfall in arid regions and reducing irrigation frequency in irrigated regions. A study conducted by Basso et al. (2013) applied flash pyrolysis biochar to sandy soil and found a 23% increase in water-holding capacity. In order to increase soil water holding capacity (WHC), the right source and application rate of biochar are essential. According to Singh et al. (2010), biochar's increased porosity increases the ability of soils to retain water, and the level of enhancement depends on biochar feedstock, soil type, and mixture rate. The excess volume of water and soluble nutrients stored in the biochar micropores is contemplated to become available for plants when the soil dries and the matric potential decreases (Uzoma et al. 2011).

Biochar application generally improves the physical and hydraulic characteristics of sandy soil (Karhu et al. 2011) and has direct effects on soil water movement. Akhtar et al. (2014) found that biochar significantly improved the water use efficiency (WUE), relative water contents (RWC), and increased stomatal density of drought-stressed tomato leaves. Biochar was also found to increase the WUE of maize in sandy soil (Uzoma et al. 2011). Plants may be better able to take up nutrients dissolved in water if they are retained in the soil instead of being dissolved in water (Lehmann et al. 2009). Several experiments have indicated that biochar may alleviate water stress in plants when applied with microorganisms (Mickan et al. 2016; Liu et al. 2017). The addition of biochar to clay under moist tube irrigation significantly reduced cumulative infiltration capacity, inhibited upward water transport, and promoted downward and lateral water transport, as shown by Xu et al. (2015). The moisture content of sandy loam and silty loam increased by rice husk

Table 1.5 Impacts of biochar on nutrient leaching

Nutrient name	Impact of biochar in leaching	References
Nitrogen (N)	Brazilian pepperwood biochar application reduced NO_3^- leaching by 34% through adsorption	Yao et al. (2012), Lehmann et al. (2003), Cao et al. (2019) and Laird et al. (2010)
	Woody biochar application decreases nutrient leaching by increasing water retention	
	Biochar derived from apple branches reduced the leaching of NO_3^--N by 9.9–68.7% and nitrogen-oxide flux by 6.3–19.2%	
	Application of mixed hardwood biochar decreased N leaching by 11% in midwestern agricultural lands.	
Phosphorus (P)	The application of peanut hull biochar increased the amount of phosphate in the soil solution by 39%	Doydora et al. (2011), Yao et al. (2012), Chen et al. (2011), Gul et al. (2016) and Hussain et al. (2017)
	Biochar produced from Brazilian pepperwood at 600 °C reduced the total amount of phosphate by about 20.6% in biochar-amended soil. Biochar reduces P leaching by sorption or adsorption mechanism	
	The biochars magnetized with Fe^{3+}/Fe^{2+} enhanced phosphate sorption compared to non-magnetic char	
	Biochar can reduce ortho-P leaching from nutrient-rich soil and thus can influence P availability in soil	
Other nutrients	Sewage sludge biochar produced at 500 and 700 °C reduced the leaching loss of K in Plinthudult soil more than that of biochar produced at 300 °C temperature.	Yuan et al. (2016), Major et al. (2012) and Cheng et al. (2018)
	Woody biochar application in acidic and low fertile soil resulted in the leaching of Ca, K and Mg to the 60 cm depth	
	With an increasing temperature of biochar production, biochar-induced leaching loss of Ca can be decreased	

and rice straw biochar incorporation (Chen et al. 2020). Kameyama et al. (2016) reported an increase in available water capacity with an increased rate of biochar application in clay soil. Thus biochar can maintain soil water retention by improving different physical properties of the soil such as by reducing bulk density (Głab et al. 2016), enhancing soil aggregation (Herath et al. 2013), changing pore size distribution, and improving soil porosity (Obia et al. 2016) etc. Soil amendment with biochar may retain more water from irrigation and also reduce the frequency of irrigation, hence sustaining and optimizing the limited water available for crop production (Faloye et al. 2019). Many of the research endeavours determined the impacts of biochar amendment on the productivity and irrigation water use efficiency (IWUE) of different crops under greenhouse conditions (Uzoma et al. 2011) and in pot experiments (Akhtar et al. 2014). Thus, under no water stress conditions, the application of biochar may be proposed to reduce water and energy consumption while maximizing crop yields (Baiamonte et al. 2020). In coarse-textured soils, biochar impedes the larger soil pores, thus blocking the water flow and improving water retention (Liu et al. 2017; Trifunovic et al. 2018). So, in addition to other farming strategies (e.g., the timing of operations, broadening soil connectivity into deeper layers, nutrient management, and selecting drought-tolerant crop varieties), biochar would also contribute to improving the resilience of agriculture to climate variability by improving yield stability in water-limited regions (Agegnehu et al. 2016).

1.5.4 Biochar for Remediation of Pesticide-Contaminated Soils

Agricultural soil contamination results from pesticide abidance and accumulation can change the microbial processes, harm soil organisms and also poses a threat to human being and ecosystem health (Chen et al. 2015). There exist many reports indicating the negative impacts of pesticides on human health associated with derangement of hormonal balance, reproductive abnormalities, cancer, as well as cardiovascular effects (Hurley et al. 1998; Arora 2015). Apart from these, pesticide application also affects soil biological activities including the growth of microorganisms and different soil enzyme activities (Table 1.6). A promising in situ approach for the bioremediation of pesticide-contaminated soil can be considered when using biochar since it is easy to apply and is environmentally friendly. The biological activity of biochar is enhanced by its high porosity, abundance of functional groups, and low density (Liu et al. 2018).

The use of biochar combined with microbes applied for the remediation of pesticide-contaminated soil has been reported recently by Wu et al. (2017) and Zhu

Table 1.6 Successful observations on the impact of different biochar for remediation of pesticide-contaminated soil

Type of Biochar	Impacts in pesticide-contaminated soil	References
Wheat straw (*Triticum aestivum* L.) (300 °C)	Increased sorption of herbicide (4-chloro-2-methylphenoxy) acetic acid in soil	Tatarková et al. (2013)
Maize straw (*Zea mays*) and pig manure (700 °C)	Increased sorption of thiacloprid	Zhang et al. (2018)
Dairy manure	Reduced atrazine uptake by earthworms and atrazine concentration in soil	Gao et al. (2011)
Cassava wastes (750 °C)	Increased sorption of atrazine	Deng et al. (2017)
Olive-mill waste (550 °C)	Reduced degradation of pesticides and their bioavailability in soil	Gámiz et al. (2016b)
Cotton (*Gossypium spp.*) straw chips (450 and 850 °C)	Concentrations of pesticide is reduced (chlorpyrifos and fipronil) in soil	Yang et al. (2010)

et al. (2017). Some examples of biochar application on pesticide behaviour and its remediation in soil are mentioned below:

- Biochar application increases the sorption of pesticides in soil and increases the bioavailability of pesticide residues (Yang and Sheng 2003, Yu et al. 2006).
- Gao et al. (2011) found that biochar applied at high levels (5.0%) reduced atrazine concentrations in the soil.
- Jones et al. (2011) studied the influence of various types of biochar and rates of application on soil sorption and biodegradation in the case of the herbicide simazine.
- Pesticide concentrations of chlorpyrifos and fipronil were decreased after the application of biochar produced from cotton (*Gossypium* spp.) straw chips due to enhanced microbial degradation (Yang et al. 2010).
- Sopena et al. (2012) reported that the adsorption capacity of 2% (W/W) biochar produced from *Eucalyptus dunni*, which had a high SSA, for isoproturon was nearly 5 times higher for amended soil than in un-amended soil.
- The herbicides aminocyclopyrachlor and bentazone were completely sorbed by silt loam soil which was amended with high SSA biochar produced from wood pellets as reported by Cabrera et al. (2014).
- Biochar is one of the most structured adsorbents for various groups of pesticides including herbicides, insecticides, fungicides, and rodenticides (Gilden et al. 2010).
- According to Gamiz et al. (2016a), biochar with high sorptive capacities and specific surfaces reduces the bioavailability of pesticides such as metalaxyl and tebuconazole in soil by lowering leaching and degradation losses.

1.5.5 Role of Biochar for Improving Quality of Irrigation Water

Clean water is possibly considered the most important natural resource for accomplishing basic life requirements but clean water is under alarming threat globally. As per FAO (2017), 70% of global freshwater withdrawals are accounted for agricultural purposes. As a result of multiple water use in downstream agroecosystems, soil and water salinization and sodium accumulation can occur, resulting in rapid declines in agricultural productivity. Carbonaceous biochar has been proven effective in improving various aspects of irrigation water quality. Some examples of the role of biochar in improving water quality and ultimately crop yield are given below:

- Akhtar et al. (2015a, b) demonstrated that biochar (5% w:w) is capable of absorbing Na from irrigation water and increasing potato yield.
- Using soil with a 2.5% biochar content and irrigation with water with an electrical conductivity (EC) of 5 dS m^{-1}, Rezaie et al. (2019) reported better faba bean yields.

- Biochar is found to be very much effective in retaining nitrogen and many organic compounds which are beneficial for the growth of crop plants.
- Fine-grained biochars are also found to be effective at retaining different bacteria from irrigation water.
- In a study published in 2019, Yang et al. noted that adding 5% biochar to soil and allowing phreatic water to evaporate increased soil water holding capacity while reducing soil salinity and sodium adsorption ratio (SAR).
- Due to the weak hydration and relatively large radii of soft base cations (e.g., Na), the electronegativity of biochar may be able to sorb such cations from water more effectively than hard base cations (e.g., Ca, Mg), but for hard base cations, this effect is less noticeable because of their high hydrated energies (Zhu et al. 2004).
- Hemp biochar showed the most promise for improving simulated irrigation water SAR by sorbing Na and releasing Ca and Mg ions into the solution (Awan et al. 2020).

1.5.6 Role of Biochar in Enhancing Crop Yield and Productivity

Biochar is generally a very novel approach for achieving sustainability and self-sufficiency in modern-day agriculture. Production of a huge amount of nutritious food maintaining environmental security to feed the burgeoning billions is one of the major concerns for policymakers. Utilizing biochar, crops are grown in such a manner which does not have negative impacts on the ecosystem and is healthy for man as well as animals. Biochar is found to be more effective than other organic matter because it can retain nutrients for plants. Due to the availability of larger surface area and pore space, biochar is generally considered to be the hub of different beneficial microorganisms which helps to improve soil fertility as well as crop yield also.

The impacts of biochar addition in agricultural soil in enhancing the growth and yield of different crops are studied by several researchers and they found significant effects of biochar regarding yield and productivity of crops. Some research examples are briefly pointed out below:

- Deb et al. (2016) observed that the impact of biochar on the soil which is deficient in nutrients showed a better response, resulting in higher productivity of crops.
- As per Glaser et al. (2001), biomass improvement of *Oryza sativa* L. (rice) by 20% and *Vigna unguiculata* L. (cowpea) by 50% was found due to biochar application at 68 t ha^{-1} and at 136.75 t ha^{-1} respectively.
- Rogovska et al. (2014) found a considerable increase in maize biomass yield of about 11–55% after the application of biochar.

- Jeffery et al. (2011) conducted a series of experiments where it was found that the application of biochar significantly improved crop yield and productivity.
- Due to the amendment of biochar with fertilizers, a considerable increase in the yield of maize was reported by Yamato et al. (2006).
- In an experiment conducted by Park et al. (2011), chemically modified chicken manure derived biochar improved the dry biomass of Indian mustard by 452% and 672% for shoot and root, respectively with 1% (w/w) of biochar treatments. This increase in yield was attributed to the reduced toxicity of Pb, and Cu and amended nutrient availability such as P and K.
- Application of compost mixing with biochar resulted in 4–12 times increase in rice and sorghum yield at harvest in an experiment conducted at Brazil Amazon river basin (Steiner et al. 2007).
- Uzoma et al. (2011) reported that biochar addition @ 15 t ha^{-1} and 20 t ha^{-1} to sandy soil enhanced maize crop yield by 150 and 98% respectively.
- As per Genesio et al. (2015), a 12% enhancement in soybean yield and a 37% increase in wheat yield due to acid-modified maize stalk biochar addition to soil resulted in reduced water stress, and improved soil pH and water holding capacity.
- Schmalenberger and Fox (2016) observed improved wheat and corn grain yield after the addition of H_2O_2-modified sludge biochar in soil which occurred through proper nutrient supply and maintenance of soil microbial activities.
- Application of biochar at the rate of 25 t ha^{-1} and FYM at the rate of 5 t ha^{-1} also resulted in improved maize growth and a reduced weed population at 30 and 60 days after sowing (Arif et al. 2012) which is mainly responsible for increased yield of maize.
- Wood biochar addition increased by a 30% increase in wheat yield, with no differences in grain N content and sustained yield for two consecutive seasons without biochar addition in the second year (Vaccari et al. 2011) was found.

So, from the various scientific studies, it is clear that biochar increases crop yields by about 20% with application rates often exceeding 10 t ha^{-1}. It has also been found that applications of less than 5 t ha^{-1} can increase crop yields by over 50% in a particular type of soil (Agegnehu et al. 2017). The response of different crops to a different kinds of biochar application has been represented in Table 1.7.

1.5.7 Potential Drawbacks of Biochar Application

Biochar addition in arable soils is getting importance day by day due to various kind of benefits related to soil health, improving crop production, restoring degraded lands as well as environmental benefits like reducing stream and groundwater pollution, controlling global warming etc. (Lehmann et al. 2006; Stavi et al. 2013). However, certain risks and drawbacks are also related to biochar addition in soil which is briefly discussed below:

Table 1.7 Impact of biochar addition on crops

Source of biochar	Type of crop	Response of crop to biochar application	References
Teak and rosewood biochar	Rice and sorghum	Plant growth increases and 2–3 times yield improvement	Steiner et al. (2007)
Wood, cow manure biochar	Maize	Enhancement of crop yield from 14–150%	Major et al. (2010) and Uzoma et al. (2011)
Mango wood, and corn stover produced biochar	Maize	Increase in biomass from 30–43% and yield by 22%	Rajkovich et al. (2012)
Biochar from Acacia bark	Maize and Peanut	A twofold increase in maize and peanut yield	Yamato et al. (2006)
Oil palm fruit bunch biochar	Rice	Increase in grain yield by 141–472% under the organic system	Bakar et al. (2015)
Wastewater sludge biochar	Tomato and cherry	Yield increment of 64% over the control plots	Hossain et al. (2010)
Maize straw biochar	Choy sum and Amaranth	Yield improvement by 28–48%	Jia et al. (2012)

Possible Source of Toxicants

A biochar product can contain toxins such as heavy metals (Cd, Cu, Cr, Ni, Zn) (Hospido et al. 2005), PAHs, polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) (Sonja and Glaser 2012), volatile organic compounds, xylenols, cresols, acrolein, and formaldehyde (Chagger et al. 1998; McClellan et al. 2007) etc. The use of biochar reduced germination and plant growth due to the phytotoxic compounds present in it, as reported by Rogovska et al. (2012). Using biochar generated at high pyrolysis temperatures, Busch et al. (2012) found a reduction in the shoot and radical length in maize, but not at low temperatures.

Reduction of the Efficacy of Pesticides

By reducing soil bioavailability, increasing residual life, and reducing plant uptake, biochar generally reduces the effectiveness of soil-applied pesticides (Yu et al. 2011). A biochar-based application may modify pesticide behaviour; for example, the sorption of soil-applied pesticides by biochar may reduce their efficacy by controlling their bioavailability to organisms and leaching vulnerability (Loganathan et al. 2009). Soil amendment of 0.5% (w/w) with biochar from red gum wood (Eucalyptus spp.) improves the sorption of acetamiprid and ultimately decreased its dissipation relative to unamended soil (Yu et al. 2011). In their review, Mesa et al. (2011) concluded that soil-applied chars (generated from open-fire burning of biomass) and biochars (produced from pyrolysis) alter soil-applied pesticide bioavailability and efficacy dramatically.

Retention of Heavy Metals and Other Contaminants

Biochar can enhance the concentration of heavy metals and other pollutants or contaminants in soil which in turn can possess long-term risks to the ecosystem. For example, Beesley et al. (2010) concluded that the application of biochar increased the concentrations of copper (Cu) and arsenic (As) by more than 30 times, while simultaneously increasing soil-dissolved organic carbon and pH levels. Similarly, biochar application increased As and Cu mobility in a field profile and Pb mobility in a mesocosm, while the effect on Cd was not found significant (Beesley and Dickinson 2011). In addition, Uchimiya et al. (2010) demonstrated that high carboxyl biochar fractions were capable of mobilizing Cu from alkaline soils.

Impact on Soil Organisms

PAHs, formaldehyde, cresols, acrolein, and xylenes as well as other carbonyl compounds present in biochar may possess bactericidal or fungicidal properties when applied to soil (Painter et al. 2001). A few studies have monitored earthworm mortality and avoidance behaviour to assess the effect of biochar soil amendments on earthworm population dynamics. For instance, earthworm habitat choice was not affected by biochar (30 t ha^{-1}) amendment within 2 days, but earthworms avoided biochar after 2 weeks primarily due to a slight decline in soil water potential, rather than toxins such as PAHs (Tammeorg et al. 2014).

Emission of Greenhouse Gases

We know that biochar application in the soil can reduce the emission of greenhouse gases like CO_2, CH_4, N_2O etc. as per previous research documentation. But in some particular cases, a few studies have also reported that biochar addition in the soil can increase greenhous gas emission into the atmosphere. For example, the application of wheat straw biochar (pyrolyzed at 350–550 °C) @ 40 t ha^{-1} with or without N increases the CH_4 emission by 34 and 41%, respectively at Tai Lake plain, China (Zhang et al. 2010). Furthermore, the CH_4 emission was increased by 44.9% by municipal biowaste biochar (40 t ha^{-1}) in rice (Bian et al. 2013). Likewise, with the addition of biochar at 5 and 25 t ha^{-1}, the cumulative CO_2 flux was enhanced by 6 and 10% respectively, under a maize-soybean rotation in Central Ohio (Hottle 2013).

Poisonous Effect on Human Health

As different kinds of biochar are mostly present in dust form, so they contain various heavy metals (As, Cu, Pb etc.) and other toxic substances like silica which are very much harmful to human health during application in soil. These dust particles can create problems, particularly in the respiratory system of humans. Broad studies are needed regarding the impacts of biochar on human health in near future.

1.6 Conclusion

Biochar is a technique of reclaiming contaminated agricultural soil, boosting soil fertility by lowering acidity, and increasing nutrient availability. Thus, adding biochar to the soil is the ideal method for overcoming any biotic stress in the soil and increasing crop output. Biochar's positive effects on soil-water-plant interactions resulted in increased nitrogen and water consumption efficiency as well as improved photosynthetic performance. Soil characteristics, microbial abundance, biological nitrogen fixation, and plant development all benefit from biochar. It is suggested that biochar be used as a soil additive for long-term carbon sink repair. Biochar is a strong option for expanding soil efficiency and plant development even in outrageous climate-uncovered soils. Plants might have the option to get through outrageous temperatures, dry spell, desertification, flooding, and salinization with the assistance of biochar revisions. Biochar is definitely not an original thought in farming. Notwithstanding, there is an assortment of studies accessible on the capability of biochar in further developing soil organic carbon among smallholder ranchers; consequently, biochar's effects on environment moderation are a profoundly factor. When compared to the use of plant biomass, which biodegrades faster in soil, biochar could be a viable option for producing more stubborn carbon and so making it more stable when added to the ground. Agroecosystems are crucial for ensuring food security and reducing greenhous gas emissions. Biochar expansion tends to reduce synthetic manure inputs and lighten greenhous gas outflows by increasing soil C sequestration and, as a result, increasing manure N crop-use efficacy. Before applying biochar, it is important to make informed decisions about its type, rate, and partiality using agro-farming frameworks. Biochar is useful for delaying the arrival of nutrients and thereby protecting the environment without compromising crop output. Biochar's positive impact on agroecosystems and the creation of a sustainable climate necessitates thorough investigation, as well as economic and social inquiry. Biochar can be made from a variety of plant-based ingredients; therefore it is frequently distributed locally. Following a lab test, the biochar(s) may be used on a small scale to determine which biochar and revision rate will provide the most benefit to your crops.

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Chapter 2
Biochar to Improve Crops Yield and Quality Under a Changing Climate

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Abstract Climate change is threatening global food security, calling for advanced agricultural practices to feed an increasing population. In particular, a major challenge is improving soil quality in an ecological manner for obtaining optimum crop yield. For that, recent research shows that using biochar as a soil amendment mitigates global warming, restores soil health, and improves crop yield. Biochar improves the availability of plant nutrients by increasing nutrient and water use efficiencies, soil porosity, and cation exchange capacity. For instance, application of biochar alone or combined with other fertilizers improves the aerial biomass of maize by 189%, wheat by 18%, grasses by 93% and cereals by 20%. Biochar application enhances grain nitrogen and protein content of cereals such as wheat and maize. Nonetheless, biochar performance depends upon agro-climatic conditions. Here we review the role of biochar in improving crop performance under changing climate.

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2.1 Introduction

Problems related to climatic instability along global warming compelled the scientific community to search for techniques that ensure sustainable crop production for the ever increasing world population. Intensive agriculture is the recommendation to raise productivity which is directly related to soil health/quality and crop input requirement. Improving soil quality and inputs requirement for getting potential yields remains a major challenge. Biochar, a recent amendment in the agriculture system as a soil conditioner with proven benefits related to soil sustainability and crop productivity, has been recognized as a sustainable strategy to tackle the concern.

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Biochar a carbon rich material produced when organic solids is decomposed at low temperatures under restricted supply of oxygen (Sohi et al. 2010). Pyrolysis is a process which happens at above 350 °C temperature under no/restricted supply of oxygen for the conversion of organic material such as biomass. In Pakistan the availability of organic materials generally called feedstock's for biochar production is extensive (Rasul et al. 2017; Ahmad et al. 2022a, b). Generally these feedstocks may include i.e. wood chips, plant prunings, plant residues, organic wastes, poultry and dairy manures.

Biochar characteristics mainly depend on the temperature and heating time required for pyrolysis (Elnour et al. 2019). Due to high alkalinity we have to select appropriate biochar feedstock's and find out suitable pyrolysis temperature for Pakistani soils. Thus to keep soil fertile, biochar produced through low pyrolysis temperature, is highly nutritive, having low pH and high cation exchange capacity might be a good choice than any other amendment for Pakistani soil (Rasul et al. 2017).

Application of organic manures alone and along with synthetic fertilizers can beeffectively used as nutrient supplement. However, the effect of organic manures varies depending on soil and climatic condition. Furthermore, little literature explores the integrated effect of biochar alone and in combination with organic and inorganic amendments on crop growth, yield and quality. Keeping these observations we hypothesized that biochar application into soil enhances the efficiency of organic and inorganic nitrogen fertilizers and improve the yield of wheat crop. Therefore, in this chapter we evaluated the effects of biochar, organic manures and inorganic nitrogen fertilizer on crop yield and quality.

2.2 Biochar as Soil Conditioner

There are different ways through which biochar can be applied to soil. These methods involve application by hand or through machine. Scientists in their studies have reported that the best way of application of biochar to soil is incorporation upto 0–15 cm through tillage implements such as rigid tine cultivator (Graves 2013; Nelissen et al. 2015; Amanullah et al. 2021). Recommended application of organic materials to soil must be based on large field experiments.

To make general recommendations, biochar application rates should be maintained according to nature of biochar materials, soil types and crops (Major 2010). However, Liu et al. (2013) studied data of 59 pot and 57 field experiments and observed average increase of 11% in overall crop productivity. He noted that this increase in productivity was due to the field application of biochar probably less than 30 t ha^{-1} and further clarifies that this improvement in crop productivity differs with crop type and greater increase of 30, 29, 14, 11, 8 and 7% were observed for legumes, vegetables, grasses, wheat, maize and rice respectively. However, the highest amount of biochar 100 tons ha^{-1} that can be applied has been evaluated by Jeffery et al. (2011), and results showed positive impacts.

The application of biochar is important for improving soil biology which further have impact on microbial community and its activity (Palansooriya et al. 2019), decrease oozing of nutrient and have encouraging effects on soil physico-chemical characteristics (Rawat et al. 2019; Berek et al. 2018; Ahmad et al. 2022a, b). Though, responses of soil to application of biochar are strongly affected by its physico-chemical properties. Hence, making it difficult to predict the effect of particular biochar on soil physico-chemical characteristics and crop productivity (Biederman and Harpole 2013).

Biochar is highly porous, which creates a better soil environment and decreases the bulk density or compactness of the soil, alter the pore size distribution and possibly affects the slow passage of water in the soil or water percolation rates (Libutti et al. 2019), modifies soil hydraulic properties (Altdorff et al. 2019) thus improves soil aggregation and water holding capacity. Likewise, application of biochar increases the availability of nutrients, its uptake that ultimately increases crop productivity. It also improves soil organic carbon, total nitrogen and nitrogen use efficiency (Shah and Shah 2018; Rawat et al. 2019; Oladele et al. 2019).

Crop growth rate of maize, net assimilation rate, yield components, water use efficiency and productivity of maize significantly increases when biochar is applied at 15 to 20 t (Uzoma et al. 2011). The use of synthetic fertilizer can be minimized through biochar application due to reduction of nitrogen loses due to de-nitrification and leaching while on the other hand it enhances cation exchange capacity (Pereira et al. 2015, 2017) (Fig. 2.1).

2.3 Biochar in Optimizing Crop Quality and Yield

Utilization of wood biochar lone or in integration with other manure mends crop yield when compared to no biochar treated soils (Mensah and Frimpong 2018; Amanullah et al. 2022). Significant variation is reported in grain yield 95 to 266% for soils with no biochar and nitrogen fertilizer was applied, in contrast to those soils where biochar at 100 tones ha^{-1} was applied in combination/integration with inorganic nitrogen. Remarkable increase of 189% was recorded in maize biological yield when biochar was treated with soil (Major et al. 2010). Legume and grass above ground biomass improves by 20% and 93% respectively as compare to no biochar amended plots (Major et al. 2009).

Around 18% improvement in wheat yield is noted when both wood biochar and nitrogen is applied in combination (Solaiman et al. 2010). Furthermore, incorporation of wood biochar produces considerably higher wheat yield over no biochar amended soils (Solaiman et al. 2010). Chan et al. (2008) studied agronomic value of wood biochar in coarse textured soils is greatly needed to increase soil water holding capacity and nutrients retention ability that encourages crop growth as well as development. Furthermore, observed encouraging influence of wood biochar on wheat yield during pot experiment under Simi-arid condition.

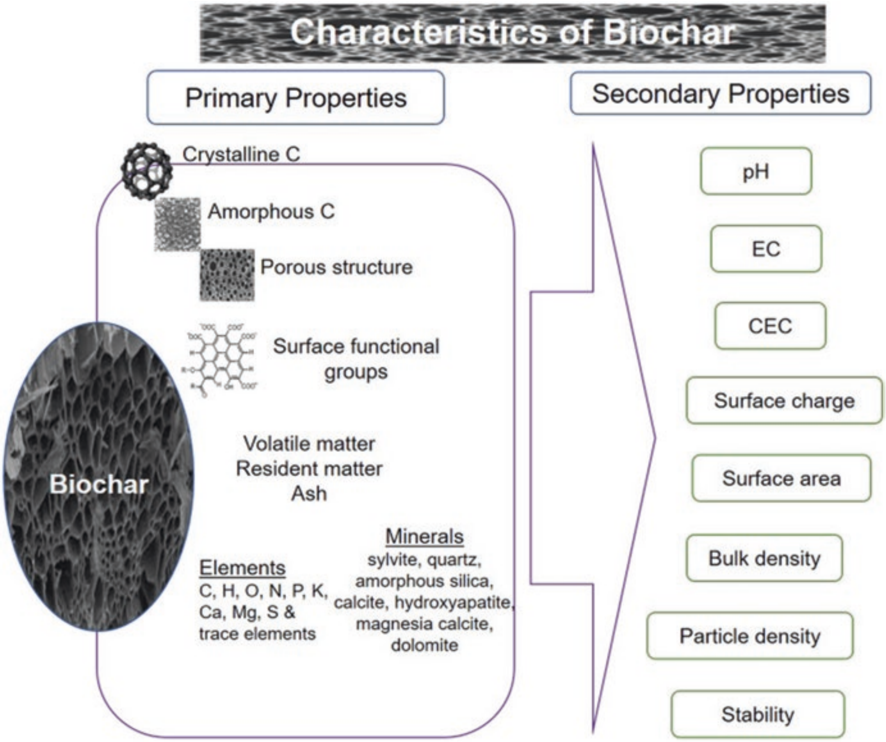

Fig. 2.1 Properties of biochar. Biochar a carbon rich material and porous by-product of slow pyrolysis, having a range of characteristics. For a particular feedstock, biochar characteristics mainly depend on the temperature and heating time required for pyrolysis. The general characteristics showed that biochar are rich with nitrogen, phosphorus, potassium, calcium, magnesium and sulfur. Furthermore, biochars prepared from different feed stocks have different properties such as pH, electrical conductivity, surface area and essential nutrients). Most woody biochars have medium-high surface area and porosity and lower bulk density as well as particle density. Furthermore, high as biochars have lower porosity and surface area. C, H, O, N, P, K, EC, CEC stand for carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, electrical conductivity and cation exchange capacity respectively. (Modifed and reprinted with permission from Xu et al. 2017)

Spokas (2010) studied no and/or adverse effect of wood biochar on crop yield when treated with soil alone. On the other hand, when integrated with inorganic fertilizer the effect was encouraging (Palm et al. 2001; Arif et al. 2021). Blackwell et al. (2009) also noted comparable results and found enhanced crop growth and yield when both wood biochar and inorganic fertilizer were co-applied as compared to sole wood biochar application. Several authors including Alburquerque et al. (2013) stated that wood biochar addition improves plant height, biological yield and grains quality. Biochar application enhances nitrogen content in different parts of wheat e.g. straw and grain by 24, 56% respectively, grain protein content by (20%) and soil total nitrogen by 63%.

Similarly nitrogen use efficiency improves by 38% in the plots receives biochar at 25 and 50 t ha^{-1} over plots without biochar (Ali et al. 2015a). It has been reported that biochar applied to wheat at 25 t ha^{-1} maximizes spikes m^{-2}, grains in spike, 1000 grain weight, economic and biological yield by 6.64, 5.6, 3.73, 9.96, and 15.36% respectively in comparison with no biochar treated plots (Ali et al. 2015b; Dawar et al. 2021). Wheat grown with mineral fertilizer phosphorous and biochar produces maximum grain yield of 46% in comparison to plot where no biochar was applied (Blackwell et al. 2010). Integrated application of biochar, nitrogen and farm yard manure at 25, 10 and 150 kg ha^{-1} delayed phenology in maize crop.

Further it is reported that addition of 30 tones biochar and 75 kg ha^{-1} nitrogen applied from urea lead to more rows/ear, heavier 1000 grain weight, greater grain yield and biological yield of maize (Arif et al. 2012). Further, use of biochar and farm yard manure by 25 and 5 ton ha^{-1} lead to reduces weeds density both 30 and 60 days after sowing (Arif et al. 2013). Biochar also enhanced fertilizer use efficiency, which resulted in maximum yield/kilogram of fertilizer used (Chan and Xu 2009). Yeboah et al. (2009) observed higher nutrient uptake as well as crop growth due to higher wood biochar addition. Soil incorporated with biochar enhanced crop establishment and better crop growth rate and net assimilation rate which ultimately lead to higher maize yield (Uzoma et al. 2011).

Similarly biochar incorporation can enhance quality of the crop and crop yield, and keep the crop safe from the attack of destructive pests and occurrence of crop diseases (Vaccari et al. 2011). Biochar in soil have encouraging effects on germination of seed, establishment of crop plants, and early crop growth (Genesio et al. 2012). Biochar as soil amendment restores soil fertility, stimulate plant growth, and promote sustainable agriculture development (Rawat et al. 2019) (Tables 2.1 and 2.2).

2.4 Biochar with Organic and Mineral Fertilizers

The degradation of the soils is one of the key limitations for providing food for the ever growing population (Gupta 2019). This soil degradation occurs due to the intensive agricultural uses and poor soil management (Lucas-Borja et al. 2019; Fahad et al. 2020). Applications of synthetic fertilizers and manures have frequently been used for restoration of degraded soils. However, constant use of inorganic fertilizers enhances acidification, decrease microbial population and biological, geological and chemical aspects of the soil, hence reduce crop productivity (Seufert et al. 2012). Adding manures to soil is a tool to improve physical environment and directly supply both macro and micro-nutrients. However, the rapid turnover of manures is the key limitation for the restoration of poor fertile soils (Mensah and Frimpong 2018).

The integrated application of both biochar and organic manures declines the decomposition of the organic manures, leading to slowly release of nutrients, which subsequently reduced nutrients losses especially through leaching (Mensah and

Table 2.1 Integrated effect of biochar and nitrogen sources on grain yield of wheat

Biochar (t ha^{-1})	Years		Mean	% Increase
	2015–2016	2016–2017		
0	3407.53 c	3645.83 c	3526.68 c	
10	3518.81 bc	3762.01 bc	3640.41 b	3.22
20	3872.25 a	4116.25 a	3994.25 a	13.26
30	3575.44 b	3822.01 b	3700.23 b	4.92
LSD $_{(0.05)}$	158.72	158.59	110.59	
Nitrogen management (kg ha^{-1})				
Control	2653.11 f	2900.19 f	2776.65 f	
90 N urea	3298.67 e	3541.08 e	3419.88 e23.17	
120 N urea	3622.17 cd	3862.58 cd	3742.38 cd	34.78
150 N urea	3944.66 ab	4185.25 ab	4064.95 a	46.40
90 N FYM	36.07.11 d	3847.69 d	3727.40 cd	34.24
120 N FYM	3575.79 d	3819.87 d	3697.83 d	33.18
150 N FYM	3866.56 abc	4105.22 abc	3985.89 ab	43.55
90 N PM	3574.39 d	3814.81 d	3694.60 d	33.06
120 N PM	3762.86 bcd	4011.03 bcd	3886.95 bc	39.99
150 N PM	4037.25 a	4277.50 a	4157.38 a	49.73
LSD $_{(0.05)}$	250.96	250.75	174.86	
Mean	3594.26 b	3836.52 a		
Interactions				
Y x BC	ns	Y × N	ns	
BC x N	*	Y × BC × N	ns	

LSD mean least significant difference (α=0.05) while N, FYM, PM, Y, BC and ns means nitrogen, farmyard manure, poultry manure, year, biochar and non-significant respectively

Frimpong 2018). Furthermore combined application of biochar and conventional fertilizer reduces the quantity of biochar needed to reduce soil pH and increase inorganic fertilizer retention (Nielsen et al. 2018; Khalid et al. 2019). However, scientists also reported antagonistic effect due to combined addition of biochar and organic or inorganic fertilizers when compared with the sole application (Seehausen et al. 2017). Biochar with high sorption capacity can decrease the availability of nitrogen and phosphorus (DeLuca et al. 2015). Though, biochar sorption capacity may be considerably dependent on biochar properties, e.g. pH, acidic surface, amount of biochar applied, feedstocks used and pyrolysis temperature (Yao et al. 2012).

Addition of organic and mineral fertilizer improved productivity and is also environmentally friendly (Zahoor 2014). It is further reported that application of organic materials and inorganic fertilizer contributes to the proper nutrition of the crops and improve soil fertility. Application of poultry manure 6 tons, farm yard manure 6 tons and 90 kg nitrogen ha^{-1} significantly affected no. of spikes, length of the spike, plant height, days to harvest maturity, biological and grain yield of wheat. The addition of organic and mineral fertilizers to wheat crop might give a substitute under field condition (Abbas et al. 2012).

Table 2.2 Integrated effect of biochar and N sources on biological yield in kg ha^{-1} of wheat (Figs. 2.2 and 2.3)

Biochar (t ha^{-1})	Years 2015–2016	2016–2017	Mean	% Increase
0	11382.23 c	11724.93 c	11553.58 d	
10	12205.57 b	12550.07 b	12377.82 c	7.13
20	13093.32 a	13446.48 a	13269.90 a	14.86
30	12377.24 b	12729.18 b	12553.21 b	8.65
LSD $_{(0.05)}$	195.64	194.47	135.96	
Nitrogen management (kg ha^{-1})				
Control	10863.44 e	11203.61 e	11033.53 f	
90 N urea	12045.50 d	12397.08 d	12221.29 e	10.77
120 N urea	12296.58 cd	12642.42 cd	12469.50 d	13.01
150 N urea	12626.00 ab	12981.83 ab	12803.91 ab	16.05
90 N FYM	12333.61 bcd	12677.28 bcd	12505.44 d	13.34
120 N FYM	12391.37 bc	12733.62 bc	12562.50 cd	13.86
150 N FYM	12552.14 abc	12903.31 abc	12727.72 abc	15.35
90 N PM	12319.81 bcd	12669.97 cd	12494.89 d	13.24
120 N PM	12449.45 bc	12800.78 bc	12625.11 bcd	14.42
150 N PM	12768.00 a	13116.75 a	12942.38 a	17.30
LSD $_{(0.05)}$	309.33	307.48	214.98	
Mean	12264.59 b	12612.66 a		
Interactions				
Y x BC	Ns	Y x N	Ns	
BC x N	*	Y x BC x N	Ns	

LSD mean least significant difference (α=0.05) while N, FYM, PM, Y, BC and ns means nitrogen, farmyard manure, poultry manure, year, biochar and non-significant respectively

Integrated management of poultry manure and inorganic fertilizers results in maximum height and grain yield of wheat (Abbas et al. 2012). Addition of higher level of farm yard manure alone had considerably improved weed density, weed fresh and dry biomass as compared to low level of farm yard manure (Arif et al. 2012). Furthermore, combined application of biochar, farmyard manure and nitrogen levels had also significant impact on weed infestation in wheat crop. Moreover higher weed density such as 35 and 70 days after sowing, weed fresh and dry biomass were observed at higher level of farmyard manure, similarly maximum weeds fresh and dry biomass were also observed for 120 kg nitrogen ha^{-1} and 50 tons biochar (Arif et al. 2013; Khan et al. 2022).

Atif et al. quoted that application of farm yard manure by (9 tons ha^{-1}) results in highest spike length, number of grains in each spike and maximum grain yield. Also application of farmyard manure, poultry manure and urea had significant effect on cobs per plant, 1000 grains weight and grain yield of two maize hybrids (Pioneer 3062 & 3012) (Khalid et al. 2004). It is further reported that addition of

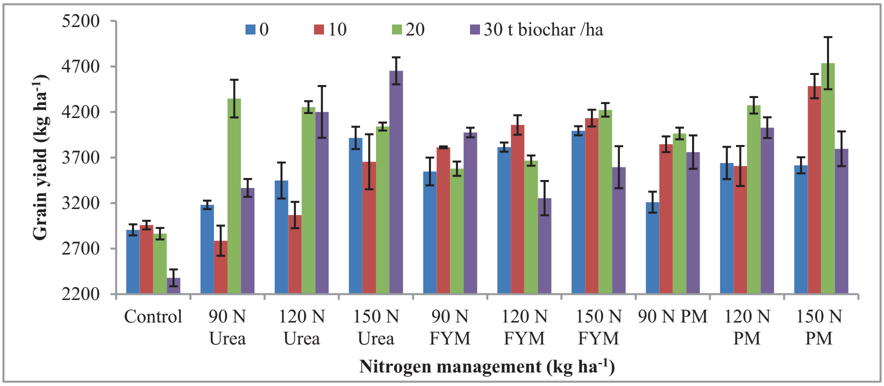

Fig. 2.2 Interactive effect of biochar and nitrogen sources on grain yield of wheat. Generally, the interaction between biochar × nitrogen management showed that sole application of biochar significantly increased grain yield of wheat over no biochar treated plot. However the results were more pronounced when biochar was applied with either of the nitrogen source. Specifically, plots amended with 20 t biochar produced maximum grain yield of wheat when combined with 150 kg ha^{-1} nitrogen applied from poultry manure. N, FYM and PM stand for nitrogen, farmyard manure and poultry manure respectively. (Modified and reprinted with permission from Khan et al. 2020)

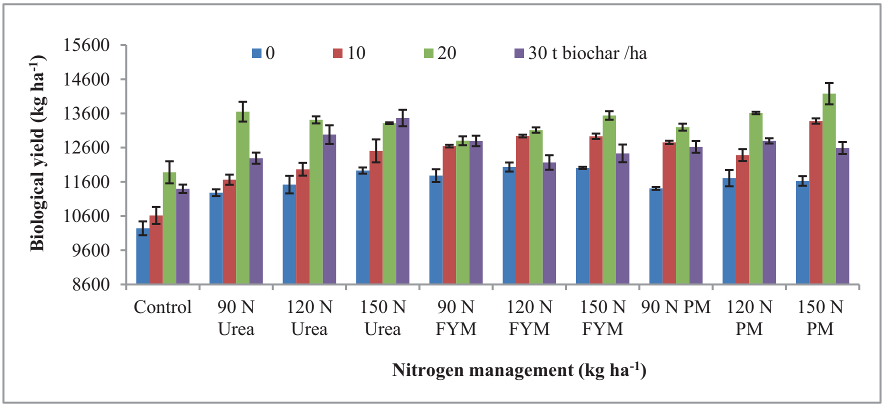

Fig. 2.3 Interactive effect of biochar and nitrogen sources on biological yield of wheat. Generally, the interaction between biochar × nitrogen management showed that sole application of biochar significantly increased biological yield of wheat over no biochar treated plot. However the results were more pronounced when biochar was applied with either of the nitrogen source. Specifically, plots amended with 20 t biochar produced maximum biological yield of wheat when combined with 150 kg ha^{-1} nitrogen applied from poultry manure. N, FYM and PM stand for nitrogen, farmyard manure and poultry manure respectively. (Modified and reprinted with permission from Khan et al. 2020)

poultry manure alone and with urea increase grain yield, 1000 grains weight, soil total nitrogen and organic matter (Shah et al. 2013). Further, reports are available that utilization of 12 t farmyard manure and 28/12 N/P have considerable impact on affected leaf area index, plant height, grain yield of maize but not harvest index and saved almost 75% cost of commercial fertilizer for both years (Zerihun et al. 2013).

Mukhtiar et al. (2018) observed improvement in all wheat parameters due to variations in nature of the organic materials. Furthermore, the application of manures with synthetic fertilizers is cost-effective (Kumar et al. 2017). Poultry manure has been known from the past as an important and utmost needed organic fertilizer because it develop fertility of the soil by providing the necessary nutrients and build up soil organic matter which ultimately increase moisture and nutrient retaining potential of the soil, furthermore poultry manure alone at 12 t ha^{-1} results in maximum yield and yield components of maize (Farhad et al. 2009; Mehmood et al. 2021). Efthimiadou et al. (2010) further reported that plots receiving poultry manure (5 t) has high grains/spike, 1000 grain weight, biological and grain yield. However, combined application of organic and mineral fertilizers increases soil organic matter and soil total nitrogen (Fig. 2.4).

Organic fertilizer or manures is relatively poor in nutrients content, moreover the nutrients emancipating power is also lower in order to fulfill the nutritional needs of the crops (Baghdadi et al. 2018), thus the incorporation of organic manures alone could not sustain the normal intensity of agriculture production (Bandyopadhyay et al. 2010). Moreover, application of lone inorganic fertilization improves mineralization of soil organic matter (Mahal et al. 2019; Mian et al. 2021), deteriorated soil structure and increase loss of nutrients (Nin et al. 2016). Therefore, integrated nutrient management is the most promising practice to keep soil fertile (Dejene and Lemlem 2012).

Incorporation of organic manures, decreased soil pH (Mahmood et al. 2017). Kawsar (2013) noted decline in soil pH from 7.54 to 7.47 when farmyard manure (FYM) was applied at higher level 10 t ha^{-1} to alkaline soils. However, Mahmood et al. (2017) quoted that lone mineral nitrogen application abridged soil pH, however addition of organic and synthetic fertilizer considerably increased soil pH. A conceivable justification for the above statement is that organic manures consist of basic cations as well as carbonate to neutralize the acidification effect (Duruigbo et al. 2007). Moreover, high alkalinity of manures is the key cause for the raising soil pH (Xu et al. 2006).

Further, reduced soil bulk density due to improved soil bio pores and soil aeration, greater soil organic carbon content, and improved soil aggregation that eventually enhanced soil porosity as well as water holding capacity (Gangwar et al. 2006). Similarly, Papini et al. (2011) also noted that the addition of manures improved soil aeration, moisture content, water holding capacity and decreased soil bulk density. The lower C:N ratios of the soil due to the addition of synthetic and organic fertilizers might be ascribed to greater availability of nitrogen and its retention in the soil (Chen et al. 2010). Organic manures considerably improved soil organic carbon therefore had a positive impact on soil microbial population.

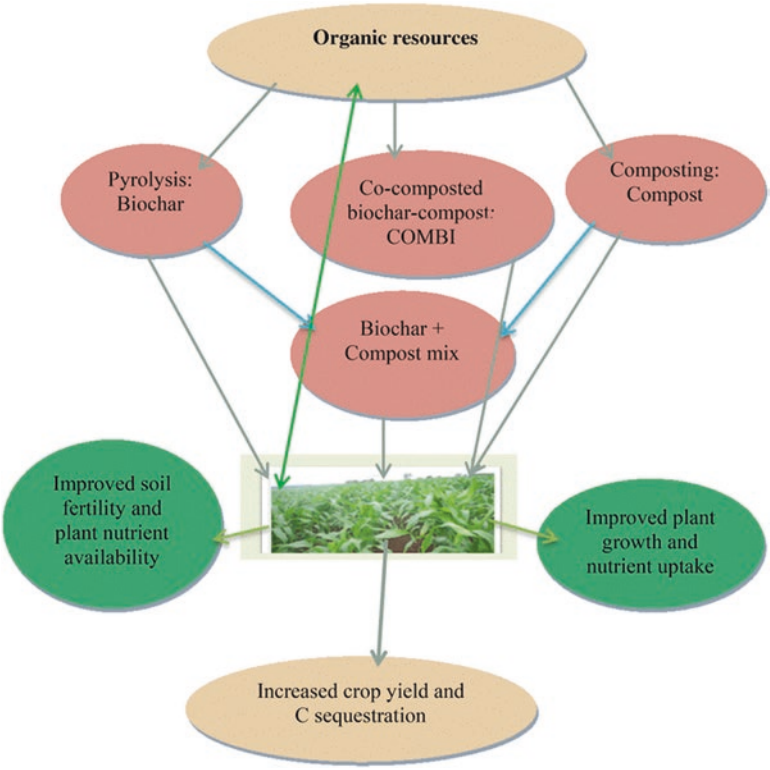

Fig. 2.4 Conceptual framework for organic amendments and plant – soil relationships. This framework shows the effect of biochar, biochar-compost and co-composted-biochar-compost on crop growth, yield, soil phyico-chemical properties and carbon sequestration. Application of biochar and biochar-compost mixtures from various feedstock's have promising choice for improving soil fertility, plant nutrient availability, nutrient uptake, restoring degraded land and mitigating the emissions of greenhouse gasses associated with agriculture. (Modified and reprinted with permission from Agegnehu et al. 2017)

The exogenous application of organic matter having high C:N ratio encourage faster mineralization of the already existing organic matter (Shahzad et al. 2015; Saleem et al. 2021). Mahmood et al. (2017) quoted that sheep manure has greater C:N ratio and minimum soil organic carbon when compared with farmyard manure and poultry manure. Purakayastha et al. (2008) stated that integrated use of organic and synthetic fertilizer boosted soil organic carbon and soil total nitrogen by 1180 and 56–92% in the soil. Addition of organic manures like sheep manure, poultry manure and farmyard manure with mineral fertilizers causes considerable improvement in soil nitrogen, phosphorus and potassium concentration that sustain improved nutrient use efficiency (Mahmood et al. 2017).

Furthermore the improvement in soil nitrogen, phosphorus and potassium content was possibly be related with organic manure such as farmyard manure or poultry manure absorbing more leachate, which lead to decreased nutrient leaching

(Murmu et al. 2013; Adekiya et al. 2019; Ullah et al. 2022). Organic manures combined with reduced amount of synthetic fertilizers generally enhance microbial activity as well as nutrients availability more than the lone incorporation of synthetic fertilizer. Furthermore, enhanced soil aggregation, structure, and water retention capacity are also associated with the addition of both organic and synthetic fertilizers (Walsh and McDonnell 2012; Mahmood et al. 2017).

2.5 Conclusion

Agriculture under changing climate scenario is facing major challenges. Crop yield response to biochar may differ with biochar type, application rate and soil conditions. Organic fertilizer or manures is relatively poor in nutrients content and the nutrients releasing power is also poor in order to fulfill the nutritional needs of the crops. Biochar has been reported to improve crop yield, grain nitrogen and protein content. Its application as soil amendment restores soil fertility, stimulate plant growth, and promote sustainable agriculture development but its performance varies depending upon soil and climatic conditions. Therefore, further research is necessary to understand the performance of biochar on different crops under diverse agro-climatic conditions.

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Chapter 3
Biochar for Improving Crop Productivity and Soil Fertility

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Abstract Biochar application to soils can both sequester carbon in the long term, and improve soil fertility by storing nutrients and water. Biochar is produced by pyrolysis of biomass and biomass residues at high temperature. Here we review biochar application to soil with focus on improving crop productivity and soil fertility. The effect of biochar are highly variable depending on the type of biochar and the experimental conditions. Biochar modify significantly soil properties.

Keywords Biochar · Temperature · Plants · Climate change

3.1 Introduction

Soil is a medium for plant growth and provide support, minerals and water to the plant for survival. Various factors such as environment, soil condition, cultural/management operations and fertilizer application affect plants growth and development (Reis et al. 2016). The use of nitrogen-based fertilizers can't be ignored because of disfavor, but

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it's fabulous for the worldwide global aggregation but its excessive use can contaminate the environment through leaching, runoff and volatilization of the nutrient (Serra gas emission) (Norse and Xiaotang 2015). Therefore, the use of biochar in low-fertility soils is a useful technique for improve soil carbon, soil health its crop productivity (Van Zwieten et al. 2010). Biochar is a carbonaceous compost that comes from the thermal decomposition of vegetable residues and organic waste. The application of biochar has generated an ever-increasing interest in the recovery of nutrients from the ground. The use of biochar can improve the growth of the plant by improving the availability of nutrients, enhancing the microbial activity, the capacity to treat and nutrient of the water and increasing the apparent density. The application and management of biochar and climatic factors influence notably the physical-chemical property of the soil due to the slow rate of decomposition and the prolongation of soil fertility (Lima et al. 2002). However, biochar is highly recalcitrant to microbial decomposition and guarantees long-term benefits for soil fertility (Lima et al. 2002).

The integration of biochar with synthetic fertilizers can meliorate the addressable culture (Lima et al. 2002). Because the accumulation of biochar in the soil implies a diverse nitrogen pool, further study is necessary to increase the length of nitrogen restriction and the rate of riling (Kochanek et al. 2016). The biochar can be grown at temperatures below 350 °C or 550 °C with a C:N rate of 43 and 49 and is used in the ratio of 10 g kg^{-1} to its clayey soil. This has favored the mineralization of the more undecomposed fractions probably due to the effect of in scone biochar (Shaheen et al. 2019). The biochar product through the low temperature at the end has increased the pH of the soil and has also increased the exchange of soil microbes (Zhao et al. 2013; Esfandbod et al. 2017).

Climate change is affecting our agriculture sector (Irfan et al. 2021; Wajid et al. 2017; Yang et al. 2017; Zahida et al. 2017; Depeng et al. 2018; Hussain et al. 2020; Shafi et al. 2020; Wahid et al. 2020; Subhan et al. 2020; Zafar-ul-Hye et al. 2020a, b; Zafar et al. 2021; Adnan et al. 2020; Ilyas et al. 2020; Saleem et al. 2020a, b, c; Rehman 2020; Frahat et al. 2020; Wu et al. 2020; Mubeen et al. 2020; Farhana 2020; Wu et al. 2019; Ahmad et al. 2019; Baseer et al. 2019). Biochar can play a vital role in response to climate change because it can improve crop yield, soil microbial activity and decrease nutrients leaching. However, little attention has been given to biochar application in the process of biological N_2 fixation through its application to legume crops.

Potential benefits of applying biochar to agricultural soil include improved soil structure and soil moisture retention, changes in soil pH and micro-nutrient availability, positive effects on soil microorganisms, e.g. increased biological N_2 fixation by rhizobia in legumes and high levels of colonization by mycorrhizal fungi and plant growth promoting organisms in the rhizosphere. Biochar incorporation into agricultural soils not only changes their biology, but is also likely to have a strong correlated effect on their nitrogen dynamics. Since the C/N ratio of biochar is usually relatively high, initial mineralization of its available C would result in nitrogen (N) immobilization in the short term. This has been reported primarily in N-limited tropical soils (reduced N uptake and plant yields). The effects on soil nitrogen dynamics of biochar applications alone or in combination with mineral nitrogen fertilizers have been the focus of few recent studies. These experiments were carried out with the aim of studying the direct effect of biochar on legumes and the residual effects of biochar and legumes along with different nitrogen levels for subsequent crops of maize and wheat in the increase in productivity, in the improvement of soil quality and in the achievement of sustainability in the cultivation system based on cereals (Cao et al. 2010) (Table 3.1).

3.2 Biochar and Crop Productivity

Biochar is one of the efficient soil amendments which are used predominantly for the commercialized crops production. However, the data related to biochar effect on the crop production is limited as compare to his use and composition. Therefore, the

Table 3.1 Plant responses to biochar application

Source of biochar and application rate	Test crop	Crop responses	Reasons of crop response given by author	Reference
Unknown 0.5 t ha^{-1}	Soybean	Biomass increased by 51%	Increased soil water holding capacity and color of soil	
Unknown 5 and 15 t ha-1	Soybean	Yield reduced by 37%	pH induced micro-nutrients deficiency	
Wood biochar	Cereal	Enhances plant growth	Improving soil physical and biological properties	
Bamboo	Tea tree	Height and volume increased by 20 and 40%	Nutrient retention and balance pH	
Bark of acacia 37 t ha^{-1}	Maize and legumes	200% in yield with fertilizer application	Enhance the availability of P and N also reduce nutrient losses	
Wood biochar	Sorghum and rice	Increased yield when biochar applied with fertilizer as compared to biochar alone	Nutrient retention	
Rice husk 10 t ha^{-1}	Maize soybean	10–40% yield increased	Increased pH	
Green waste 0–100 t ha^{-1}	Wheat	Yield increased up to 40%	Improving physical properties of soil	
Wood charcoal	Wheat	–	Reduced N leaching	
Forest wood charcoal	Maize	–	10% lower bulk density	
Biochar created from modern pyrolysis techniques	Legumes	Positive crop responses	Reducing soil acidity and aluminum toxicity	Glaser et al. (2002)

numbers of tests related to soil and field evaluations are required to recommend different mount of biochar to amend the soil for the qualitative and quantitative production of the crop. Due to lack of limited information and research in the current literature, biochar application is a need of the day for getting more information and benefits. Characteristic of a particular biochar depends on the composition of its material, thus application rates if a particular biochar largely relates to the composition matrix. Several scientific evidences depicted a significant effect of biochar on crop yield and overall growth and development while applied at a rate of 5–50 t ha^{-1} along with adequate plant nourishment (Jalal et al. 2020). Biochar application can increase the value of the standing crops (Cao et al. 2010; Jalal et al. 2020). Thus enhance the yield and development of plants. An increased yield (28–40%) in maize crop was observed after 50 t ha^{-1} biochar application in Pakistani climatic condition (Jalal et al. 2020; Oguntunde et al. 2004) along with biochar at the rate of 90 g kg^{-1} to a manimum-fertile tropical soil, this is not only enhances the Nitrogen fixation rate in bean plants (*Phaseolus vulgaris*) from 50% to 72%, it is also have positive effect on the yield and biomass of bean (Oguntunde et al. 2004; Rondon et al. 2007).

Biochar ammendents in Northern Laos region of United States, categorically known for low Phosphorus availability results in higher grian yield of highlands rice (*Oryza sativa*) (Asai et al. 2009; Silber et al. 2010). All these above mentioned soil characteristics are closely interlinked and may act synergistically towards overall improvement crop productivity and efficiency. Numerous research findings justify the efficient use of biochar for crop improvement (Lehmann et al. 2003), however in certain specific agro-climatic zone the positive effect of biochar inadequate, while some scientist reported negative responses (Mikan and Abrams 1995). Several studies conducted in tropical and temperate agro-climatic conditions reported positive crop response to biochar application, increasing plant growth and development, robust microbial activity, enhanced water retention capacity and reduce nutrient leaching issue (Silber et al. 2010).

Application of biochar enhances nitrogen fixation and useful mycorrhizal relationship in beans (*Phaseolus vulgaris*) (Zhang et al. 2010). Research findings exposed that the positive effect of biochar on plant biomass and development of a crop enhances over time after its incorporation into the soil. Biochar can influence the physiochemical properties of soil, thus it has been reported to increase the fresh and dry yield of sesbania and cowpea (Arif et al. 2015). Furthermore, a research study depicted that biochar can enhance the water holding for more time water and soil nutrient preservation, it make sure the availability and optimum uptake of nutrients from the root zone for synthesis of higher photosynthate which can results in high dry matter content (Elmer et al. 2010).

In case of a study on cowpea and sesbania, the fresh and dry yield was recorded high in second year as compare to first year of experimental trial, illustrating the abundant of nutrients discharge both from legumes as well as biochar breakdown after a year (Arif et al. 2015). Grain and biological yield of mung bean significantly improved in the biochar applied experimental plots, attributes to the direct accessibility of nutrients mostly nitrogen all over the growing season from various biochar sources (Gruss et al. 2019), thus contributing to soil and crop productivity. Likewise, combined application of biochar from charcoal sources and organic fertilizers displayed positive plant growth responses suggesting a strong synergistic relationship for plant development (Yoshida et al. 2008). Biochar showed increased grain yield for different crop species in growing areas with minimum phosphorus (P) availability and also improved the reaction to nitrogen (N) and NP fertilizer applications.

Soil moisture, nutrient matrix and various yield traits such as grains ear^{-1} and grain output of corn is predominantly affected by biochar amendments in soil (Marshall et al. 2019). Various yield components contributes to the overall Grain yield. Application of biochar increased the grain and their overall weight level and seed pod^{-1} (Arif et al. 2015). Soil application with biochar amendments enhances yield and all yield related parameters of legume crops (Mikan and Abrams 1995), explaining the optimum influence of biochar is to provide more nutrient to the soil (Hafiz et al. 2018; Tariq et al. 2018; Fahad and Bano 2012; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b; Hesham and Fahad 2020. Iqra et al. 2020; Akbar et al. 2020; Mahar et al. 2020; Noor et al. 2020; Bayram et al. 2020; Amanullah 2017, 2018a, b).

Biotic activity of nitrogen fixing organisms improves with application of biochar thus effecting crop total biomass (Joseph et al. 2010). Nutrient leaching rate decreases with providing of Biochar into the soil which enhances the nutrient cycling and therefore creates a positive influence on crop yield and quality. Biochar has the capability to maintain and make available bio-available nutrients for growth of plant uptake in the root zone. For instance, plant can readily utilize the potassium found within biochar composition (Elmer et al. 2010). Biochar creates a varying effect on soil pH and other related chemical properties, depending on the nutrient source and growing situation (Joseph et al. 2010). Moreover, many type of microbes including fungi, nematodes and acidobacteria i.e. mycorrhizae are higher in population in soils amended with biochar (Woolf et al. 2008).

Soil type classified as “Problem Soil”, possessing organic properties such as poor combined stability, high salinity, excessive pH levels (very high or very low) or deficient in nutrients (Paul et al. 2018; Amanullah et al. 2020, 2021; Rashid et al. 2020; Arif et al. 2020; Amir et al. 2020; Saman et al. 2020; Muhammad Tahir et al. 2020; Md Jakirand Allah 2020; Mahmood et al. 2021; Farah et al. 2020; Sadam et al. 2020; Unsar et al. 2020; Fazli et al. 2020; Md. Enamul et al. 2020; Gopakumar et al. 2020; Zia-ur-Rehman 2020; Ayman et al. 2020; Mohammad I. Al-Wabel et al. 2020a, b). This may be successfully rectified and reclaimed by using biochar as an active remedial agent alone or mixed with other organic amendments (Sohi et al. 2010a, b). Sustainable health of soils may rectify with adequate use of biochar (Spokas et al. 2010).

Several studies had reported multiple ways through which biochar can improve the overall soil health and growing condition (Zhang et al. 2018). For instance, enhanced microbial population diversity throughout the soil volume can immensely increase soil fertility and nutrient levels (Ayaz et al. 2021). The protection provided by biochar pores allows microbial populations to multiply and propagates as well increase the nitrogen fixation rate for plant uptake (Paul et al. 2018; Zhang et al. 2020). This phenomena is beneficial for crops mainly non-legumes crop that are not capable to fix their individual nitrogen. In context to plant-soil feeding relationship, it is quite evident and interesting that potassium found in biochar composition is already present in form that is readily available for plat uptake (Senol 2020; Amjad et al. 2020; Ibrar et al. 2020; Sajid et al. 2020; Muhammad et al. 2021; Sidra et al. 2021; Zahir et al. 2021; Sahrish et al. 2022). Also, Biochar is essentially beneficial for crops where nitrogen fixation phenomena is limited or absent (Heitkötter et al. 2015).

Moreover, the amount of carbon in soil enhances and for the short term minimized the pH level in soils, while soils with alkaline activities tends to be most positive for normally grown cash crops such as maize (Dempster et al. 2012). Addition of biochar can improve different soil properties (Haque et al. 2021). While analyze the soil physicochemical characteristic, it was recorded that the application of biochar had improved nitrogen levels as compare toward only fertilizer treatments (1.16% vs. 0.15% soil nitrogen).increasing of biomass up to 9–18%, it was observed that there were high levels of nitrogen within biomass leaves. Utlizing carbon in its solid form also allows soil to improve its nutrient availability and retention (Haque et al. 2021). Type of soil which are subjected to natural weathering due to any possible reason can't retain the nutrients and mineral available in the soil and thus recorded with low Cation Exchange Capacity (CEC) (Haque et al. 2021). It also has positive relationship of increasing water holding capacity but on surface bonding that occurs with enhanced CEC adds to the nutrient maintenance (Haque et al. 2021).

Furthermore, biochar also hold the capability to openly provide nutrients for plant uptake. For instance, the potassium avaliable in biochar obtained from its creative feed stock is mainly bring into being in forms readily existing for plant uptake (Ameloot et al. 2013). Like illustrated in the Fig. 3.1, the rise and fall of soil pH

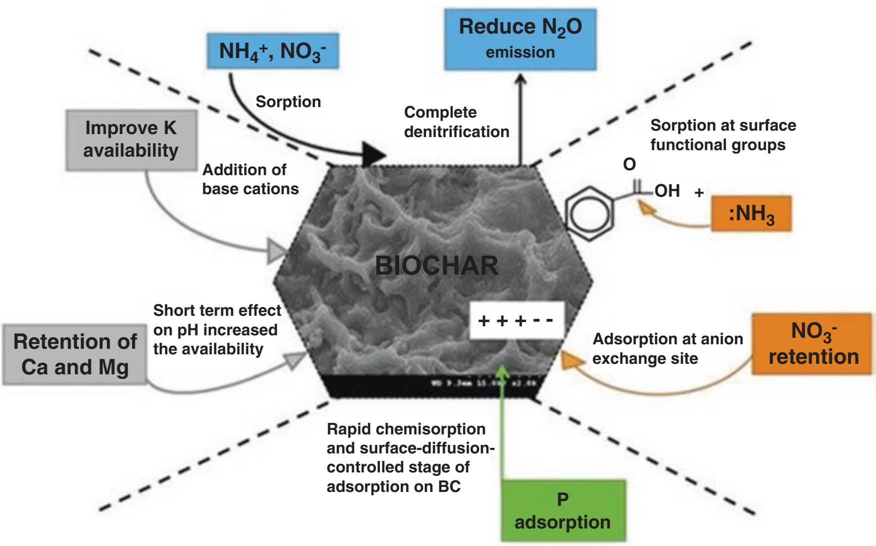

Fig. 3.1 Role of biochar after its application to the soil

after biochar amendments totally depend on the nature, source and characteristics of biochar (Zheng et al. 2013). Generally, bio-chars mixtures formulated from the agricultural residues are likely to be extra alkaline and thus cooperate to enhance soil pH (Borchard et al. 2014; Glaser et al. 2002). Agri- prone biochar compositions have maximum amount of the ash which gives maximum salts quantity to twist more alkaline (Ameloot et al. 2013). Contrary, biochars compositions sourced mainly animal waste product, including bovine manure or chicken litter, are predominantly acidic due to the chemical property they supply to the biochar composite (Yuan et al. 2011).

3.2.1 Biochar as a Soil Amendment

Soil improvement and development is an essential for better quality crop production in most part of the world (Sajjad et al. 2021a, b; Rehana et al. 2021; Yang et al. 2022; Ahmad et al. 2022; Shah et al. 2022; Muhammad et al. 2022; Wiqar et al. 2022; Farhat et al. 2022; Niaz et al. 2022; Ihsan et al. 2022; Chao et al. 2022, Qin et al. 2022; Xue et al. 2022; Ali et al. 2022; Mehmood et al. 2022; El Sabagh et al. 2022; Ibad et al. 2022). Scarcity of basic food elements leading towards meal security is substantially high in sub-Saharan Africa and South Asian regions, recorded for 32% and 22% malnutrition rates in the overall population, respectively (Keske et al. 2020; Deepranjan et al. 2021; Haider et al. 2021; Huang Li et al. 2021; Ikram et al. 2021; Jabborova et al. 2021; Khadim et al. 2021a, b; Manzer et al. 2021; Muzammal et al. 2021; Abdul et al. 2021a, b; Ashfaq et al. 2021; Amjad et al. 2021; Atif et al. 2021; Athar et al. 2021; Adnan et al. 2018a, b, 2019; Akram et al. 2018a, b; Aziz et al. 2017a, b; Chang et al. 2021; Chen et al. 2021; Emre et al. 2021). Even though, the world predominantly work and managed to reduce the malnutrition and famine situation in many countries during the years 1990–1992 and 2001–2003, but countries in Africa, Asia and Latin America are facing this mimic humanitarian disaster.

The historical initiative-"Green Revolution" took by Nobel Laureate Norman Borlaug in 1940s at the International Centre for Maize and Wheat Improvement (CIMMYT), Mexico results in remarkable increase in all sorts of agricultural produce in Asia and Latin American regions. All these advancement in productivity accounts for efficient and improve agricultural practices as well as use of modern technology, including better quality crop varieties, effectual irrigation system and adequate fertilizer and pesticides inputs (Habib et al. 2017; Hafiz et al. 2016, 2019; Ghulam et al. 2021; Guofu et al. 2021; Hafeez et al. 2021; Khan et al. 2021; Kamaran et al. 2017; Muhmmad et al. 2019; Safi et al. 2021; Sajjad et al. 2019; Saud et al. 2013, 2014, 2016, 2017, 2020, 2022a, b; Shah et al. 2013; Qamar et al. 2017; Hamza et al. 2021).

Concept of sustainable soil management and manipulation is presently urged in various applicable forms to implement a 'Doubly inexperienced Revolution' comprising different available conservation technologies (Al-Zahrani et al. 2022; Rajesh et al. 2022; Anam et al. 2021; Deepranjan et al. 2021; Haider et al. 2021; Amjad et al. 2021; Sajjad et al. 2021a, b; Fakhre et al. 2021; Khatun et al. 2021; Ibrar et al. 2021; Bukhari et al. 2021; Haoliang et al. 2022; Sana et al. 2022; Abid et al. 2021; Zaman et al. 2021).

In present day, biochar provides range of opportunities to transform the basic concept of green revolution into a well-developed sustainable agricultural environment. High economical returns even after use of expensive inputs such as fertilizers are closely linked with adequate level of soil organic health and fertility, which can be sustainably maintained by using biochar amendments (Kammann et al. 2016). Biochar is predominantly produced in absence of oxygen via heating of biomass from various sources. Application of biochar can amend physical and chemical properties interacting with soil microbial population, soil matrix and plant root zone interaction with soil (Lehmann et al. 2009). The level of interaction and amendments depicted in a soil types is variable depending on biochar composition nature of biomass, biochar preparation procedure, biochar physical factors and soil environmental properties including soil temperature and moisture's.

Biochar provides immense advantages to any kind of soil, basically working as a soil conditioner refining its physical and organic properties along with enhancement in water conservation capacity and soil nutrient retention (Sohi et al. 2010a, b). Addition of biochar to a soil type depends on various soil properties such as soil ability to produce high quality product, soil nutrient retention, water holding capacity, permanent carbon sequestration, low release of GHG emissions especially nitrous oxide (N_2O) and methane (CH_4) (Kammen et al. 2005; Bracmort et al. 2010; Steiner et al. 2010).

Farmers could be prompted to use biochar on their farms if these blessings can be verified explicitly. In common agricultural practices, the level of carbon degree naturally available in soil can determine the normal regulation of agro-ecosystem and impact the soil fertility and its physical properties majorly soil mixture balance, cation alternate potential and water holding ability (Milne et al. 2007). Ability of soil to provide soil vitamins and nutrients in cation form can be enhanced with biochar application which will ultimately improve plant growth and development. Numerous research studies provide evidences for significant potential of biochar to enhance soil pH levels, decrease lower aluminum toxicity, decline soil tensile capacity, improve the soil conditions for earthworm population and improved efficient fertilizer utility.

Furthermore, several research findings depicts that biochar application and utility can enhance the soil physical properties and grain yield of upland (*Oryza sativa* L.) in region of northern Laos (Spokas et al. 2009). Incorporation biochar can enhance the saturated hydraulic conductivity of upper soil layers and xylem sap glide in rice plant. Predominant soil amendments in form of soil pH improvement, natural carbon and exchangeable cation levels as well as considerable decline in tensile energy (>50 t/ha) can closely linked with biochar utility in different soil types. Biochars improves the cation exchange capability (CEC) for various spoil types especially in case of highly weathered and low nutrient sandy soil, depends on the level of already availability biochar residues and sources f biochar composition.

Application of biochar can also provide various environmental services such as stepped forward soil shape, enhanced microbial pastime and nutrient cycling retention of soil moisture (Sohi et al. 2010a, b). Another significant effect of biochar also well-documented, elaborating the lime effect of biochar often linked with the improved cop yield in tropical acidic soil. Furthermore, application of biochar to alkaline soil But, the addition of biochar to the alkaline soil showed no significant improvement in soil pH and nodultion levels in soil, which is mostly inhibited with use of low soil pH. Though the initial transient flush of labile compounds to the rhizosphere region subsequently followed by use of biochar can improve the nutrient cycling. The yield of legume crops grown in a nutrient poor alkaline soil are observed to get enhance in the second season of the specific crop, suggesting that longer-term advantages of biochar application can improve the crop growth as compare to the primary season. All these applications into the soil for better plant growth and development makes biochar a unique efficient substance, keeping the exchangeable and consequently plant available nutrients in the soil, and supplying the possibility of enhancing crop yields at the same time as reducing environmental pollution via vitamins. Overall, biochar application can be used a modern day concept for improving the soil fertility and higher cop productivity, with environment efficient approach (Ogawa et al. 2009) (Table 3.2).

Furthermore, Black carbon may affect the retention of nutrients and play an important role in extensive range of biogeochemical approaches within the soil, especially for cycling of nutrients (Spokas et al. 2009). Investigated the impact of rate and kind of biochar made from poultry litter under distinctive conditions on the soil exceptional parameters. It was observed that addition of Biochar to the various potting soils resulted in vast special modifications in the chemical and physical properties of soil, inclusive of increase in pH, C, N, and P. It was concluded that specific outcomes of the two Biochars (Produced at 450 °C and 550 °C, respectively) could be associated with their exclusive traits. Drastically, unique modifications in soil biology including microbial biomass and earthworm desire residences were recorded within the two Biochars.

Table 3.2 Effect of biochar on soil properties

Constituent	Consequence	Reference
Cation exchange capacity (CEC)	Increase 50%	Glaser et al. (2002)
Fertilizer use efficiency	Enhance 10–30%	
Liming agent	Enhance pH 0.5–1	
Soil moisture retention	Increase up to 20%	
Crop productivity	Increase 20–120%	
Emission of methane	Enhance 80–100%	
Emission of nitrous oxide	Decrease 40–50%	
Bulk density	Depend on soil	
Biological nitrogen fixation	Increase 30–40%	

3.3 Conclusion

The problem of depletion of agricultural land is due to the pressure caused by the constantly growing population and therefore requires the sustainable exercise of cultivation. It has been suggested that biochar be used as a method to clean up contaminated agricultural soils and improve soil fertility. Additionally, adding biochar to the soil can be one of the best practices to triumph over any biotic stresses in the soil and increase crop productivity. Biochar's high-quality means in soil-plant-water interactions resulted in higher photosynthetic yield and higher nitrogen and water use efficiency. Subsequently, from this comprehensive overview, it could be concluded that biochar has the ability to enhance microbial population and its activities, improve soil habitats, organic nitrogen fixation and plant growth. Therefore, it is recommended to use biochar as a soil amendment for long-term carbon sink healing.

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Chapter 4
Biochar Application to Soil to Improve Fertility

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Abstract Biochar application to soils improves fertility by facilitating the uptable of essential nutrients by plants. Biochar is carbon-rich and is produced by pyrolysis. Different types of biochar are obtained depending on the raw material and on the process. Biochar improves plant growth at low concentration but induces toxic effects at high concentration. Here we will review the application of biochar to soil for plants for improving soil fertility. Biochar allows to minimize the negative effect of climate change. Biochar improves the water holding capacity. Biochar coupled with arbuscular mycorrhizal fungi stimulates the plant length by enhancing the root system.

Keywords Biochar · Climate · Plants · Roots · Nutrients

4.1 Introduction

Biochar is a very important stable compound that have carbon item in larger concentration that is produced via pyrolysis, which is thermal degeneration of various organic sources under limited O_2 circumstances (Harter et al. 2014). Plant waste material or biomass is passed by a process which is known as pyrolysis, in which

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material is heated in anaerobic condition to form biochar. Its production and retention into soil is unique methods for creating a long term CO_2 sink with low chance of environmental return (Lehmann et al. 2005a). It has greater water holding ability, anion and cation conversion capacity, and assimilation by functional groups which is present on surface (Basso et al. 2013). It has long been known for its ability to boost growth of the plant by storing greater amount of water (Hien et al. 2021), providing greater nutrients as well as advantageous for microbial activity (Nielsen et al. 2014). It also has the potential to decrease the nitrogen waste concentration from the soil by decreasing the process of volatilization and leaching (Kamali et al. 2022). Charcoal was originally used as a fuel by humans in Southern Europeand Middle East around 5500 years ago, according to archaeological findings (Elad et al. 2011).

Biochar significantly increased the microbial colonies in the soil by arbuscular mycorrhizal fungi (AMF), which improved structure, biochar affect accessibility of nutrient for plants in soil (Sohi et al. 2010) as well as water holding in growth media (Atkinson et al. 2010). Arbuscular mycorrhizal fungi action is boosted by biochar (Mickan et al. 2016), most likely through altering the physical as well as chemical properties of growth medium, facilitating germination of spore and hyphal branching due to growth and elongation (Hammer et al. 2015). Biochar (9% of the container content) improved morphology of root system of plants grown on media in combination with arbuscular mycorrhizal fungi, while arbuscular mycorrhizal fungi had a favorable influence on the morphology of this plants grown on same media. These findings clearly display the impact of biochar in the substrate in conjunction with arbuscular mycorrhizal fungi in hydroponically growing plant (Gujre et al. 2021; Luo et al. 2017).

Nitrogen cycle of microbes and their activities in soil also improved by the addition of biochar (Cayuela et al. 2014: Harter et al. 2014; Van Zwieten et al. 2010b, c, 2014). Soil nitrate reduction, for an example, is the progressive reduction of nitrite to N_2 by microorganisms via transitional nitrous oxide (N_2O) and nitric oxide (NO) via the soil denitrification process (Harter et al. 2014). Environmental elements like as soil pH, humidity and temperature, O_2 availability, and N_2 delivery influence the process (Harter et al. 2014).

Biochar composition may be altered by alteration in the process like lowering soil bulk density, enhancing structure of soil, boosting water holding capacity of soil particles, and lowering nitrogen leaching (Lehmann et al. 2011; Van Zwieten et al. 2010c). Biochar has also been presented as a conceivable strategy to reduce nitrous oxide emission, which lowers N-loss from soils by minimizing N_2O emissions (Harter et al. 2016; Cayuela et al. 2014; Wang et al. 2011).

Biochar rectification lowers Nitrogen level that resulted into fertilizer deficiency and enhances usage of fertilizers (Laird et al. 2010). Greater biochar quantity boost plant biomass output at smaller nitrogen application rates (Van Zwieten et al. 2010a; Laird et al. 2010). Backer et al. (2017) discovered that adding softwood chips biochar to sandy loam soils boosted maize root development and root metabolic activity, and that adding biochar made by olive trees or straw of wheat to soil that enhanced the proliferation of wheat root (Olmo et al. 2016). The use of acacia bark biochar boosted maize root biomass by 88–92% (Yamato et al. 2006). During critical plant growth phases, biochar increases the soil's nitrogen content, and the changes it causes to the root system's physiology and architecture enable better nitrogen uptake and fertiliser recovery (Backer et al. 2017). For the purpose of estimating root longevity and recognising the root's active biomass that can absorb nutrients and water, root function is essential (Rewald and Meinen 2013). The activity of an enzyme called nitrate reductase in the root is a crucial sign of nitrogen uptake and assimilation by plant roots (Taghavi and Babalar 2007).

4.2 Effects of Biochar

Biochar helps the plants to resist against harsh climatic conditions. Charcoal was widely used as a metallurgical fuel by the time the Bronze age, began in the Britian around 4000 years ago. However, charcoal was used for more than only fuel in the past. "After all waste has been charred, concentrated excrements should be mixed in and stored for a while." "This manure is effective for yielding any crop when applied to the fields" (Elad et al. 2011).

In agriculture and horticulture fields of North America and Europea, Charcoal was frequently utilized throughout the nineteenth and early twentieth centuries, according to agronomy literature. Seeds germination and early development of the plants increases 4–10 times, when seeds were treated with charcoal dust. Charcoal is strewn across the ground, absorbing and condensing the nourishing gases inside its pores to a volume 20–80 times its own bulk. It controls diseases like mildew and rust in several cereal crops as well as mitigate the damage they cause in all cases, even if it doesn't completely prevent it. A charcoal dressing has been demonstrated to be an effective prophylactic of rust in many circumstances, and it has proven to be so useful in France that it is commonly employed for the wheat harvest there (Zimmerman 2010).

Charcoal's use in agriculture declined dramatically over the twentieth century, owing to its greater importance as a fuel and the advent of advance inorganic fertilizers as well as in insect control technologies. However, there has been notable upsurge of interest in agriculture use of charcoal since the beginning of the twenty-first century for following four interrelated reasons:

(i) Pyrolysis, the method for producing charcoal, produces renewable energy products. Pyrolysis is expected to be part of a growing arsenal of low-price renewable energy technologies targeted at lowering emissions of net greenhouse gas from fossil fuel combustion and diversifying energy sources.
(ii) Pyrolysis can be used to treat and transform a variety of organic wastes into energy. Pyrolysis is more adaptable than biodiesel and ethanol generation from crop, and it couldn't meet resources with food production. Pyrolysis can be used to treat a broad range of municipal, agricultural, and forestry biomass wastes and residues.

(iii) When it is used in conjunction with fertilizers (organic and inorganic) for increasing the soil fertility that charcoal application ultimately improve soil and plant structure (Glaser et al. 2002). Thus, charcoal application it has greater utilization as agrochemicals for increasing he plant growth and development (Steiner et al. 2007, 2008b), charcoal application can aid in production of fuel and production of conservable food, limited organic resources and inadequate water and supply of chemical fertilizers.

(iv) Biochar halflife on soil might vary depending on feedstock and pyrolysis conditions (Zimmerman 2010). As a result, carbon is stored in soil and depleted from the atmosphere (Lehmann 2007). Furthermore, biochar addition even in small concentration in the soil system minimize greenhouse gas emission from agricultural soil, with nitrous oxide emission reduced by up to 80% and methane emissions completely suppressed (Yanai et al. 2007; Rondon et al. 2007; Lehmann et al. 2006). When considered as part of a four part "charcoal vision" that includes generation of renewable energy, waste treatment, improvement of soil fertility (Laird 2008).

4.3 Status of Biochar

Current agricultural practises underutilize biochar, and it is unknown whether this has any positive effects on crops or the health of the soil from an agronomic standpoint. The significant heterogeneity in biochar features as a function or raw material and pyrolysis circumstances, notably pyrolysis highest treatment temperature, are among the many impediments to biochar application in modern agriculture (HTT). Biochars made at low temperatures (<500 °C) have significantly different properties than biochars made at high temperature (>550 °C). These qualities can have an impact on biochar's potential as a soil improvement in unknown ways, as well assist environmental stability, which affect it long lasting sinks utility (El-Naggar et al. 2019).

4.4 Biochar Effect on Plant Growth

Soil amendment with the biochar typically has good impact on crops and trees produced under greenhouse and agricultural circumstances, according to various sources. Early research found that adding charcoal to the soil enhanced production of soybean, moong, and pea. The biomass of birch and pine shoots and roots was higher in soil treated with charcoal (Wardle et al. 1998). Similarly, biomass output of sugi trees (*Cryptomeria japonica*) was significantly boosted 5 years after soil application of biochar (charcoal) (Kishimoto and Sugiura 1985; El-Naggar et al. 2019) (Table 4.1).

Table 4.1 Potential of biochar to boost plant productivity. (Elad et al. 2011)

Plant	Quantity of biochar	Increase in Yield	References
Maize	20 tha^{-1}	28–140%	Major et al. (2010)
Bean	90 gkg^{-1}	50–72%	Rondon et al. (2007)
Durum wheat	30 and 60 tha^{-1}	30%	Vaccari et al. (2011)
Barley	10 tha^{-1}	45%	Agegnehu et al. (2016)
Soyabean	20 tha^{-1}	7%	Liu et al. (2017)
Peanut	20 tha^{-1}	7%	Liu et al. (2017)
Maize	20 tha^{-1}	6%	Liu et al. (2017)
Bean	50 tha^{-1}	53%	Raboin et al. (2016)
Sorghum	15 tha^{-1}	14%	Laghari et al. (2015)
Wheat	0.1 tha^{-1}	40%	Joseph et al. (2015)
Wheat	30 tha^{-1}	28%	Vaccari et al. (2011)
Wheat	60 tha^{-1}	30%	Vaccari et al. (2011)
Cucumber	6.75 tha^{-1}	55%	Jaiswal et al. (2014)
Tomato	67.5 tha^{-1}	20%	Akhtar et al. (2014)
Rapeseed	2.5 tha^{-1}	22%	Liu et al. (2014)
Grape	8 tha^{-1}	2%	Schmidt et al. (2014)
Moong	0.5 tha^{-1}	22%	Glaser et al. (2002)
Raddish	100 tha^{-1}	266%	Chan et al. (2007)
Maize	15 tha^{-1}	150%	Uzoma et al. (2011)
Rice	30 tha^{-1}	294%	Noguera et al. (2010)
Maize	20 tha^{-1}	28%	Major et al. (2010)

Plants which are inoculated with AMF produced greater number of roots and had increased root biomass. A cascade of molecular signaling is triggered during the relation between the fungus and the host, including a thinner roots are produced by diffusible factor of AMF (chitooligo saccharides) (Ol'ah et al. 2005). AMF changes root structure to increase nutrient and water availability (Wu et al. 2010). As a result, these findings help in the establishment of long-term nutritional management, reducing the demand for phosphate fertilizers. Because this interaction boosts the root system's function, joining biochar with AMFin the growth media which is another source for strawberry growing on substrate. The root systems of plants grown with 9% biochar application and inoculated with C. etunicatum, a fungus, are more extensive (Wu et al. 2010).

The process of crops by which biochar increases crop responsiveness include direct benefits from biochar-supplied nutrients (Silber et al. 2010) as well as a number of indirect effects, such as: improvement in the retention of nutrients (Chan et al. 2007, 2008; Chan and Xu 2009); soil pH (Yamato et al. 2006; Steiner et al. 2007; Novak et al. 2009); soil cation exchange capacity (Cheng et al. 2006) transformations in phosphorous and sulphur (Pietikainen et al. 2000; Deluca et al. 2009); neutralization of soil phytotoxic compound (Wardle et al. 1998); soil physical properties comprising water retention (Ballestero and Douglas 1996; Glaser et al. 2002);

growth of mycorrhizal fungi (Wamock et al. 2007); and alternation of microbial population and functions in soil (Steiner et al. 2008a; Kolton et al. 2011). Biochar improve soil composition, soil chemistry, and soil condition all have an impact on the agronomic benefits of biochar. Furthermore, different biomass pyrolysis conditions produce biochar with variable physical and chemical characteristics, resulting in different plant responses (Keiluweit et al. 2010).

The elements that genuinely contribute to the "Biochar Effect" are difficult to separate given the interaction of the biochar, soil, plants, water, and environment. In order to reduce the number of potential influences, Graber et al. (2010) explained that removing the nutritional and soil physical components of biochar may have an impact on plant growth. This was done by examining how nutrient-poor, wood-derived biochar affected the growth of *Capsicum annuum* and *Solanum lycopersicum* in a coconut. For both tomato and pepper plants, it was discovered that biochar treatment (1–5% w:w) boosted a number of plant development metrics (length, leaf area, canopy). The advantages of biochar on *Capsicum annuum* and *Solanum lycopersicum* plant response were not linked to direct or indirect impacts on plant nutrition, nor were they related to increases in the soilless mixture's capacity to hold water (no difference due to biochar addition). As a result, higher plant nutrition and improved soil's physical and chemical properties are advantages of biochar-induced plant growth stimulation. It offered two related ideas to explain why plants perform better after being treated with biochar:

(i) Low doses of biochar-borne chemicals, at high concentration there use is phytotoxic, at low doses stimulated plant growth
(ii) At different concentration of biochar improve the plant growth and yield, at low concentration it was most effective and at high doses it was phytotoxic.

4.5 Biochar Production

Pyrolysis, which entail heating a biomass raw material under managed conditions to create burnable synthesis gas and the oil that may be burned to give heat, electricity, or both electricity and heat, are used in modern industrial bioenergy systems. The carbon-rich residue of pyrolysis is biochar, the third combustible product. It is possible to optimize the energy release and biochar creation balance. It's essentially a 'combustion' process that can be stopped once any preferred ratio of these defined products has been gained. This ratio then can be optimized to meet shifting goals. Whereas per unit mass energy yield is maximized by simple burning of a fuel, pyrolysis syngas provides a substantially higher energy yield per unit of carbon release when optimized for biochar. If composite biochar into soil can dependably achieve the numerous environmental benefits, the carbon equivalent savings from biomass conversion by pyrolysis can be boosted even further, compared to energy production alone. According to Gaunt and Lehmann (2008)'s calculations, applying

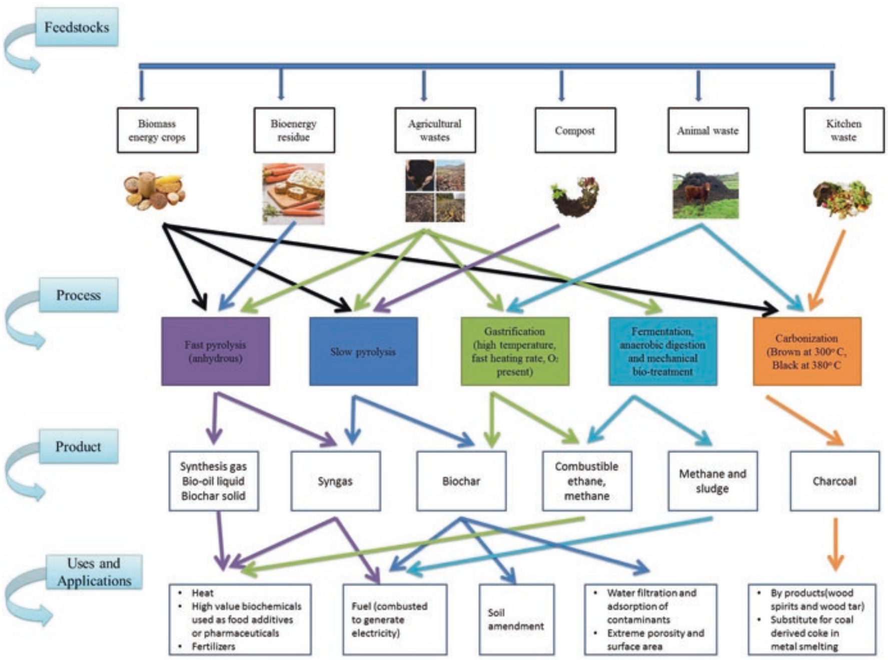

Fig. 4.1 Different types of raw material and procedure for biochar synthesis and its utilization

biochar to this land area once every 10 years result in a carbon dioxide equivalent gain of 0.65 GtC per year (Fig. 4.1).

Pyrolysis necessitates the usage of starting energy, similar to how heat in flames utilized to start the combustion of raw material in direct combustion. However, the proportional requirements must be carefully examined, as well as any differences in feedstock transportation and drying energy requirements between pyrolysis and alternative bioenergy methods. The advantage of pyrolysis-derived bioenergy over other options in terms of gas emissions that contribute to ozone depletion results not only from the retention of up to 50% of the carbon from the raw materials in the biochar but also from indirect preservation from the use of biochar in agriculture, particularly the soil (Gaunt and Lehmann 2008).

Well established methods for the biofuels and syngas production are Biomass pyrolysis and gasification. Commercial use of biochar byproducts as soil application, on the other hand, is still in its infancy. For soil use, in Japan around 15,000 ton year^{-1} is traded annually which has the huge market for such items (Okimori et al. 2003). Biochar is typically gasified to extract residual energy or utilized in the manufacturing of high-value goods like carbon (Demirbas et al. 2006). The pyrolysis process has large influence on biochar properties and potential use to agriculture. The procedure and approach, in particular the furnace's temperature and residence duration, are essential. However, the nature of the outcome depends on how the

Table 4.2 Production of different compounds during process of pyrolysis (Sohi et al. 2009)

Process	Liquid (bio-oil)	Solid (biochar)	Gas (syngass)
FAST PYROLYSIS (Moderate temperature (~ 500 °C) short hot vapor residence time (<2 s))	75% (25% water)	12%	13%
INTERMEDIATE PYROLYSIS low moderate temperature moderate hot vapor residence time	50% (50% water)	25%	25%
SLOW PYROLYSIS low moderate temperature long vapor residence time	30% (70% water)	35%	35%
GASIFICATION high temperature (>800 °C) long vapor residence time	5% tar (5% water)	10%	85%

process and the manner of the process interact with the kind of feedstock (Demirbas et al. 2006).

The physical, biological, and chemical properties of biochar products are greatly influenced by these factors, which restricts the applications that may be made of them. Each pyrolysis process type is identified by a particular biochar, syngas, or bio oil (Table 4.2). Although the precise ratio of these products varies from plant to plant and can be optimised at a particular installation, it is important to keep in mind that increasing biochar productivity in relation to initial feedstock mass always comes at the expense of liquid or gaseous energy (Demirbas 2006). Although an approach of mitigation of greenhouse gas may favour increasing biochar output (Gaunt and Lehmann 2008), the final balances determined by market and engineering restrictions. In a broad analysis, the economic cost of maximizing carbon retention in biochar utilising slow pyrolysis has been contrasted to the net gain possible in equivalent CO_2 emissions from the product after accounting for the extra fossil carbon offset that can be obtained through full use of the feedstock (Gaunt and Lehmann 2008). The net carbon gain from fossil fuels is 2–19 tons of CO_2 ha^{-1} year, 2–5 times larger than that obtained from biomass burning techniques. The CO_2 offset of these additional savings should be large enough to cover the remaining USD \$47 ton^{-1} energy value in biochar (Gaunt and Lehmann 2008).

4.6 Physical and Chemical Characterization

For a quality assessment of agronomically utilized biochar. Kuwagaki and Tamura (1990) advocated measuring seven properties: pH, volatile chemical concentration, ash content, bulk density, pore volume, water holding capacity and specific surface area. The chemical and physical properties of biochar are largely determined by the feed stock. Table 4.3 compares the elemental makeup of a variety of bio oil and biochar products derived from diverse feed stocks.

In general, the yield of biochar is inversely related to its carbon content. When the pyrolysis temperature was raised from 300 to 800 °C, the generation of biochar decreased from 67% to 26%, but the carbon content increased from 56% to 93%

Table 4.3 The elemental composition of biochar products (Demirbas et al. 2006)

Product	Elemental composition (%)				HHV[a] (MJ/Kg)
	C	H	N	O	
Beech-trunk bark biochar	87.9	2.9	0.6	10.6	33.2
Beech-trunk bark bio-oil	68.8	8.9	0.8	21.5	34.6
Rapeseed cake biochar	66.6	2.5	6.1	24.3	30.7
Rapeseed cake bio-oil	73.9	10.8	4.7	10.6	36.5
Wood bark biochar	85.0	2.8	–	12.2	30.8
Wood bark bio-oil	64.0	7.6	–	28.4	31.0
Cotton stalk biochar	72.2	1.2	–	26.6	21.4
Cotton stalk bio-oil	59.7	7.8	1.8	30.6	26.0
Bio-char from hazelnut shell	95.6	1.3	–	3.1	32.0
Sunflower bio-oil	72.1	9.8	5.2	12.9	36.2

[a]*HHV* HIGHER HEATING VALUE

Table 4.4 Bagasse-derived biochar's properties (Ueno et al. 2007)

Parameter or property	Biochar				Feedback
Present temperature (°C)	500	600	700	800	
Average temperature (°C)	490	690	740	830	
Specific surface area (m^2/g)	Nd	270	322	273	Nd
EC (mSm^{-1})	7.78	7.15	6.95	7.83	Nd
pH	7.46	7.59	7.68	7.89	Nd
TN (%)	0.58	0.45	0.32	0.44	0.19
TC (%)	70.5	71.0	65.2	73.9	46.1
Minerals (mg 100 g^{-1})	3361	4601	5359	4363	841

Nd Not Determined

(Tanaka 1963). The mass of biochar may fall beyond a certain threshold without affecting the quantity of carbon stored inside it; never the less, as mass is decrease, the biochar ash content increases. Between 300 and 800 °C, the fraction of ash in biochar grew from 0.67% to 1.26% in one research (Kuwagaki and Tamura 1990).

The processing temperature and pyrolysis residence time can still have a big impact on the composition of molecules for making final pyrolysis products for a given feedstock (Ueno et al. 2007). Table 4.4 displays the impact of temperature on the chemical makeup of biochar generated from sugarcane bagasse. This modification caused the biochar pH to alter from 7.6 (least alkali) at 310 °C to 9.7 (alkali pH) at 850 °C (Kuwagaki and Tamura 1990).

It is impossible to avoid differences in the physical and chemical characteristics of biochar. The physical structure of biochar is extensively described using scanning electron microscopy (SEM), and the architecture of cellulose plant material is prominently preserved (Fig. 4.2). It has been suggested that the porous structure of biochar may account for its influence on soil water retention and adsorption capacity (Ogawa et al. 2006; Yu et al. 2006).

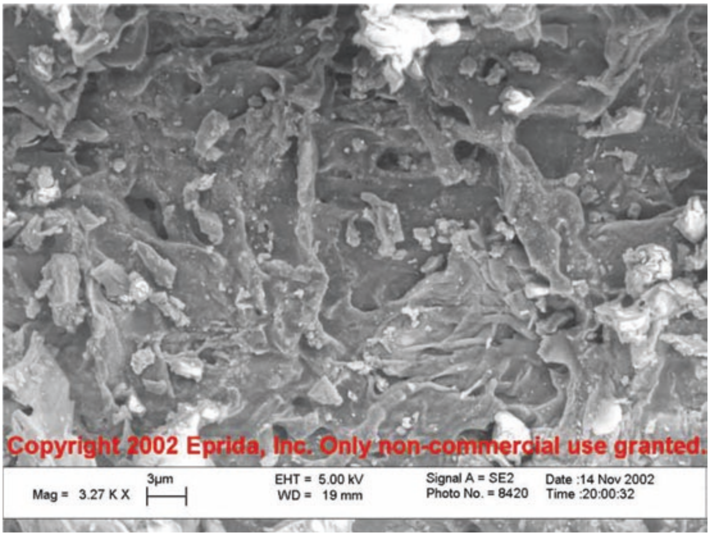

Fig. 4.2 A picture of biochar created at 400 °C using pelletized peanut shell was taken using a scanning electron microscope. (Day et al. 2005)

The process temperature has a significant impact on the surface area of the pyrolysis products. In one study, surface area improved from 120 m^2 g^{-1} at 400 °C to 460 m^2 g^{-1} at 900 °C. Given this effect of temperature, it has been proposed that biochar produced at low temperatures is effective for controlling the release of fertiliser nutrients and that biochar produced at high temperatures would be better suited for use as activated carbon. On the other hand, low-temperature biochar surfaces are hydrophobic, which may lessen the soil's ability to retain water. The type of feedstock and the pyrolysis outcome have an impact on how biochar is used. The ratio of total surface area that is initially exposed depends on the biochar's particle size. Low temperature biochar, on the other hand, is prone to grind into fine fractions once absorbed, despite being stronger than high temperature products. As a result, this parameter may not have a significant impact on surface area, i.e. weathered biochar, in the long run (Ogawa et al. 2006).

Biochar belongs to a group of compounds known as "black carbon" (Schmidt et al. 2001). Using techniques that have been used to define this larger category of materials, which includes charcoal, char, and soot from plant fires, biochar can be found in soil, sediments, and the air. (Lehmann et al. 2005b; Baldock and Smernik 2002) Wildfire naturally transforms soil into biochar, which is supposed to act as a distinct carbon storage in the ground (Krull et al. 2003). There are limitations of number of analytical techniques when applied to soil for the physical separation of char from other soil organic matter have been addressed in research to quantify and character of this material. The mineral matrix's influence, especially its interactions with highly stable soil organic matter, which chemically appears similar to char, is a significant problem. This problem has been solved by using high-energy ultra violet light for oxidation, which oxidizes most non-charcarbon (Smernik et al. 2000; Smernik and Oades 2000).

Chemical oxidation with hydro fluoric acid to remove mineral interferences and thermal oxidation to remove lignin have also been utilized (Simpson and Hatcher 2004). Biochar collaborates with the environment in a variety of ways. A few examples are soil carbon sequestration, greenhouse gas (GHG) emissions from the biochar value chain, variations in surface albedo from applying biochar to agricultural soils, and very soon. These problems are intricate and situational. For more details on the controlling variables and the size of the effect, go to this section's presentation of the elements and how they interact. By capturing and storing atmospheric carbon in refractory form, biochar works to slow down global warming. However, the combined effects of increased soil organic carbon (SOC) stability and biomass yield after biochar application may also increase soil carbon in agroecosystems. The gathering and transportation of biomass waste uses energy and emits greenhouse gases (Collins et al. 2013). Black carbon is a significant warming aerosol, and prospective field emissions need to be carefully analyzed. During pyrolysis, black carbon and particulate matter can also be released, especially in low-technology conversion processes (Cornelissen et al. 2016; Bond et al. 2013) (Fig. 4.3).

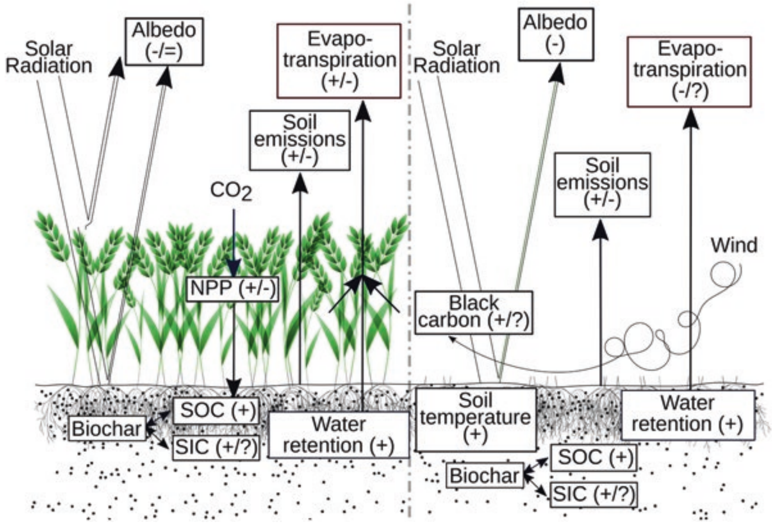

Fig. 4.3 Climate effects of biochar in cultivated (left) and follow (right) fields. Biochar has the following effect on the variable when compared to a control group that did not use biochar: (+) grew, ( ) shrank, (=) remained the same, (?) There is a scarcity of evidence on which to base a judgment. (Sohi et al. 2009)

4.6.1 Soil Organic Carbon

By supplying recalcitrant carbon, biochar directly benefits soil organic carbon. Additionally, soil carbon stability indirectly benefits soil organic carbon. Some carbon from biochar may be leached from soil so carried by the wind (Sohi et al. 2009).

4.6.2 Soil Inorganic Carbon

Although scientific information on biochar's influence on Soil Inorganic Carbon (SIC) is currently scarce, a pilot investigation reveals that biochar enhances SIC stock in both conditions; directly and indirectly (Sohi et al. 2009).

4.6.3 Albedo

Biochar tends to darkens oils, lowering albedo on the surface. The existence of a vegetative canopy or snow cover, on the other hand, can mitigate these impacts. Soil emissions are affected by the gas, the biochar characteristics, and the soil conditions (Sohi et al. 2009).

4.6.4 Water Retention

More water can be utilised for transpiration and evaporation during sowing thanks to biochar's improved soil water retention and plant water availability (Sohi et al. 2009).

4.6.5 Evapotranspiration

Biochar has conflicting influence on evapotranspiration under cultivation, depending on soilcon addition and climate, e.g., precipitation level and evapotranspiration energy constraint, and can boost or reduce plant water usage efficiency. Biochar reduces evaporation when left fallow, although further research is needed (Sohi et al. 2009).

4.6.6 Net Primary Productivity

Depending on the soil, biochar has varying effects on net primary productivity; higher net primary productivity have the ability to fix more carbon in plants, increases residues left on the field and root, and increases in root exudates, all of which may contribute to higher soil organic carbon (Sohi et al. 2009).

4.6.7 Black Carbon

Microparticles of black carbon can be transported with the help of wind during biochar application and tilling operations.

Climate is also influenced by the Earth's surface (Bonan 2015). Biochar reduces albedo, it enhances absorption of short wave, allowing greater solar energy to reach the surface. The warming benefit of biochar is expected to be reduced by 13–30% due to changes in soil albedo following application (Bozzi et al. 2015). The effect of albedo on climate is determined by the amount of incoming radiation (Bright et al. 2016). At higher latitudes, decreased soil albedo will have a less warming effect, while biochar's effects on soil moisture and aerosol may have an impact on cloud formation and the quantity of radiation that reaches the soil. The potential transport and deposition of black carbon from biochar will likely reduce ice albedo in cold climes and snowy conditions, and biochar-amended snow-free areas may possibly speed up the rate at which snow melts on the field. The surface temperature will be controlled by managing the ratio of sensible, latent, and ground heat fluxes. This will happen because biochar reduces soil albedo, alters soil water availability, and alters the actual features of soil. Genesio et al. (2012) observed fluctuations in albedo in an Italian wheat field and forecasted the balance of surface energy. According to the researchers, biochar increases all energy fluxes on a seasonal and early scale and raises soil temperatures during the bare soil regime (Genesio et al. 2012). Drought can be alleviated by increasing soil moisture. It also helps to reduce heat waves by increasing total potential of evapotranspiration, which has cooling impact. Finally, soil moisture is inversely proportional to precipitation. Using biochar to boost soil particles' ability to hold water may allow plants to adapt to climate change in a novel way (Seneviratne et al. 2010).

4.7 Uses of Biochar

Biochar isknown toenhance soil physical and chemical qualities, such as enhancing soilfertility and production, when used as soil supplements. Soil fertility should be monitered and understand before the application of biochar, which can be determine by examining application methods and rates, as well as checking the benefits of using them as agricultural amendments. Many recent research have focused on the broader effects of biochar, such as potential for mitigation of global climatechange. Other advantages of supplementing soils with biochars include reducing pollutant levels in soils, reducing nitrous oxide and methane emissions, and minimising nutrient leakage into groundwater (Zama et al. 2018).

4.8 Influences of Biochar on Agriculture

The potential and features of biochar depending upon material and processing technique used during its production as well as on the soil type. Biochars store fertiliser and beneficial nutrients and release over time to agronomic crops. Agriculture benefits from biochar's capacity to keep water and essencial nutrients in the soil layers for greater durations by reducing the loss of nutrients discharge from root zone of crops, significantly enhancing crop yeild, and lowering fertilizer need. As a result, utilising biochars in production agriculture should increase yields while reducing degrading environmental impacts. For the sake of clarity, a difference should be established between biochars and composts. Biochars differ from composts frequently used in agricultural soils in that compost provides nutrients directly through the decomposition of organic components (Schnell et al. 2012; Arif et al. 2020; Ashfaq et al. 2021; Athar et al. 2021; Atif et al. 2021; Hesham and Fahad 2020; Ibad et al. 2022; Irfan et al. 2021; Khadim et al. 2021a, b; Muhammad et al. 2022; Rashid et al. 2020; Subhan et al. 2020; Wiqar et al. 2022; Zafar et al. 2020; Fahad et al. 2020, 2021a, b, c, d, e, f).

Biochars, on the other hand, do not disintegrate over time, therefore no extra applications should be required. According to a recent biochar papers by Spokas et al. (2012) while biochar application result in good effects in agricultural production, some instances biochar cannot improve the yield of crop or sometimes it significantly reduc the crop yield (Lentz and Ippolito 2012; Schnell et al. 2012). Low yields have been reported, which could be due to limited release of nutrient uptake by plants, application of biochar even in very small quantity on fertrile soil has also greater impact. High yields reported in some biochar applications are difficult to explain, however they may be influenced by biochar characteristics, soil fertility, and the agronomic crop in question. The majority of current biochar research has been done on extremely worn and infertile soils, where the benefits of biochar application have been frequently observed. Researchers at UF/IFAS are working on the effects of biochar on low-fertility sandy soils in Florida, as well as potential increases in crop development and output (Ippolito et al. 2012).

4.9 Impact of Biochar on the Respiration Rate of Plants Roots

Biochar application resulted in greater important for root surface area, root length, and root volume in comparision of control group. Around 80 kg^{-1} biochar treatment increased root surface, root length, and root volume by 57%, 58%, and 63%, respectively, compared to the control. Little effect of biochar was seen on root diameter. In the biochar treatments, the rate of root respiration was much higher than in the control. With applications of 0, 5, 20, and 80 kg of biochar, the root respiration significantly enhanced, reaching 745, 863, 960, and 1239 nmol O_2 min^{-1} g^{-1} FW, respectively.

Because biochar had a stronger effect on roots than on above ground plant components, the root and shoot ratio rose in the 80 kg^{-1} biochar treatment. Biochar treatment enhanced maize root length mass and density considerably in another investigation. Biochar boosted the root length, surface area, volum and root dry weight. These effect could be attributed to increased concentration of carbon after biochar addition phenolic chemicals by biochar, lessening their negative impact on the growth of root (Brennan et al. 2014). The process of respiration by root is a crucial part of root metabolism, as it helps with nutrient intake, root regeneration, and boots the the plants growth. Natural agricultural waste like manure, straw, compost and seaweed have greater concentration of carbon as well as macronutrients and micronutrients. When these organic waste is used as a charcoal feedstock, the availability of macronutrients like N, K, and P, as well as some micronutrients like Mn, Ca, and others, may be affected. As a result, nutrients in biochar may driveroot growth of plant while also improving respiration in root (Atkinson et al. 2010).

4.10 Conclusion

Biochar improve the plant growth and yield by using its different concentration. It improves the soil composition by increasing the nutrients in the swoil that boots the plant helth. It increase the soil fertilitity that improves the soil composition as well as significantly increase the microbiota in the rhizospheric soil. These microbes have potential to convert the nutrients into avialable form. Most of the bacteria fixes the nitrogen and in the way abdundant nitrogen reached to the plants. All these factors increases the plant improves the efficiency of the photosynthesis that gives the plant strength and improves yields. So, all types of agricultural wastes should be processed and produced different types of biochar that not only increase the soil fertility but also helps to improve/extend root system of plant. Moreover, biochar help plants to cope with changing the climatic conditions by increasing strength of plants.

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Part II
Alleviation of Plant Stress

Chapter 5
Biochar as Soil Amendment for Mitigating Nutrients Stress in Crops

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Abstract Global food security is threatened by decreasing soil fertility and climate change. Moreover, soil erosion and salinity are depleting mineral nutrients through leaching, precipitation, and complexation and gas emissions. This issue can be solved by the addition of biochar, which improves soil fertility, crop productivity and carbon sequestration in soils. Biochar has a high sorption capacity which minimizes nutrient leaching in groundwater and surface water, and thus promotes the timely release of nutrients to crop plants. Biochar also increases the nutrient stocks in the root zone, which improves nutrients uptake. Biochar reduces greenhouse gas emissions by improving soil quality. This chapter details the role of biochar in mitigating nutrients stress, sequestering carbon and improving crop yield.

Keywords Biochar · Climate change · Crop yield · Food security · Nutrients stress

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5.1 Introduction

Among major challenges, poor soil fertility is one of the key problems around the globe which is directly linked to low productivity (FAO 2011). Soils in arid region are often characterized by poor physical properties, water scarcity, low organic matter and nutrients deficiency for plants (Khalifa and Yousef 2015; Ullah et al. 2022).

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Similarly, tropical climates of the world also face such types of problems for practicing sustainable agriculture. Because, the major plant nutrients are washed out from the root zone due to extreme weather such as high rainfall and temperature and presence of decomposers which results in improved soil organic matter mineralization (Bruun et al. 2015). Moreover, the decline in soil organic matter have undesirable affects soil fertility by affecting physico-chemical properties of the soil (Annabi et al. 2011), and ultimately threaten soil productivity (Lal 2015).

During 1960s (Era of Green Revolution), the application of sole mineral fertilizer was the main cause of increasing food production (Bationo and Waswa 2011). Though, sole application of mineral fertilizer is not the most appropriate remedy (Usman et al. 2015; Saleem et al. 2021). Therefore, the world needs sustainable and economical soil amendments. Biochar is a carbon rich material produced by the pyrolysis of organic solids (Lehmann et al. 2006). Its application might recover degraded and poor fertile soil and ultimately improve crop productivity. Improving soil quality through application of organic soil amendments is the key objective of this chapter, having specific emphasis on biochar.

5.2 Biochar Versus Other Organic Amendments

In nature the stability in carbon cycle is sustained by the production/evolution of CO_2 from the breakdown of the organic materials such as plant debris, which is a much quicker process (Wang et al. 2016). Therefore, the primary purpose of the introduction of wood biochar technology decreases the flow of carbon, deter the rapid degradation of plant materials, and store carbon in biochar, which is highly more stable compared to any other form of organic matter and strongly resilient to degradation (Beesley et al. 2011). Wood biochar reduces the return of CO_2 from soil to air and store carbon in a long-term soil carbon pool.

Higher probabilities of adopting biochar are observed in countries having huge farming, agricultural or forestry industries that generate greater quantity of waste materials for feedstock (Khan et al. 2020). Furthermore, El-Naggar et al. (2019) found that the influence of wood biochar on soil properties as well as on crop production is mainly determined by the feed stock used in production of wood biochar and temperature during pyrolysis. Moreover wood biochar of similar nature might have a different effect on both Alkaline and acidic soil (Peake et al. 2014; Mian et al. 2021).

The most differentiating property of biochar is its stable nature when compared to other organic materials (Beesley et al. 2011). Organic materials have a comparatively short life in the soil however wood biochar is highly stable (Hansen et al. 2016). Once practiced wood biochar has life span of 100–1000s of years in soil (Duku et al. 2011; Mehmood et al. 2021) which is much greater than any other organic substance. Lehmann and Joseph (2015) described that the total life of wood biochar in soil is ten to thousand times greater than other organic materials; therefore the addition of wood biochar to soil is a possible sink for carbon. Furthermore, stability of the wood biochar can be set by the particular feed stocks (materials used for production of biochar), the type of soil used and pyrolysis temperature.

5.3 Biochar Effects on Soil Properties

In general, various agricultural benefits has been recorded for biochar due to its uses as a soil amendment, these benefits mainly consists of high soil sorption capacity, minimizes nutrient leaching with groundwater or loss with surface water, and a slow nutrients release to crop plants (Salim 2016; Mensah and Frimpong 2018). It increases the nutrient stocks in the rooting zone, hence increased nutrients uptake and improve crop yield (Muhammad et al. 2017; Khan et al. 2022). The presence of plant nutrients in the biochar and its greater specific area, high porosity and its ability to create a favorable environment for microorganisms are the key causes for the enhancement in soil properties and improve plants nutrients uptake in soil amended with biochar (Nigussie et al. 2012).

Application of biochar is important and valuable because it cleans the polluted soils through adsorption and immobilization (Deng et al. 2017). In addition to the above biochar has also the ability to absorb pesticides contamination from the soils and subsequently decrease the overwhelming effect on the local environment (Rawat et al. 2019). To counter the conceivably of inaccessible nirogen, it has been discovered that utilization of biochar alongside nitrogen fertilizer can have beneficial outcomes, thus improve the effectiveness of mineral nitrogen fertilizer by decreasing the use of inorganic fertilizers and hence the cost as well (Sarfraz et al. 2017; Khalid et al. 2019).

It has been demonstrated previously that biochar application modifies the nitrogen dynamics in the soil (Lim et al. 2018) and decomposition of biochar in soil can prompt nitrogen immobilization in soil (Singh et al. 2010). Typically biochar has higher adsorption ability for nitrate and ammonium (Fidel et al. 2018), thus enhances the amount of ammonium-nitrogen in the soil (Clough and Condron 2010). Hence induces higher nitrogen uptake in plants (Cao et al. 2019). Reports are available that biochar application without nitrogen fertilizer does not improve crop yield; however, application of biochar at different levels 10, 50 and 100 t ha^{-1} and nitrogen at 100 kg ha^{-1} enhances yield as a result of enhancing use efficiency of nitrogen of crop plants (Ding et al. 2010).

Frequent and consistent applications of biochar to soil are not needed since biochar is not warranted as a fertilizer (Lehmann and Joseph, 2009; Fahad et al. 2020). Enhanced soil fertility status through wood biochar application is a renowned fact though the response of crop to biochar addition mainly depends on the type of materials used for preparation of biochar, its production process, soil properties and the nutritional composition of biochar (Schulz et al. 2013) (Fig. 5.1).

Chemical properties of the soil like such as electrical conductivity, pH, Soil nitrogen, phosphorus and potassium and physical properties like soil bulk density, soil structure, water holding capacity and pore spaces of the soil are greatly responsive to addition of wood biochar into agricultural soils. As a result adequate availability of water to crops is enhanced and soil erosion is reduced (Steiner et al. 2007). Furthermore biochar enhances/improves biological properties of the soil as well,

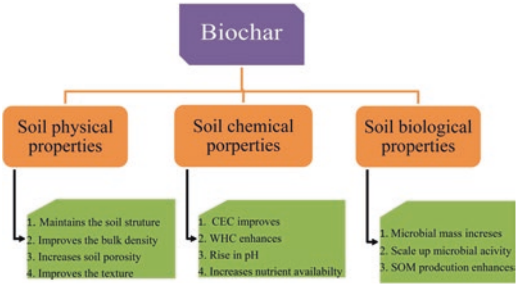

Fig. 5.1 Impact of biochar addition on different soil properties. The above figure showed summary about modifications in soil physical, chemical and biological properties in response of biochar application. CEC, WHC and SOM stands for cation exchange capacity, water holding capacity and soil organic matter respectively. (Modified and reprinted with permission from Murtaza et al. 2021)

which results in better growth of the crop plants that ultimately leads to improved crop productivity (Habtegebrial et al. 2007; Dawar et al. 2021).

The soil physical properties depend upon the interactive effect of the biochar with the physico-chemical properties of the soil. In contrast to the findings of Lehman (2007) wood biochar responses positively in acidic soils, and Van et al. (2010) who observed increased pH due to biochar, reduced micronutrient concentration in soil, which ultimately reduced crop growth and yield. Mohammad and Alamgir (2013) expressed a persuading impact regarding wood biochar on productivity of maize in alkaline soils. Biochar made from the waste of the pine forest was utilized to assess plant growth using two levels 2 and 4% wt/wt amended with alkaline, loamy sand soil. Similarly, Major (2010) also observed that incorporation of wood biochar results in reduce or high soil pH depends upon on the kind of feed stocks used to make biochar and also on the soil type.

After the addition of biochar, decomposition of the small organic molecules by the action of microbes get stared which liberate CO_2, organic acids and release initial ammonia content that cause reduction in soil pH, furthermore this reduction in pH might be different due to the nature of the applied wood biochar. While the rise in pH, might be due to the bacterial hydrolysis of protein that liberate $NH4^+$. The bulk density of wood biochar is considerably lesser when compared to soil bulk density; therefore incorporation of wood biochar decreases the soil bulk density (Ulyett et al. 2014). Substantial improvement in bulk density is possible in certain situations. At the point when the soil pores space is not absolutely filled by the biochar particles, it will bring about decline of the soil bulk density. Otherwise; wood biochar incorporation might improve soil bulk density if the applied biochar disintegrates rapidly into little particles and occupy the soil pores (Verheijen et al. 2010; Arif et al. 2021).

Khan et al. (2013) revealed considerable reduction in soil bulk density through the addition of wood biochar. Furthermore incorporation of wood biochar declined the soil bulk density and enhanced the soil water content both under field as well as pot moisture capacity conditions (Artiola et al. 2012). Chan et al. (2008) described that application of biochar decrease the threat of soil compaction through reduction in tensile strength. The incorporation of wood biochar decreases soil total nitrogen after 1st year of its application whereas no or significant effect were noted on soil total nitrogen content after 2nd years of field trial (Arif et al. 2012).

Generally alone application of wood biochar promote nitrogen immobilization in the soil (Gao and Deluca 2016) thus, causes deficiency of nitrogen in plants and decrease crop yield primarily because of higher C:N ratios (Lehman and Joseph, 2009). Incorporation of organic materials having higher C:N ratios (>20) results in immobilization of nitrogen (through microbes) and change inorganic nitrogen to organic form (Kizewski et al. 2019). When both wood biochar and mineral fertilizer particularly nitrogenous, are applied to soil in integrated form than the process of mineralization dominant over immobilization. Hence, soil nitrogen content is enhanced. Though, the exact quantity of easily biodegradable organic substances present in biochar is not the single choice for microorganisms to encourage immobilization of the available nitrogen.

Ameloot et al. (2015) are of the opinion that biochar can potentially enhance nitrogen mineralization by sorting organic molecule from the soil solution when applied to the field. Likewise, Oladele et al. (2019) revealed that the use efficiency of nitrogenous fertilizer possibly be improved if the soil is amended with a certain quantity of wood biochar. Various woods biochar may positively alter soil biology due to their potential to increase the microbial biomass with considerable changes in microbial community composition (Lehmann et al. 2011; Amanullah et al. 2022). Wood biochar as soil amendments results in improved colonization of mycorrhizal fungi (Solaiman et al. 2011). The enhanced biological nitrogen fixation potential by legumes was observed following biochar application (Mia et al. 2014).

Similarly, Wu et al. (2016) observed an improved production of soil total nitrogen content through application of wood biochar. Sohi et al. (2009) indicated that cation exchange capacity is the capability of the soil to store and release cations of essential nutrients in a form which is easily available to plants and to decrease loses due to leaching. Biochar improve soil fertility and the concentration of the cation in soil when treated with soil. In case of high leaching situations, anthrosols amended with biochar has a greater ability to adsorb and retain greater cations (Lima and Marshall 2005), thus considerably increases the availability of all major cations (Topoliantz et al. 2005).

Glasaer et al. believe that the formation of carboxyl groups could be the main reason for greater cation exchange capacity of the soil amended with biochar. Zornoza et al. (2016) observed improved cation exchange capacity in biochar applied soil might be clarified by the presence of several chemical functional groups that render the biochar as an active chemical exchange surface. Nigussie et al. (2012) stated that the inherent cation exchange capacity of wood biochar is steadily greater than that of soil and soil organic matter.

The cation exchange capacity of biochar is greatly variable which mostly depends upon the pyrolysis conditions. Cation exchange capacity is lower at low pyrolysis temperatures and considerably higher when produced under high temperatures

(Lehmann 2007). Newly made biochar have minimum potential to hold cations in soil causing lower cation exchange capacity (Cheng et al. 2008; Amanullah et al. 2021), but considerably increase with the passage of time in soil with surface oxidation (Cheng et al. 2006). However, Mukherjee and Zimmerman quoted that fresh biochar had more power to release reasonable amounts of nitrogen and phosphorus.

5.4 Biochar for Carbon Sequestration

Soil carbon sequestration is the capture of air CO_2 into the soil carbon pool through addition of plant and animal residues. Decreasing soil fertility of cultivated lands due to running down of soil organic carbon content is a serious issue for the farming community. Soil organic carbon being the foundation stone to soil quality and key indicator of agricultural sustainability (Lal 2004). Restoring soil carbon is significant for food security, ecosystem functioning, and environmental health, particularly in light of global climate change (Majumder et al. 2019). There are many recommended management practices which under suitable environments improve soil organic carbon sequestration. One among these management practices is the addition of organic material into the soil that is moderately resistant to microbial decomposition such as biochar (Lal 2016).

Biochar amendment to soil have been suggested as a means of reducing greenhouse gas emission and abating climate change by improving soil quality, protecting natural resource and sequestering carbon into the soil (Zheng et al. 2010; Fidel et al. 2019), so the burden of additional atmospheric CO_2 will be diminished (Lehmann et al. 2006). Biochar in soil not only leads to a net carbon sequestration and mitigation of atmospheric CO_2 emission, but as a one potential strategy to reduce the release of other gases like N_2O and CH_4 (Harter et al. 2014).

In order to achieve the purpose of carbon sequestration under different climates first we need to address the farming community to grow the appropriate crop plants as they are being used to make biochar hence the first phase of CO_2 sequestration and with the help of biochar is exclusively be determined by photosynthesis in plants. It is generally revealed that the overall plant biomass produced through the process of photosynthesis can release their carbon quickly due to fast decomposition. The decomposition of plant biomass contrary to the biochar process plays a crucial role in climate change as it releases the heap of carbon into the atmosphere which is fixed by the plant through photosynthesis.

However, unlike decomposition when the same biomass is converted to biochar, it decomposes gradually (Lehmann 2007). Secondly, the biochar is highly stable when compared with original plant biomass. Since the stability level of biochar is the key parameter that can generally be achieved through the process of pyrolysis and can be used to assess its carbon sequestration potential. Furthermore, the pyrolysis process has significant consequences on the stability of biochar. Because during the process of pyrolysis most of the cellulose and lignin are completely destroyed and the appearance of aromatic structures in the biochar leads to a significant change in the composition.

To gauge the carbon sequestration potential and measure the amount of atmospheric CO_2 carbon sequestrated through biochar several methods have been documented. These methods are considered to be a preliminary estimate of the large-scale potential of biochar sequestration and subsequently its benefit in the form of greater crop productivity (Laird 2008); however these methods need must be refined against economic as well as ecological constraints and extended to a complete carbon emission balance. Furthermore, the overall balance of carbon emission must be compared with a baseline scenario and simultaneously it must be shown that what emission of carbon has been reduced by changing of the product from plant material that utilizes biochar.

We therefore need more studies that clearly demonstrate the potential of carbon sequestration with biochar. Many studies have found that the earth's soil is stored about 4 times higher organic carbon when compared to atmospheric CO_2 (Stockmann et al. 2013; Ahmad et al. 2022a, b). Likewise, the annual CO_2 absorbed by the plants during photosynthesis is about eight times higher as compared to today's anthropogenic emissions of CO_2 into the atmosphere. Therefore, there is strong evidence that a substantial quantity of CO_2 flow between the plants and atmosphere while soil is one of the best source where most of the organic carbon is already stored.

Thus, if we are trying to transfer a small fraction of this massive quantity of cycling carbon into the soil through biochar. It will have a large impact on the concentrations of atmospheric CO_2 but on the other hand it will have a small impact on the global soil carbon storage. It was previously projected/estimated that by diverting almost 1% of the annual net plant uptake into biochar perhaps it may reduce nearly 10% of current anthropogenic carbon emissions into the atmosphere (Laird 2008). The biochar stability define that how long carbon remains sequestered in the soil in the form. The conversion of plant biomass to biochar through pyrolysis and its application to the soil has been shown to increase the life of carbon in the soil compared to the same organic materials application (Nachenius et al. 2013).

The encouraging effect of carbon sequestration through addition of biochar can be better observed in soils having lower amount of carbon compared to soils having higher amount of carbon. Research data revealed that the selection of appropriate biochar technology can address the emerging challenges of agricultural sector and improve environmental quality (Yadav et al. 2017).

5.5 Biochar Role in Nitrogen Availability

Nitrogen is one among the essential macro nutrients which decreased wheat yield if not supplied in appropriate quantity as it is required for vigorous growth of the plants and ultimately for higher production (Grant et al. 2016). It play significant role in all the metabolic processes occurring in plants (Bloom 2015; Ahmad et al. 2022a, b). All the biochemical processes going in plants are mostly governed by nitrogen and its related compounds which make it crucial for the growth and development of wheat (Khan et al. 2015). Thus, it is compulsory to apply nitrogen fertilizer to the soil in order to get maximum wheat yield (Ahmad et al. 2008). The varieties which have greater genetic yield potential needs high amount of nitrogen to produce higher production (Emam 2011).

In order to get the higher wheat yield, application of nitrogen in sufficient quantity is measured as an important key to success (Fageria 2014). Use of inorganic nitrogen at 120 kg enhanced wheat yield and yield attributes while non-significant influence on soil carbon, phosphorus and potassium concentration (Ali et al. 2015b). Among the essential nutrients, nitrogen plays a vital role in sustaining vegetative growth of the crop (Kibe et al. 2006). Visually high stature plants and more grains ear^{-1} of maize was obtained from plots where only mineral nitrogen was used (Arif et al. 2012). Ullah et al. (2018) observed highest fertile tillers, maximum plant height, 1000 grain weight and biological yield where nitrogen was applied at 203 kg ha^{-1}.

Improved physiological parameters such as plant height, leaf area plant, leaf number at 120 kg nitrogen ha^{-1} (Ayub et al. 2003). Increasing nitrogen rates (up to 69 kg ha^{-1}) on durum wheat had improved yield, yield components, nitrogen uptake parameters and protein content (Woyema et al. 2012). Similarly maximum plant height, more grains spike^{-1}, single spike grain and thousand grain weight, more biological and grain yield were produce by nitrogen and P_2O_5 by 120 and 90 kg ha^{-1} (Khan et al. 2007). Patra and Ray (2018) listed that plant height, leaf area index, crop growth rate, number of tillers, grain yield and biological yield and all other yield attributes except 1000 grain weight were considerably improved with increase the nitrogen level up to 150 kg.

More tillers m^{-2}, maximum plant height, spike's length, yield and its components of wheat were considerably improved by increasing the levels of nitrogen from 0, 80, 130 & 180 kg ha^{-1} over control (Ali et al. 2011). Furthermore, application of 120 kg nitrogen produced greater tiller m^{-2} which further improves productivity of wheat (Shahzad et al. 2013). Iqbal et al. (2012) attained considerably maximum plant height, grain yield, biological yield and harvest index at 125 kg nitrogen when compared to control. Higher dose of nitrogen improved grain yield of wheat by 30% (Dang et al. 2006). Kousar et al. (2015) observed that 120 and 150 kg nitrogen considerably enhanced fertile tillers, plant height, spike length, number of spikelet per spike, number of grains per spike, 1000 grain weight, grain yield per plot and grain yield of wheat.

Shere et al. had noticed maximum days to anthesis, maturity, leaf area tiller^{-1}, leaf area index, plant height and biological yield by 150 kg nitrogen. Ullah et al. (2013) experienced considerable improvement in wheat phenology, growth and physiological attributes when nitrogen was applied by 210 kg. Ali et al. (2015b) also observed delayed booting, anthesis and maturity stage in wheat plots treated with 120 kg nitrogen. Similarly application of 100 kg nitrogen improves grain protein content (Maqsood et al. 2000). Moreover, Ali et al. (2015a) observed higher wheat leaf nitrogen content, stem nitrogen content, grain nitrogen content, grain protein content, grain nitrogen uptake, total nitrogen uptake in those plots where nitrogen was treated by 120 kg (Fig. 5.2).

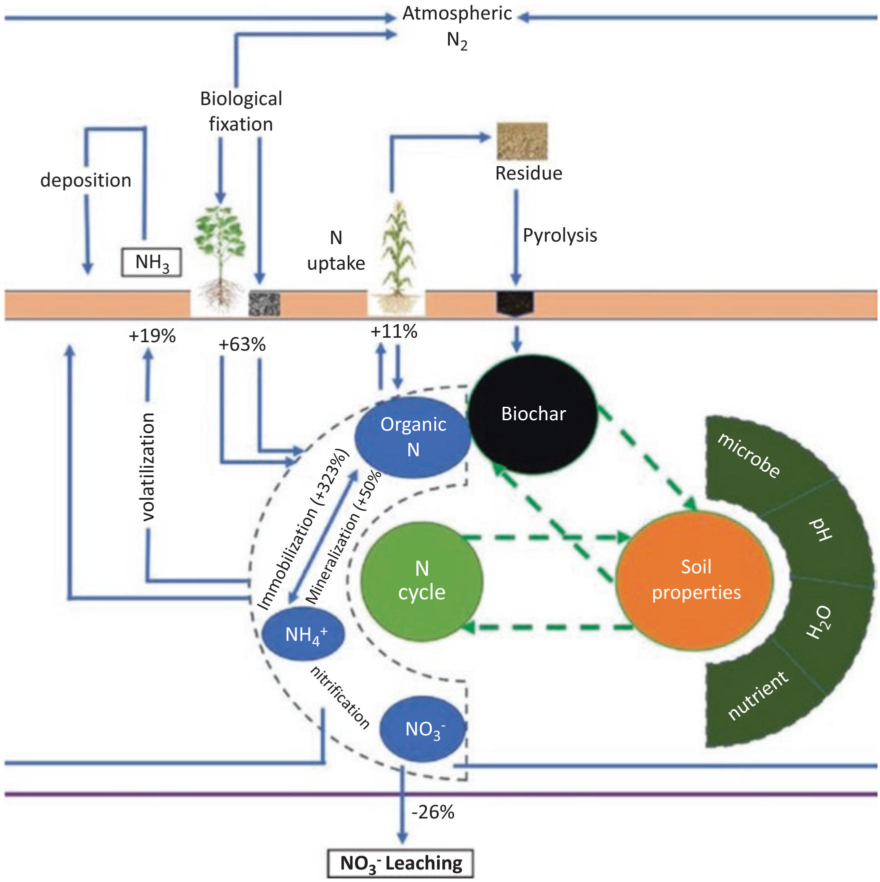

Fig 5.2 Biochar-mediated nitrogen cycle. Summary about nitrogen cycle in response of biochar application showed that the application of biochar reduced NO_3^- leaching by 26%. However, biochar could temporarily increase volatilization of nitrogen by 19% as NH_3, which will be ultimately deposited into the soil. Similarly application of biochar has been shown to improve nitrogen uptake by 11%. N stands for nitrogen. (Modified and reprinted with permission from Liu et al. 2018)

5.6 Biochar and Phosphorus Availability

Phosphorus is major plant nutrient which is required for crop growth and yield. Many soils around the globe are facing phosphorus deficiency, particularly in both tropical and subtropical areas due to both high rainfall and phosphorus fixation (Blake et al. 2000). To fulfill plant phosphorus requirements, globally about 15 million tons of phosphorus based fertilizer is applied every year (Wang et al. 2012). Under best condition only 5–30% of the applied fertilizer phosphorus is utilize by crop (Price 2006). The remaining quantity of the applied phosphorus is lost due to runoff.

At present, most of the phosphorus fertilizer is obtained from mined rock phosphate, which is a non-renewable resource. Streubel et al. (2012) predicted that the availability of rock phosphate may be reduced because of the ever increasing demand of phosphorus on global basis. Therefore, we need to discover new strategies on urgent basis which can provide phosphorus in plants available forms, which can be used as alternate source to traditional phosphorus fertilizer and further minimizes the loss of phosphorus from the soil. Many studies around the world have now shown that biochar can be utilized as phosphorus source for soils and reasonable amount of this phosphorus is available for plant use. However, the type of feedstock used and pyrolysis conditions of biochar are the key parameters which determine the amount of phosphorus in biochar.

Siebers and Leinweber (2013) stated that phosphorus in biochar prepared from animal bone was 152 and extractable phosphorus was almost 7 g kg^{-1}. Uzoma et al. (2011) described that Olsen- phosphorus was 23 g kg^{-1} in wood biochar prepared at 500 °C, while the amount of Olsen- phosphorus was found 1.2 g kg^{-1} when biochar was made from the same material at 300 °C. Naeem et al. (2014) noticed that raising temperature during pyrolysis (300–500 °C), the amount of phosphorus in biochar did volatilize. This is because of the loss of hydrogen and oxygen ions. The use of biochar in acidic soil, the released phosphorus is easily available for plants uptake. Yao et al. (2013) stated that biochar can retain phosphorus applied as fertilizer in soil. Though, data regarding retention of phosphorus in soil due to biochar application is limited.

5.7 Biochar and Micronutrients Availability

Micronutrients are important for plant growth and play crucial role in balanced crop nutrition. The availability of micronutrients is mainly determined by soil pH. The concentration of micronutrients declines with raising soil pH except molybdenum. In high alkaline soil the availability of zinc, iron and boron, is of great concern. During the pyrolysis process not all micronutrients are volatilized until 1000 °C temperature. Amonette and Joseph (2009) found that iron and manganese are mainly retained in biochar during biochar preparation.

Naeem et al. (2014) observed that raising pyrolysis temperature upto 500 °C increase the total micronutrient contents of biochar. At different temperatures, total zinc were 46 to 68 mg kg^{-1} and 66 to 96 mg kg^{-1} in wheat and rice straw biochar respectively. While Fe were 156 to 419 mg kg^{-1}, and 193 to 517 mg kg^{-1} respectively. However, manganese was 104 and 393 mg kg^{-1} for biochar prepared from the above sources. Except manganese, plant available micronutrients contents e.g. iron and zinc decline in both wheat and rice straw biochar with raising temperature. Gaskin et al. (2008) prepared biochar from poultry manure, peanut hull and pine chips at 400 and 500 °C.

Maximum zinc, copper, manganese and iron contents of 0.75, 1.03, 0.73 and 8.03 g kg^{-1} were found in case of poultry litter biochar produced at 500 °C when compared to biochar made from the same feedstock's at 400 or 500 °C. It must be worth noted that the nutrient concentration change from feedstock to feedstock. Moreover the pyrolysis conditions also alter the plant available concentration of micronutrients. Biochar has also the ability to hold nutrients like those have positive charges on it. Moreover, biochar having high pH may decline the concentration of micronutrients in the soil. Care must be exercise to select those Biochar having acidic or neutral pH. Greater nutrient concentration is desirable characteristic of biochar but greater concentration of basic cations may cause several issues, like high pH and high electrical conductivity of produced biochar. To keep soil quality good, we have to select suitable biochar feedstocks and pyrolysis conditions.

5.8 Conclusion

Poor soil fertility is the major constrains in ensuring food security around the globe. Biochar contributes to soil fertility either by acting as a direct nutrient source or by altering the physiochemical properties in the soil. Biochar not only improves soil fertility and crop productivity but also promotes soil carbon sequestration. It has high soil sorption and cation exchange capacity thus minimizes nutrient losses with surface/ground water, and promotes timely nutrients release to crop plants. It also increases the nutrient stocks in the root zone, hence increased nutrients uptake and improve crop yield. Therefore, biochar shall be applied as soil conditioner to improve soil health and crop yield by mitigate nutrients deficiency.

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Chapter 6
Biochar to Mitigate Crop Exposure to Soil Compaction Stress

Anis Ali Shah, Munazza Kiran, Sadia Zafar, and Muhammad Iftikhar

Abstract Soil compaction stress is a major obstacle in improving soil health and performance, calling for advanced agricultural practices such as biochar amendment. Biochar contains organic and mineral substances, which are useful for growth and yield of crops. Application of biochar enhances soil properties such as water holding capacity and soil organic content. Here we review biochar supplementation with focus on the improvement of plant growth and physiology of plants exposed to soil compaction stress, and to biotic and abiotic stress. Moreover, application of soil fungi and microbes reduce the negative effects of soil compaction on plants by improving soil physiochemical characteristics.

Keywords Biochar, soil · Compaction · Plants · Abiotic stresses

6.1 Introduction

The term "char" means a product which is made up of natural and inorganic substances. Both charcoal and biochar are considered same but can be differentiated on the basis of their usage. Charcoal is used as energy source and biochar is utilized for the carbon chemical processes and environmental benefits. Biochar, also named as 'pyrochar,' which is the product of biomass passed through a chemical reaction named pyrolysis (Ralebitso-Senior and Orr 2016). According to International Biochar Initiative (IBI 2015), the thermochemical transformation of biomass in an environment having less concentration of oxygen produces a solid material called biochar. Biochar isn't always a natural carbon as it consists of nitrogen, sulfur, hydrogen, oxygen and ash (Lehmann et al. 2003). Amazon area which has

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'terra-preta' (black earth) a highly fertile soil with biochar component and is used for the enhancement of soil fertility.

Specifically, biochar is a product of biomass including manure, wooden and crop residues at a temperature below the 900 °C beneath oxygen-limited pyrolytic conditions (Zhang et al. 2019). Nevertheless, current researchers have reported that biochar can also be made with the aid of different thermochemical methods e.g., hydrothermal, gasification, carbonization, microwave assisted transformation and torrefaction (Yuan et al. 2017). The chemical and physical components additionally rely upon different factors which include warming rate, kiln strain, the mixture of the atmosphere (CO_2 and nitrogen surroundings within kiln) and the kind of set up or pre-management of biochar (Joseph and Taylor 2014).

6.2 Types of Biochar

Joseph and Taylor (2014) consider three major groups of biochar.

1. Biochar constructed from biomass with minimum ash contented material (<3–5%), which include plant material, few seeds, bamboo, nut shells and mass of leaves. This biochar has huge porosity, base section and preserve greater water than the biochar in other groups.
2. Biochar as a product of various biomasses having normal quantity of ash smug range from 5% to 13% which also include the maximum amount of bark, agricultural wastes and enormous amount of green waste with less infection of plastics, soil and metals.
3. Biochar as a product of biomass with full ash contents (>13%), which exclude waste paper, municipal waste, manures, sludges and rice husks.

Biomass including waste water sludge, grasses, crop waste, manures, agricultural waste converts at high range of temperature in minimal amount of oxygen called pyrolysis. It has higher energy dispersion bio-oil and comparatively low-capacity tightness gasoline (non-compressible) which provides excessive energy compactness to strong biochar (Kapoor et al. 2022). The extensive chain polymers alongside lignin, starch, hemicellulose, cellulose fat, obliterate down and exchanged over into gases (e.g., carbon dioxide, carbon mono oxide, methane and hydrogen) all through the transformation response. Biochar is produced through aromatization of compressible gasses which are gained from the liquid fuel and various hydrocarbon compounds.

6.3 Biochar Types Based on Pyrolysis

Khan et al. (2016) reported predominant types of biochar as following:

1. *Slow pyrolysis* is a batch reactor or a relentless framework that gradually warms the biomass to more than 350 °C. It is almost broadly utilized pyrolysis plot

owing to simplicity and this pyrolyzer yields around 35% fuel, 35% biochar and 30% bio-oil by mass. Charcoal furnace is less controlled in which slow pyrolysis framework is included. Detachment of gases and bio oil is incredible in this framework. Hence, the biochar production in slow pyrolysis can change among 25–60% (El-Naggar et al. 2019).

2. *Flash pyrolysis*, is especially intended to boost the bio-oil production, in which the yields are generally 60% bio-oil and 40% biochar and gas.

6.4 Importance of Biochar for Crop Productivity

Biochar enhances the soil fertility resulting in better crop yield (Zhang et al. 2017). Kimetu et al. (2008) reported that using biochar from the leaves of *Eucalyptus* enhanced maize production (*Zea mays* L.) two times in the degraded African soil. Using Biochar of pine wood on *Sorghum bicolor* L. improved growth in a spare sandy soil in pot experimentation (Laghari et al. 2015). Results also revealed that dry weight of *Sorghum* enhanced by 18–22% as compared to control soil. The effect of biochar on soil increasing the fertility and crop product was also reported by Lehmann and Joseph (2015). Glaser et al. (2002) observed biochar usage enhanced biomass in *Vigna unguiculata* (L.), *Oryza sativa* (L.) and *Vigna unguiculata* (L). *Triticum durum* L. showed more growth ahead to 30% in biochar mixing soil (Vaccari et al. 2011).

Biomass and grain in (*Zea mays* L.) maize showed maximum growth in charcoal added soil compared with normal soil (Oguntunde et al. 2004).

Similarly maize crop productivity also increased with charcoal application in soil (Kimetu et al. 2008). Many studies have shown the powerful potential of biochar usage for rising crop yields, especially on nutrient less soils (Zhang et al. 2012a, b). Jeffery et al. (2011) reported that biochar application improves soil structure, composition and chemical characteristics. Jeffery et al. (2011) studied bird litter for biochar feed stock was best (28%) as compared with the biochar from biosolid waste (28%) on crop productivity. Feng et al. (2015) studied the productivity of summer maize and winter wheat crop for 3 years. They reported biochar usage has significant effects for the yield productivity with additive production over the first four increasing periods.

Most of the studies were run for short period of time 1–2 year's duration to find out the effects of biochar on crop productivity (Ashfaq et al. 2021; Athar et al. 2021; Ibad et al. 2022; Irfan et al.2021; Khadim et al. 2021a, b; Muhammad et al. 2022; Subhan et al. 2020; Wiqar et al. 2022; Zafar et al. 2020). Thus, long time duration experiments are required to check the effect of biochar on soil for better yield productivity in the long run. Spokas et al. (2009) searched out forty-four research articles that revealed the effect of biochar on crop and found that half of the articles data gave results for the improvement of crop yield while rest of them not showed any better results about the yield amount.

Application of biochar on soil enhanced the surface area and soil consistency (Thies and Rillig 2012), water holding capacity, nutrient possession (Yamato et al. 2006) and limiting impact (Liu et al. 2013) is particularly responsible for stepped forward crop productiveness. Biochar from plant biomass residues including ashes, waste of plants having much concentration of phosphorus and nitrogen similar to commercial fertilizer containing the nutrients (Luo et al. 2019). Similarly, Major et al. (2010) reported biochar increases crop productivity due to presence of Ca and Mg.

For increasing crop yield with fertilizer, biochar has a positive interactive impact on the soil (2007) getting more yield four to twelve times in the rice and sorghum crop with the mixing of biochar in soil with compost as compared using fertilizer alone. Fertilizer including nitrogen, phosphorus and potassium with biochar provided two folds more yield of sorghum and rice in comparison with only NPK fertilizer (Christoph et al. 2007). Accumulation of biochar with inoculation of arbuscular mycorrhiza (AM) fungal spores which is a great source of phosphorus for uptake, availability to maize yield and crop productivity enhanced, but in case of limited biochar there was no improvement in maize yield or phosphorus intake for increased yield crop (Mau and Utami 2014).

Biochar is known to produce a vast positive impact for better yield of crop under some soil conditions including salinity and drought stress of crop (Haider et al. 2015). Consequently, the development in wheat harvesting crop of biochar finished soils might be utilized as a sign of the general vertical push in plant accessible water (Liu et al. 2014). An experimental study conducted in the boreal sandy clay loam, biochar application in such soil recorded (10 t ha^{-1}) improved yield in dry season (2011).

Such results showed enhancement of water holding capacity of soil by biochar (Tammeorg et al. 2014). Biochar is a source of crop yield production in low fertile soils (Laghari et al. 2015). Crop production may be increased by way of the usage of biochar utility in less fertile soil (Zhang et al. 2017). Biochar usage in less nutrient and degraded soils giving rise to growth of the crop and productiveness is also reported (Laghari et al. 2015; Van Zwieten et al. 2010; Zhang et al. 2012a, b, c) (Fig. 6.1).

6.5 Soil Physical and Chemical Properties

Climate changing is affecting soil and agriculture productivity globally (Fahad and Bano 2012; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019, 2020, 2021a, b, c, d, e, f, 2022a, b; Al-Zahrani et al. 2022; Atif et al. 2021). To combat the adverse effect of climate change, biochar can play an important role. Biochar enhances the pH of soil, porosity, water holding capacity and stabilizes soil organic content through increased soil accumulation and reduced soil bulk

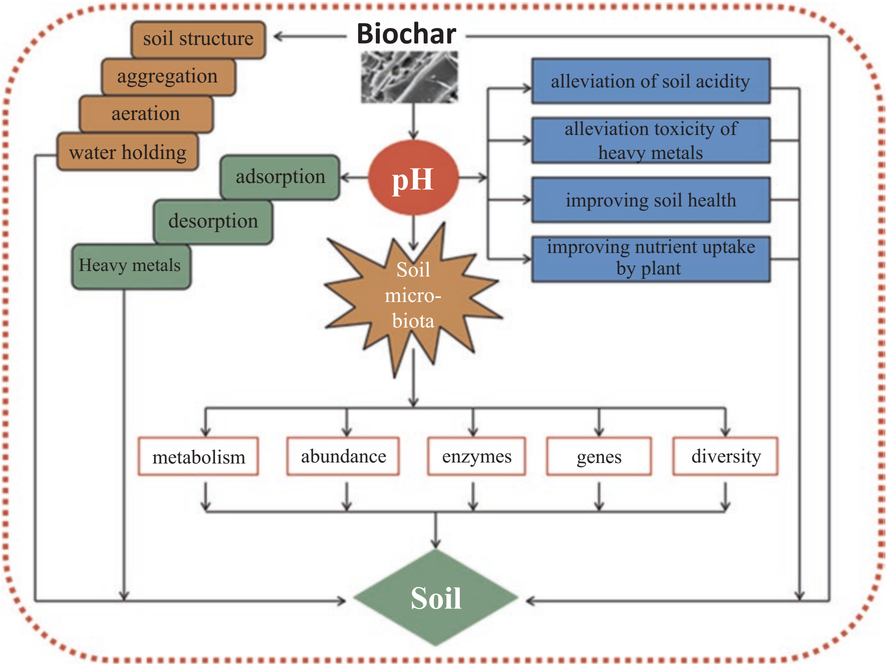

Fig. 6.1 Biochar impacts on soil properties. (Source: Shabaan et al. 2018)

distribution ductile energy (Liu et al. 2016). The soils having small amount of debris and density with excessive porosity compared to the biochar which has high values and preserves much amount of air and water. This is the reason for diminishing the soil majority tightness (Downie et al. 2012). Soil mixing up with the biochar enhanced the water holding capacity which affects the root growth and enhances microbial pastime.

Zhang et al. (2012a, b, c) mentioned that biochar enhanced the growth factors in soil due to decreased soil bulk density and rice production in some cycles of rice increase. In another look, soil bulk density also reduced due to biochar addition in efficient clarion loam (Laird et al. 2010. Tammeorg et al. (2014) demonstrated that plants need excess amount of water in its first 360 days within the height 20 cm of soil and this will be improved by biochar by reducing the soil bulk density. The researcher also conclude that biochar usage might decrease the soil tensile energy to decrease tillage expenses (Vaccari et al. 2011).

Biochar usage in soil reduced −18 kilo pascal in soil energy power (a hundred ton per hectare) which is especially advantageous for growth of root, mycorrhizal nutrient production and enhanced the germination of seed (Chan et al. 2007). Laird et al. (2010) reported after applying the biochar in clarion loam soil showing 69% growth rate increased after in super optimal broth with catabolite repression.

Biochar acted otherwise to super optimal broth with catabolite repression liquid association due to its very inert disintegration rate, it yield significant gain to soil via accumulation, water and holding of nutrients (Atkinson et al. 2010).

6.6 Biochar for Better Nutrient Availability in Soil

Application of biochar significantly alters soil pH, electrochemical properties thereby positively regulating the nutrient availability in crops (Oguntunde et al. 2004). Biochar enhanced the magnesium and calcium accessibility due to its confining impression, enhanced the productivity of maize yield (Liu et al. 2013). In rice field due to addition of biochar, nitrogen content increased with 20 and 40 t ha^{-1} by 5.43% to 18.77% respectively (Zhang et al. 2012a, b, c). Utilization of biochar not only increases the concentration of nitrogen as well but also increases some other micro nutrients including boron (Rondon et al. 2007). Research data describes the importance of biochar for increasing the crop productiveness in degraded soil, barren land by enhancing the crop growing capability using biochar in such soils (Randolph et al. 2017). However, some researches have reported that biochar is not a powerful source for enhancing the productivity of crop in less fertile or compact soils (Schmidt et al. 2015).

6.7 Nutrient Supply and Retention

Biochar is a matter having the capability to maintain macro nutrients at once, including nitrogen (Gul and Whalen 2016; Zhang et al. 2017). This can be attributed to the nutritious contented material of biochar itself (Shepherd et al. 2017). Biochar is a material which holds out the macro nutrients including nitrogen concentration involved for the growth of plant (Zhang et al. 2017). This can be worked by biochar for maintaining the nutrient content material (Shepherd et al. 2017). Biochar is a product of biomass having various amount of content including soil vitamins used as organic fertilizer for enhancing the soil fertility (Gul and Whalen 2016).

Biochar has various other advantageous for plant nutrient cycling having potential to reduce the leaching with increasing retention thereby enhancing soil growing capability (Randolph et al. 2017). Laghari et al. (2015) reported that biochar usage in the soil enhancing the total capacity of soil due to addition of nutrient content including calcium by 69–75%, phosphorus via 68–70%, potassium by using 37–42%, carbon 7–11%. In this way, some other results revealed through X-ray visible radiation analysis which does not neglect the full distribution of compounds on surfaces of material and does not depicting their accessibility in soils. Nevertheless, the alternative fertility factor along with soil physical characteristics and crop growing showed sizeable intensification in biochar (Fig. 6.2).

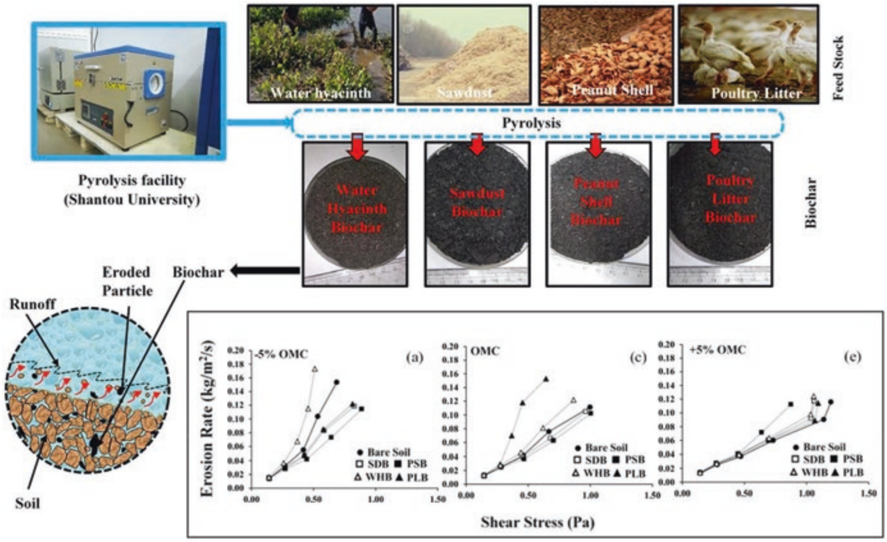

Fig. 6.2 Biochar pyrolysis and usage. (Source: Kumar et al. 2019)

6.8 Biochar Increased Soil Fertility

The function of biochar in soil fertility is connected with the material consistency, water protective potential, liming capability, redox properties and nutrient possession (Guo et al. 2020). Biochar can be assessed by the pore size distribution, water protecting capability, particle density to assess the bodily structure of biomass (Yi et al. 2020).

Due to spongy shape of biochar, having macropores (pore diameter >50 μm) provides vast surface area for the soil fuel transport, hydrology and for the dispersion of other microbes. Chemically biochar is made up of total carbon and nitrogen, pH, comprehend sorption (Al-Wabel et al. 2019), electrical conduction (Cantrell et al. 2012). Biochar also have natural coating and various elements on its surfaces (Yi et al. 2015).

Biochar boosts the plant activity and growth of microbes but with its advantages some of dangerous material also leach which caused the toxicity of biochar (Godlewska et al. 2021). In this way toxicity of biochar mean fabrication temperature and feed stock transforms the pH of biochar, electric conductivity, polycyclic aromatic hydrocarbons, massive metals that leaching into environment and effects of toxic materials on organism. In every field of study, biochar has its particular possession for particular execution primarily based on its physiochemical characteristics. Hence, it's far critical to correspond biochar domestic earlier any soil usage.

Chemical restriction which impacts plant life are salinity, alkalinity, acidity and nutrient deficiency. Overflowing pH > eight reduces bio availability of vitamins to the vegetation. Chemically soil spoilage by the addition of acidity, alkalinity, salinity and nutrient deficiency. High pH > eight reduces bio availability of vitamins to the plant life. Less amount of Mg, Ca and K ions refer to the enhancement of Na ions causing sodicity and high salts in the soil causing salinity. Plant growth reduced by the salinity via osmotic pressure and root growth reduced by the sodicity all of this causing reduction of crop (Ramrez-Rodrguez et al. 2007).

The cation exchange potential will be increased by the usage of charge tightness per unit of living thing count. Nutrients leaching regulated by biochar due to its unique adsorption mechanism (Xiao et al. 2018) and decorate plant productivity in peculiar while united with various natural matter inclusive of organic and compost (Wang et al. 2019). Biochar is made up of biomass containing elemental composition, different vitamins and nurture substances. It is used for enhancing the soil fertility by increasing the nutrients in the soil due to its special characters of nutritious storage on biochar channel (Hagemann et al. 2017). Biochar incorporated into the agricultural soils which stimulated the soil character. Bulk compactness of soil crinkle and its holey construction is modified resultant in adjustments in water retentive ability (Al-Wabel et al. 2019).

Research data describes that reduced miserableness favors rhizosphere microbial pastime aerobatic conditions intensify N_2O, CH_4 discharge and suppresses the compacted soil drops off the productiveness of soybean and corn (Yu et al. 2019). Thus, the biochar attributes makes it a suitable candidate for rising soil fitness. The forthcoming subdivision gives the biochar utilization consequences on soil fitness and its numerous physio-chemical and organic attributes as mentioned in piece of ground trials. Soil is fruitful if it contains up to capacity to deliver critical nutritious and water convey to enhance development of plant life without the presence of poisonous factors, which can prevent development of plant (Voltr 2012). Fertility of soil is governed by using chemical, physical and organic attribute of soils (Igalavithana et al. 2017).

Less fertile soil is a common place content in various regions of the sector (FAO 2019). For instance, semi-arid and arid area soils specifically have less water maintaining ability and deficient nourishing demand ranges for maximum crops (Khalifa and Yousef 2015). For tropic rain forest area, it's far basically provocative to support rural assembling as significant plant nutrients are fast drained from texture of soil because of high precipitation in total with low cation restricting limit. Besides, shockingly high warm conditions and decomposer' overflow led to better accumulation of minerals soil improvement normal count (Bruun et al. 2015).

Modification in soil porosity is in particular because of the permeable internal construction (intrapores), the attribute and sharpness paces of among biochar, biochar pores and soil flotsam and jetsam (inter-pores), molecule length game plan of the changed soil, and assimilation location of biochar's (Yi et al. 2020).

As biochar property, abiotic floor responses modify surface science, substitute the molecule length conveyance, and decline hydrophobic quality, development of dissolved organic carbon draining on the grounds that it in essence breaks down with water influence (Liu et al. 2016).

6.9 Physical Enhancement of Soil Fertility by Biochar

Yadav et al. (2018) described biochar has uncovered to build the capability of soil to keep water. Razzaghi et al. (2020) contemplated meta-assessment at the after effect on soil of biochar water maintenance and established that the capability of soil to protect water, particularly in coarse-finished soils. Peake et al. (2014) expressed that biochar had a magnificent effect in the loamy sand and sandy topsoil soils to protect water.

Oladele (2019) reported soil limit for saving the water stretched out with enlarge biochar usage. Biochar decreased malleable property and split of subsurface soil (Mandal et al. 2020a, b) and stifled soil decrement by utilizing expanding the capacity of dirt to save water in this manner, soil composition become progressed (Fu et al. 2019). Nair et al. (2017) confirmed that biochar ventured forward soil water maintenance, diminished mass thickness and balanced out soil regular recall. Likewise, it transformed into affirmed that were hydrophilic helpful organizations on the floor and pores of biochar with an exorbitant relationship for water biochar utilization became demonstrated to soil development water maintenance more in a sand like soil than a loamy soil or a dirt soil (Mandal et al. 2020a, b). Biochar furthermore affirmed a decent impact on surface locale of soil (Anawar et al. 2015), which changed with biochar variety (Tomczyk et al. 2020).

6.10 Biochar Interactions in Soil

The role of biochar is diverse due to its physical and biochemical characteristics (Czimczik et al. 2002; Downie et al. 2009; Schimmelpfennig and Glaser 2012). Microbial activities in soil are greatly influenced by biochar (Glaser et al. 2002; Kuzyakov et al. 2009; Glaser and Birk 2012; Yin et al. 2000). Bacterial and fungal communities largely make up the microbial community in rhizosphere. Apart from bacterial communities, fungal diversity performs a variety of functions such as organic matter decomposition and nutrient recycling (Duponnois et al. 2005; Zeilinger et al. 2016; Ye et al. 2020). These complex communities in rhizospheric region play significant role in interactions with soil (Will et al. 2010). Unfortunately, very little is known about the effects of biochar amendment on ecological roles that are played by soil fungi.

Physical structure and pore size of biochar effects the degree of fungal colonization. Diameter of fungal hyphae mostly lies between 3 and 6 μm and therefore, that they can colonize pores only larger than their hyphal diameter (Allen 2007; Ritz 2007; Ottow 2011). It has been known for many years that biochar can act as a habitat for mycorrhizal fungi (Ogawa and Yamabe 1986; Saito 1990; Gaur and Adholeya 2000; Ezawa et al. 2002). An increased rate of mycorrhizal root colonization was found on wheat after adding a biochar-mineral fertilizer mixture despite periods of drought (Solaimann et al. 2010). Other than structural feature of biochar, elemental and biochemical properties are also important for fungi. Nutrient availability on biochar surface (charcoal) is one of the possible reasons for saprophytic white rot fungal colonization (Ascough et al. 2010). Microorganisms also use these pores as protection against natural predators (Saito and Muramota 2002; Warnock et al. 2007). Compaction is a kind of soil deterioration that involves deterioration of soil structure, texture and a pronounced reduction in pore sizes. Growth and development of the fungal hyphae will be limited under high soil compaction (Goicoechea 2020).

Further as a consequence of drought, the respiration of microbes is decreased by about 30% at low moisture, and growth productivity estimates based on carbon immobilization vs. net mineralization of nitrogen is affected. Thus, indicating disturbance of cellular activities in microbes (Schimel 2018). Soil amendment with biochar results in an increased soil porosity, which helps in the transport of water, nutrients, and gases. These alterations encourage root formation and increased microbial respiration (Dai et al. 2017). The mechanisms for improved fungal diversity and abundance appear to be correlated more with the physical microstructure of biochar and the recalcitrant organic carbon than other factors (Li et al. 2019). Biochar also acts as a niche form mycorrhization helper bacteria (Warnock et al. 2007).

Mycorrhization helper bacteria trigger morphological and physiological changes in plant roots. Thus, in return facilitate their colonization by mycorrhizal fungi (Rigamonte et al. 2010). There is scientific evidence for production of biochar like compounds by fungi as well (Glaser and Knorr 2008). Aspergillin, the black pigment of *Aspergillus niger* being ubiquitous in soils contains condensed aromatic structures (Lund et al. 1953) similar to those of biochar (Brodowski et al. 2005).

Complex interactions exist between soil properties, biochar properties, the plant, and the microbiome, making it difficult to predict the outcome of biochar amendment. Evidence suggests that the biochar application rate, its properties, or the production conditions are the key factors influencing the fungal communities and the supply of nutrients for the sustainable management of agricultural ecosystems (Wiedner and Glaser 2013). However, it can be broadly said that soil fungi can help to improve compaction along with biochar amendment.

6.11 Conclusion

Burning biomass in low-oxygen situations creates biochar, a carbon-rich substance that a few researcher revealed as the key to soil fertilization. Relatively moderate-weight and porous, biochar can act like a sponge and serve as a habitat for masses beneficial soil microorganisms which can be useful for soil and plant fitness. Biochar has properties to increase surface area, high carbon and nitrogen content. Such substances needed to improve soil health for better growth of plants. Here it is concluded to improve the soil quality for maximum yield of crops biochar mitigate the soil compaction stress.

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Chapter 7
Biochar for Mitigation of Heat Stress in Crop Plants

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Abstract Global warming is accelerating heat stress in plants, thus requiring agricultural strategies for the global food security. For instance, soil modification can be used to minimize the effect of heat stress on crops. Here we review the incorporation of biochar in soil to mitigate heat stress, and its detail mechanisms. Soil amendment with biochar improves the physio-chemical characteristics of soil, with an increase of 56% of organic matter and of 5% of the bulk density under heat stress. Similarly, 235–561% higher surface area, root length, and dry weight of rice plant under stress are observed by addition of biochar under heat stress. Biochar also

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restores pollen fertility of rice. Biochar amendment in soil can increase the supply of photosynthetic products, thereby enhancing crop biomass, grain weight by 15% and yield by 13%.

Keyword High temperature · Soil amendment · Climate change · Food security

7.1 Introduction

Abiotic factors are the most prominent threats to achieving the global food demand for a rapidly growing population in the present era (Zeeshan et al. 2021, 2022; Habib et al. 2017; Hafiz et al. 2016, 2019; Ghulam et al. 2021; Guofu et al. 2021; Hafeez et al. 2021; Khan et al. 2021; Kamaran et al. 2017; Muhammad et al. 2019; Safi et al. 2021; Sajjad et al. 2019; Saud et al. 2013, 2014, 2016, 2017, 2020, 2022a, b; Shah et al. 2013; Qamar et al. 2017; Hamza et al. 2021; Irfan et al. 2021; Wajid et al. 2017; Yang et al. 2017; Zahida et al. 2017; Depeng et al. 2018). Globally high temperature (HT) is a key environmental cause that adversely influences the plants' growth and production (Fahad et al. 2016a, b, 2017, 2018a). Human activities are the major causes for environmental disturbance. For example, the emission of different gases from industries such as methane, nitrous oxides, chlorofluorocarbons and more importantly CO_2 considerably increases greenhouse gas concentration, a major contributing factor to temperature alteration (Hasanuzzaman et al. 2013a). Inter-governmental Panel on Climatic Change (IPCC) statement mentioned that a rise of 0.3 °C temperature will be seen per decade (IPCC 2007), indicating an increase of 1 and 3 °C by the years 2025 and 2100b respectively. This raises the temperature and may alter the cultivation seasons for some crops and their geographical allocation (Porter 2005). High HS has diverse effects on the plant's developmental, and physiological processes and negatively affects crop yield (Hasanuzzaman et al. 2012, 2013a).

High temperature stress promotes a high accumulation of reactive oxygen species (ROS) (Fahad et al. 2016c, d), which leads to oxidative stress (Hasanuzzaman et al. 2012, 2013b). Therefore, high temperature/heat stress is a matter of high concern to the current world food security. Plants, up to some extent, can tolerate the adverse effects of heat stress by modifying their metabolism in several ways, mostly (i) maintaining the turgidity of a cell by osmotic changes, (ii) regulate plant proteins by the help of compatible solute, and (iii) activate the self-defense system (antioxidant system) to scavenge the reactive oxygen species (ROS) and restore the cellular redox homeostasis (Valliyodan and Nguyen 2006; Janská et al. 2010). Similarly, the alteration in gene expression such as regulation of some of the transcription factors and osmoprotectants genes provide direct defense from heat shocks (Krasensky and Jonak 2012; Semenov et al. 2014). Furthermore, under heat stress, changes in physio-biochemical processes by altering the gene regulation, enhanced the tolerance to temperature stress via promoting plant acclimation, and/or otherwise adaptation (in ideal cases) to high adverse temperature (Moreno and Orellana 2011).

7.2 Effect of Heat Stress on Crop Production

Since last decades, the unprecedented and unexpected increase in temperature exposed many problems related to living organisms. Significant yield losses were observed globally in different important food crops (Lobell and Field 2007; Lobell et al. 2008). Like most of the other regions of the world, most of China, particularly in the northern parts, has also noticed a rise in the temperature since half century. For instance, hot days and heatwaves have been reported in China particularly in region of Xinjiang and Yangtze River (Ding et al. 2010). Due to this, Yangtze River Valley (YRV), which is consider main rice-growing area in China, is severely affected, and leads in large losses of rice yield (Tian et al. 2009). Such heat stress episode of 2003 caused an area of 3 million ha to loss about 5.18 million tons in rice yield in China (Tian et al. 2009; Li et al. 2003). Lobell et al. (2008) also found that rice production declined 4–14% in South -East Asia, because of a single degree increase in temperature. You et al. (2009), concluded from previous data (1979–2000), that 10% of the reduction of wheat crop in China, might be associated with the rise in temperature (Easterling 2007). Moreover, several studies have emphasized the ever-increasing liability of the vital wheat-growing areas by high temperature (Chatrath et al. 2007; Joshi et al. 2007; Singh et al. 2007). These areas include part of India, Bangladesh, Eastern Gangetic Plains (EGP), and other part of South Asia.

Similarly, in France, increasing temperatures above 32 °C showed significantly negative impact on maize yield (Hawkins et al. 2013). In the Pannonian zone (Bulgaria, Hungary, Romania, and Serbia) also recorded the undesirable consequences of rising temperature on crops (Olesen et al. 2011). Likewise, part of Europe known for wheat production, desiccated and warm summer reduced the maturity period and an apparent decrease in grain yield (Semenov et al. 2014). A study conducted in Africa comprised of 20,000 maize experiment droughtful and rainfed regimes concluded that each degree rises in temperature over 30 °C resulted in 1% to 1.7% yield reduction (Lobell et al. 2011a, b). In the USA, the analysis of change in temperature patterns during 1976–to 2006 revealed future yield reduction of 16% and 13% in soybean and corn crops, respectively (Kucharik and Serbin 2008). The shocking is that a 30% yield reduction in corn and 46% loss in soybean were predicted in the USA by 2100 using the asymmetric and nonlinear temperature and yield relationship analysis (Schlenker and Roberts 2009). According to the temperature change models, a potential 16% yield reduction has been reported from 1976 to 2006 in USA (Kucharik and Serbin 2008). High temperature resulted in, according to an estimate, a $1.0 billion loss due to the reduction of a significant amount of 8 million tons per year in barley yield from 1981 to 2002 (Ding et al. 2010). Because of the increasing agricultural systems problems and higher confirmations of the adverse effects of heat stress on crops worldwide, instant information and knowledge is needed about sustainable and renovate methods that can produce more yield during the climate change scenario.

Lately, Lobell et al. (2012) from a satellite data of 9 years on wheat growth demonstrated significant losses in grain yield due to temperature going above 34 °C. In the same way, maize crops, because of rising temperatures, lose 12 million tons, with a financial loss of $1.2 billion per year from 1981 to 2002 (Ding et al. 2010). Furthermore, a study reported a 10% reduction in maize yield resulted from 6 °C enhancement in temperature at the time of reproductive phase (Thompson 1975). Kucharik and Serbin (2008) estimated further yield losses in maize was based on the models of temperature change recorded from 1976 to 2006 in the USA. The global temperature trend analysis revealed a reduction of 3.8% in maize yield from 1980 up to 2008 (Lobell et al. 2011a, b).

7.3 Heat Stress Toxicity in Plants

Researchers have been proposed that high heat stress may trigger the production of excessive reactive oxygen species such as hydrogen peroxide (H_2O_2), superoxide (O_2^-), and hydroxyl radical (H^-) which can directly damage the plants cellular machinery (Hasanuzzama et al. 2013a, b; Fang et al. 2015; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b; Hesham and Fahad 2020). Stimulating reactive oxygen species in mitochondria and chloroplasts are key consequences of abiotic stress in plants (Zeeshan et al. 2020a, b). Of which, H_2O_2 has a longer shelf life (~1 ms), is also more diffusible reactive oxygen species than others and can easily escape from the organelle in which it was produced (Levine et al. 1994). Some recent studies have suggested that H_2O_2 acts as a crucial molecule in the complex network of tolerance to plants (Liu et al. 2016). Besides, in higher concentration, it could also initiate program cell death (Quan et al. 2008).

A study on cytoplasmic male sterility in rice confirmed reactive oxygen species role in program cell death, which is directly linked with pollen sterility (Wan et al. 2007). When plants were exposed to high heat stress or other abiotic stresses, calamitous events were initiated such as membrane inefficiency, reactive oxygen species activity due to metabolic toxicity and reduction in nutrients (Fahad et al. 2016b, d; Zeeshan et al. 2020a; Hussain et al. 2020; Hafiz et al. 2018, 2020a, b; Shafi et al. 2020; Wahid et al. 2020; Subhan et al. 2020; Zafar-ul-Hye et al. 2020a, b; Zafar et al. 2021; Adnan et al. 2020; Ilyas et al. 2020; Saleem et al. 2020a, b, c; Rehman et al. 2020; Farhat et al. 2020; Wu et al. 2019, 2020; Mubeen et al. 2020; Farhana et al. 2020; Jan et al. 2019; Ahmad et al. 2019; Baseer et al. 2019; Tariq et al. 2018; Fahad and Bano 2012).

To scavenge reactive oxygen species and maintain redox homeostasis to avoid unnecessary accumulation, plants activate its internal defense system that includes ascorbate peroxidase, glutathione, catalase, peroxidase, and superoxide dismutase (Zhao et al. 2018; Zeeshan et al. 2020a; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b; Hesham and Fahad 2020). Among them, ascorbate peroxidase (EC 1.11.1.11), is consider a crucial antioxidant, belongs to class 1 haem containing peroxidase and detoxifies H_2O_2 into water molecules and oxygen molecules using ascorbate as an electron donor (Teixeira et al. 2004). Enhanced expression of ascorbate peroxidase genes in rice has been reported in biotic and abiotic stress, including heat stress (Jiang et al. 2016). For example, the overexpression of cytosolic ascorbate peroxidase genes protected the plant from cold and salt stress by enhancing H_2O_2 scavenging by ascorbate peroxidase enzyme (Zhang et al. 2013). Similarly, catalases also play a vital role in removing H_2O_2 from mitochondria and peroxisomes (Mhamdi et al. 2010). Several studies on cytoplasmic male sterile plants have noted the high amount of reactive oxygen species in their anthers compared to their wild types with normal fertility. The interaction of antioxidant enzymes and removal of reactive oxygen species/oxidative stress from the pollen of cytoplasmic male sterile plants strongly relates to pollen viability. Furthermore, under certain abiotic stresses, i.e., high temperature and drought, the modulation in the antioxidants enzymes in anthers are induced (Nguyen et al. 2009; Zhao et al. 2016; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b; Hesham and Fahad 2020).

7.4 Effect of Biochar on Plant Growth and Physiology Under Heat Stress

Global warming, an increase in average temperature near the surface of the earth during the two centuries, is a crucial cause of climate change that threatens net crop yield (Horie 2019). Rise in average temperature can significantly reduce the morpho-physiological growth of crops resulting in limited yield. Though, soil modification can be used to reduce the consequences of heat stress. There is ample evidence that soil amendment by using biochar positively affect the soil physio-chemical properties, thus promoting plant growth and nitrogen utilization (Huang et al. 2013, 2018).

Biochar is defined as a carbon-rich finely grained material produced from the pyrolysis of biomass in partial or absence of oxygen (Sohi et al. 2010). Biochar is believed that can store carbon in the soil for thousands of years prompting the reduction in greenhouse gases. Biochar improves the physical (i.e., hydraulic conductivity, soil water retention), chemical (i.e., cations, pH, N, P, Ca), and biological characteristics of soil as shown in Fig. 7.1. Moreover, biochar has prodigious potential in ameliorating soil aggregation, porosity, and structure. It also favors the proliferation of beneficial microorganisms in the soil. With these attributes, biochar may offer a win-win strategy in alleviating food security and global warming (Peng et al. 2011; Fahad et al. 2016a, b, c, d; Yang et al. 2022; Ahmad et al. 2022; Shah et al. 2022; Muhammad et al. 2022; Wiqar et al. 2022; Farhat et al. 2022; Niaz et al. 2022; Ihsan et al. 2022; Chao et al. 2022; Qin et al. 2022; Xue et al. 2022; Ali et al. 2022; Mehmood et al. 2022; El Sabagh et al. 2022; Ibad et al. 2022).

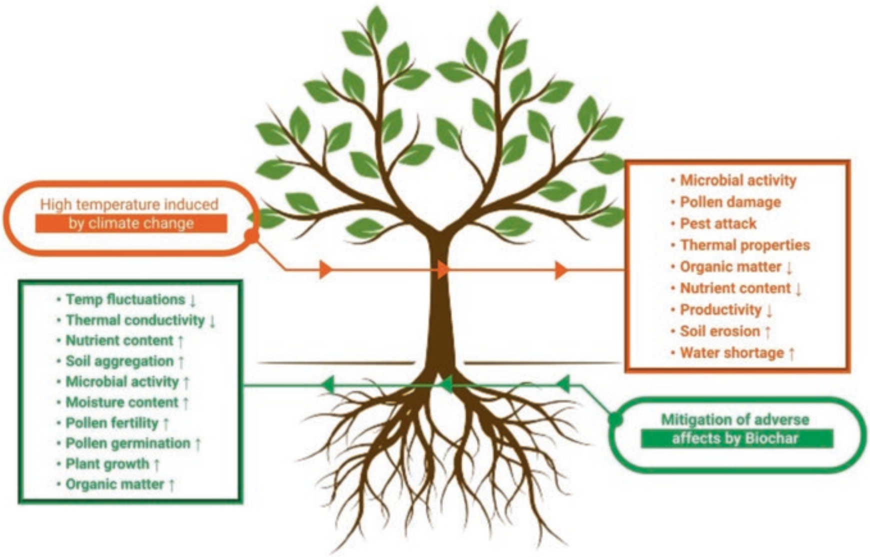

Fig. 7.1 Effect of heat stress on plants and their alleviation with biochar amendments. The text in yellow on right side shows the effect of heat stress/high temperature on plant and root zone, while the text in green on left side indicates the impact of biochar on plants and root zone. The up and down arrows inside the boxes indicate positive and negative effects of biochar and heat stress respectively

Previous studies have proven that improving nitrogen use efficiency can alleviate the adverse impact of heat stress on many economically important crops including potato, maize and rice among others (Liu et al. 2019; Ordóñez et al. 2015; Tawfik et al. 1996; Anam et al. 2021; Deepranjan et al. 2021; Haider et al. 2021; Amjad et al. 2021; Sajjad et al. 2021a, b; Fakhre et al. 2021; Khatun et al. 2021; Ibrar et al. 2021; Bukhari et al. 2021; Haoliang et al. 2022; Sana et al. 2022; Abid et al. 2021; Zaman et al. 2021; Rehana et al. 2021). A study has shown that under heat stress, the application of optimal nitrogen (N) rate and its uptake induced the heat shock protein accumulation (Heckathorn et al. 1996), which in term consider a vital component of bringing heat stress tolerance in plants (Nussenzweig et al. 1997).

Huang et al. (2021) mentioned that biochar amendment has changed the physiochemical characteristics of soil, such as improved the organic matter as well as reduced in bulk density of soil in heat stress condition. Furthermore, they observed that when rice plants were treated with biochar, has improved the surface area, facilitated the root length, and accumulated high dry weight under heat stress with lower soil bulk density than the relevant control. It was reported that lower bulk density of soil promotes root architecture and allow the roots penetration deeply into the soil (Xie et al. 2013). The improvements in root architecture parameters and dry weight of plant under biochar incorporation attribute to the presence of higher content of organic matter in soil. Li et al. (2018) mentioned that higher soil organic matter is playing crucial role in improving soil health by reducing soil compaction. Under stress conditions, biochar may support plant growth by holding nutrients in contaminated soil and improving microbial biomass as well as soil physio-chemical characteristics (Parvage et al. 2013) and by increasing porosity and surface area that results in retaining soil moisture (Glaser et al. 2002). These changes suggest that biochar application result in improving nitrogen uptake and its accumulation in above the ground tissues as well as promoting the root architecture which eventually lead to alleviating the negative influence of heat stress on plants.

Prasad et al. (2006) reported that heat stress/high temperature at anthesis stage affect the growth of flower tube together with pollen grain germination, resulting in low fertilization efficiency. Biochar effectively decreases the negative influence of heat stress on plants and soil. Moreover, high tomato yield was obtained from the biochar added soil due to the increase water holding capacity of soil under biochar application (Akhtar et al. 2014). Similarly, biochar application improve anther dehiscence and pollen development through simultaneous alteration in soil organic matter and increasing nutrient release specifically nitrogen and phosphorus into the soil (Thies and Rillig 2009). Fahad et al. (2015) found that high temperature caused depletion in pollen of indica rice varieties (IR-64 and Huanghuazhan) when happened at night, while biochar and phosphorus (P) addition substantially decreased this heat induced adverse effects and augmented pollen germination rate along with pollen fertility retention and, anther dehiscence in comparison with corresponding control.

Biochar addition into soil can increase the supply of photosynthetic products, thereby enhancing crop biomass, weight and yield of grain of plants (Minhas et al. 2020; Hafez et al. 2021). Moreover, study has stated that biochar addition increased gas exchange attributes such as net photosynthesis rate (*Pn*), stomata conductance (*Gs*), and transpiration rate (*Tr*) under heat stress (Wang et al. 2021). Increase in gas exchange attributes is positively correlated with increase in growth and biomass of plant (Gul et al. 2019; Salam et al. 2022). As the global temperature is rising and severe heat events are forecasted to occur in future. Recent studies have focused on the influence of heat stress on growth and production of crops and the application of biochar is one of the possible approach for enhancing crop tolerance to heat stress (Deepranjan et al. 2021; Haider et al. 2021; Li et al. 2021; Ikram et al. 2021; Jabborova et al. 2021; Khadim et al. 2021a, b; Manzer et al. 2021; Muzammal et al. 2021; Abdul et al. 2021a, b; Ashfaq et al. 2021; Amjad et al. 2021; Atif et al. 2021; Athar et al. 2021; Adnan et al. 2018a, b, 2019; Akram et al. 2018a, b; Aziz et al. 2017a, b; Chang et al. 2021; Chen et al. 2021; Emre et al. 2021).

An increase in variability, intensity, and frequency of temperature has appeared as a potential menace to the sustainability and productivity of crops. Elevated temperature stress induces morphological, physio-biochemical, and anatomical variations in plants. High-temperature stress prompts leaf transpiration and lessens water availability to plants. Heat stress can simultaneously stimulate oxidative stress due to reactive oxygen species production (Fahad et al. 2016a, b, c, d). It also induces hormonal imbalance, excess or deficit of selective metabolites, and can impair respiration and photosynthesis in plants (Ahmad and Prasad 2012; Iqra et al. 2020; Akbar et al. 2020; Mahar et al. 2020; Noor et al. 2020; Bayram et al. 2020;

Amanullah and Fahad 2017, 2018a, b; Amanullah et al. 2020, 2021; Rashid et al. 2020; Arif et al. 2020; Amir et al. 2020; Saman et al. 2020; Muhammad Tahir et al. 2020; Md Jakir and Allah 2020; Mahmood et al. 2021; Farah et al. 2020).

7.5 Biochar Mitigation of Heat Stress by Decreasing Greenhouse Gas Emission

Global warming has engendered cloud cover which results in the reduction of radiation heat loss causing high intense atmospheric temperature and vigorous reoccurring heat waves (Mendoza et al. 2021; Al-Zahrani et al. 2022; Rajesh et al. 2022). Elevated heat/temperature induces CH_4 and N_2O fluxes from soil which results in warming. Scientific approaches have proposed that the biochar amendment can alleviate the global climate crisis via the reduction of green-house gases. Biochar can alter different N_2O processes by transmuting soil pH, sorption of labile C, N-availability, water retention, and soil aeration leading to variability in nitrifying and denitrifying microorganisms in the soil. Depending upon soil amendment, biochar could also alter CH_4 uptake from arable soil by revamping sorption of C and N, pH, soil moisture, and aeration (Bamminger et al. 2018). Biochar changes the surface albedo of agricultural soil which reduces the climate crises (13–22%) (Meyer et al. 2012). Biochar addition into agricultural soil alters the carbon cycle and CO_2 emissions by altering soil properties and its microbial community. Meta-analysis study concluded that biochar improved the crop yield by 10%, however, the results may differ in different soil and with different crops (Jeffery et al. 2011).

7.6 Biochar Mitigation of Heat Stress by Improving the Root Zone Environment

7.6.1 Improvement of the Soil Water Holding Capacity

Enhancing the water-holding capacity of the agricultural soil could be an important work in terms of improving the crop yield. In this regard, biochar has come forward as a potential solution to retain water. Biochar amended soil could retain more rainfall water and reduce the need for irrigation water. Biochar is derived from different biomass feedstocks; therefore, they have variable pore sizes depending upon the feedstock used. Such pores are important in improving the available water capacity. Biochar interacts with soil to create more interstitial pore space within the soil, reduces the bulk density of soil to improve water retention, as high bulk density reduces the water content (Li et al. 2021). However, the method used, and the depth of biochar incorporation greatly influence the water retention capacity. There are two methods i.e., deep banding and uniform top mixing. Biochar can be mixed with manure, lime, or fertilizers prior to application on the field which could reduce the number of operations needed: however, mixing is not suitable in all cropping systems. In deep banding, biochar is placed close to the roots or below the seeds which also reduces the need for fertilizers (Major 2010). Enough scientific data have been published to back the use of biochar for improving the soil water holding capacity. For example, application of switchgrass biochar increased water retention by 15.9% of sandy loamy soil (Novak et al. 2009), while green-waste biochar enhanced the water holding capacity of Alfisol (Chan et al. 2007). Similarly, biochar produced from hardwood increased 15% water holding capacity of Mollisol of Midwestern agricultural soils (Laird et al. 2010).

7.6.2 Improvement of Soil Bulk Density

Biochar could be improvised as a long-term adaptive strategy as it has the potential to improve the physiochemical properties of soil. It promotes the water holding capacity, porosity, decreases the bulk density, and increases the sodium (Na), calcium (Ca), magnesium (Mg), and potassium (K) concentration in soil (Nelissen et al. 2015). Determining the physical and chemical impact of biochar on soil helps define the fertility of the soil. One mechanism by which biochar improves soil fertility is by retaining water in small pores. Other mechanism includes the formation of stable soil aggregates which enhances the crop yield and prohibit degradation of soil (Ding et al. 2016; Sadam et al. 2020; Unsar et al. 2020; Fazli et al. 2020; Md. Enamul et al. 2020; Gopakumar et al. 2020; Zia-ur-Rehman 2020; Ayman et al. 2020; Mohammad I. Al-Wabel et al. 2020a, b; Senol 2020; Amjad et al. 2020; Ibrar et al. 2020; Sajid et al. 2020; Muhammad et al. 2021; Sidra et al. 2021; Zahir et al. 2021; Sahrish et al. 2022). For instance, rice husk biochar increases soil aggregation (8–36%), soil pore structure (20%), and soil shear strength (Lu et al. 2014). However, the effect of biochar directly on roots traits is still controversial. Root biomass may enhance (Prendergast-Miller et al. 2011; Varela Milla et al. 2013) reduce (Aguilar-Chávez et al. 2012; van de Voorde et al. 2014) or either remain unaffected (Macdonald et al. 2014; Keith et al. 2015) by biochar amendment. Such variability in results is not astounding because response of roots toward biochar depends on multiple factors. For instance, the type of biochar, the pyrolysis conditions or the material used for production are all important in determining the efficacy of biochar. The cumulative amount, application rate and characteristics of biochar are crucial in altering the root environment. Biochar improves the soil environment, nutrient availability, and microbial community which consequently affect the plant root growth (Palareti et al. 2016). Moreover, biochar is often combined with fertilizers which interactively promotes plant root architecture (Alburquerque et al. 2015).

7.6.3 Biochar Application Increases Soil Organic Matter Content

The incorporation of biochar into the soil enhances the soil organic matter, decreases organic nitrogen (N) turnover, accelerates N dynamics, or can alter the carbon (C) cycling. The impact of biochar is subtle because soil organic matter is a heterogeneous mixture containing various compounds of variable degradability. Therefore, biochar effect is studied on different fractions of soil organic matter individually (Tian et al. 2016). For instance, light fraction organic C, microbial biomass C, and dissolved organic C content were enhanced in biochar amended soil (Liang et al. 2010). In contrast, during field experiment it had no impact on dissolved organic C and dissolved organic nitrogen (Jones and Willett 2006) and on the other hand, it reduced the dissolved organic C (Prommer et al. 2014). These controverting results have been ascribed to the varying climate, soil biological characteristics, fertilization, and crop rotation. Biochar produces micropores because of its own porous nature. These micropores sorb and immobilize the organic as well as inorganic matter in soil. Dissolved organic matter is also sorbed by biochar. However, the potential of biochar to sorb dissolved organic matter can be affected by alkaline ash produced along with biochar in pyrolysis process, because ash affects the solubility of dissolved organic matter. Therefore, if its solubility increases by biochar amendments, this may lead liberate the sorbed dissolved organic matter in soil. Which might enhance the carbon flux and dissolved organic matter bioavailability in soil (Smebye et al. 2016).

7.6.4 Reshaping Soil Microbial Community's Structures

Apart from soil physio-chemical properties, biochar amendments also improve the biological soil properties. The management of soil biota by the addition of biochar is gaining increased interest. Biochar can affect the soil microbial community by altering the nutrients availability, plant-microbe signaling, or by affecting other microbial communities (Palansooriya et al. 2019). Domene et al. (2015) noted an increase of 5–56% in microbial population when using corn stover biochar. Possible reasons may include less competition, increased habitat suitability, increased porosity, enhanced water holding capacity, and abundance of organic matter and nutrients on biochar surface (Domene et al. 2015). Carbon and nutrient availability affect the microbial population in soil, and they are influenced by the type of biochar used for amendment. In nutrient deficient soil, microbial abundance increases after the excess of nutrient supply by biochar as biochar retains or releases the nutrients (Lehmann et al. 2011).

Biochar also changes soil pH according to its nature which provides favorable conditions to specific microbial communities. Pietri and Brookes (2008) gradually increased the pH from 3.7 to 8.3 and observed an increase in microbial biomass ninhydrin-N (0.5–4.5 μg ninhydrin N^{-1}) and microbial biomass C (20–180 μg biomass C g^{-1}). Similarly, (Rousk et al. 2010) showed that increasing soil pH to 7 only enhances the bacterial population while the fungi population remains unaffected. Microorganisms can also sorb to biochar surfaces which makes them less susceptible to leaching. Biochar also protects the microbial community from periodic drying of soil by retaining water in the soil (Ding et al. 2016). Furthermore, the pore structure of biochar can provide microorganisms with a living environment. This pore habitat protects both fungi and bacteria from their competitors and predators (Thies and Rillig 2009).

7.7 Conclusion

Soil amendment with biochar improves plant health and productivity by enhancing cation exchange capacity, nutrient use efficiency and water holding capacity. The mechanism behind this aforementioned potential: it increases root-zone surface, organic matter content and transforms the microbial community composition. Biochar plays a key role in climate change mitigation through reduction of greenhouse gases emission, methanogens activities and carbon sequestration. Plant and soil responses to biochar depend on its doses, use methods and context (soil chemistry, crop, environment) and feedstock and pyrolysis temperature, hence a comprehensive study on biochar needs before application. The effect of adverse environmental conditions on biochar heterogeneous nature is also unexplored. Systematic study is needed to investigate the relationship of biochar with different plant species, soil type in various environmental conditions.

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Chapter 8
Biochar Application to Soil for Mitigation of Nutrients Stress in Plants

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Abstract Nutrient stress is a worldwide problem which may alter the biochemical, physiological, and molecular processes in all kinds of plants. In addition, such nutritional stress is the major cause of malnutrition in the developing and poor countries. Generally, plants require 17 macro and micro nutrients for the optimum growth, development, and yield. Moreover, some other additional mineral elements are very crucial for the survival of the plants under stress conditions or help the farmer to produce the quality products. The proper and timely management could reduce its

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impacts. The impact of nutrient stress depends on plant age, soil types, plant species, ecology, climatic conditions, and genome of it. Usually, morphological characteristics of the plants are considered the quick, valuable, accurate, and strong identification of nutritional deficiency of the specific nutrients. Biochar (BC) is a cheap potential source of Carbon (C) which not only improves health and fertility of soil but also improves the quality and productivity of crops both in normal and under stress conditions. Here we reviewed that BC is the source of various kind of elements such as C, H, N, P, K, Mg, Ca, S and some other nutrients that are key for healthy plant growth. Moreover, it improves the soil physico-chemical properties such soil porosity, surface area, CEC, soil hydrophobic capacity, soil aeration and soil surface oxidation which results into increase in soil nutrients availability and further their retention in the rhizosphere. In conclusion, all these properties of BC could help the plant to survive under the nutrients stress conditions.

Keywords Nutrient stress · Biochar · Environmental factors · Climate change · Plant growth

8.1 Introduction

The human global population will expected to reach 9.7 billion in 2050 (Rodés-Guirao 2013) and definitely will increase the demand of human food and feed requirements (Golden and Cotter 2021). Numerous abiotic stresses are threatening the global food security (Crandall et al. 2022). In addition to water and carbon dioxide, the plant growth needs balanced and sustainable nutrient acquisition to roots from soil for the production of carbohydrate (Amsili et al. 2021). Nutrient stress is a significant environmental factor that influences the plant growth and development (Bechtaoui et al. 2021). In addition, all stages of plant growth and development, including the whole plant, individual tissues and cells, and even subcellular levels are significantly affected (Holland et al. 2020). Some time, longer period of stress can harm plants by disturbing the protein aggregation and increased membrane lipids fluidity (Ogden et al. 2018; Li et al. 2020b). The healthy cell can create the cross link of different polymers and proteins and hence improve the stiffness of cell wall (Wang et al. 2016). The cell wall structure and components dictate the cell and tissue morphology depending the nutrient availability. Moreover, some time, it changes the pattern of cell growth and development (Ogden et al. 2018). The enzymes inactivation in mitochondria and chloroplast can be happened in some sever nutrient stress (Borysiuk et al. 2022).

Balanced proportions of macro-nutrients (carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium and sulfur and micro-nutrients (iron, zinc, manganese, copper, boron and molybdenum are vital for optimal growth and plant harvest (Pandey 2018). Nutrient stress could be resulted into nutrient specific phenotypes, growth inhibition, incomplete plant phenology and oftentimes, reorganization of root architecture (van der Bom et al. 2020; Al-Zahrani et al. 2022; Rajesh et al. 2022; Anam et al. 2021; Deepranjan et al. 2021; Haider et al. 2021; Amjad et al. 2021; Sajjad et al. 2021a, b; Fakhre et al. 2021; Khatun et al. 2021; Ibrar et al. 2021). Crops have some native ability in coping and tolerating these stress signals that communicate with one another (Bukhari et al. 2021; Haoliang et al. 2022; Sana et al. 2022; Abid et al. 2021; Zaman et al. 2021; Sajjad et al. 2021a, b; Rehana et al. 2021; Yang et al. 2022; Ahmad et al. 2022; Shah et al. 2022). The productive phase includes the development of male and female floral components, the variation of both gender flowery parts and the formation of both gender characteristics is heavenly dependent on the nutrition (Souri and Hatamian 2019). Although each phase reacts to nutrient stress differently leading to decrease in net production. However, any stress during the productive stage (Zhang et al. 2018a;) has substantial implications since productive parts are essential elements of yield and the primary source of nutrition for the whole human population (Souri and Hatamian 2019; Muhammad et al. 2022; Wiqar et al. 2022; Farhat et al. 2022; Niaz et al. 2022; Ihsan et al. 2022; Chao et al. 2022, Qin et al. 2022; Xue et al. 2022; Ali et al. 2022; Mehmood et al. 2022; El Sabagh et al. 2022; Ibad et al. 2022).

Reactive oxygen species have a detrimental effect on cellular metabolic processes and harm all biological components (Nieves-Cordones et al. 2019). Therefore, it is crucial to detoxify these reactive oxygen species, and plants have evolved extensive defenses against them (Hasanuzzaman et al. 2018a; Fahad and Bano 2012; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b). Plant cells often increase the action of reactive oxygen species sifting enzymes and boost their creation of anti-oxidants in response to elevated reactive oxygen species levels in order to maintain redox equilibrium (Mittler et al. 2022).

Different management practice is being used to combat the different kind of stresses (Saud et al. 2013, 2014, 2016, 2017, 2020, 2022a, b). Biochar a carbon-based solid created through the burning of organic substances, including wood, animal dung, poultry manure, and municipal sludge (Amoakwah et al. 2020; Adnan et al. 2018a, b, 2019, 2020). It is sometimes referred to as burned biomass or black carbon. Controlling plant nutrition can help plants become more resilient to other different kind of environmental stresses (Fig. 8.1). The discovery and breeding of nutrient stress tolerant cultivars are now being worked on with better root architecture (Campobenedetto et al. 2021). One of these uses is utilizing a soil conditioner like biochar to shield plants from the harm caused by salt stress (Ameur et al. 2018).

8.2 Biochar to Alleviate Nutrient Stress

In the current climate change era, poor crop productivity has been obstructed due to unexpected seasonal climatic variations such as decreased precipitation/intense precipitation for short period, a length dry period, a short duration increases in moisture, frequent thunder storm and abrupt increase in temperature. These issues are

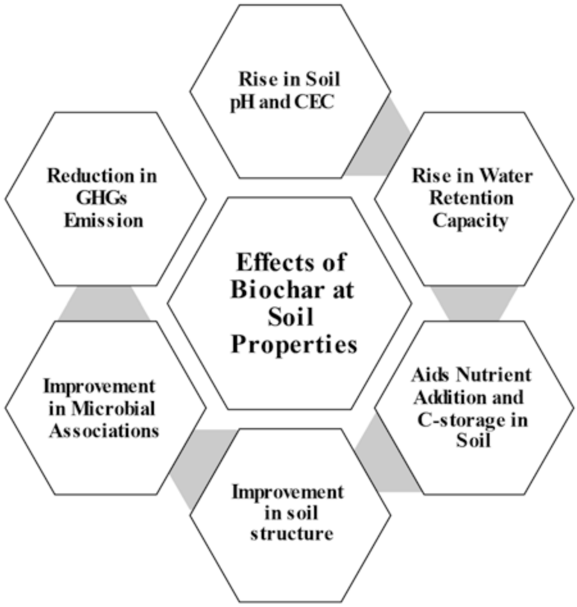

Fig. 8.1 Effect of biochar on physicochemical properties of soil. *CEC* cation exchange capacity, *GHG* greenhouse gases

very much challenging for agriculture in arid and semi-arid regions (Hasanuzzaman et al. 2018a). It is not possible to stop these challenges but can be managed and their destructive effects on the crops can be minimizes. Nowadays, a serious issue of nutrients stress tolerance is seen in Pakistan and around the globe. Althoufh scientist are working on it but it takes time. The plants show different kind of responses against the nutrient stress in different environmental conditions. But, all kind of plants show multiple biological responses such as production of reactive oxygen species. All the plant species can easily manage reactive active species in their systems but they require the proper dose of all nutrients.

Processed carbonous material can sustain for longer period of time as compared to non-processed organic material in arid and semi-arid climate where high temperature always burned the organic matter (Dalal and Carter 2019) resulting into to no addition of organic masses into the soil systems. Therefore, plant-based materials such as biochar is an integrated approach for soil fertility management under environment-based nutrient stress which may help achieve sustainable agricultural outputs; nevertheless, these methods require significant land modification and financial commitment (Fig. 8.2). Such kind of organic amendments has been widely used in many developed but least in developing countries which are revitalizing the nutrient deficiency in all kind of soils. Additionally, producing biochar from organic waste is an economical way to recycle the agricultural waste materials (Dai et al. 2016).

Burning agricultural waste significantly negatively affects the environment because it produces carbon dioxide, the main greenhouse gas generated by human activities. To overcome the drawbacks of direct burning, it has been proposed to

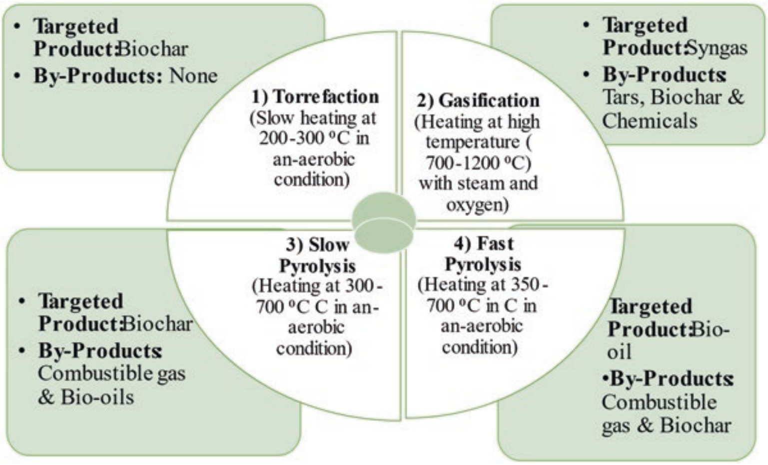

Fig. 8.2 Methods of biochar production from raw biomass

carbonize woody wastes to produce biochar, a material like charcoal. Due to its resistance to biological deterioration, biochar's acoustic impacts may last far longer in terrestrial settings than compost or plant leftovers. Carbonization by pyrolysis to generate biochar is a useful technology to reduce negative impacts on environmental and health. Global warming is lessened by a dark material called biochar, which includes refractory organic carbon. High solubility of water and nutrient could be a reason of biochar addition to soil as a soil conditioner to increase soil nutrient content (Da Silva Mendes et al. 2021). Furthermore, biochar increases pH, cation exchange capacity, organic carbon, and nutrient content in soils while reducing carbon dioxide emissions. Thus, the soil amendments should be an alternative and short-term solution for sustainable nutrients under the nutrient stress (Clough et al. 2013; Chintala 2014; De Jesus Duarte et al. 2019; DeLuca and Gao 2019).

8.3 Nutrients Stress and Plant Growth

In order to maintain cell sustainablity and ensure life under the nutrient stress, plants have developed several adaptive/resistance mechanisms. Sever nutrient stress disturbs the flexibility of membrane lipids, which might alter the structure of the membrane (Peng et al. 2019b). By sifting reactive oxygen species produced under nutrient stress, nitrogen oxides may serve as an antioxidant and defend plants against stress (Rai 2022). According to several prior studies, nitrogen oxide signals to development of thermotolerance in plants by activating enzymes that use oxygen (Hasanuzzaman et al. 2018b; Ahmed et al. 2020; Li et al. 2020b; Fonseca-García et al. 2021). Moreover, enhancing a plant's ability to withstand environmental shocks requires proper nourishment for the plant (Adetunji et al. 2020). Similarly, potassium is crucial for agricultural plants to survive under challenging environmental conditions (Kong et al. 2020). It can improve the process of photosynthesis, turgidity maintenance and stress-induced enzyme activation under nutrient stress (Saghaiesh and Souri 2018). In most of cases, the potassium stress may hamper the carbon dioxide fixation, cell ion channels and cell wall permeability (Zhang et al. 2018b). Such turbulences lead to an excess of photosynthesis-generated electrons, which increases electron transport to oxygen and subsequently stimulates reactive oxygen species production (Kong et al. 2020). The sustainable transport of photosynthetic electrons transportation is heavenly disturbed during the nutrient deficiency because it causes oxygen to be converted to reactive oxygen species (Nieves-Cordones et al. 2019). Sometime, the cell sustainablity may be shielded against oxidative damage brought on by nutrient signalling in low potassium soil media (Wu et al. 2018). However, increasing the potassium concentration of irrigation water significantly protected the cell and its function.

8.4 Nutrient Stress and Plant Cell Functions

In order to achieve the necessary gains in food production, it is predicted that fertilizer use will need to double over the next 20 years (Fischer and Connor 2018). In order to increase crop production and maintain soil fertility, research on plant nutrition looks to be a top priority in the future decades (Hackman et al. 2022). To survive and produce when faced with environmental obstacles, crop plants must develop adaptive mechanisms to prevent or minimize nutrient stress (Ahmed et al. 2020). Phosphorus is required for strength generation, magnesium and nitrogen are structural components of chlorophyll that are necessary for photosynthesis while potassium is necessary for osmotic control and enzyme activation, and phosphorus is a structural part of essential plant compounds (de Souza Osório et al. 2020). Therefore, a plant that receives enough nutrition should produce more smooth and sustainable growth (Sung et al. 2018). Moreover, the hydraulic conductivity of the cortical root cells was much lower in plants that were nitrogen and phosphorous deficient (Praveen and Gupta 2018). In addition, availability of proper plant nutrient concentration are crucial to increase the water use efficiency and nutrient use efficiency enhancement of the crops (El-Nakhel et al. 2019).

Numerous studies have shown the sufficient availability of different kind of nutrients may help the plant in reducing the effects of different abiotic stressors. For example, silicon and potassium have been shown to boost tolerance of wheat crop against nutrient and salt stress (Sales et al. 2021). Nitrogen deficiency reduce the plant ability to tolerate the different kind of stresses i.e. cold, heat and salinity stresses (Ahmed et al. 2020). In addition, these stresses impaired impair plant growth and nutrient uptake. The suitable concentration of nitrogen may trigger the light harvesting and hence accelerate the process of photosynthesis (Ahmed et al. 2020). So that is why, health plant growth and yield could be achieved. Sometime, the surplus of unused light energy is anticipated in nitrogen deficient leaves, increasing the likelihood of photo-oxidative damage (Rai 2022). Similarly, a lack of nitrogen in rice plants exposed to intense light is associated with increased lipid peroxidation in the cell system (Yoo et al. 2018).

The role of sun energy in electron movement during kelvin was greater in nitrogen sufficient crops compared to nitrogen-deficient crops (Bloch et al. 2020). Additionally, nitrogen deficient plants may withstand high levels of photosynthetic activity and the production of defensive mechanisms (Rai 2022). To protect against photo-oxidative damage caused by excessive light, the thylakoid membrane provides an additional energy release mechanism, which releases heat (Manoj et al. 2020). However, in nitrogen-deficient plants, the generation of zeaxanthin and the conversion of xanthophyll cycle pigments increased, decreasing the chlorophyll concentration (Gebregziabher et al. 2021). Compared to nitrogen adequate spinach plants, nitrogen deficient spinach plants lose up to 64 percent more of the light energy that is absorbed (Moriwaki et al. 2019). This gap was attributed to alterations in the xanthophyll cycle pigments, with zeaxanthin and antheraxanthin accounting for around 65% of total xanthophyll pigments in plants havening less nitrogen (Moriwaki et al. 2019). Similarly, the use of captivated sun energy in carbon dioxide fixation is decreased in nitrogen deficient plants, leading to a more significant need for protection against excessive light energy (Prescott et al. 2020). As a method of releasing excess light energy, it was discovered that bean leaves provided with nitrate converted violaxanthin to zeaxanthin more strongly than those supplied with ammonium (Holzmann et al. 2022). Similarly, the bean plants grown in nitrate were more resistant to photodamage than bean plants grown in ammonium (Posso et al. 2020). Ammonium-grown plants showed greater lipid peroxidation levels and antioxidative enzymes due to the increased light intensity (Fonseca-García et al. 2021).

8.5 Physiological Alteration and Role of Micronutrients Under Nutrient Stress

Different element had different function inside the plant body and the deficiency of any other them may halt the numerous physiological processes and require for serval co-factors and enzymes of metabolism (Janpen et al. 2019). Moreover, some elements play their role at the earlier stage of plant growth and some require at the grain filling and ripening of crop. Plants are unable to complete their life cycle successfully without availability of specific elements (Zhou et al. 2021). Generally, macro-element is available to plants but they do not have micro-elements which are equally important for plant health active. Acute nutrient (micro-nutrient) stress directly harms plants by causing protein denaturation and aggregation and increased membrane lipid fluidity. The balance presence of different elements is very vital and sometime their antagonistic effect may lead to abnormal growth. Therefore, it may induce different changes in the biosynthesis of different compounds and structural components.

Such nutrients stress for longer period can lead to over production and accumulation of reactive oxygen species that could had toxic effect to nucleic acids, metabolites, proteins, and lipids of plant cells (Ogden et al. 2018). Most common ROS that plants produce under the nutrient stress including singlet oxygen, superoxide anion, and hydrogen peroxide which are generated in to all cell organelles i.e., mitochondria, peroxisomes, and chloroplast (Kim et al. 2021). However, the maintaining of some specific physiological level of reactive oxygen species is a matter of life and death for the aerobic living organism otherwise leading to death within a few hours. The proper concentration of different types of micronutrients helps the plant cell to produce the antioxidant defensive systems which is dully supported by the enzymatic and non-enzymatic compounds to tackle the harmful effects of reactive oxygen species (Nadeem and Farooq 2019).

Calcium ion is a vital ubiquitous intracellular messenger, which play a lead role in several signal cell trans transduction pathways. Moreover, the transient perturbations such as free cytosolic calcium are indispensable and translate the cell signals into various biological responses. The increase in cytosolic calcium levels resulted into higher production of calcium sensor relay proteins such as calmodulin that is called calcium biding proteins. calmodulin regulated the several transcription factors which involved in many physiological, bio-chemical, and molecular functions in the cell. Some time, cytosolic calcium activates the calmodulin-binding transcription activator which is major contributor of transcription factors. Moreover, calcium is thought to be essential for healing from stress free because it promotes the cellular membranes protein adenosine triphosphatase, which is required to transport back nutrients depleted during cell damage. calcium modulates the pressure throughout freezing damage, repair work, and cold tolerance adaptation (Pathak et al. 2020). Moreover, it also fastens the process of repairing of the damage cells and it is observed that it also enhances the tolerance against the freezing injury (Thor and Kathrin 2019; Zhang et al. 2020). In addition, it stimulates the adenosine triphosphatase enzymes which help the cell wall to recover aggressively in cold damage by mobilizing the available cell resources. Calcium is also an important element in maintaining cell structure and cell integrity (Zhang et al. 2020).

Through several physiological and biochemical processes, magnesium influences plant growth phase (Pickering et al. 2020). It is necessary for several metabolic processes, including photosynthesis (Xie et al. 2021). Even slight variations in magnesium levels significantly affect numerous necessary chloroplast enzymes (Peng et al. 2019a). Both a magnesium shortage and an excess are harmful to plant photosynthesis (Veronese et al. 2020). However, the rate of photosynthesis is noticeably decreased in the leaves of magnesium deficient plants. The nutrient stress causes several metabolic pathways in various cellular compartments, such as chloroplast, mitochondria, and peroxisomes, to continuously produce reactive oxygen species. Mineral nutrient deficit stress includes oxidative stress (Zhang et al. 2019). In addition, magnesium increased the content of antioxidant molecules and the activity of antioxidant enzymes in bean (Torabian et al. 2018), maize (Iqbal et al. 2020), wheat (Tian et al. 2021), rice (Ahmed et al. 2021) and pepper (Zirek and Ozlem 2020).

Additionally, plants lacking in micro-nutrients such as iron, boron and magnesium which decrease the accumulation of malondialdehyde into the cell (Oustric et al. 2021). The sustainable availability of these nutrients increase the root growth and surface area that helps the plants to absorb water and nutrients from the deeper layer of soils (Ali et al. 2020). In addition, they also rise the quantity of sucrose in the leaves and improves sucrose transfer from the leaves to the roots. Sometime, they also improve phloem export to boost glucose translocation under temperature stress (high or low). Moreover, the improved feeding of micronutrients increase the photosynthetic rate leading to higher yield by maintaining chloroplast structure in Cassava plants (Busener et al. 2020). However, sometimes, protein synthesis is inhibited leading to inhibition and membrane integrity is lost due to higher level of deficiency.

8.6 Management of Nutrient Stress

Traditional agriculture has been replaced by intensive crop cultivation due to food demand and supply (Garnier et al. 2019). Intensive (or tiring) agricultural farming has reduced the availability of plant nutrients, which harms plant protentional badly (El-Nakhel et al. 2019). Healthier crop nutrition may help plants become more resilient to different kind of stresses and increase the production of antioxidant system. The anti-oxidants protect chloroplast membrane integrity, reduce photo-oxidation, scavenge reactive oxygen species, and promote photosynthesis in the plants (de Souza Osório et al. 2020). It was also seen the availability and management of healthy concentration of macro-and micronutrient may increase the chlorophyll contents (Purbajanti et al. 2019). It was worth noted that availability of nutrients can increase of generation of strong chlorophyll pigments and general plant progress in cow pea plants even under water stress (Laranjeira et al. 2021). Moreover, the sufficient concentration of potassium and calcium encourage water uptake, assisting stomata and improves the ability of plants to withstand temperature pressure by sustaining a steady temperature.

8.7 Sustainable Plant Growth Under a Stressed Environment with Biochar

The rosehip seeds biochar applied at the rate of 2% (200 gram per pot) improved the shoot dry weight of sugar beet (29.82 gram per plant) under drought stress condition as compared to control (with no biochar treatment) (Durukan et al. 2020). Due to typical nature of biochar towards the binding of various micro and macro-nutrients on its charged sites due its electrostatic attractions, can increase the biding of water particles and thus decrease the frequency of irrigation and plant may save the plants from drought susceptibility (Khan et al. 2021). In addition, under nutrition stress environment, comparative higher surface area and porous structure of biochar that increase its adhesive and cohesive forces with the water and nutrients in the soils may result into slow release and gradual availability of nutrients and water to plants (Kätterer et al. 2019; Abideen et al. 2020). It was also noted that the functional groups especially oxygen related functional groups help the biochar to conserve more water molecules and plant may use in stressed environment (Suliman et al. 2017).

Enough Biochar addition to plants can elevate the stresses on stomatal conductance transpiration, photosynthesis, respiration, and turgor pressure by improving the nutrient and water availability (Phillips et al. 2020). The addition of biochar (600 °C) at rate of 2% increase the biomass (shoot and root) of licorice by 80% and 40% under the saline environment (50 mM NaCl). In addition, it also improved the root architectural characteristics such as root surface area, root length, root volume, project area and nodulation (Egamberdieva et al. 2021). Moreover, in alternate root-zone drying irrigation, overall growth (plant height and shoot biomass) and yield (grain yield) of quinoa by 11.7%, 18.8 and 10.2 % respectively compared to deficient irrigation (Yang et al. 2020). During the growth period of quinoa, it was noted that the water use efficiency, stomatal conductance and leaf photosynthetic rate and leaf Abscisic acid was also improved under the saline stress conditions as compared to non-saline environment (Yang et al. 2020).

Acceleration of nutrient cycling and carbon sequestration in the upper soil layer (0–15 cm) was achieved in the rice straw biochar treatments and improved the reduced the soil bulk density and increase the availability of nutrients. Ultimately, this phenomenon was enhanced vegetative biomass and yield (Wu et al. 2021). Similarly, the microbiome population in the soil reduced the production of reactive oxygen species under nutrients stress and improved the carbon stock leading to better nutrient availability to plants (Tang et al. 2020). Stress tolerance with biochar are associated with the release of considerable concentration of micro-nutrients (carbon, nitrogen, phosphorus, and potassium) and macro-nutrients (calcium, manganese, iron, zinc, coper) (Abd El-Mageed et al. 2020). In addition to earlier reports, positive effects of biochar materials were noted on the plant growth and development. But it was concomitant with the release of essential soil nutrients such as nitrogen, potassium, calcium and magnesium into the soil media (Zhao et al. 2020).

8.8 Physiochemical Changes in Soil After Biochar Addition

The physiochemical properties of all kind of soils play vital role towards the alleviation of nutritional stress and availability of nutrients. Hence, biochar is magical material which had the ability to enhance the plant growth and improve the soil health (Sattar et al. 2020). Biochar had the ability to play magical role even in nutritionally dead soil (Minhas et al. 2020). Generally, it can change the pH, cation exchange capacity, electrical conductivity, inherent nutritional capacity, electrical conductivity, solubilization ability and hence, improve the access of plant to nutrients into the soil media (Zhu et al. 2020). Biochar had the ability to clean the soils from different organic and inorganic pollutants which are increasing the soils after the haphazard application of chemicals to agricultural crops (El-Naggar et al. 2020; Khalid et al. 2020). Moreover, the leaching of fertilizers and runoff of soil is very common phenomenon in the arid and semi-arid areas. It reduces the efficiency and loss of outputs and other hand its polluting the fresh water resource. Hence, continuous and repeated application of biochar not only reduce the runoff and leaching but also sustaining the soil productivity (Ippolito et al. 2020).

Biochar application into the soil increase the soil moisture and resistant to microbial degradation which slows down the degradation process (may decrease to 0.3% per year) leading to long term sustainable availability of nutrients and accelerated the process of carbon sequestration in the arid climate (Papageorgiou et al. 2021). It was worth noted that the activities of proteases, acid phosphomonoesterases and soil fluorescein diacetate hydrolase was improved under the saline condition by the addition of biochar (600 °C) at rate of 2% under the saline conditions (50 mM NaCl) (Egamberdieva et al. 2021).

Significant concentration of some minerals i.e., magnesium, iron, and calcium and inorganic carbonates has been increased after the application of biochar into soil that improved the plant growth and development. In addition, soil carbon contents, soil permeability and soil productivity were also improved when was observed during the crop growing period and at harvest (Antala et al. 2019; Leng et al. 2019). Moreover, the biochar stimulate the microbial activities in the rhizosphere that increase the yield by improve the soil nutrients availability and soil water contents (Zhu et al. 2017). The soil porosity and cation exchange capacity was also enhanced but it was more prominent in the clay soils as compared to sandy and silt soils (Nguyen et al. 2017). Due to change in electrostatic charges of soil, it increase the release and retention of nutrients in soils, improving the plant nutrient use efficiency resulting to higher plant yield (Akhtar et al. 2014).

Addition of biochar could initiate and accelerate the process of different biochemical and enzymatic activities in the soil. Initially, the soil microbial abundance and activities has been started and provided the food to all kind of soil biota. Furthermore, they may coordinate and fasten the nutrients cycling process (Liu et al. 2017). Many nutrients solubilizing microbes like *Bacillus mucilaginosus*, *Bacillus edaphicus* and *Azotobacter chroococcum* may starts their actives from sluggishness due to unavailability of nutrition (Rahimzadeh et al. 2015). They mineralize the fix/Nex/chelate nutrients into solution form. The activities of some Bacillus species could be promoted by 5-fold when they are incubated with biochar of corn stover (0.6%). The nutrients release activities of soil is increased by 80% (Liu et al. 2017). It has been worth noted that application of B. mucilaginosus into mica rich soil boost up the growth and development of lemon grass. This could be due to more mobilization of the potassium from the available resources of mica (Basak et al. 2021) (Fig. 8.3).

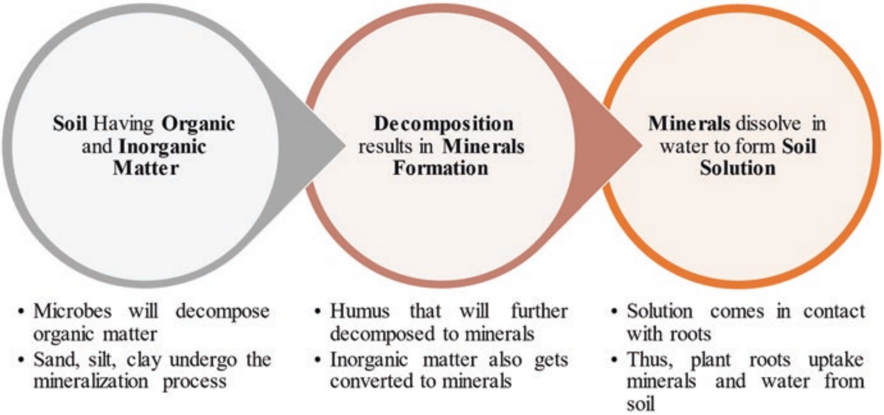

Fig. 8.3 Soil nutrient availability to plants

8.9 Management of Nutrients by Biochar Under Nutritional Stress

The biochar had the ability to mitigate numerous environmental stresses such as drought, salinity, heavy metals, nutritional stress, heat stress, climate change effects and pollution effects etc. from the plants. Usually, it was noted that all plants accumulates ethylene under the stresses including the nutritional stress (Khan et al. 2015). That production of ethylene under stress condition is high dangerous to plant cell and starting its damage from degradation of cell membrane lapis of chloroplast and then further activates the chlorophyllase gene (chlase) (Michaud and Jouhet 2019). The chlorophyllase may lead to degradation of chlorophyll and finally chlorosis may result. Biochar could slow down the process of ethylene production by providing of nutrients through its slow-release mechanism. Thus, a large number researcher reported that biochar could eliminate the nutrient stress in all kind of soils (Wacal et al. 2019; Chen et al. 2022; Shaheen et al. 2022).

Biochar is generated from biomass that has been paralyzed in a low-oxygen environment and is a fine-grained charcoal with a high concentration of refractory organic carbon (Lehmann and Joseph 2015; Amoakwah et al. 2020). Its application in agricultural soils to capture carbon, enhance soil functioning, and other purposes has been hotly contested (Lehmann 2007). Carbon-rich biochar may increase soil fertility by enhancing the ability of soil to retain nutrients. All the crop nutritionist suggested that carbon-rich biochar is the game changer to enhance the soil fertility of poor soil in the arid and semi-arid climate. Moreover, the structure of carbon based material is aromatic which give it a lot of characteristics like low density, large surface area, high ion exchange capability, and great porosity which make it more resistive to disintegration (Agegnehu et al. 2017). The material and pore volume of carbon-based material can greatly enhance the physical and chemical properties of soil, which are essential for soil cooling and crop production. These properties include water retention, hydraulic properties, aggregate stability, pH, organic carbon, and cation exchange capacity (Dai et al. 2016; Baiamonte et al. 2019). Moreover, the physical properties of soil has been improved because of presence of micropores and less density of carbon based particles (Lehmann et al. 2011). Additionally, the presence of nitrogen in biochar may alter the dynamics of soil nitrogen by influencing the quantity of soil nitrogen that is available to plants, and it increases its ability to absorb more nitrogen, and accelerate the biological processes of nitrification (Ameur et al. 2018; Amoakwah et al. 2020).

Moreover, by enhancing the physical environment of the soil, which prevents or lowers anaerobic denitrification, carbon dioxide flow, and methane gas generation, applying biochar to soil may also reduce greenhouse gas emission (Ali et al. 2017). Additionally, adding biochar to field improves infiltration and water-holding capacity, particularly in soils with a coarse texture or a high concentration of macrospores (Agegnehu et al. 2017). Biochar contains different amounts of nitrogen and carbon depending on its feedstock and production conditions and its additives sequester more carbon and nutrients in the soil because of their promotive properties. The natural ability of biochar in controlling nutrients uptake that is ultimately reduces the reactive oxygen species and abscisic acid in the cabbage seedlings. Under the nutrients stress conditions, biochar was effective at reducing Nitrate (NO_3), Ammonium (NH^{4+}), phosphate ($PO_4{}^{3-}$), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) (Gao and DeLuca 2018). In addition, it is worth noted that potassium leaching is significantly reduced with the addition of biochar.

Physical and chemical soil factors such as, water-holding capacity, cation exchange capacity, pH, surface area, porosity, bulk density, carbon, nitrogen, nitrogen used efficiency, and total accessible nitrogen and phosphorus are between the physical and chemical soil parameters that biochar affects. It was noted that majority of macro and micro-nutrients such as hydrogen, oxygen, magnesium, and macronutrients including nitrogen, phosphorus, and potassium are all present in biochar and can help most crops throughout the globe grow more quickly. It was seen the biochar increased the nitrogen retention efficiency that in return decrease the use of synthetic fertilizer to the crops. Upon the addition of maize residue biochar at the rate of 1–2% (weight/weight), the amount of total nitrogen increased by 41%, the amount of accessible P by 165%, the amount of available potassium by 160% (Saffari et al. 2020). In addition, Adekiya et al. (2020) recorded that soils that have amendment of biochar had higher levels of essential nutrients.

Biochar improved the nitrogen concentration in the stem, root, fruits, and leaves under the normal and stress conditions as compared to control treatments (no biochar). Under drought stress condition, the rosehip seeds biochar applied at the rate of 2% (200 gram per plant) increased the nitrogen concertation at 1.72% as compared to control treatments (no biochar) (Park et al. 2019; Durukan et al. 2020). Moreover, the electrostatic attraction among the various micro and macro-nutrients and the charges sites of biochar may increase the concentration of ammonium and nitrate ions. However, this higher release of ammonium ions was seen when the biochar was produced at low temperature (400–500 °C) (Xu et al. 2019; Zhou et al. 2019).

Biochar can alter the amount of accessible phosphorus in soil in solution form to plants and prevent its fixation and sorption on the clay minerals (Uchimiya et al. 2015; Zhao et al. 2016). Moreover, biochar could help the farmers of poor and developing countries in increase the soil phosphorous use efficiency and reducing the phosphorus losses due to its ability of slow releasing of nutrients. Hence, it may work as phosphorus fertilizers for future generations and could increase phosphorus use efficiency for longer term especially in nutrient deficient period (Li et al. 2020a). The success stories of its residual effects on crop growth and development are also confirmed. Due to different surface properties like as basic, acidic, heterogeneous a and hydrophilic characteristics, biochar can increase solubility and availability of phosphorus under the various climatic conditions (Trazzi et al. 2016; Glaser and Lehr 2019). The rosehip seeds biochar applied at the rate of 0.5% (50 gram per plant) increased the nitrogen concertation at 1.01% as compared to control treatments (no biochar) (Durukan et al. 2020).

Soil potassium is divided into four types basis on its availability such as exchangeable/soluble potassium, non-exchangeable potassium, water-soluble potassium, and mineral potassium. All these potassium fate into the soil systems is in dynamic equilibrium and play vital role for its availability and update into the plant system (He et al. 2015). Although the potassium reserves are large in the soil system of arid and semi-arid system of the globe but are in non-exchangeable potassium form. However, application of biochar at different rates was significantly increased the proportion of exchangeable potassium into the soil media that is readily available to plant rooting system from the longer period. In addition, some time, potassium is present in mineral potassium or exchangeable potassium forms that is sparingly or partial available in the rhizosphere (Oram et al. 2014). A lot of research question are still unexplored regarding to interaction of biochar time/amount and potassium or biochar application and type of clay minerals. Moreover, the specific interactions and process between the biochar application timing and its interaction with the soil components and the processes involved in it. Moreover, the rosehip seeds biochar applied at the rate of 2% (200 gram per plant) increased the potassium concertation at 2.33% as compared to control treatments (no biochar) (Durukan et al. 2020).

On the other hand, potassium is conserved during the biochar production process and easily available in the form of potassium containing salt having high solubility but its ability is heavenly dependent on the input material from which it is produced. So, that is why, several past studies indicated that potential source of potassium in the form of biochar could be a chief substitute of conventional and synthetic fertilizers. Some studies exhibited that quick release of potassium may result into unavailability of potassium after first year but non the other hand, it was noted in the previous studies that role of soil properties such as including soil texture, type, pH, inherent potassium-reserves, and concentration of clay minerals is determined the dynamic of potassium into the soil and rhizosphere.

The rosehip seeds biochar applied at the rate of 2% (200 gram per plant) was improved the micro-nutrient concentration (magnesium and manganese) in the stem of sugar beet (Durukan et al. 2020). The electrostatic attraction among the opposite charges ions may increase the concentration of many micro-nutrients such as calcium, iron and magnesium etc. (Chandra et al. 2020). In addition, biochar helps the soil media to release the significant concentration of fixed micro-nutrients such as manages, iron, calcium, copper, and zinc. Hence more concentration these micro-nutrients was noted in the plant body (Abd El-Mageed et al. 2020). In long run, the application of handful amount of biochar into soil may reduce the need of synthetic fertilizers and pesticides because it can improve the concentration of micro-nutrients, organic matter, soil carbon concertation, nutrients cycling, soil enzymes activities, soil fertility and soil microbial activities leading to achieve the sustainablity and profitability of the farming community (Abd El-Mageed et al. 2020).

It was seen the under nutrient stress, the addition of biochar to the crop may correct the imbalance concentration of calcium, iron, zinc, and sulfur etc. that are vital from plant growth and development (Mwando et al. 2020). Moreover, biochar plays vital role in improving the human and animal nutritional status that are heavenly dependent on the plants for its nutrition. Generally, it was observed that micro-nutrients (magnesium, calcium and manganese) was fixed into the soil particles but was easily released into soil system in long term field experiments when biochar (corn straw biochar) was added to soil before the seed sowing (Zhao et al. 2020).

8.10 Conclusion

Nutrient-nutrient interconnection and responses and further its impact on ions accumulation into the cell are well explored. However, the nutrient based cell signalling is still a topic to debate. Such signal may deceive the cell other signal. So, it may disturb the cell routine activities. How all the terrestrial plants crop with poor nutritional acquisition in soil is an interesting question in biology. Now a days, nutrient stress along with climate change challenges which plants are facing in nature. That is why, sudden changes in growth capacity of plants can be seen due to abrupt changes in ion homeostasis interactions with in plant cell system (Fig. 8.4).

The combinatorial signal mechanism among the different cell of the plant under the nutrient stress yet to be focused in the future research program. Moreover, there is dire need to improve the plant genetic system to tackle the combined stresses and it may lead to development of plant species with better genetic architectures that may handle each individual stress response. Therefore, future research program should be designed to exploring the answer the question of how the nutrient homeostasis in plant body push the plant to change its genetic architecture and how it identifies the effect of the combination of different nutrient stress on a single plant in the field condition. Moreover, the lack of research of the role of molecular mechanism of integrated nutrient stressed cell signals for the development process of cell is the demand of the current era. Similarly, the use of 3D network modelling could be a handy tool to understand and predict the ionome for any combination of nutrients for any specific genotype at the given time and space. The interaction of different nutrients stress singles with ionome and growth and how they change the different mechanism pathways in the cell that may re-regulate ion homeostasis and

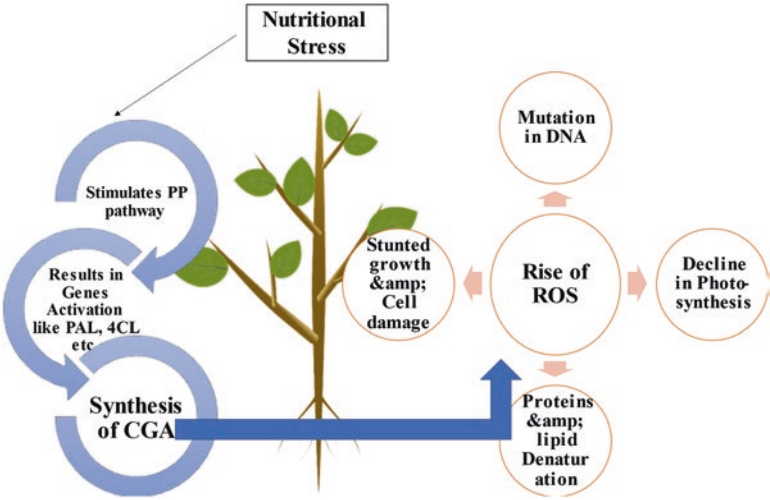

Fig. 8.4 Effect of nutritional stress on plant cell metabolism. *PP* pentose phosphate Pathway, *DNA* deoxyribonucleic acid, *PAL* Phenylalanine ammonia lyase, *4CL* 4-coumarate: *CoA* ligase gene, *amp* amplification, *CGA* chlorogenic acid, *ROS* reactive oxygen species

plant development. Sometimes, such signals deceive the plant systems with immune signaling pathways that produces different chemicals into the soil. These chemicals are very necessary to cohabitate plants with soils to manage the limited nutrients in the soil system. This interconnection between the cell signalling and immunity needs a lot of attention of plant researchers. Therefore, cellular level improvement is needed to cope with nutrient stress signalling system. So, any molecular mechanism improvement that may help the plant breeder to introduce the plant ideotypes. It will be a game changer in precision farming era and ensure the food security in the climate change scenarios.

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Part III
Improvement of Soil Health

Chapter 9
Biochar from On-Farm Feedstocks for Sustainable Potassium Management in Soils

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Abstract Potassium is an essential soil macronutrient for crop production, yet a large proportion of potassium is either lost or accumulates in plant tissues. Therefore, recycling potassium accumulated in plant tissues and reducing potassium losses from the soil is a major challenge for the agricultural system. In this context, the development of biochar from on-farm feedstocks and plant tissues appears as a sustainable solution for ensuring environmental and agricultural sustainability. In this review, we show that that potassium accumulated in on-farm feedstocks can be retained and converted into stable potassium in biochar. Potassium-enriched biochar is sustainable potassium source that reduces potassium loss.

Keywords On-farm feedstocks · Biochar · Potassium · Recycling · Sustainable agriculture

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9.1 Introduction

Potassium is a crucial macronutrient after nitrogen and phosphorus and plays an important role in sustainable crop production (Prajapati et al. 2012; Wang et al. 2018). It is involved in many physiological processes in plants, such as photosynthesis, stomatal conductance, and enzyme activation (Abd El-Rheem et al. 2015). It boosts crop growth and yield by increasing nutrient uptake by root development and increasing the roots' ability to absorb more nutrients from the soil solution (Wakeel et al. 2002; Wu et al. 2019).

Plant metabolism is severely impacted by potassium shortage because it alters metabolite concentrations within plant tissues and influences gene transcription by modifying the activity of several enzymes (Armengaud et al. 2009). Potassium not only affect assimilates transport; but also helps in regulating the photosynthetic rate in plants. It improves the physical quality and shelf life of fruits and vegetables and the feeding value of grain and forage crops, contributing significantly to crop quality (Rezaeian et al. 2014).

Chemical fertilizers are the primary source of potassium utilized all over the world. Inorganic potassium fertilizers come from two different sources: potassium chloride and potassium sulfate. The farmers cannot afford potassium sulfate because of its high price. Potassium chloride contains chlorine, and its excessive application in soil raises its chloride level, which is toxic and detrimental to crop performance (Tariq et al. 2011).

As a result, using chemical fertilizers continuously raises production costs while accelerating soil erosion and environmental risks. The plant nutritionist should seek other potassium sources in this situation to increase crop yield and soil fertility over time at the lowest cost of production. Organic farm waste can be used as a source of potassium fertilizer or developed into an organic potassium fertilizer (Arshad et al. 2007).

Organic residues considerably enhance the soil's chemical, physical, and biological properties (Olatunji et al. 2006). Continuous treatment of organic wastes improves soil properties over time (Adeniyan et al. 2005). Compared to using inorganic fertilizers, applying organic manures raised farm income (Olatunji et al. 2006). Agricultural wastes from farms can be recycled and used as a source of plant nutrients such as Nitrogen, Phosphorus, and Potassium (Aziz et al. 2010). Due to the rising cost of synthetic fertilizers and issues with waste disposal, interest in using these waste products produced on farms is becoming crucial. By addressing nutrient deficits, crop residues satisfy the crops' need for nutrients.

Biochar has attracted widespread attention in recent decades as a novel material for environmental applications and fertilizer control (Ghodszad et al. 2021; Rahim et al. 2022). Soil fertility and potassium availability issues can be solved by the application of biochar in the soil (Rahim et al. 2020). Biochar contains a lot of exchangeable potassium, which boosts soil potassium levels and plant potassium consumption (Chan et al. 2009; Wang et al. 2018). Potassium, in contrast to other elements, is typically conserved and converted into potassium containing salts with high solubility during pyrolysis (Karim et al. 2017).

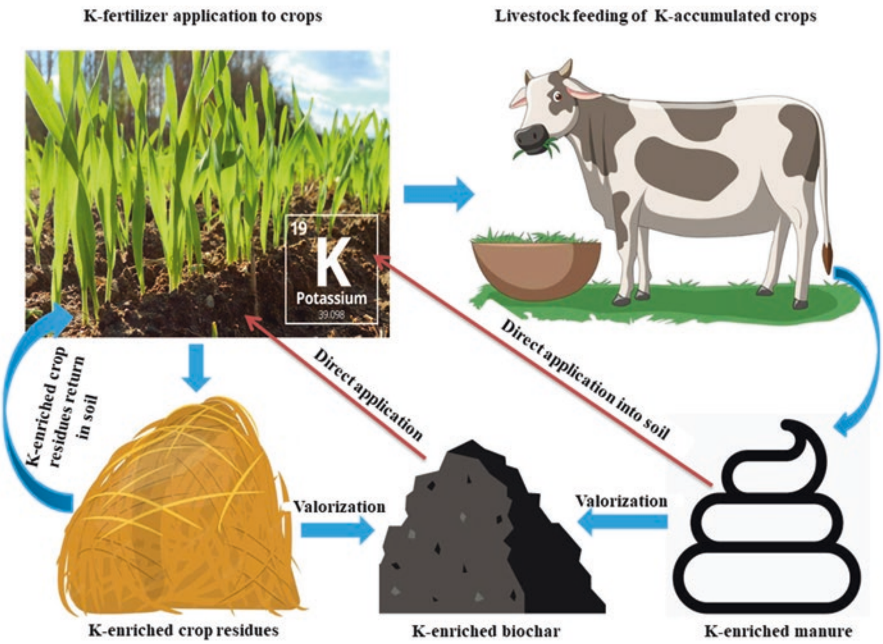

Fig. 9.1 Potassium dynamics, cycling and availability from different organic and inorganic sources

According to research, biochar can replace a sizable percentage of conventional potassium fertilizers (Angst et al. 2013). The potassium cycling and availability from different organic and inorganic sources in the soil are systematically illustrated in Fig. 9.1. In this context, this chapter briefly discusses agricultural residues and their biochar-based potassium recharge routes and ensures sustainable potassium cycling in the soil system for maximum crop production.

9.2 Forms of Potassium in Soil

Potassium in the soil is found mainly in four farms, water-soluble, exchangeable, slowly available (fixed), and mineral potassium. The uptake of potassium forms by plants and its ultimate cycling is illustrated in Fig. 9.2. These fractions coexist in a state of dynamic equilibrium, and these forms, in turn, control the potassium nutrition in plants (Lalitha et al. 2014).

Water-soluble potassium is more important because plants can quickly absorb it and are found in soil solutions or on the surface of the clay. When the amount of soluble potassium in the soil solution drops, additional potassium is released into the solution via exchangeable forms, and plants quickly absorb it. potassium in soil solution, which accounts for a minor portion of soil's total potassium, is a crucial sign of potassium availability (Afari-Sefa et al. 2004).

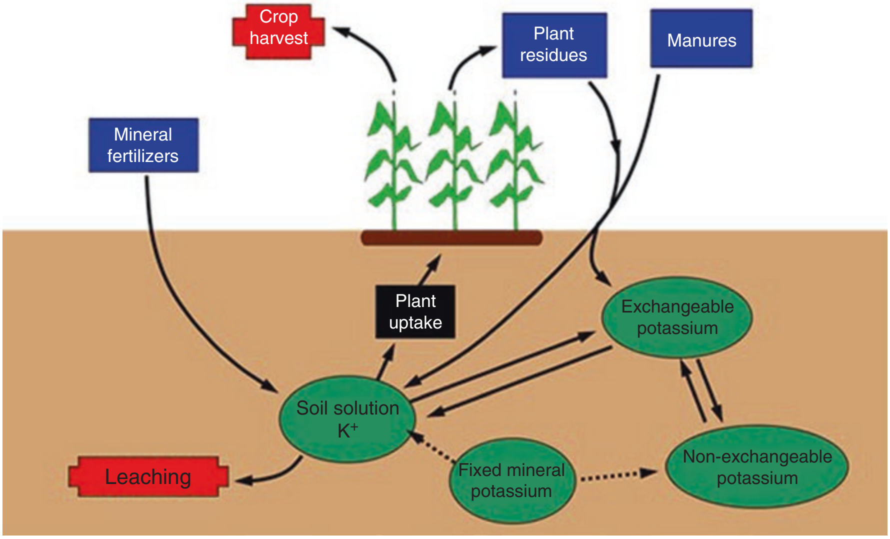

Fig. 9.2 Potassium forms in soil, associated cycling and their uptake by crops. (Source: https://www.pda.org.uk)

Fixed potassium exits between the layers or plates of clay minerals such as illite, vermiculite, and chlorite. The slow availability of potassium accumulated in this way prevents plants from making considerable use of it in a single growing season. However, the soil's capacity to supply potassium over a long period is influenced by the presence of fixed potassium. Different exchangeable potassium sites are present in the soil that is typically accessible for the plants to meet their needs. In general, 90–98% of the total potassium in soils is in the form that is comparatively difficult to get, 1–10% is available slowly, and 0.1–2% is accessible quickly (Afari-Sefa et al. 2004; Follet et al. 1981).

9.3 Potassium in Field Crops Residues and Its Release

Crop residues are an important source of potassium in soil (Andrews et al. 2021). Typically, nutrient content in crop residues is influenced by nutrient and water management, soil characteristics, crop specific nutrient demands, and phenological stage at harvest as plant potassium dynamics change over these factors (Öborn et al. 2005; Zipori et al. 2020). Plant residue potassium is predominantly present in soluble form in cell cytosol and represents its content (Li et al. 2014; Rosolem et al. 2005; Sardans et al. 2015).

Numerous investigations have shown that a water extraction mechanism causes potassium to be rapidly released from plant residues (Dong et al. 2019; Hougni

Table 9.1 Estimated potassium content in field crops residues

Source Crop	Feed stock	Estimated potassium (%)	Reference
Maize	Straw	1.48	Dong et al. (2019)
Maize	Residues	1.53–1.69	Madar et al. (2020)
Rice	Residues	2.1	Singh et al. (2014)
Rice	Straw	2.19	Su et al. (2014)
Wheat	Straw	2.26–2.60	Madar et al. (2020)
Wheat	Straw	3.78	Wei et al. (2015)

et al. 2021; Li et al. 2014). This process is typically characterized by extremely high release rates after initial water application, followed by a slower release stage (Cobo et al. 2002; Rodriguez-Lizana et al. 2010).

The quantity and frequency of applied water determine the rate and total amount of potassium solubilization from plant material. For instance, Hougni et al. (2021) found potassium released rapidly from cacao pod husks at rates that varied as a function of rainfall frequency and quantity. A study comparing straw residues found that 10–20 mm of precipitation led to the greatest potassium release while less than 5 mm of precipitation did not release significant amounts of potassium (Rosolem et al. 2005).

Maize and soybean residues released around 95% of total potassium contents under 275 mm precipitation over 2 months (Dong et al. 2019). When inundated with water, rice straw residues have been shown to release 90% total potassium after 3 days (Li et al. 2014). Considering potassium solubilization is driven by water, and plant potassium uptake occurs through water uptake, strategically timed water applications during periods of crop demand could be used to supply potassium from residues in a fashion similar to inorganic fertilizers (Table 9.1).

9.4 Potassium in Biochar and Its Release

Post-harvest processing can influence residue potassium concentrations; for example, biochar can substantially increase potassium content (Hossain et al. 2020). The potassium concentration of biochar varies with feedstock type and pyrolysis temperature, as shown in Table 9.2.

Biochar produced from rice husks, corn stalks, and apple branches had more potassium than poultry litter, chicken manure, rice straw, and bamboo biochar (Hossain et al. 2020). Abu Zied Amin (2016) found 6.05 g kg^{-1} soluble potassium content in maize cob biochar, and Nguyen et al. (2020b) obtained 8.50 g kg^{-1} replaceable potassium in rice husk biochar. Xiao et al. (2018) discovered that increasing the pyrolytic temperature from 250 °C to 550 °C raised the potassium content in chicken manure biochar from 4.16% to 5.93%.

At pyrolytic temperatures of 400 °C and 600 °C, poultry litter-derived biochar contained 3.88% and 5.88% potassium (Subedi et al. 2016). Similarly, Vaughn et al.

Table 9.2 Potassium in Biochar derived from different feedstocks at different pyrolysis temperature

Source crop	Pyrolysis temp (°C)	Potassium (%)	References
Maize straw	300	3.40	Song et al. (2018)
Maize straw	450	3.41	Song et al. (2018)
Maize straw	600	3.40	Song et al. (2018)
Rice straw	550–650	2.19	Si et al. (2018)
Wheat straw	300	0.25	Beheshti et al. (2017)
Wheat straw	350–550	0.25	Zheng et al. (2017)
Corn Stover	300	1.71	Enders et al. (2012)
Corn Stover	600	2.46	Enders et al. (2012)
Elephant grass	400	1.61	Ferreira et al. (2019)
Elephant grass	500	1.61	Ferreira et al. (2019)
Elephant grass	600	1.61	Ferreira et al. (2019)
Bamboo	600	2.78	Lu et al. (2018)
Hardwood	550	2.78	Nguyen et al. (2018)
Hardwood	600–650	0.13	Aller et al. (2017) and Khanmohammadi et al. (2017)
Sewage sludge	350	0.26	Zhao et al. (2018)
Sewage sludge	500	0.52	Enders et al. (2012)
Leaves waste	500	1.08	Enders et al. (2012)
Grass waste	500	6.13	Enders et al. (2012)
Food waste	400	1.46	Prakongkep et al. (2015)
Cofee waste	400–500	0.35	

(2018) synthesized bio-solid biochar at temperatures 300, 400, 500, 700, and 900 °C, with potassium contents of 3.89, 3.98, 4.06, 4.02, 8.12, and 9.83%, respectively.

Potassium release is influenced by microstructure, surface characteristics, and biochar degradation; these factors can be managed by altering the pyrolysis procedure (Nguyen et al. 2020a). It has been reported that pyrolysis at temperatures above 700 °C resulted in potassium losses (Johansen et al. 2011). Altering the pyrolysis temperature from 200 °C to 600 °C increased potassium solubility by an order of magnitude, demonstrating that adjusting the pyrolysis temperature is an effective approach for accelerating potassium release.

Condensation of organic C provides highly porous media and a larger interface area at these temperatures, allowing more potassium to be released from the biochar structure. Potassium release can be influenced by the structure by enhancing potassium adsorption on exchange sites or boosting phytolith dissolution, which results in phytolith encapsulated potassium releases (Dove et al. 1992; Fraysse et al. 2006;

Ngoc Nguyen et al. 2014). Prior to Si being released by OH- groups through nucleophilic attack, Si-OH groups must be deprotonated and Si-O-Si linkages polymerized. As a result, more extensive potassium releases occur when the amount of OH- on the surface of phytoliths increases.

9.5 Potassium Enriched Biochar a Way to Agricultural Sustainability

The main challenge with present agricultural systems is increasing crop yield in a more sustainable and environmentally favorable manner (Hamilton et al. 2016; Srivastav 2020). Following the green revolution, agricultural practices increased their reliance on organic fertilizer to ensure higher crop productivity. Chemical fertilizers boost crop productivity but endanger environmental sustainability by causing ecological imbalances such as biodiversity loss, global warming, and heavy metal inclusion in living species (Mandal et al. 2016).

Adopting a more natural farming method can reduce reliance on chemical fertilizers sustaining agricultural production and productivity. More recently, biochar blended with inorganic potassium fertilizer is considered an auspicious soil conditioner to sustain nutrients in the soil and ensure sustainable agricultural nutrient management (El-Naggar et al. 2018; Yu et al. 2018).

Several studies report an increase in crop yield in response to biochar mixed with inorganic fertilizer, particularly potassium. Likewise, Ye et al. (2020) reported that when biochar was added along with inorganic potassium fertilizer, benefits to crop yield increased to 48%, thus rendering a 22% greater increase in yield than the addition of fertilizer alone. A study by Song et al. (2018) reported that the application of maize straw biochar produced at different pyrolysis temperatures enriched with potassium fertilizer (KCl) resulted in an increase in crop yield and quality through substantial increment in potassium uptake by wheat crop.

Furthermore, the application of maize straw biochar produced at a pyrolysis temperature of 300 °C enriched with potassium results in potassium uptake of 0.95 g pot^{-1} and yield of 10.33 g pot^{-1}. However, maize straw biochar produced at a pyrolysis temperature of 450 °C enriched with potassium results in potassium uptake of 1.06 g pot^{-1} and yield of 11.48 g pot^{-1} in wheat crop.

Moreover, Zhang et al. (2012) also found an increase in maize yield of 10.5% in response to biochar coupled with potassium fertilizer. Zahedifar et al. (2017) found a pronouncing effect of application of biochar at the rate of 1.5% combined with potassium fertilizer at the rate of 300 mg kg^{-1}on yield of Basil (Ocimumbasilicum) increasing in fresh weight of 12.77%, dry weight of 5.74%, potassium content of 12.65 mg kg^{-1} in Basil respectively.

The synergistic effect of potassium enriched biochar on growth and yield of different crops might be due to the absorption and slow release nature of potassium from biochar resulting in over long availability of potassium improving potassium use efficiency leads to sustainable crop production.

9.6 Conclusion

With a growing global population, it is difficult to ensure sustainable crop production on nutrient-depleted soils. Among others, increasing soil carbon sequestration with biochar and consequently increased crop-use efficiency of potassium fertilizer are the two measures to reduce chemical fertilizer inputs. Before using biochar, it is crucial to choose the right type, pace, and affinity with agro-growing systems. Biochar is a technique for slowing nutrient release and protecting the environment without sacrificing crop output. Biochar application may improve soil quality, boost the resilience of agroecosystems and agroforestry, and aid in their adaptability to changing climatic circumstances. However, the effects of biochar would be site-specific. Of course, biochar is not a remedy for all agroecosystem problems. However, it could be a significant strategy worth considering in the future establishing a potassium sustainable agroecosystem.

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Chapter 10
Biochar for Crop Protection from Soil Borne Diseases

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Abstract Pest diseases in crop soils are likely to increase under the warming effects of climate change, calling for advanced practices to control pest and maintain food production. Biochar application, for example, is improving soil health by supplying nutrients, removing toxic compounds, increasing the population of mycorrhizal fungi, nutrient retention and influencing beneficial microorganisms which are known to enhance plant growth and resist phytopathogens. Few reports show that biochar protects to plants against soil borne diseases via induced systemic resistance and systemic acquired resistance. Here we review biochar uses with focus on properties, effects on plant-soil microflora interactions, plant health, plant growth improvement, and control of soilborne diseases.

Keywords Biochar · Induced resistance · Disease control · Soilborne pathogens · Organic amendment · Microbial community

10.1 Introduction

Two most significant and tough challenges being faced by our society, are to feed the continuously rising populace and to evade the change of climate (Fahad et al. 2019, 2020, 2021, 2022). To diminish the effect of utilization of more land on various ecosystem amenities, the scientists must enormously focus on the eco-friendly and good approaches which are sustainable for our agriculture (Kolton et al. 2017; Shah et al. 2022; Al-Zahrani et al. 2022). The sustainability of agriculture is at stake due to various factors which are deteriorating the soil properties and soil health including soilborne diseases (Shaaban et al. 2018; Toju et al. 2018; Naz et al. 2021a; Bamagoos et al. 2021).

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Healthy soil can efficiently improve the plant health and production while soil-borne diseases are majorly affecting the soil health as well as quality production of food and feed (Yang et al. 2019; Riaz et al. 2021). The repeated cultivation of the same crop is known to deteriorate the soil physico-chemical properties and its nutrient status which can further worsen the soil for succeeding crop productivity and cause soil sickness (Wang et al. 2019; Liu et al. 2019; Zia et al. 2021). Seedling blight, damping-off, seed and root rots are the most communal soilborne diseases in plants which are particularly being instigated by *Rhizoctonia solani* and *Pythium* spp., causing significant crop yield losses for instance eggplant, cucumber, melon, pepper, corn, potato and tomato (Fischer and Glaser 2012; Nikraftar et al. 2013; Jaiswal et al. 2014).

Farmers usually rely on the use of certain chemicals and fungicides to eliminate the pathogens; however, these chemicals and fungicides may damage the plants and the beneficial microflora, besides being expensive (Naz et al. 2018; Jaiswal et al. 2019). Thus, control of soil borne pathogens is the essential step for preserving soil health and may be supportive for sustainable soil management to strengthen the agriculture (Xiang et al. 2019).

Consequently, there is a need to find the non-chemical, alternative approaches to reduce the incidence of soilborne diseases. One developing method that holds potential for eradicating the pathogens causing soilborne diseases is the addition of biochar which has fascinated extensive consideration owing to its key role in improving soil (Jaiswal et al. 2019). Biochar, the compact co-product of biomass pyrolysis, has increased significant research and profitable interest over the past time for a variety of reasons comprising increased soil fertility status (Frenkel et al. 2017; Ibad et al. 2022; Irfan et al. 2021; Khadim et al. 2021a, b; Khan et al. 2021; Khatun et al. 2021; Muhammad et al. 2022; Subhan et al. 2020; Tariq et al. 2018; Wiqar et al. 2022; Wu et al. 2020; Wu et al. 2019; Xue et al. 2022), pollutant fixation (Ho et al. 2017), improved plant efficiency (Ahmed et al. 2017). Soil amendments with biochar applications has been reported to increase tomato, maize, pepper, soybean and wheat plant growth and yield attributes (Graber et al. 2010; Islami et al. 2011; Alburquerque et al. 2013; Egamberdieva et al. 2016).

Moreover, the exogenous treatments of plants with biochar have also reduced the incidence of soilborne diseases by inducing ISR against fungal phytopathogens (Elad et al. 2011) including *Botrytis cinerea* (Mehari et al. 2015), Fusarium oxysporum in tomato (Akhter et al. 2016) *R. solani* in cucumber (Jaiswal et al. 2014). Hence, the biochar application has mitigated the harmful effects of soil reaction by adjusting the soil microflora (Wang et al. 2020) and have revealed the potential proficiency to subdue the soilborne plant diseases (Beesley et al. 2011). Meeting the twin challenges of rising food call and climate alteration, it is imperious to take environmental performs for maintainable farming.

Various studies have described that biochar applications also have impending role for modifying climate change by lasting reclamation of carbon and inducing greenhouse gas changes in soil, and biochar treatments has been recommended as an active countermeasure to lessen emissions of nitrous oxide and methane

(Kolton et al. 2017). The biochar treatments have increased leaching of nutrients and supplementation for better plant growth (Xiang et al. 2019) and biochar adjusted soils had higher cation exchange, water holding, pH, larger surface area and lower soil bulk density, compared with the unamended soils (Enders et al. 2012).

10.2 Biochar to Improve Soil Health

Growth and expansion into biochar, the addition of charcoal to soil, has been growing significantly over the last few decades. As a consequence of rising alarm over worldwide climate variation caused by synthetic, anthropogenic greenhouse gas releases, there is a global effort to move from a petro economy powered by fossil carbon to a budget driven by renewable energy assets, containing biomass. Biochar is a dense by-product of biomass formed by pyrolysis or by higher temperatures about 250 °C, under limited supply of or in the whole absenteeism of air (Mao et al. 2012). Being an exothermic procedure, pyrolysis of biomass gathers more energy than is keen in the heating procedure (Murakami et al. 2007). The gaseous and liquid co-products are used for energy or chemicals, while the biochar is useful to the soil.

Biochar is trumped up of vital elements for instance hydrogen, carbon, nitrogen, sulfur and oxygen as well as reserves in the ash portion. Biochar is highly spongy, black and finely grained, with light mass, enormous surface area and pH, all of which have a progressive influence on its use to soil. The raw material (biomass) used and handling parameters grasp the properties of the biochar.

Wood chips, cow manure, grass, wheat straw, casava rhizome and rice husk are being used as raw resources by pyrolysis technology to make biochar (Ronsse et al. 2013). Various other materials including agronomic wastes (husks, peels, bark, straw, sawdust, seeds bagasse, wood chunks, corn cobs and stalks, urban waste and industrial wastes and urban/civic wastes (Kameyama et al. 2016) have been expansively utilized, therefore also attaining waste managing through its manufacture and usage (Woolf et al. 2010). The biomass utilized for the manufacture of biochar is chiefly composed of hemicellulose, cellulose and lignin polymers (Sullivan and Ball 2012). Between these, cellulose has been originated to be the chief constituent of maximum plant-derived biomasses, but lignin is also imperative in woody biomass.

Essentially, biochar additions to soil have been displayed to expressively increase soil nutrient preservation and accessibility to vegetation, and crop output (McCormack et al. 2019). The modification of topsoil with biochar has been stated to increase plant growth and yield indices. Furthermore, biochar grips the ability as an appropriate carrier of microbial inoculants to expand plant growth. The biochar uses improved water holding capacity, soil cation exchange capacity and organic material.

10.3 Improvement of Soil Microflora and Plant Growth by Biochar Amendment

Various studies have been reported in displaying the ability of biochar to improve the soil microflora, resulting in greater accretion of carbon in soil. Also adsorbing nutrients organic constituents, and gases, biochar is expected to offer a locale for actinomycetes, bacteria and fungi (Thies and Rillig 2012). The improvement of water holding after biochar utilization in soil has been well known (Busscher et al. 2010) and this could disturb the microbial inhabitants of soil. Numerous interpretations stated that phosphate solubilizing fungi in combination with biochar improved growth and yield attributes of *Glycine max* and *Vigna radiate* plants, compared to untreated control (Saxena et al. 2017). The usage of biochar enhanced mycorrhizal growth because this association has provided the best conditions to plant roots for more colonization (Solaiman et al. 2010).

Biochar applications are also reported in *Phaseolus vulgaris* to improve the biological N_2 fixation largely due to larger accessibility of micronutrients to plants. Moreover, biochar reduced leaching of NH_4^+ by supporting it in the apparent soil where it was existing for plant approval (Lehmann et al. 2003). Mycorrhizal fungi were frequently involved in crop administration approaches as they were broadly utilized as additions for soil inoculum (Schwartz et al. 2006). The bacterial and fungal hyphae that inhabit the biochar bits (or other porous materials) may be threatened from soil predators such as *Collembola*, mites, nematodes and protozoans (Ezawa et al. 2002). Biochar can upsurge the cost of unharvested crop yields and confirm the efficient plant growth (Oguntunde et al. 2004). Biochar applications to the soil, has significantly enhanced the rice yield with small P availability (Silber et al. 2010).

Several properties are interrelated and may turn synergistically to enlarge crop output. The straight helpful properties of biochar mixing for the suitability of nutrients are largely because of the higher content of phosphorus, zinc, and potassium accessibility and, to a reduced level of copper and calcium. Very few studies have examined the ability for altering biochar in soil to influence plant competition against pathogens. Alterations regarding charcoal additions reported to have negative impact on the proliferation of phytopathogens (Matsubara et al. 2002). It has been reported that the powdered hardwood when used to make biochar and supplemented to asparagus grown soil exhibited a prominent decrease in root lesions instigated by *F. asparagi*, *F. oxysporum* and *F. proliferatum* compared to control soil where biochar was not added (Novak et al. 2009).

10.4 Effects of Biochar Application on Plant Diseases

Few studies have described the strength of biochar soil adjustment against soilborne diseases to influence the level of plant resistance. The charcoal based biochar application has been documented for their suppressive effects against soilborne *Fusarium* sp. (Matsubara et al. 2002; Elmer and Pignatello 2011). The suppression of soil-borne pathogens owing to biochar applications is dependent upon several mechanisms, including: (i) nutrient solubilization and distribution to plant for improving growth and resisting pathogenic microflora (ii) improving the defense system of soil microbes against phytopathogens via enhancing antibiotic production and parasitism (iii) presence of organic compounds in biochar compositions result in propagation of resilient communities of beneficial microbes; (iv) the elicitors released by biochar applications may persuade the systemic defense pathways (Atkinson et al. 2010; Frenkel et al. 2017).

Microorganisms which cause reduction in toxic organic pollutants are usually considered extra resistant to a diversity of lethal organic compounds as well as pathogenic attacks. Moreover, volatile compounds and antibiotic producers are also found to be resilient to an assembly of antibiotics (Ahmed et al. 2017). Microorganisms producing antibiotic compounds have been reported in biochar-amended soil for instance *Pseudomonas aeruginosa* and *Pseudomonas mendocina* (Graber et al. 2010). The prospect that biochar encourages plant systemic resistance responses against disease microorganisms has been thoughtful in numerous different systems linking foliar pathogens. The severity of diseases triggered by biotrophic (*Oidiopsis sicula*) and necrotrophic (*Botrytis cinerea*) pathogens in tomato and pepper (Graber et al. 2010) was sigificantly reduced in biochar-amended treatments. Biochar soil adjustments in strawberry plants additionally resulted in destruction of pathogens including *Podosphaera aphanis*, *B. cinerea,* and *Colletotrichum acutatum* (Meller Harel et al. 2012).

Induced resistance in plants, was found to be effective against a wide range of pathogens and parasites comprising fungi, viruses, bacteria and nematodes. ISR is a functional state of enhanced defensive capability provoked by exact stimuli, whereby the plant's innate defenses are potentiated against succeeding diseases (Vallad and Goodman 2004).

10.4.1 Biochar to Control of Soilborne Phytopathogens

The concerns as food safety, decreasing soil richness, profitability and climate variation are the active components after the introduction of new skills or new agricultural schemes. The alteration of soils for their stress alleviation goals at dipping the danger of pollutant handover to entities in closeness. Biochar can aid as a standard select for this drive because its basis is biological and it might be applied directly as pretreatment to soils (Beesley et al. 2011). There are dual features which mark biochar adjustment higher to other organic supplies: the main is the high permanency against deterioration, with the aim of persisting in soil for lengthier times showing enduring helps to soil and the another is having extra competence to keep the nutrients available. Biochar adjustment increases the soil quality by increasing the number of beneficial microbes, improving pH, cation-exchange capacity and moisture-holding ability (Mensah and Frimpong 2018).

The mixing of biochar to the soil has exposed the increase in accessibility of prime cations as well as in absorptions of nitrogen and phosphorus (Lehmann et al. 2003). Various studies have revealed the dominance of biochar in controlling phytopathogens. Biochar has been found to be very suppressive against soilborne (*R. solani* and species of *Phytophthora* and *Fusarium*) as well as airborne pathogens (powdery mildew and *B. cinerea*) (Bonanomi et al. 2015). The claim of the biochar resulting from citrus wood was proficient of decreasing the incidence of air-borne gray mold in chili caused by *B. cinerea*. However, the available data is very scarce regarding the disease suppressive potential of biochar against soilborne pathogens (Elmer and Pignatello 2011).

Additionally, biochar application was established to lessen plant diseases by influencing systemic resistance in plants in contradiction of different fungal pathogens, containing *R. solani* in cucumber, *F. oxysporum* and *B. cinerea* in tomato (Azeem et al. 2021). Biochar applications alone as well as in combination with mycorrhizal fungi to asparagus soils, has not only increased the asparagus biomass but also decreased the root rot infections caused by *Fusarium* (Elmer and Pignatello 2011; Thies and Rillig 2012; Akhter et al. 2016); Ogawa (2009) stated the usage of biochar and biochar edited manures for monitoring the diseases caused by fungi and bacteria in topsoil.

10.4.2 Role of Biochar in Induced Resistance Against Soilborne Phytopathogens

Generally, there are two well defined systems of induced resistance which are termed as are induced systemic resistance (ISR) and systemic acquired resistance (SAR). The chemical composition of elicitors as well as controlling pathways for both of these systems are prominently different from each other. SAR is connected with the production of pathogenesis-related (PR) proteins and arbitrated through a salicylic acid dependent procedure (Naz et al. 2018, 2021a). The hypersensitive reaction is known as the initiative response of SAR against pathogenic. However, certain fungal and bacterial species particularly PGPR colonization with plant roots develop systemically the ISR mechanism (Van der Ent et al. 2009; Ullah et al. 2020).

The ISR resistance mechanism is arbitrated by jasmonic acid and ethylene signaling however, the induction of PR-proteins is not included in such type of resistance mechanism (Van der Ent et al. 2009). The biological as well as chemical elicitors which can be released from nonpathogenic or pathogenic microorganisms, can elicit SAR (Ali et al. 2018; Naz et al. 2021b). For instance, the compounds released from *Trichoderma* spp. can influence SAR as much as they stimulate ISR (Nawrocka and Małolepsza 2013). Chemical stimulators of systemic resistance comprise the synthetic SA-analogues acibenzolar-S-methyl and 2,6-dichloroisoniciotinic acid, methyl jasmonate, chitin and chitosan, β-aminobutyric acid and laminarin, silicon, fatty acids, amino acids, and phosphate salts, remains can also produce systemic resistance, as can ecological agents such as moisture, osmotic, temperature stresses and mechanical wounding (Romero-Puertas et al. 2008).

Primed plants show sooner and sturdier instigation of cellular defense following pathogen challenge relative to the un-primed or untreated plants (Zimmerman et al. 2011; Naz et al. 2021a, 2022), comprising earlier oxidative eruption and strongly up-regulating the expression of defense genes (Zimmerman et al. 2011; Meller Harel et al. 2012; Naz et al. 2014; Butt et al. 2019). While the molecular and physiological mechanisms underlying well-informed responses are widely unidentified, priming has been detected to be an essential part of both ISR and SAR (Yasmin et al. 2020). Molecular indication for the induction of plant defenses systemically via both ISR and SAR paths by biochar was observed (Meller Harel et al. 2012; Jaiswal et al. 2020). Biochar addition to the hitting medium of strawberry plants repressed fungal diseases produced *B. cinerea*, *C. acutatum*, and *P. apahanis*.

The biochar amendments to plant roots confirmed the ethylene and SA-induced expression by increasing the expression of defense-related genes including FaWRKY1, FaPR1, Falox, Faolp2 and Fra a3 (Meller Harel et al. 2012). The question increases, which mechanism(s) are employed by biochar to induce ISR and SAR defense systems, PGPF and PGPR root colonization is known to develop ISR systemically in plants (Hossain et al. 2017). The Bacteroidetes associated *Flavobacterium* was found to be the most intensely tempted by the biochar. Adherents of the *Flavobacterium*, usually own a storage of extracellular enzymes for example chitinases and proteinases with having the potential to damage fungi, insects, nematode and bacteria residents (Bernardet and Bowman 2006). Also, many other species of genus *Flavobacterium* are commonly known to release secondary metabolites including antibiotics (Enisoglu-Atalay et al. 2018).

In addition, some *Flavobacterium* strains were proficient of instigating a fighting response of plants to diverse diseases (Kolton et al. 2011; Enisoglu-Atalay et al. 2018). Further, hydrolytic enzyme-producing genera including Cellvibrio (Betaproteobacteria) were also persuaded in the rhizosphere of the biochar-altered pepper plants (Kolton et al. 2011). Stimulatingly, biochar alteration was found to antagonize the *Pseudoxanthomonas* genus (Rajkumar et al. 2008; Kolton et al. 2011). It rests to be grasped what types of biochar can persuade conflict responses, seeing the very big inconsistency in chemical and chemical properties that biochar display, contingent on original pyrolysis and conditions (Sohi et al. 2009). Yet, we imagine that disease control efficiency will differ with other biochar production, biomass sources, temperatures, plant growth systems, plant species and diseases (Table 10.1).

10.5 Status

Biochar as an important constituent of soil-less substrates has been tried in several experiments; which were focused with numerous types of biochars, and several studies intricate mixtures of biochar with other additions for instance fertilizers and mycorrhiza (Costell et al. 2012) and humic acid harvests (Vickers 2017). The studies verified elevated percentages of biochar: growing media frequently reaching very high biochar percentages (>60%) (Dumroese et al. 2011). Analyses

Table 10.1 Impact of biochar amendments on diseases caused by soilborne pathogens

Host	Pathogen/ disease	Biochar feedstock	Biochar concentration	Type of experiment	References
Asparagus	*Fusarium oxysporum* f. sp. *asparagi*; *F. proliferatum* (fusarium crown and root rot)	Hardwood dust Charcoal	0, 1.5 and 3% (w/w)	Pots (greenhouse conditions) and field conditions	Elmer and Pignatello (2011)
Tomato	*Botrytis cinerea*	Olive pomace Citrus wood Greenhouse waste Eucalyptus wood	0.05, 1 and 3% 3 and 5% 0.05, 1 and 3% 0.05, 1 and 3%	Pot experiment	Elad et al. (2011) and Mehari et al. (2015)
Tomato	*Fusarium oxysporum f.sp lycopersici*	Wood & Green waste biochar	3%	Growth chamber and field conditions	Akhter et al. (2016)
Red oak and	*Phytophthora*	Pine	0, 5, 10 and 20%	Pots (greenhouse conditions)	Zwart and Kim (2012)
Red maple	*Cinnamomic* and *P. cactorum* (stem canker)				
Rice	*Meloidogyne gramini*	Oak wood	(0.6, 1.2, 2.5, 5%)	Pot experiment	Huang et al. (2015)
Bean	*Rhizoctonia solani* (damping-off and root rot)	(i) Eucalyptus wood chips (ii) Greenhouse waste	0, 0.5, 1 and 3% (w/w)	Pots (greenhouse conditions)	Graber et al. (2014)
Cucumber	*Rhizoctonia solani* (damping-off and root rot)	(i) Eucalyptuswood chips (ii) Greenhouse Waste	0, 0.5, 1 and 3% (w/w)	Pots (greenhouse conditions)	Jaiswal et al. (2014)
Asparagus	*Fusarium oxysporum* f. sp. *asparagi* (Fusarium root rot)	Coconut fiber Charcoal	0, 10 and 30% (v/v)	Pots (greenhouse conditions)	Matsubara et al. (2002)

encompassed chemical properties and several parameters of plant development and additional measurements for instance photosynthetic pigments (Fascella 2015). Mostly, biochar had an impartial or helpful influence on plant growth paralleled with peat media when present in absorptions lower than 30%, and in some works even an abundant concentration was found to be not injurious (Méndez et al. 2015; Nieto et al. 2016).

A helpful impact of biochar on reducing plant fungal diseases was first reported about 170 years ago and described consideration in the last decade where numerous pathosystems particularly soilborne pathogens, were considered by different crowds globally (Elad et al. 2011; Postma et al. 2013; Iyyer et al. 2014). Later, Bonanomi et al. 2015 summarized the data from 13 pathosystems that shown the result of biochar on plant diseases. In their study, they described that 85% of the studies exposed a helpful effect of biochar in reducing the severity of plant disease, 12% showed no result, and only 3% presented that biochar mixing up were favorable to plant disease (Zhang and Lin 2014). Though, their analysis did not deliberate the detail that many of these revisions exposed that plant resistance and(or) vulnerability to disease was reliant on the critical aspect of the biochar dosage (Conversa et al. 2015).

10.6 Conclusion

Biochar can be potentially amended to soil for improving the plant growth, performance and alleviating the negative impacts of soilborne diseases which eventually can reduce the crop yield losses. Biochar amendments cause such changes of controlling pathogens and enhancing the community of beneficial microbes by making adjustments in the soil microflora. Biochar alterations has been reported in this chapter to significantly enhance the beneficial bacterial community which is known to improve the soil and plant health by improving the physico-chemical properties of soil. Moreover, the biochar treatment should be taken as ecofriendly and very efficient practice as it can effectively suppress the pathogenic growth and, applied as a sustainable approach in agriculture systems for soil management.

Therefore, it can be decided by this inclusive review in this chapter that biochar has the potential to increase the soil properties, microbial abundance, plant growth, inhibiting soilborne pathogens and biological nitrogen fixation. Consequently, it is suggested to practice biochar as a soil adjustment for long-term carbon sink renovation.

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Chapter 11
Biofertilizers to Improve Soil Health and Crop Yields

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Abstract Current soil management practices depend highly on mineral fertilizers, which are costly and unsustainable. Alternatively, eco-friendly strategies such as applications of plant growth-promoting rhizobacteria, endo-mycorrhizal fungi, cyanobacteria, and other beneficial microorganisms, have recently emerged to enhance nutrient uptake and plant tolerance to abiotic stress. These biofertilizers have thus become vital in agriculture due to their potential to improve food safety. Here we review the role of biofertilizers in improving soil health and sustainable agriculture production. Applying biofertilizers promotes plant water and uptake, growth, and

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tolerance to abiotic and biotic factors. We explain how biofertilizers control crop functional attributes such as growth and yield of plants, nutrient characteristics, plant defensive performance and protection. Here we focus the activation of growths and defense-related genes in the signaling network of cellular pathways, causing cellular response and thus crop improvement.

Keywords Chemical fertilizers · Soil · Bio-fertilizers · Biotic factors · Microorganisms · Crop production

Abbreviations

PGPR	Plant growth promoting rhizobacteria
AARI	Ayub Agricultural Research Institute, Faisalabad, Pakistan
NIAB	Nuclear Institute of Agriculture and Biology, Faisalabad, Pakistan
ACC-deaminase	Amino cyclopropane-carboxylic acid
NIBGE	National Institute for Biotechnology and Genetic Engineering, Faisalabad, Pakistan
NARC	National Agricultural Research Centre, Islamabad, Pakistan
ISES	Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

11.1 Introduction

Soils are one of the world's most significant natural resources, and protecting, maintaining, and improving them is crucial for the survival of life on Earth. The soil's fertility allows for supplying critical chemical elements in the quantities and ratios required for the growth of plants (Itelima et al. 2018). It is critical for crop production, yet poor soils and runoff remain a management concern in many world regions. The basic reason is that researchers and farmers commonly assess soil fertility using different theories and ambiguous literature findings (Yageta et al. 2019). As a result,

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understanding soil fertility is critical for enhanced soil production and appropriate land management strategies. Soil researchers have created numerous chemical, physically, and biological methods for measuring soil fertility, but the assessment is not confined to scientific measurements and is based on farmers' qualitative judgments (Karlen et al. 2003; Ali et al. 2020; Iqbal et al. 2020; 2021a).

Disparagement of the ineffectiveness of major technology implementation and scientific allocation of material by extension facilities has increased interest in the importance and incorporation of farmers' understanding (Berazneva et al. 2018; Guzman et al. 2018). Farmers apply their local soil skills to make daily land managerial decisions by observing and evaluating (Bado and Bationo 2018). Incorporating indigenous data assists extension staff in matching their energies to native requirements and may increase the uptake of co-produced technologies (Ingram et al. 2018). Farmers' assessments of soil health are widely reported as 'regional' or 'farmer's soil awareness' in many ethno-pedological research Fields (Barrera-Bassols and Zinck 2003), demonstrating that farmers may be aware of the mechanism and scientific attributes of soil type but use different connotations or conceptions to interact and plan their soil productivity. As a result of how local information systems differ from scientific knowledge systems, shared understanding among farmers and researchers is difficult (Agrawal 1995). According to (Barrios et al. 2006), while both systems share indispensable concepts, like the importance of water in plant growth, every information system comprises gaps that others fill. They also claimed that attempting to strike a balanced scientific precision and local relevance broadens common information, resulting in a new, hybrid knowledge base. Farmers and agronomists both begin their appraisal of soil fertility with the same question: crop growth efficiency (Murage et al. 2000). Apart from that, growers also define the qualities of healthy or unfertile topsoil, primarily through physical and morphological traits like color and texture, which are regarded as universal soil fertility criteria (Mairura et al. 2007). Soil scientists use quantitative analysis to assess soil as a natural resource, whereas growers assess soils as part of their day-to-day work in the field. Producers have more knowledge or 'technical experience' of soil, whereas scientists have more scientific expertise or understanding of the soil (Ingram et al. 2010). Such distinctions can be classified into three parts: awareness of additional environmental knowledge, spatial scale, and timing. Examining the various approaches by growers and researchers reveals the potential worth of increased consciousness regarding indigenous descriptions of soil quality, which indicate full forms of information and livelihood knowledge and have implications for developing an integrated soil approach to the management (Yageta et al. 2019).

Sustainable development in the agricultural system might be accomplished without affecting future generations' environmental resources or capacity to meet their needs (Umesha et al. 2018). Excessive usage of synthetic fertilizers depletes favorable living circumstances since residues that act as secondary contaminants might infiltrate food chains and eventually humans (Kumar et al. 2019). Secondary pollutants can linger in the ecosystem for an extended time, posing a health risk (Uosif et al. 2014). The use of biofertilizers rather than agrochemicals may usher in a new era of industry.

Biofertilizers could help plants get the necessary nutrients while not harming the environment (Mishra and Dash 2014). This section could assist as a helpful guide for developing biofertilizers and using them to accomplish agricultural sustainability.

11.2 Current Fertility Status of Pakistani Soils

The optimum crop yield depends on good soil fertility (Hesham and Fahad 2020. Iqra et al. 2020; Akbar et al. 2020; Mahar et al. 2020; Noor et al. 2020; Amanullah, Fahad S 2017, 2018a, b; Amanullah et al. 2020, 2021; Amir et al. 2020; Mahmood et al. 2021; Farhana et al. 2020; Farhat et al. 2020, 2022; Liu et al. 2023). Soil analysis over time is essential and provides basic and present soil quality. For several reasons, soils in arid and semi-arid parts of the globe are often infertile Fields (Vanlauwe et al. 2011). Nutrient loss reduces soil fertility when restoration with organic or inorganic inputs impacts crop development and production (Chukwuka 2009; Luo et al. 2020, Ullah et al. 2020). The loss in soil quality is thought to be a major contributor to the low productivity of crops such as rice, wheat, sugarcane, maize and tobacco (Belachew and Abera 2010; Yuan et al. 2022).

Pakistan is primarily a dryland region, with 80% of its land area classified as desert or semi-arid, 12% classified as sub-humid, and 8% classified as humid (Khan et al. 2013). As a result, soils in arid and semi-arid locations are subjected to various degradation processes. The significant reasons for soil deterioration, desertification, and reduced agronomic productivity are salinization, drought stress, soil erosion and reduction of soil fertility and soil organic matter contents (Smith et al. 2020). Therefore, knowing the climate-soil-productivity nexus is critical for satisfying the expanding population's food and nutrition needs. Pakistan's population grew from approximately 30 million to 201 million from 1947 to 2018 and is expected to reach 244 million in 2030 and 352 million in 2100 (Lal 2018).

However, the current annual growth rate of approximately 2.0% is falling and is anticipated to reach 0.3% by 2100. As evidenced by the rapid growth of the population of particular cities, the rise in global population is indicative of Pakistan's strong urbanization tendency (Alam et al. 2007). From 1960 to 2018, Pakistan's population grew by 4.5 million, while overall cereals (wheat, sorghum, maize, rice, millet, etc.) increased by 6.5 million metric tons (from 6.6 to 43.0 million metric tons). Therefore, per capita cereal crop yields increased significantly between 1961 and 1980 but remained stable between 1980 and 2016 at 220 kg per person. Despite the tremendous improvements, there is no reason to be complacent because much greater difficulties are already soon. Not only will the population double between now and 2100, but nutritional tastes may move towards animal-based goods because of rising wealth and overall economic success. Promoting food security and nutrition is exacerbated further by the ever-increasing hazards of soil pollution, expanding suburbanization, global warming, and decreasing aquifers (Lal 2018).

Indus plains in Pakistan have the lowest soil organic carbon contents, ranging from 0.5% to 0.1% in the root zone. Low soil organic carbon content impacts agronomic production and input performance Field (Lal 2018), particularly in Pakistan's rice-wheat and other crop cultivation. However, implementing effective management techniques can regain soil organic carbon concentration. The goal is to improve the soil/ecosystem by expanding the use of biofertilizers. As a result, site-specific best management practices such as cover crops, irrigation tillage, conservation tillage, mulches, Integrated Nutrient Management incorporating manure/compost input, usage of biochar, biofertilizers, contour farming and crop interaction with livestock and plants are always recommended (Sarfaraz et al. 2020).

11.3 Biofertilizers

Biofertilizers are organic and include metabolites derived from microbes or bacteria themselves (Mishra and Dash 2014). Microorganisms extracted from soil (rhizosphere), air and water are used to make bio-fertilizers, then purified for use in the field. Microorganisms start creating agriculturally important metabolites in response to particular environmental conditions, and plants may use these metabolites to support numerous biochemical processes (Salar et al. 2017). Microbes and microbial metabolites facilitate the breakdown of complicated soil minerals/particles into simpler forms, and the resulted forms work as a growth stimulator for specific crops. Certainly, biofertilizers could be applied for various purposes (Kaur and Purewal 2019; Xie et al. 2021) (Fig. 11.1).

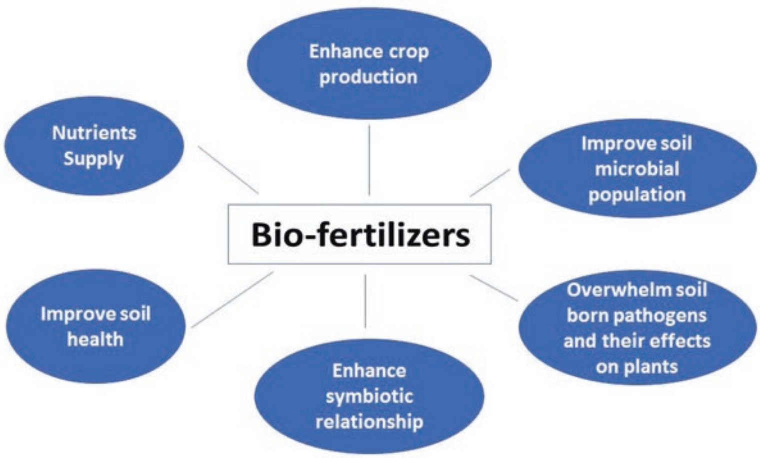

Fig. 11.1 Biofertilizers functions in soil

11.3.1 Types of Biofertilizers

Biofertilizers are one of the most effective current agricultural fertility contributors. Organic fertilizers are used in agriculture as an alternative to traditional fertilizers, including compost, domestic garbage, and green manure (Mishra et al. 2013; Ali et al. 2021; Iqbal et al. 2021c). Synthetic fertilizers are more successful in this regard. As a result, farmers frequently use chemical fertilizers for crop production. Still, on the other hand, their excessive use harms the ecosystem by polluting water, air, and soil (Iqbal et al. 2019, 2021b). Furthermore, they can potentially deplete soil health in the long-term (Itelima et al. 2018, Wu et al. 2021). Biofertilizers comprise microorganisms that encourage appropriate nutrient supply to the host plants and maintain optimal growth and physiological regulation. Organic fertilizers are made using several living microorganisms (Xie et al. 2021). Only microorganisms with specialized functions to improve plant growth and reproduction are employed (Gupta et al. 2015). Biofertilizers, as fundamental constituents of organic agriculture, develop the quality and stability of soil classified into several types based on their kind, action, and availability (Kaur and Purewal 2019).

11.3.2 Phosphate-Solubilizing Microbe Biofertilizers

Phosphorus is an important macronutrient because it influences root growth, protein synthesis, signal transduction, respiration, and Nitrogen fixation in plants, (Ahmad et al. 2019; Izhar Shafi et al. 2020). Plants cannot utilize it as it is present in unavailable forms in the soil. The proper use of plants and routine taking must be converted to plant-available forms from unavailable Fields(Shafi and Sharif 2019). Many strains of useful bacteria can reduce phosphorus into its most basic form, allowing it to be easily absorbed by the root system. Phosphate-solubilizing microbes are, although naturally common, different in numbers depending on the soil type and place from isolated (Awais et al. 2017). In developing nations, phosphate-solubilizing microbe biofertilizers, in combination with rock phosphate of poor quality, could be a substitute for pricey phosphate fertilizer fields (Rafique et al. 2017; Mahanta et al. 2018). In this regard, research activities are being done worldwide to identify microbes that may be important in maintaining agricultural sustainability. According to various researchers, bacterial strains such as *micrococcus*, *achromobactin*, *erwinia*, *pseudomonas* and *aerobacter* play a prominent role in the solubilization of unavailable insoluble complexed forms of phosphate (Chen et al. 2006). Aerobic and anaerobic microbes coexist in the rhizospheric soil. Bacterial strains or spores have different degrees of phosphorous solubilization depending on the places from where they are collected, and among all, the spores isolated from the rhizosphere had the highest phosphorus solubilization capacity. Phosphorus can bind with iron, aluminum and potassium to generate complex compounds,(Wahid et al. 2019). The entire conversion process is made up of a series of biochemical processes involving the action of several enzymes caused by bacterial strains. The conversion of strongly bounded phosphorus into organic and inorganic acids takes place in the first stage, which reduces the soil pH and maximizes the accessibility of phosphorous to growing plants.

11.3.3 *Rhizobium Biofertilizers*

In developing countries, critical nutrient deficiencies in food crops are more difficult to overcome (Kumari et al. 2018). To solve these issues, there is a strong focus on employing microbial consortiums, particularly for continuous plant growth and meeting food requirements in the future (Khatoon et al. 2020). Rhizobium is a nitrogen-fixing, continually evolving of the Rhizobiaceae family. Rhizobium infects plant roots, causing the production of particular rhizosphere soil (Gouda et al. 2018). According to (Kumari et al. 2018), the more common rhizobium isolates BHU-M and BHU-B13-398 were extracted from mung bean roots. These strains enhance the shoot and root growth, the plants' height and yield as they are associated with plant roots and capture nutrients for plant growth. Moreover, the rhizobium inoculation was reported to regulate phytochelatin-related gene expressions in Medicago sativa and defend the plants against excessive copper stress (Chen et al. 2018). Their findings revealed that rhizobium strains inoculation enhanced the plant's growth through higher Nitrogen uptake by the plants. When untreated and rhizobium-inoculated treated plants were compared, a significant increase in copper uptake was noted. Several scientific studies have found that inoculating chickpeas with efficient microbial strains at planting time increases the total grain yield, (Funga et al. 2016).

Microorganisms in root nodules degrade molecular nitrogen to ammonia, which is then used by the plant system to synthesize proteins, vitamins, and other Nitrogen containing substances,(Belhadi et al. 2018). The use of Rhizobium in particular legumes and other host plants aids in maintaining major agricultural benefits (Sahu et al. 2019). These bacteria are harmless and have shown no negative environmental impact (Singh et al. 2011). Despite their occurrence in leguminous plant nodules, several artificially created Rhizobium formulations are also available in the market.

11.3.4 *Arbuscular Mycorrhizal Biofertilizers*

Natural resources are constantly subjected to abiotic stressors at various growth and development phases where soil microbes can cope with it (Wahid et al. 2019). Plants begin manufacturing a particular type of minor metabolites when stressed to battle the excessive production of reactive oxygen species (Kaur et al. 2018a; b). To some extent, the creation of certain ingredients aids the plant's survival under severe conditions. One of the essential factors contributing to crop plant health is the symbiosis interaction. Arbuscular mycorrhizal fungi are essential symbionts with roots that aid in nutrient uptake and numerous enzymatic activities in most plants (Yang et al. 2018; Ortas et al. 2021). The Arbuscular mycorrhizal fungi connections with plant rhizospheres give a variety of growth-promoting effects such as improved nutrition, increased resistance, drought tolerance, and modified soil composition (Berruti et al. 2016; Rafique and Ortas 2018). Water-soluble chemical fertilizers are avoided in organic farming, and it involves a variety of crop rotations. According to scientific investigation, this increases Arbuscular mycorrhizal fungi infection in soils with maximum nutrient uptake (Ortaş et al. 2017). As a result, Arbuscular mycorrhizal fungi may be a viable alternative to chemical fertilizers.

11.3.5 Azotobacter Biofertilizers

Azotobacter is anaerobic bacteria from the family Azotobacteraceae (Sethi and Adhikary 2012). It is no symbiont, gram-positive diazotrophs, that give numerous benefits to plants and its interaction with growing crops enables them to maintain stable growth with enhancing production. The use of azotobacter as a bio-fertilizer to maximize production and cropping yield is recommended by several researchers. It also helps improve plant dry matter, yield and secondary metabolite synthesis (Damir et al. 2011). Azotobacter strains with imperative practical qualities (enhancing the health of soil and nitrogen fixation, promoting growth and production of crops, and assisting plants against drought and pathogens) could be a boon for sustainable farming techniques (Shirinbayan et al. 2019). In certain conditions, Azotobacter and related bacteria begin to develop cysts- a normal defensive mechanism against various environmental factors (Socolofsky and Wyss 1962). The strains commence the production of pigments from deep brown to yellowish-green and purple color throughout the Nitrogen fixation process. The fundamental reason strains produce pigment during the nitrogen fixation process is to shield nitrogenase from the destructive impact of the oxygen (Shivprasad and Page 1989). Azotobacter is now produced using a fermenter and a mixer on a commercial scale. The use of a fermenter is a scientific and automated method for the proliferation of microbes. Specific nutritional media essential to maintain microorganism development are created and pasteurized, and the pH of the medium may be controlled to commence appropriate microbial populations. Mother culture (1–2% of the total) may be employed to enhance growth. Other significant needs include a constant supply of oxygen and the ability to maintain a constant temperature. Depending on the required demand, growth can be accelerated by utilizing a shaker, which increases the rate of nutrient absorption in a brief period.

11.3.6 Azospirillum Biofertilizers

Azospirillum is another type of biofertilizer that aids crops in maintaining different biochemical reactions essential for agricultural production (Llorente et al. 2016). It is an essential member of the group Rhodospirillales and is closely associated with grasses and occasionally with monocots, particularly rice and corn (Ruíz-Sánchez et al. 2011). Their interaction is directly related to nitrification, the release of particular fungicides and plant hormones (Gonzalez et al. 2015). *Azospirillum* is capable of producing phytohormones such as salicylic acid (Sahoo et al. 2014), auxins (Spaepen and Vanderleyden 2015) and indole-3-acetic acid (Fukami et al. 2018). *Azospirillum* improves the moisture and nutrient retention by plants and defends the plants against environmental stress, resulting in a higher total production (Fukami et al. 2018). *Azospirillum* inoculation in plants results in dramatic morpho-physiological alterations, including shoots and grains with increased nitrogen content. When *Azospirillum* is used on the field, it requires less synthetic fertilizer than the fields without its application (Cassán and Diaz-Zorita 2016).

11.3.7 Azolla and Blue Green Algae Biofertilizers

Azolla is a member of the Salviniaceae family, which includes seven different species of duckweed phototrophic ferns (Roger and Ladha 1992). Depending on numerous circumstances, including soil properties, Azolla could develop to generate massive biomass in as little as 10 days. Azolla is a tiny free-floating plant having rough leaves and flowing roots. It is well known for its Nitrogen fixing symbiotic relationship with *Anabaena azollae* in developing and underdeveloped nations (Emrooz et al. 2018). Rice crops are widely recognized for their high-water use, and growers use Azolla to prevent extreme weed development. It can deliver up to 10 tons of proteins and other critical nutrients to rice crops in the cultivation (Yao et al. 2018). Blue green algae are Nitrogen fixing microorganisms filamentous by nature and have a type of cell called a heterocyst (micronodules). Heterocysts demonstrate nitrogen fixation process functioning. These microorganisms form symbiotic partnerships with fungal strains, ferns, and flowering plants for nitrogen fixation (Soma et al. 2018). Blue-green algae are particularly important in agriculture because of their fast activity and effective nitrogen fixation. Despite Nitrogen fixing, they also fix phosphorus, potassium, zinc, sulfur and other nutrients (Adeniyi et al. 2018).

11.3.8 Silicon-Solubilizing Microbe Biofertilizers

The disintegration of silica and silica-based rocks and minerals can change the soil layer (Vasanthi et al. 2018). Microbial consortia of several types play a significant part in silicon's decay, transformation and activation and its derivatives. Microbial consortia's action is determined by the soil's availability of condensation, pH conditions, and growth regulators. These are involved in synthesizing various enzymes and metabolic products that may be useful in the mineralization (Gadd 2010). Biological methods of converting tough silicon derivative products into the simplest eatable forms have gained significance over chemical and physical methods. Biological methods include microbial activities, which are self-manageable and inexpensive and can result in conversation in a small period. *Thiobacillus thiooxidans* and *Bacillus globisporus* showed the greatest ability to leach silicon (Friedrich et al. 1991; Sheng et al. 2008).

11.4 Biofertilizer Effect on Cucumber

Several studies have been conducted on studying the effect of bio-fertilizers on soil for different crops and vegetables. When applied to various crops in combination with synthetic or other fertilizers, it showed promising results in meeting the plant's nutritional demand in an eco-friendly manner. A detailed study about the efficiency of bio-fertilizers in cucurbits is available (Kumar et al. 2018). The useful insight and use of bio-fertilizers and their effects on cucumber as a case study are outlined in Table 11.1.

11.5 Market Characteristics for the Release of Biofertilizer

Farmers' use of biofertilizers for increased crop production is one of the foremost constraints in the farming sector. Although various biofertilizers are now commercially available, their quality and quantity may fluctuate based on the manufacturing division. Biofertilizers should have the following characteristics before it is released to the market. Biofertilizers should be widely available in the marketplace. Farmers benefit from reduced transportation costs and save time. The formulation should be water-soluble to decrease costs and allow for spray application in larger field areas. Biofertilizers' formulations must be reliable in a broad range of climate circumstances. The strength of the preparation must not deteriorate over time. Biofertilizers should be used in small quantities in the field and must successfully provide a balanced mix of nutrients to the plants. The formulation should provide crops with an immediate supply of nutrients while causing no adverse effects. It should be simple to use and have no negative effects on the health of growers. It must be affordable

Table 11.1 Use of Bio-fertilizer and Integrated Nutrient Management practices in cucumber crop

	Treatments	Characters enhanced in cucumber crop	References
1	Application of mineral (25%) and organic N (75%)	Increase in plant growth, yield, and quality	Mahmoud et al. (2009)
2	Use of bio-fertilizers	Increase the fruit count, fruit length, average fruit weight and fruit yield	Jilani et al. (2009)
3	Use of farmyard manure/ vermicompost	An increase in the yield was observed	Narayanamma et al. (2010)
4	Use of biofertilizers	Enhanced yield and yield attributing characters	Isfahani and Besharati (2012) and Saeed et al. (2015)
5	Use of vermicompost	An increase in yield and fruit weight was noted	Ghasem et al. (2014)
6	Use of poultry manure with NPK	A significant increase in the weight, number of leaves, fruit count and size with quality and yield were found	Okoli and Nweke (2015) and Solaiman et al. (2020)
7	Use of biofertilizers	Significant increase in the fruit length and diameter, fruit count, average fruit weight, and yield	Kanaujia and Daniel (2016)
8	Use of poultry manure at 20 ton/ha	An increase in yield was noted	Khan et al. (2017)

to growers, as it impacts crop prices. It should be season-independent and accessible to farmers throughout the year.

11.6 Pakistan and Biofertilizers

Presently, Pakistan spends significant money on importing and producing 8.41 million nutrient tons of synthetic fertilizers. On the other hand, a huge opportunity exists to enhance biofertilizers use in sustainable agriculture. In Pakistan, saving 10.0 billion rupees annually is possible through adding a 10% contribution of biofertilizers to the total fertilizer consumption (Ali et al. 2012). Various groups/organizations are engaged in biofertilizers research and innovation in Pakistan. They have stated substantial rises in yield and yield components of important crops due to microorganism inoculation (Zahir et al. 2005; Alam et al. 2007) . The extent to which these bio-fertilizers benefit depends on their quantity and efficiency, which is ruled by a diversity of environmental and soil elements. In comparison to chemical fertilizer plants, the system used for biofertilizers production is much simpler and the costs for its installation are very negotiable. Furthermore, using biofertilizers for a long time is efficient, more cost-effective, eco-friendly, and readily available to growers. A list of major problems, limitations, and recommendations regarding producing biofertilizers on large-scale and future technologies in the county have also been discussed in detail.

11.6.1 History of Biofertilizers in Pakistan

Rhizobium is the world's oldest biofertilizer for leguminous plants and soil quality enricher "Theophrastus, 372 287 BC" as observed by (Danso 1992). J.B. Boussingault, a French chemist and agronomist, proposed the classic concept of biological nitrogen fixation in 1834 and later on, (Hellriegel and Wilfarth 1888) confirmed it. Beijerinck isolated the Nitrogen fixing organisms Rhizobium in 1888, Azotobacter in 1901 and *Azospirillum* in 1925. Rhizobium is a nitrogen fixer, was first commercialized in the United States in 1895 under the trade name "Nitragin" and was developed by Noble and Hiltner in 1896. Stalstrom (1903) was the first to report microbial phosphorus solubilization and Pikovskaya isolated microbes in 1948.

Before establishing Pakistan in early 1920, India's first Agricultural College, named the Punjab Agricultural College and Research Institute Lyallpur, began research on biological Nitrogen fixation. After 6 years, in 1926, these research activities were boosted when an independent post of "Agricultural Bacteriologist" was established at the institute. The microbiological center was developed in 1927 in Lyallpur (Naveed et al. 2015). The laboratories were developed, and field trials were conducted at a larger scale in Lyallpur and Gurdaspur area to evaluate the effectiveness of synthetic inoculum on chickpea, Egyptian and Persian clover, alfalfa, sweet clover, mash beans, mung bean, and cluster bean. It was concluded from the early research that seeds treated with inoculum generated more yields of higher quality than untreated seeds (Naveed et al. 2015). After this, the commercial production of Rhizobia inoculum began in 1956 in the region.

11.6.2 Biofertilizer Research and Development in Pakistan

The uniqueness and capabilities of microbes, particularly in specific cultural and environmental conditions, have shown that they have the potential to resolve food security issues in agriculture and other fields of life. Several organizations, research groups and institutes in Pakistan are working on the research and development of biofertilizers to overcome food scarcity and increase the country's agricultural production. As summarized in the following sections, research and development efforts are underway to expand the role of biofertilizers in Pakistan.

11.6.3 Ayub Agricultural Research Institute, Faisalabad

The Ayub Agricultural Research Institute in Faisalabad, formerly known as the Punjab Agricultural Research Institute Lyallpur, is a parallel research institute of the Punjab Agricultural College. Lyallpur was the country's first and earliest biological nitrogen fixation and biofertilizers research institute. Work on research and innovation began in the early 1920s and was aimed at various times. Since 1956, AARI scientists have provided organic fertilizers with the trade name "Associative Diazotrophs". The fruitful and steady approval of legumes rhizobium cultures in the field (Naveed et al. 2015) prompted the AARI's "Soil Bacteriology" portion to collaborate for useful microbial associations prevalent in different crops in the early 1990s, *Azospirillum* and Azotobacter inoculants were introduced. Their consortia were released as a commercial product in the mid-1990s under the trade name "Fasloon ka jarasimi teeka". It contains phosphate solubilizing microbes familiarized, which achieved the attention of many growers who were struggling with P-fertilizer scarcity market prices. Data from the field experiments resulted in a 20% increase in the yield of leguminous and non-leguminous crops by applying rhizobial, diazotrophic and phosphate solubilizing microbes' inoculants. On a limited scale, the AARI's Soil Bacteriology Section was manufacturing and providing 38800.0 carrier-based 250.0 g inoculum culture bags in the region. It was adequate for the inoculation of 14,000 ha of plants during 2000–2011 (Naveed et al. 2015).

11.6.4 The Nuclear Institute of Agriculture and Biology and National Institute for Biotechnology and Genetic Engineering

In 1972, NIAB established a very energetic biological nitrogen fixation-research center in the department of Soil Biology, having published work at the national and international levels. They have conducted some research by using *Azolla anabaena* as nitrogen fixing blue green algae used as symbiont on rice biofertilizers "Azolla" a water-fern. Punjab's severe hot environmental conditions did not respond according to its potential on a larger scale. In contrast, this technology provided its best in rice production in northern areas where the environmental conditions were mild and humid (Malik et al. 2002).

With the foundation of NIBGE in 1992, Dr. Kausar Abdullah Malik led the "Biofertilizers Division" by securing funding from several donor agencies like the International Centre for Nuclear Research, International Atomic Energy Agency, International Centre for Genetic Engineering and Biotechnology: and Islamic Development Bank for the development of a Biofertilizers Resource Centre in the South Asian region. In 1996, they successfully introduced the commercial organic fertilizer "BioPower". *Rhizobium* species are isolated from chickpea, mash bean, soybean, mung bean, cowpea and alfalfa was used during legume bio-fertilizers. In contrast, implicit nitrogen-fixing and plant growth-promoting rhizobacteria (PGPR) were used in crops such as wheat and maize. The research revealed that biofertilizers could meet 40–70% of crop plant nitrogen requirements, improving crop yield by 60–80% (Hafeez et al. 1998). After pot and field trials, the "BioPower" was used commercially on an area of 11,000 ha with different testing crops in Punjab, and a

50–70% reduction in nitrogen fertilizer costs with a 20% increase in crop production was claimed by the research team (Naveed et al. 2015). It was revealed that the half-recommended dose of basal fertilizer's (i.e., nitrogen, phosphorus, and potassium) with "BioPower" produced the same results as with the full recommended dose of basal fertilizers alone. NIBGE joined public and private sector entrepreneurs to popularize biofertilizers, transfer manufacturing capabilities, and provide proper training to the farmers. Farmers were able to save a significant amount of money (up to \$292 USD ha^{-1}) by using "BioPower" in several crops, as per the benefit-cost ratio of the technology (Naveed et al. 2015). The NIBGE has a fully established biofertilizers pilot production unit to scale up biofertilizers production to meet rising demand. "BioPower" has been supplied between 9000 and 12,000 Hectares (Naveed et al. 2015).

11.6.5 The National Agricultural Research Centre

During the early 1980s, the Soil Biology and Biochemistry Department of NARC's Land Resources Research Program began investigating Nitrogen fixation in legumes. They investigated the effects of imported rhizobial strains (from NifTAL, Hawaii) on legume production in Pakistan. Later, local rhizobium spp. was isolated and used to inoculate important crop legume crops (lentil, chickpea, mash bean, mung bean, groundnut, soybean, Egyptian clover, pea, alfalfa and sesbania). The NARC "Rhizobium Gene Bank" contains over 200 isolates of various rhizobia. In 1990, the center introduced "Biozote," a biofertilizer product. The efficacy of "Biozote" was assessed commercially during a combined project of the Pakistan Agricultural Research Council, Islamabad, and Engro-Chemical Pakistan Ltd. This project ran for 3 years to assess different leguminous crops, and approximately 60,000 packets of the "Biozote" were provided to growers. Data from 300 growers' fields revealed a 20–50% improvement in crop production using "Biozote". Additionally, it was added that the benefit-cost ratio of technology was 30:1, and if applied to 50% of the leguminous area, it has the potential to improve the national economy by enhancing crop yield (Naveed et al. 2015). The center could produce 150,000 culture bags per year and currently, it is supplying about 2000 culture bags to the growers annually.

11.6.5.1 Institute of Soil and Environmental Sciences (ISES), University of Agriculture, Faisalabad

In 2003, the University of Agriculture, Faisalabad's Department of Soil Science, was upgraded to the status of "Institute of Soil and Environmental Sciences." The institute is vigorously involved in basic and applied research on soil microbiology and biotechnology etc., by isolating soil microbes with various beneficial strains creation and using it as biofertilizers. The researchers are not using only living cells of inoculants but also proposed using microbial metabolites or plant growth regulators, which could be the best approach to improve crop growth (Khalid et al. 2009). In 2002, they created a liquid preparatory work of microbial metabolite-based biofertilizers called "Rice-Biofert".

Data collected from multi-location experimental fields for 3 years indicated an increase of 20% in rice production (Zahir and Arshad 2004). The Soil Microbiology and Biochemistry Group has also isolated various cultures of Azotobacter from various soils, and their performance in rising crop production has been extensively studied. Many PGPRs such as *Burkholderia*, *Pseudomonas*, *Serratia*, bacillus and others, have been isolated and demonstrated their value as plant-growth promoters. Amino cyclopropane-carboxylic acid (ACC-deaminase) is an enzyme that hydrolyzes ACC (ethylene precursor) into ammonia and -ketobutyrate in various PGPR strains. The growth promoting rhizobacteria having ACC-deaminase acts as ACC reservoir when colonized with plant roots and lowers the plant ethylene concentration. This mechanism has the potential to inhibit the impact of high ethylene concentrations in plants and promote stronger root structure and function. These plants also develop anti-environmental stressed qualities like anti-drought, salinity, heavy metals etc. (Nadeem et al. 2010; Ahmad et al. 2011) .

A series of field trials were conducted by ISES at growers' land to demonstrate the potential impact of PGPR-based bio-fertilizer "Uni Grow" for the purpose of encouraging the biofertilizers in farmer community and received highly encouraging results (Shahzad et al. 2008). According to the literature, the combined application of chemical, bio and organic fertilizers has the potential to increase crop yield and meet the food demands of the country. Under field conditions, inoculation of rhizobia in leguminous as well as in non-leguminous crops produced prominent results (Hussain et al. 2009; Mehboob et al. 2011). The ISES recently developed a combined culture of ACC-deaminase containing PGPR and rhizobium named as "Rhizogold", which enhanced 40–45% yield of legumes. Another multi-strain biofertilizer named as "RhizogoldPlus" was obtained from effective strains of PGPR having ACC-deaminase with the purpose of mitigating the salinity stress on cereal crops (Khan et al. 2013; Naveed et al. 2015).

11.6.6 The Nature Farming Research and Development Foundation

The effective microorganism technique was introduced by a former scientist of the Soil Science Department of the University of Agriculture, Faisalabad, who brought it from a Japanese Scientist Dr. Teruo Higa and used it as biological input for sustainable yield. After his tremendous work, the foundation of the Nature Farming Research Centre was laid at University of Agriculture, Faisalabad-Pakistan to work on this technology. Further, the soil fertility and productivity were enhanced by using Beneficial Microorganisms in combination with manure, crop residues, waste from industries, green manures, and composts from various sources. This technology reduced the costly application of chemical fertilizers. A new type of beneficial microorganisms fermenter/super fermenter has been developed to achieve the minimum number of organisms available and to use salt water to irrigate with beneficial microorganisms Technology (Hussain et al. 2009). This center has done many experimental projects in the grower's field to assess the efficacy of this technology for preserving soil fertility and productivity, encouraging the sustainable use of soil, proliferating soil biological activities, reducing pollution and recycling waste of plants and animals. It was concluded that using the technology improved the soil's biological activities, increased crop yield and profit per hectare and improved the quality of soil and water resources. Many of the products of effective microorganism -technology are under practice by the farmers in Punjab, e.g., for crop production and fish farming, EM-BIOAAB is used, whereas for animal and poultry production EM-BIOVET is preferably used. EM-BIOCONTROL, which is not a pesticide or insecticide, is used to control insect/pests diseases in crops, vegetables and fruits (Hussain et al. 2009).

11.6.7 Biofertilizer Studies in Higher Education Institutes of Pakistan

At various higher education institutions across the nation, researchers are studying soil-microbial prospects and plant-microbe relations to understand how they affect the health of soil and plants. Various higher institutes of Pakistan like Quaid-i-Azam University Islamabad, Comsat University, Islamabad; Karachi University Karachi, PMAS-Arid Agriculture University, Rawalpindi; Punjab University, Lahore; The University of Agriculture, Peshawar; Azad Jammu Kashmir University, Muzaffarabad, University of Poonch, Rawalakot and many others have outstanding contributions. An extended list of research work published in national and international journals has been documented. Relationships among rhizobium and leguminous and non-leguminous crops, isolation and identification of various microorganism sp. for disease management (Hussain et al. 2009; Mehboob et al. 2011) have been studied deeply. Microflora supplying resistance to various stresses (Saleem et al. 2007; Arshad et al. 2008), microorganisms production of phytohormones (Qureshi et al. 2013), exploitation of bacterial and fungal populations for improved health of soil and plants, assessment of variations and development of markers for maintaining and evaluating microbial efficacies (Malusà et al. 2016), phytoremediation of soil and environment (Naveed et al. 2015). Research is being conducted at various universities and higher research centers, providing applied research strategies. Interaction among research and educational institutes can lead to the translation of scientific concepts into authenticity. Academia and industrial linkages for the cheap, sustainable, and easy supply of the product to the consumers (farmers) are the need of the time.

11.7 Problems of Mass Scale Production and Commercialization of Biofertilizers in Pakistan

Although microbes' technology has shown its value when used in various agricultural and environmental issues with remarkable success over the past 50 years, it has not been widely accepted. It is often difficult to replicate its positive effects in various fields. Conditions are most common in the upper and lower extremities. The following are the major barriers to mass production and technological advancement in the country.

1. Regulations for the production and selling of biofertilizers have yet to be established at the national level in Pakistan. As a result, substandard inoculants are among the significant limitations.
2. An insufficient community of growers know microbial inoculants.
3. As most biofertilizers are environmental and ecological specific, they do not produce the required results sometime and eventually; the growers lose faith in this technology.
4. The communication difference between marketing, extension work and end-users.
5. Lack of qualified labor and the excessive cost of making high-quality organic fertilizers.
6. The country lacks transportation and storage facilities to prevent contamination.
7. Extreme climatic conditions frequently cause biofertilizers result to be inconsistent.
8. A low amount of soil organic matter prevents beneficial microorganisms from surviving and interacting positively with plants.
9. An insufficient supply of appropriate excipients for biofertilizers production.
10. Poor labelling and packaging of biofertilizers damage their reliability.

11.8 Recommendations

Several concerns need to be addressed by the government in future studies for a more comprehensive production and application of biofertilizers.

1. Necessary legislation to monitor bio-fertilizers, its quality, and any harmful effects on humans and plant species. This grave concern must be evaluated and necessitates government and private sectors collaboration.
2. The government should sponsor the production of biofertilizers, or there should be the availability of loans from the government to produce biofertilizers on a small-scale e.g., seed money, agriculture preneurs startups etc.
3. The country is in desperate need of microbial strains banks. All characterized microbes/potential bio-fertilizer candidates from various institutes and inde-

pendent scientists should be collected, conserved, molecular tagging internationally and validated chemo taxonomically if necessary.
4. Farmer's community and stakeholders should be trained by adopting intensive training and extension workshops to use bio-fertilizer technology with its full potential.
5. Development of biofertilizers by using microbial consortia having active, competitive, and stress-tolerant microbial strains.
6. The ability of biofertilizers to provide micronutrients and bio fortify food plants should be investigated.
7. Phosphate solubilizing microorganisms and phosphorus mobilizers such as vesicular-arbuscular mycorrhizae, which are less commonly used bio-fertilizers, show promising results providing phosphorus and other micronutrients. So, the laboratory-produced strains of these symbionts will allow testing of their performance in the field. The genetic basis for competitive advantage must still be determined.
8. Selection of a low-cost synthetic carrier capable of maintaining a high viable count and developments in inoculation procedures to guarantee the soil establishment and perseverance.
9. Creation of poly microbial biofertilizers such as PGPR, Rhizobia, phosphate solubilizing microorganisms, and vesicular-arbuscular mycorrhizae.
10. Locally available organic wastes should be converted into value-added biofertilizers.
11. Endophyte molecular breeding is also required to improve endophyte host plant interactions. Endophytic bacteria genetic engineering should be a much simpler process than crop genetic engineering. Endophytes that have been genetically modified by using helpful genes will introduce new characteristics to host plants that have been inoculated with these strains.
12. Synthetic fertilizers coated with promising microbial strains may mark the start of a new understanding of synthetic/natural sources of nutrition, potentially providing knowledge of "microbial-enhanced fertilizer use efficiency.

11.9 Conclusion

Understanding the production and application of biofertilizers is needed for a country's economic growth. Knowing the basic sustainability principles in agriculture requires understanding the design, method of production, utilization, and storage conditions. Sustainability in agriculture is extremely beneficial in resolving the actual problems in the agriculture sector with crop production. Furthermore, marginal farmers in developing countries must be trained in the biotechnological features of biofertilizers in agricultural system planning. This chapter is an in-depth examination of the efficacy of biofertilizers in achieving sustainable agriculture. Biofertilizers can meet agro-industry challenges and create novel prospects for growers' benefit in the agriculture sector and business and for the research, academia, and other government sectors.

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Chapter 12
Biochar Application to Soils to Improve the Management of Irrigation Water

M. Abdulaha-Al Baquy, Jackson Nkoh Nkoh, Mahedy Alam, and M. M. Masud

Abstract Climate change has accentuated extreme events such as drought and flooding, thus altering the supply of water to plants. To solve this issue, the application of biochar to soils appears promising for managing soil water loss and improving the quality of irrigation water. Here we review the impact of biochar on irrigation with focus on soil water holding capacity, surface runoff and erosion, hydraulic conductivity, nutrients and pollutants. We found that biochar can improve soil water holding capacity by 12–60%, or by 98% when biochar is engineered, reduce surface runoff and erosion by 5.1–77.2%, increase hydraulic conductivity by 328%, reduce nitrate leaching by 75%, and accelerate phosphate leaching by 72%. The underlying mechanisms are discussed.

Keywords Biochar · Water quality · Climate change · Soil

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12.1 Introduction

With the growing world population, water usage in agricultural systems may become a vital factor in ensuring food security. There is increasing evidence that climate change will affect water availability in some areas which will lead to intense drought and increased food shortage. Even in areas where water is available for agricultural use, increased contamination of this water by untreated wastes is causing serious health and environmental risks (Fahad and Bano 2012; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b; Hesham and Fahad 2020; Al-Zahrani et al. 2022). To address this concern, several studies have looked into the potential of different soil amendments in enhancing soil water retention ability (Yu et al. 2017; Mansoor et al. 2021) and reducing pollutants uptake by plants (Nkoh et al. 2022).

Soil amendment materials have diverse properties and tend to affect soil physicochemical properties in several ways (Ibad et al. 2022; Irfan et al. 2021; Khadim et al. 2021a, b; Khan et al. 2021; Khatun et al. 2021; Muhammad et al. 2022; Subhan et al. 2020; Tariq et al. 2018; Wiqar et al. 2022; Wu et al. 2019, 2020; Xue et al. 2022). Of these amendments, biochar has received considerable attention due to its role in the management of acid soils (Shi et al. 2017), pollution remediation (Jiang et al. 2012; Xu and Zhao 2013), improvement of soil fertility (Baquy et al. 2020), carbon sequestration (Xie et al. 2015), and mitigation of climate change (Wang et al. 2015). Biochar is a porous carbon-rich material comprised chiefly of aromatic carbons and/or heteroatoms (Zhu et al. 2020). Biochar can be derived from the pyrolysis of a range of materials including plants, animal wastes, and sewage sludge, under a limited supply or in the absence of oxygen, and at varying temperatures (Nkoh et al. 2021).

Due to its high porosity and large specific surface area, biochar can improve soil water-holding capacity and reduce drought-related stress on plants (Yu et al. 2017; Mansoor et al. 2021). The use of biochar in soil management has experienced geometric growth in the recent four decades. The last decade alone has over 60% of the total number of publications on biochar from the web of science database (Nkoh et al. 2022). This shows that the last decade has experienced greater public awareness of the importance of biochar in improving soil quality, and the scientific community is putting more effort into exploring other uses of biochar such as biofuel production (Bolan et al. 2021).

Generally, the observed effects of biochar in influencing soil chemical or physical properties are to a larger extent influenced by biochar feedstock, production conditions, and soil properties. Some experimental studies have shown that biochar can negatively influence soil adsorptive (Almaroai and Eissa 2020) and physical properties (Yargicoglu et al. 2015). Nevertheless, a comprehensive review that highlights the role of biochar in soil water retention is still lacking. Thus, this chapter summarizes the positive and negative impacts of biochar application on soil water retention properties and the different factors influencing the properties of biochar vis-à-vis its role in influencing soil water retention.

12.2 Impact of Biochar on Irrigation Water Movement, Retention, and Quality

The alteration of soil physicochemical properties by biochar can play an important role in influencing irrigation water movement, retention, and quality. When biochar is added to soil, chemical and physical interactions occur. In the case of chemical interactions, biochar functional groups (or base cations) interact with soil minerals to form soil-biochar complexes (e.g. Soil-O-biochar or Soil-cation-biochar-cation-soil). These chemical interactions result in the formation of soil aggregates with modified physicochemical properties. For instance, soil-biochar composites usually have higher pH, contents of base cations, cation exchange capacity, and pH buffering capacity compared to unamended soils (Shi et al. 2018a; Nkoh et al. 2022). Figure 12.1 summarizes this section and shows the relationship between biochar, the production conditions, its effect on soil physicochemical properties, and soil water quality indicators.

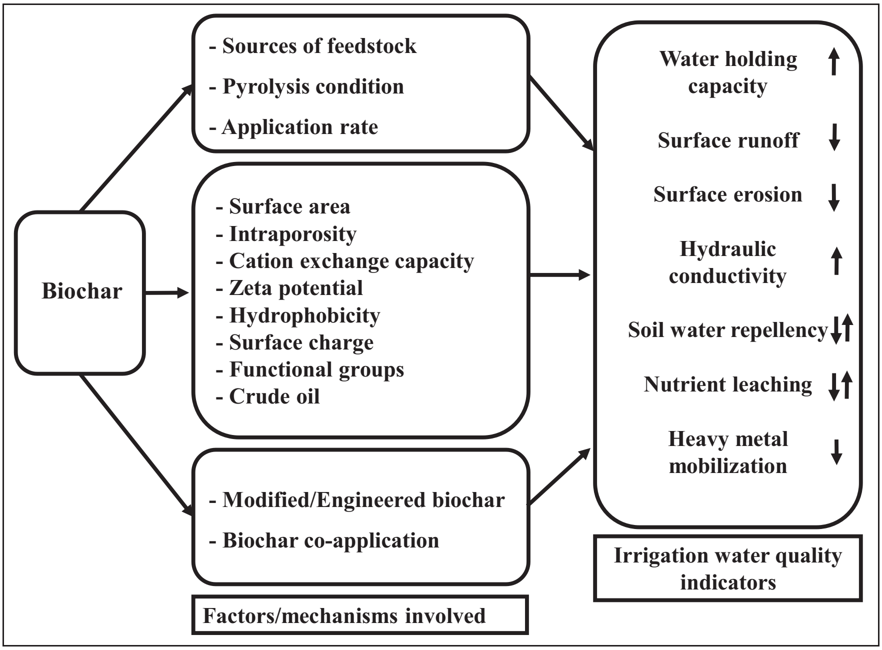

Fig. 12.1 Biochar production conditions and basic properties and the relationship with irrigation water quality. Biochar's influencing factors such as feedstock and production conditions greatly influence its basic properties including surface area, hydrophobicity, the content of function groups, and general reactivity. These also tend to influence biochar's effect on soil water quality indicators

12.2.1 Effect of Biochar on Soil Water Holding Capacity

The addition of biochar to soils can increase water-holding capacity and reduce the amount of groundwater used in agricultural applications. This effect of biochar on improving soil water holding capacity is related to biochar's porosity and surface area, implying that biochar with larger porosity and surface area will induce a more significant effect on soil water retention. Previous studies have found that biochar has a significant impact on enhancing water retention capacity across a variety of metrics. The study by Toková et al. (2020) revealed that the interaction of biochar with soil could increase soil porosity by up to 12% which contributed significantly to enhancing soil water holding capacity.

The incorporation of hardwood biochar into sandy loam soil raised the gravity-drained water content by 23% compared to the control (Basso et al. 2013). According to Yu et al. (2013), biochar increased the water-holding capacity of loamy sand soil by about 1.7% by mass for each 1% of added biochar over the agriculturally relevant range and improved irrigation effectiveness, reduced non-point source agricultural pollution, and mitigated runoff. In another study, it was found that the addition of biochar to a hydrophilic soil with a low total organic carbon level enhanced the soil water holding capacity (Mao et al. 2019) while fine-textured biochar particles increased gravimetric water holding capacity by 60% (Verheijen et al. 2019).

Surface modification of biochar either through chemical or biological methods can improve biochar's chemical properties, porosity and specific surface area. This implies that when applied to soils, these engineered biochars can as well alter soil water-holding capacity. For instance, biochar produced with 10 wt.% K_3PO_4 + 10 wt.% clinoptilolite as catalysts increased soil water holding capacity by 98% and 57% compared to the treatments without biochar and with 10 wt.% clinoptilolite, respectively (Mohamed et al. 2016). Additionally, the incorporation of manure-based biochar enhanced the water-holding capacity of soil and improved crop yield with the conservation of rainfall water in arid regions (Rehman et al. 2020). Nevertheless, the observed effect of biochar on soil water holding capacity is much under the influence of biochar's basic properties and feedstock type, as well as soil type and physicochemical properties (Nkoh et al. 2021).

12.2.2 Effect of Biochar on Soil Surface Runoff and Erosion

Surface runoff and soil erosion are major environmental issues (Adimassu et al. 2014) since they induce land degradation and soil productivity reduction. As a result, protecting agricultural soil from runoff loss and erosion is a hot topic for managing long-term productivity. According to previous studies (Jien and Wang 2013; Hseu et al. 2014), biochar application might be a strategy for reducing runoff and erosion. It was found that biochar-treated soil reduced runoff volume and soil loss with the runoff by 5.1–15.4% and 43.5–77.2%, respectively (Shen et al. 2021).

This plays a significant role in reducing the mobility and bioavailability of heavy metals. The authors also observed that while biochar particle size had no significant effect, biochar produced at higher pyrolysis temperatures induced less runoff and more infiltration, and performed better at preventing erosion. Elsewhere, the incorporation of vinasse-produced biochar in sandy clay loam soils showed promising results in decreasing runoff and soil erosion (runoff volume decreased by 46.4–98.5% and soil loss by 1.12–1.44 g L^{-1}) (Sadeghi et al. 2016).

12.2.3 Effect of Biochar on Soil Hydraulic Conductivity

Hydraulic conductivity of soil is an essential physical quantitative property that evaluates the ease with which water may flow from saturated soil when subjected to hydraulic gradients with the permission of pores. Soils amended with biochar from a variety of feedstocks and pyrolytic conditions changed the hydraulic conductivity of the soils in positive ways, as shown in the cases of sandy soil (Zhang et al. 2016); biochar-sand mixture (Liu et al. 2016a); and silty clay soil (Li et al. 2018). For compacted kaolin clay, biochar addition at rates of 5% and 20% increased saturated hydraulic conductivity from $1.2*10^{-9}$ to $2.1*10^{-9}$ and $1.3*10^{-8}$ ms^{-1}, respectively (Wong et al. 2018). The interaction of biochar with soil particles to form soil-biochar complex results in some of the intrinsic properties of biochar being transferred to the complex. Often, this results in a decrease in soil bulk density, an increase in soil porosity, and enhanced hydraulic conductivity (Burrell et al. 2016; Omondi et al. 2016). It was found that the hydraulic properties of silty loam (Toková et al. 2020) and compacted clay soil (Wong et al. 2018) improved with an increment in the rate of biochar application. These results were even more significant in a study by Barnes et al. (2014) who showed that biochar increased the hydraulic conductivity of clay-rich soil by 328%.

12.2.4 Effect of Biochar on Soil Water Repellency

Biochar production conditions have a significant effect on its hydrophobicity and thus, its effect on water repellence. Low-temperature biochars are generally more hydrophobic and water-repellent than high-temperature biochars. For instance, it was shown that biochars produced at 300 °C were about 13-times more hydrophobic than those produced at 500 °C (Kinney et al. 2012). The process of biochar production induces chemical transformation processes such as dehydrogenation, oxidation, decarboxylation, de-hydroxylation, and de-methylation. When this occurs, aliphatic carbons of the feedstocks are converted to aromatic carbons and become fused, forming larger clusters which are connected by aliphatic or aromatic side chains (Nkoh et al. 2021). As aliphatic functional units are removed from the biochar's surface at higher temperatures, its hydrophobicity increases (Gray et al. 2014).

Soil water repellency affects a variety of hydrological channels, including runoff, infiltration rate, water retention and bypass flow. It also affects water entrance and distribution in the soil as well as organic matter breakdown and microbial activity (Blanco-Canqui 2017). Severe soil water repellency can obstruct water penetration by forming preferential flow, promoting soil erosion and increasing the risk of groundwater contamination (Mao et al. 2019). According to the findings of Ebrahimzadeh Omran et al. (2020), fine-sized biochar can reduce soil hydrophobicity due to the presence of functional groups and crude oil in biochar.

Contrasting effects of biochar on water repellency have been reported. For example, Herath et al. (2013) observed that treating an Alfisol and an Andisol with biochar did not affect soil water repellency. Also, Briggs et al. (2012) demonstrated that fresh biochars are more water-resistant and would negatively impact soil water repellency. Even though the basic properties of biochar (e.g. hydrophobicity) suggest that when added to soil it can enhance water repellence, little experimental evidence exists to support this. The study by Devereux et al. (2012) reported that soil water repellency was reduced by about 5-folds when soils were treated with 5% biochar and the reduction of water repellence was observed even at a 15% biochar application rate. In another study, Głąb et al. (2016) observed that while 4% biochar slightly increased water repellence compared to 0.5%, 1% and 2% biochar application showed no effect.

12.2.5 Effect of Biochar on Nutrient Leaching and Mobility

Biochar as a soil supplement improves soil fertility by reducing nutrient loss through leaching. The degree of leaching inhibition varies for different soil types and biochar feedstocks. For instance, Ghorbani et al. (2019) observed that when rice husk biochar was applied to different soils, there was a significant inhibition of nitrate leaching in clay soil compared to loamy sand soil. Similar results also revealed that biochar application could decrease nitrate leaching by 75% due to increased water sorption and retention capacity in amended soils (Knowles et al. 2011; Ventura et al. 2013; Kanthle et al. 2016; Haider et al. 2017). In addition to nitrate leaching, biochar application can reduce phosphorus leaching when water-saving irrigation is considered for crop production in biochar-amended soils (Xie et al. 2021).

Due to a large number of negative charges on biochar surface, there are bound to be repulsive forces between biochar and anionic species such as PO_4^{3-} and NO_3^-, thereby reducing the retention of these nutrient ions in soils and enhancing their mobility. For example, rice husk biochar accelerated phosphate leaching from loamy soil by up to 72% (Pratiwi et al. 2016). Another study found that applying biochar to an Oxisol resulted in considerable amounts of inorganic nitrogen, calcium, magnesium and potassium being leached (Major et al. 2012). Also, the co-application of biochar and nutrients enhanced nitrogen, phosphorus and potassium leaching by 53–78, 5–11and 69–112%, respectively (Hardie et al. 2015).

To prevent the high mobility and continuous contamination of water bodies by anionic species, engineered biochars have been tested in soils and shown to have a higher affinity for these anions (Peng et al. 2021). For instance, the phosphate adsorption capacity of biochar was increased by 88.5% after modification with magnesium (Yao et al. 2013). The $MgCl_2$ modification of biochar introduced small masses of nanoparticles on the surface of biochar, thereby enhancing its ability to adsorb phosphate (Haddad et al. 2018). Also, magnesium- and aluminum-modified biochar can significantly reduce phosphorus leaching due to the greater (59.9%) phosphate interception capacity (Zheng et al. 2020).

12.2.6 Effect of Biochar on Heavy metals and Organic Pollutants Reduction in Irrigation Water

Biochar could be a feasible alternative for reducing the harmful effects of heavy metals in untreated household and industrial wastewater irrigation systems due to its high adsorption capacity for both inorganic and organic pollutants (Kamran et al. 2020; Nkoh et al. 2022). Tahir et al. (2018) showed that when co-applied with manure, biochar decreased nickel concentrations in soil irrigated with wastewater. In another study, it was observed that biochar can reduce cadmium and nickel uptake by crop plants in sewage-irrigated polluted soils (Younis et al. 2015). Furthermore, biochar can significantly adsorb cadmium and zinc from wastewater-irrigated soil and reduced the uptake by crop plants (Nzediegwu et al. 2019).

The ability of biochar to reduce heavy metal bioavailability in soils is related to its high alkalinity, cation exchange capacity, and pH, as well as the large content of oxygen-containing functional groups. The high alkalinity and pH of the soil-biochar complex favor the hydrolysis of heavy metal cations and improve their retention in soils while the increased cation exchange capacity provides abundant negative sorption sites to retain cationic species (e.g. metal cations and hydrolyzed cations) (Jiang et al. 2012; Nkoh et al. 2022). Besides, the oxygen-containing functional units of biochar provide both negative sorption and complexation sites for heavy metals in soil.

Although biochar has been widely utilized to reduce soil and irrigation water pollution, there are several recent studies which have focused on the detrimental influence of biochar in terms of contamination. Some biochars produced from low-quality feedstock may contain contaminants such as zinc and manganese, existing as monovalent and divalent cations (von Gunten et al. 2017). Also, some heavy metals may be easily adsorbed into the matrix of biochar and released when soil is being irrigated for crop production (Forghani et al. 2012). Biochar may cause environmental hazards by acting as an active carrier in the co-transportation of carbonaceous nanocomposites (Song et al. 2019), and these nanocomposites can promote cadmium mobilization in water-saturated soils by forming nanocomposites-Cd complexes (Chen et al. 2019).

Other pollutants of concern found in biochar are metal cyanides (e.g. KCN and NaCN). The highly toxic CN^- ion was found to be highly concentrated in feedstock containing large amounts of nitrogen, potassium, and sodium. Of the 18 feedstock studied, the largest amount of CN^- ion was reported for biochar produced from food waste, phycocyanin, and corn protein modified with K_2CO_3, with concentrations of 40,286, 85,870, and 23,251 mg kg^{-1}, respectively (Luo et al. 2020). Also, polycyclic aromatic hydrocarbons and polychlorinated dibenzo-p-dioxins are carcinogenic pollutants formed in biochar as a result of incomplete combustion (De la Rosa et al. 2019). When added to soils, these contaminants in biochar may become available via dissolution reactions of biochar's soluble organic fractions and cause serious environmental concerns.

12.3 Factors Influencing the Effectiveness of Biochar

12.3.1 Source of Feedstock

Irrigation water quality and moisture-determining features in soil depend on the properties of biochars which mainly vary with the source of feedstock. Under similar conditions, the application of biochar derived from switchblade grass enhanced water holding capacity in soil by 228% whereas biochar derived from hemlock increased it by 133% (Yu et al. 2017). Furthermore, the application of biochars from rice husk, wheat straw, and oilseed rape straw improved water use efficiency by 17.3%, 10.1% and 16.2%, respectively (Bitarafan et al. 2020). A similar observation was reported for biochar derived from wood pellets, softwood bark, and switchgrass straw (Streubel et al. 2011).

The differences in feedstock effects on soil properties can be attributed to differences in the types and nature of biochar functional groups and contents of base cations. For instance, biochar produced from peanut straw had 81.9, 39.2, 64.1, and 147.5 cmol kg^{-1} more functional group units than biochar derived from corn, wheat, rice, and faba bean straws, respectively (Nkoh et al. 2022). Changes in biochar's functional units with feedstock will therefore have a significant effect on its hydrophobicity and water repellence. Thus, it is evident that the source of feedstock for biochar is one of the important factors that influence irrigation water quality.

12.3.2 Pyrolysis Conditions/Process

Different types of biochar are produced using various pyrolysis settings and processes, and each biochar has a particular impact on soil water characteristics. Concerning the pyrolysis temperature, biochar's aromaticity increases with temperature as aliphatic carbons are converted to aromatic carbons. This results in a relative increase in carbon content and a decrease in the contents of hydrogen, oxygen and heteroatoms (Nkoh et al. 2021). During this transformation, there is a significant decrease in biochar's acidic functional groups, an increase in surface negative charge groups, an increase in the concentration of alkali salts, and a corresponding increase in biochar's alkalinity (Shi et al. 2017). Thus, the process of aromatization and alkalization at higher temperatures produces biochar with larger surface areas and greater influence on soil water behavior.

According to Ebrahimzadeh Omran et al. (2020), biochars produce at higher pyrolysis temperatures have functional units with greater affinity for crude oil functional groups. Thus, when added to crude oil-contaminated soils, high-temperature biochars can alleviate water repellency better than low-temperature biochars. Also, sawdust-derived biochar produced at 400 and 700 °C increased soil water holding capacity by 14% and 57%, decreased soil hydraulic conductivity by 15% and 42% and increased soil moisture retention capacity by 16% and 59%, respectively (Laghari et al. 2016). This observation was also reported when biochar produced at 700 °C increased available soil water content by 23% compared to that produced at 400 °C (Marshall et al. 2019). Thus, biochars produced at higher temperatures interact favorably with soils, creating suitable soil-biochar complexes for water retention and cation immobilization.

12.3.3 Biochar Application Rate

Biochar application rate has a significant impact on soil physicochemical properties. Soil properties such as pH, cation exchange capacity, soil organic carbon, the content of base cations, and pH buffering capacity increase with biochar application rate (Shi et al. 2017, 2018a, b). Given that these parameters also influence soil aggregate properties; it is convenient to infer that biochar application rate can also impact irrigation water parameters. Specifically, the application of biochar significantly increased soil water content and plant available water, with the effect being dependent on the biochar application rate (Toková et al. 2020).

In crude oil-contaminated soils, biochar application reduced water repellency, and the effect increased with application rate as more biochar functional units were added at higher biochar dosage (Ebrahimzadeh Omran et al. 2020). Also, the increasing effect of biochar on gravity-drained water content was dependent on the biochar application rate (Basso et al. 2013). This differential effect of biochar on soil water properties can be attributed to an increase in soil carbon and water holding capacity at higher amendment rates (Streubel et al. 2011). However, these effects often vary from one soil or biochar type to another and with biochar production conditions.

12.3.4 Biochar Basic Properties

The incorporation of biochar into the soil increases soil porosity thereby contributing to the enhancement of water-holding capacity. Because biochar's porosity is directly connected with soil's physical attributes, e.g. water retention, surface area, it has a considerable impact on irrigation water requirements. A high intraporosity of irregularly shaped biochar can significantly boost water storage conditions in coarse-textured soils (Liu et al. 2017). In sandy soil, biochar with a higher pore capacity enhances water retention and reduces water loss through evaporation (Zhang et al. 2016). Also, amending soils with biochar of particle size 0.15–2 mm significantly enhanced soil porosity and had a stronger synergistic effect on water retention and water availability compared to biochar with larger particle sizes (de Jesus Duarte et al. 2019).

Furthermore, cation exchange capacity and zeta potential are also vital factors that influence water holding capacity because they are related to the adsorption of hydrated ions on the biochar surface. Generally, the higher the cation exchange capacity and negative zeta potential, the greater the water-holding capacity (Batista et al. 2018). Interestingly, the zeta potential and cation exchange capacity of biochar are directly related to the types and nature of functional groups on the surface of biochar. A high cation exchange capacity and negative zeta potential suggest a biochar surface covered by anionic functional groups, e.g. $R\text{-}COO^-$. This implies that biochars whose surfaces are saturated with more negative functional groups are likely to promote soil aggregation as biochar–mineral–organic matter complexes. Moreover, the surface charge and hydrophobicity of biochar also play a crucial role in the water retention capacity of biochar-amended soils (Marshall et al. 2019).

Also, the content of biochar's exchangeable base cations, which is related to the cation exchange capacity, equally plays an important role in bridging negatively charged minerals during soil aggregation (Kleber et al. 2015; Song et al. 2020). Given that soil aggregates play an important role in soil water retention, it is inferred that biochar's ability to influence water retention will be related to its effect on soil aggregation, and different biochars will affect these processes differently.

12.3.5 Co-application of Biochar with Other Amendments

When applied together with other soil amendments materials (e.g. compost, chemical fertilizers and organic nutrient sources), biochar's effects on soil's physical and chemical properties are altered. For example, the application of biochar with both maize compost and sewage sludge improved available water content in soil by 4% when compared to maize compost and sewage sludge alone (Głąb et al. 2018). When lignite fly ash was applied in combination with biochar in heavy metal-polluted soil, interactive water, air, and nutrients circle was generated as the growth of different enzymes was favored (Masto et al. 2013). This suggests that the negative effects of biochar on certain soil microbes (Chen et al. 2015) can be mitigated when applied in combination with other amendments. Also, the combined application of co-composted agricultural manure and biochar reduced the availability of heavy metals such as Cd in soil and cereal crops (Bashir et al. 2020). Nevertheless, in the presence of biochar, other amendment materials such as organic manure can promote the biodegradation of organic matter in soil and induce water repellency (Scott 2000).

12.3.6 Biochar Modification

The modification of biochar is generally aimed at producing function-specific biochar. These modifications can often produce biochars with increased surface functional groups, increased/decreased porosity and surface area, improved surface charge characteristics and increased cation exchange capacity. Such changes in biochar's physical, mechanical, and chemical properties may influence soil-water interaction, and consequently the irrigation water quality. For instance, the use of engineered orange peel-derived biochar significantly lowered soil bulk density, enhanced porosity and hydraulic conductivity, and altered the irrigation water quality (Kalderis et al. 2019).

Biochars are often engineered to have enhanced surface positive/negative charges to improve anion/cation retention and/or adsorption from irrigation water (Yao et al. 2012; Liu et al. 2016b; He et al. 2020). Given that biochar engineering alters biochar's basic properties by introducing other functional units besides organic functional groups (e.g. metals, metal oxides, clay minerals and carbonaceous materials), very few studies have investigated the effect of these modified biochars on soil properties. Thus, more studies are required to investigate the fate of modified biochar in soil and its effects on soil physicochemical properties and irrigation water quality.

12.4 Conclusion

Biochar utilization in agriculture has shown the potential in mitigating the adverse effects of different pollutants on plants, improving soil water quality, and enhancing soil fertility. The different strategies used to produce biochar are often aimed at improving the basic properties and functionality of biochar, and this often has extended effects on biochar's behavior in the environment.

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Chapter 13
Role of Biochar in the Adsorption of Heavy Metals

Muhittin Onur Akca and Osman Sonmez

Abstract Some heavy metals are highly toxic and can be stored for long periods in any ecosystem. This is a very sensitive issue because heavy metals can enter the food chain and exert negative effects on human health. This hazard should thus be reduced or eliminated. For that, biochar, a carbon-rich material can be added to soils for adsorbing heavy metals. Here we review the mechanisms of biochar applications on heavy metal adsorption in soil, with focus on feedstock of biochar, pyrolysis conditions, biochar properties, and soil characteristics. Biochar application does not entirely remove heavy metals from the soil environment. Hence biochar-applied metal-contaminated soils should be regularly monitored for heavy metal toxicity since the biochar's immobilization capacity may decline with time.

Keywords Biochar · Heavy metal · Adsorption mechanism · Carbon · Environment

13.1 Introduction

Like global warming, which threatens the livelihood of all organisms, heavy metal pollution poses a major environmental threat on global scale. Heavy metals are types of toxic pollutants that are emitted into the environment in great amounts through industrial activities – like iron and steel production – volcanic eruptions, erosion of rocks, fertilizer applications, pesticide use, and mining (Lu et al. 2014; Mendez et al. 2014; Palansooriya et al. 2020). In the wake of rapid urbanization,

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industrialization, industrial product manufacturing activities, and global-scale environmental disasters, many environmental problems resulting from heavy metals have emerged (Sun et al. 2018; Bilal et al. 2019). These anthropogenic impacts have been disrupting the ecosystems relied upon by humanity throughout the course of history (Ma et al. 2016). Heavy metals generate many negative effects on the atmosphere, soil, oceans, and ground water (Bai et al. 2020). These negative effects have been regarded as a significant environmental issue, especially in the United States, the European Union, Australia and many Asian countries (Ahmad et al. 2019; El-Naggar et al. 2020).

Heavy metals, with high toxicity, long-term persistence in environments, carcinogenic properties, and bioaccumulation risks, in even very low concentrations, are regarded as very hazardous environmental pollutants (Zahida et al. 2017; Anam et al. 2021; Manzer et al. 2021; Ashfaq et al. 2021; Zafar et al. 2020a). As a result of these characteristics, heavy metals pose a high-risk threat to food security and human health (Hou et al. 2018; Peng et al. 2018; Zama et al. 2018). Heavy metals can be present in soil, water, and aerial mediums in varying concentrations. When the concentrations exceed a certain threshold, heavy metals result in environmental pollution and have adverse consequences for any organisms exposed to them. For example, heavy metals can enter the food chain and ultimately lead to negative impacts on all living organisms, not least of all, humans (Wang et al. 2019). It is reported that with the increasing entry of heavy metals to the food chain, illnesses and deaths within a population will rise (Rai et al. 2019). To protect soil from all the above-mentioned hazards and ensure the sustainability of ecosystems, strategies aimed at the remediation of soil from heavy metal pollution need to be developed. Unless precautionary measures are taken, the world will face the risk of losing these soils and of the pollution of ecosystems (Liu et al. 2022).

Many methods have been utilized to remove heavy metals from soil, including membrane technology, ion-exchange, electrochemical treatment, soil washing, and phytoremediation (Shannon et al. 2008; Ge and Li 2018; He et al. 2019; Wang et al. 2020; Saleem et al. 2020). However, many of these solutions are complex and costly and leave residual chemicals in the soil (Tan et al. 2020; Yang et al. 2020). As an alternative to these methods, an adsorption process can be applied to remove heavy metals from the soil environment (Deng et al. 2020). In this process, it has been shown that the use of carbon containing materials prevents heavy metal toxicity (Yang et al. 2019). There has been an increasing demand for remediation of heavy metal-contaminated soil applications that are novel, applicable, and economically feasible, and that include raw materials obtained from waste (Ahmad et al. 2014; Bolan et al. 2014; Wang et al. 2018). It is furthermore important that these materials used in the applications be retrieved from resources abundant in nature, renewable, and potentially recyclable (Bolan et al. 2014; Rinklebe and Shaheen 2015).

Recently, biochar, a carbon-rich solid product of biomass pyrolysis, which takes place under an anoxic or limited oxygen environment, has been reported to be an efficient tool for removing heavy metals thanks to biochar environmentally-friendly, low cost, and high adsorption capacity properties (Shaheen et al. 2019; Arif et al. 2020; Hesham and Fahad 2020; Rashid et al. 2020; Subhan et al. 2020; Ashfaq et al. 2021; Athar et al. 2021; Atif et al. 2021; Irfan et al. 2021; Dawar et al. 2021 a, b;

Ibad et al. 2022; Muhammad et al. 2022; Wiqar et al. 2022; Zafar et al. 2020b). The biochar use in soil remediation via heavy metal adsorption has become increasingly more common owing to biochar's wide specific surface area, porous surface structure, and high functional group content (Peng et al. 2019; Sun et al. 2020). Overall, the inherent characteristics of biochar, such as abundance of binding sites on the surface (hydroxyl, carboxyl, and phenolic hydroxyl groups), porous structure, high cation exchange capacity, and high specific surface area, make it a useful, practical, and efficient adsorbent material for heavy metal remediation purposes (Li et al. 2019). The porous structure of biochar is variable. In terms of size, the pores can be nano- (<0.9 nm), micro- (<2 nm) or macro (>50 nm), characteristics that are crucial for heavy metal adsorption. When the pore size is too small, regardless of the charges or polarities, biochar will be unsuccessful in adsorbing heavy metal, or large sorbates in general (Ahmedna et al. 2004).

The pyrolysis temperature and type of biochar raw material are the two main factors that determine the functional groups of biochar. The pyrolysis temperature, heating rate, and retention time characteristics of the biochar production process are crucial for the biochar heavy metal adsorption capacity (Senthilkumar and Prasad 2020). These characteristics have an overall considerable effect on the functional group content and surface area of biochar. Recent studies have revealed that the pyrolysis temperature has an important impact on pH, cation exchange capacity, specific surface area, surface functional groups, and mineral concentrations of biochar (Sizmur et al. 2017; Zhang et al. 2018). An increase in the pyrolysis temperature reduces the content of H_2, N_2, S and other elements and reduces the cation exchange capacity and oxygen containing functional groups on the biochar surface. Moreover, an increase in pyrolysis temperature will increase aromaticity. Although these said effects of higher pyrolysis temperatures negatively impact the heavy metal adsorption of biochar, higher pyrolysis temperatures also increase biochar's specific surface area, porosity, and alkalinity, which in turn increase heavy metal adsorption capacity (Gai et al. 2014; Qiu et al. 2021).

In terms of adsorption properties, the most suitable pyrolysis temperature was determined to be 400 °C under a slow pyrolysis method (Wu et al. 2012). In one study, the adsorption sites of biochar that was pyrolyzed above 400 °C were clogged (Jung et al. 2016). Increasing the pyrolysis temperature gradually reduces the absorption peaks corresponding to –OH, C–O–C, –CH_2-, C=O groups, which means a reduction in their content (Wang et al. 2021). For instance, higher temperature in pyrolysis provides wider surface area, which prevents the negative effects of different proximal function groups that complexate one another and reduce overall heavy metal adsorption. When biochar is applied to heavy metal contaminated soils, the soils do not destroy heavy metals, but rather, adsorb them and reduce heavy metal's water solubility and bioavailability (Guo et al. 2020). It is imperative to understand the mechanism governing heavy metal adsorption on biochar surface to obtain biochar with the desired heavy metal adsorption capability (Fig. 13.1). A comprehensive review that highlights the role of biochar in soil heavy metal relations is still lacking. This chapter summarizes the direct and indirect mechanisms of biochar applications on heavy metal adsorption in soil.

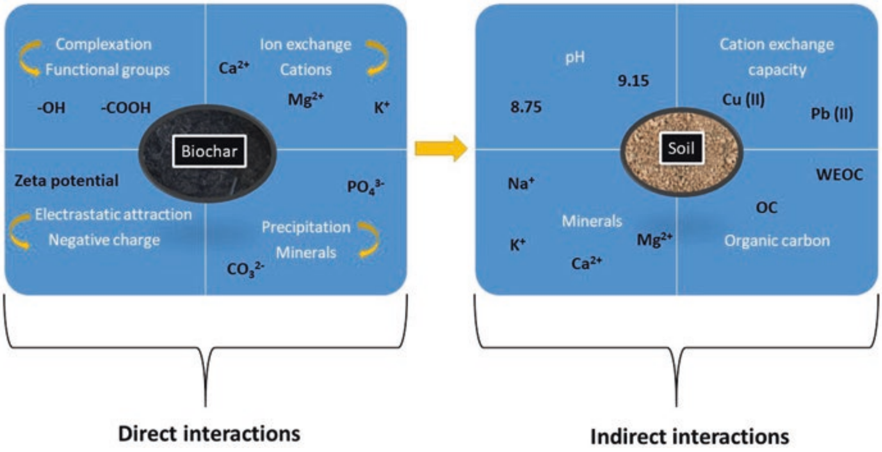

Fig. 13.1 Heavy metal-biochar interactions in contaminated soils. (Source: He et al. 2019)

13.2 Interactions Between Biochar and Heavy Metals

Different raw materials and pyrolysis conditions produce distinctive characteristics in biochar that consequently affect the heavy metal adsorption on biochar surfaces. These differences lead to variations in the pH, organic carbon content, cation exchange capacity, micropore structure, specific surface area, active functional groups, and mineral content of biochar. In addition to the variations in soil characteristics, these differences also affect the soil-heavy metal interactions and result in changes in heavy metal mobility-bioavailability (Qi et al. 2017). The heavy metal adsorption of biochar in a soil environment is explained on the basis of two main factors. As Fig. 13.1 illustrates, the first factor is related to the direct interactions of biochar and heavy metals, while the second factor is related to the changing soil characteristics after the biochar application and the indirect results these have on the soil mobility of heavy metals (He et al. 2019).

13.2.1 Direct Interactions Between Biochar and Heavy Metals in Soils

The adsorption mechanisms occurring via direct interactions are mainly complexation, ion-exchange, precipitation, and electrostatic attraction (Table 13.1) (He et al. 2019). It has been reported that these aforementioned mechanisms – electrostatic interactions, ion-exchange and complexation – are closely related to the binding sites, electrostatic forces, and the interactions of heavy metal and surface functional groups via covalent bond formation (Yang et al. 2019).

Table 13.1 The direct impact mechanisms for heavy metal adsorption of biochar

Biochar	Heavy metal	Mechanism	Reference
Orange peel	As (V)	Complextion	Yoon et al. (2020)
Rice husk	Cr (III)	Ion exchange	Dias et al. (2020)
Pine wood sawdust	Pb and cd	Precipitation	Xia et al. (2019)
Corn stalk	Zn (II)	Electrostatic attraction	Song et al. (2020)

13.2.1.1 Complexation

The presence of abundant functional groups on biochar surface constitutes rich binding sites for heavy metal (Yang et al. 2019). These functional groups, especially for low mineral content biochar, immobilize heavy metals via the surface complexation pathway. For instance, biochar derived from plant wastes mainly adsorb heavy metals through the surface complexation path (Xu et al. 2017). The functional groups present on the biochar surface (e.g. –OH, –COOH, –C=O– and C=N) create binding sites for heavy metal complexation that increase biochar specific adsorption. The primary impact of oxygen-containing functional groups on adsorption capacity is the enhancement of surface reactions and hydrophilicity (Li et al. 2021). If the obtained biochar contains inorganic ions, such as Si, S, and Cl, these ions can react with heavy metals and decrease heavy metal's mobility (e.g., reduced mobility of Cd) (Tan et al. 2017). In a study performed on the heavy metal adsorption of functional groups, it was reported that total adsorbed Pb (II) was in the range of 38.2–42.3% (Lu et al. 2012). In another study, Uchimiya et al. (2011) reported that the adsorption of Cd^{2+}, Cu^{2+}, Ni^{2+}, and Pb^{2+} loaded heavy metals via biochar was carried out largely through surface complexation in ligand-like functional groups of biochar (e.g., carboxylic, hydroxyl, phenolic groups).

13.2.1.2 Ion Exchange

Ion exchange is governed by the electrostatic interaction between the negative charges on biochar surfaces and the positive charges in soil media. Carboxyl (-COOH), and oxygen-containing functional groups in general, adsorb heavy metals via ion-exchange processes (Ho et al. 2017). Variations in surface charges can originate from different chemical reactions involving protonation, deprotonation, and ligand-binding changes in amphoteric functional groups (Chintala et al. 2016). Over time, the increase in the number of biochar functional groups (particularly in carboxyl groups, but also in phenolic, hydroxyl, carbonyl or quinone carbon forms) alters the surface positive charge of biochar particles and increases the negative charge (Cheng et al. 2006; Cheng et al. 2008). These negatively charged particles increase the charge load on biochar, resulting in pH reduction in soil and a consequent cation exchange capacity increase (Liang et al. 2006). This situation is considered to be related to the increase in heavy metals adsorption via increase in cation exchange capacity (Tang et al. 2013). Under certain conditions, the immobilization of metals through the use of biochar is not solely associated with ion-exchange. The metal adsorption process of biochar is an endothermic process (Liu and Zhang 2009; Harvey et al. 2011), where the positively-charged metal cations are retained by their electrostatic interactions with C=O or C=C-related π-electrons.

The heavy metal ions on soil water solutions are initially adsorbed by biochar via heavy metal ions cation exchange in cases where the biochar contains Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and H^{+} ions (Fidel et al. 2018). Owing to soil's high cation exchange capacity, biochar emits Ca (II) and Mg (II) from soil's surfaces, and these cations are exchanged with heavy metals (Li et al. 2015). It is known that animal-based biochar contains higher concentrations of Ca (II) compared to those of plant-based ones. This property of animal-based biochar makes them more effective in ion-exchange and immobilization of Cd (II) and Cu (II) (Lei et al. 2019).

13.2.1.3 Precipitation

Precipitation is another mechanism of biochar applications that removes heavy metals from soil. It is reported that biochar can effectively reduce the activity of heavy metal via adsorption/solution/precipitation of mineral contents (Rees et al. 2014). Under different conditions, however, there are also phosphate and carbonate precipitations. For instance, from the biochar obtained from Pb-loaded sewage sludge, only lead phosphate silicate precipitation was observed under pH of 5.0 (Lu et al. 2012). Lead oxides, which are bound to specific minerals found in some biochar, can also form chloride and sulfate precipitates (Meng et al. 2014; Liu et al. 2016). In another study, the adsorption capacity of the biochar produced from rice stalk under 700 °C via precipitation was found to be 57%, while another biochar obtained from sewage sludge under the same pyrolysis temperature had 62% adsorption capacity (Gope and Saha 2021).

13.2.1.4 Electrostatic Interaction

Electrostatic interaction takes place between charged biochar and heavy metal ions, with the resulting impact being a reduction in heavy metal mobility (Mukherjee et al. 2011). For this mechanism, the zeta potential of utilized biochar material is used to describe its electrostatic potential. Studies in the literature have demonstrated that in cases where biochars have high electronegativity, this can facilitate the electrostatic attraction of positively-charged heavy metal ions (Ahmad et al. 2016, 2018). Biochar density is important in electrostatic interaction. This density varies depending on the surface charge generated by the pH-induced increasing negativity of a negatively charged functional group (Faria et al. 2004; Cho et al. 2010). Studies conducted on this topic have shown that the initial concentrations of heavy metals will also increase the electrostatic interaction with biochar (Dai et al. 2015), and that a one-unit increase in pH is sufficient for increasing Cu (II) adsorption to the biochar (Tong et al. 2011).

13.2.2 Indirect Interactions Between Biochar and Heavy Metals in Soils

The indirect effects of biochar on heavy metal mobility and bioavailability result from the changes in soil properties and metal-soil interactions. After the introduction of biochar to soil, the soil pH, cation exchange capacity, dissolved organic carbon, and mineral content properties are altered, resulting in a change to heavy metal-soil interactions.

13.2.2.1 Changes in Soil pH Resulting from Biochar Application

Soil pH is an important parameter insofar as it controls the mobility of heavy metals (Dong et al. 2009). Many studies have reported that biochar applications to soil increase soil pH (Van Zwieten et al. 2010; Bell and Worrall 2011). The solubility of metal varies according to pH, where higher pH generally reduces metal solubility (Beesley et al. 2015). Increasing the pH in soil results in increasing adsorption of heavy metals on negatively charged surfaces. As biochar has alkaline properties, especially when applied to acidic soils, it can act as a "soil conditioner" (Yu et al. 2019). With this alkaline property, biochar can increase hydrolysis of heavy metals and heavy metals adsorbance by soil. Moreover, alkaline properties can also increase the oxide forms of heavy metals (Bolan et al. 2014). One study reported that a biochar application increased heavy metal complexations in a soil media, which consequently decreased Pb (II) desorption (Jiang et al. 2012).

13.2.2.2 Changes in Soil Cation Exchange Capacity Resulting from Biochar Application

The relatively high cation exchange capacity of biochar corresponds to the higher number of functional groups on the surface. Knowing the cation exchange capacity value of biochar allows for a better understanding of its capacity to adsorb heavy metals, that is, cation exchange capacity acts a guide for the biochar's heavy metal adsorption capacity. Usually, biochar has high cation exchange capacity values, which means biochar application to soil also increases the soil's cation exchange capacity value (Zhang et al. 2017). The studies conducted on this subject have indicated that increasing doses of a biochar application decreases heavy metal concentrations and solubilities via the increase in cation exchange capacity (Li et al. 2016; Bashir et al. 2018). Biochar added to soil was found to increase the soil cation exchange capacity after 30 days, which in turn increased Pb (II) adsorption (Jiang et al. 2012). Similarly, increasing soil cation exchange capacity was shown to increase the adsorption of Cu (II) and Pb (II) (Ma et al. 2010). Another study reported that when biochar has a high mineral content, such as Na^+, Ca^{2+}, Mg^{2+}, K^+, these positively charged cations are released to the soil and establish different mineral phases on the biochar surface, furthering increasing heavy metal adsorption (Rees et al. 2014).

13.2.2.3 Changes in Dissolved Organic Carbon in Soil Resulting from Biochar Application

A biochar application to soil increases the dissolved organic carbon content of the soil pore water (Beesley and Dickinson 2011). Higher amounts of organic matter in the soil also increases the amount of water extractable organic carbon. Although dissolved organic carbon represents a small fraction of organic matter in soil, its mobility and reactivity give it significant value in the soil ecosystem (Lin et al. 2012). Increasing the amount of organic carbon in soil increases heavy metal adsorption, and thus, reduces heavy metal bioavailability (Zhu et al. 2016). This mechanism is explained via the complexation between oxygen-containing functional groups in biochar and heavy metals (Dong et al. 2014). Beesley et al. (2011) reported that biochar applications on arid and semi-arid soils resulted in the stabilization of organic matter in organo-metal complexes with a Cu element. Abdelhafez et al. (2014) reported that the increase in organic matter resulting from a biochar application converted Pb (II) to less mobile organic-bounded lead and therefore reduced plant Pb (II) uptake.

13.2.2.4 Changes in Mineral Matter Content of Soils Resulting from Biochar Application

Biochar contains high amounts of mineral matter, such as Na, Ca, P, Mg, K. This mineral content is emitted when the biochar is applied to soil. Heavy metals are able to be adsorbed more due the established mineral phases on the surface of biochar (Rees et al. 2014). In one study, when increasing amounts of biochar were added to the soil, greater increases in the P ratio were observed. This increase resulted in the development of stable phosphate minerals in the soil and Pb (II) adsorption (Cao et al. 2009).

13.3 Conclusion

Biochar has been shown to have major potential for heavy metal adsorption, and more recently, it has attracted attention for being a carbon-rich material. In terms of remediating heavy metal-contaminated environments caused by anthropogenic activities, biochar is a very promising application. This chapter specifically focused on the role of biochar in the soil adsorption of heavy metals. Biochar adsorbs heavy metal directly via numerous paths, including complexation, ion-exchange, precipitation, and electrostatic interaction, and indirectly via the changes it brings about to the soil pH, cation exchange capacity, dissolved organic carbon, and mineral content. It is important to note that biochar does not completely remove heavy metals from the environment, which means heavy metal-contaminated soil where biochar has been applied should be regularly monitored for heavy metal toxicity, as the immobilization power of the biochar might decline over time.

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Part IV
Microbial Interactions

Chapter 14
Positive and Negative Impacts of Biochar on Microbial Diversity

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Abstract Excessive exploitation of agricultural land has degraded the environment. Biochar application to soil has gained attention as an ecofriendly method to improve soil fertilization and crop production. Despite many advantages, some concerns regarding the benefits of biochar in the long run need to be addressed. For instance biochar can sequester nutrients and water, and thus make them unavailable to microorganisms and plants. Here we review the advantages and drawbacks of applying biochar in agricultural fields.

Keywords Climatic changes · Food security · Soil microbiome · Sustainable agriculture

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14.1 Introduction

In the past few decades, soil quality and health have been improved by the extortionate use of chemical fertilizers which has raised concerns regarding environmental problems (Bogusz et al. 2021). So the use of alternate strategies has become a necessity to improve soil fertility. In this regard, biochar has emerged as a promising solution and has gained much attention (Ayaz et al. 2021). Biochar is a carbon-rich material produced by pyrolysis of the feedstock under the limited or absence of oxygen (Lehmann et al. 2002). Biochar can be prepared from both woody i.e. residues of trees and forests and non-woody biomass i.e. industrial, urban, and soil waste, agricultural residues, and crops (Jafri et al. 2018). The nature of biochar is defined by the source from which it is prepared (Bourke et al. 2007).

Biochar alters the physical, chemical, and biological properties of soil. Biochar increases the water retention capacity of soil because of its porous nature. Biochar absorbs the water molecules as well as nutrients in the soil thus reducing nutrients leaching. In this way, it serves as a long-term storage house for nutrients and water (Matuštík et al. 2020). Biochar can also be used for the mitigation of pesticide-polluted soils (Ren et al. 2016). Such physiochemical modifications directly or indirectly affect the soil microbial community positively or negatively (Li et al. 2019). Most of the work done, cites the benefits of using the biochar in developing the beneficial microbial species and very less information is gathered on the negative impacts of biochar on soil biota. This chapter focuses on the benefits as well as detrimental effects of biochar on the diversity of soil microbial populations.

14.2 Positive Impact of Biochar on Microbiota and Their Secretions

Soil serves as a natural habitat for the diverse population of microbial species. Advancements in molecular studies have enabled researchers to dig deep into the complexity of processes involved in bringing the interactions between plants, microorganisms, and soil (Mueller et al. 2019). There are three domains of life in soil, e.g. archaea, prokaryotes, and third fungi, protists, animals, and plants. The diversity of microorganisms in soil is altered by the biochar amendment. For instance, compared to temperate forest soil, biochar amended soil have more abundance of microorganisms which proves that biochar provides a favorable environment for community development (Muhammad et al. 2018). Many researches have backed the amendment of soil by biochar to favor the microbial communities in the soil as discussed in Table 14.1.

Table 14.1 Effect of biochar on microorganisms

Feedstock	Type of soil	Impact of biochar	References
Chicken manure (500 °C)	Sedimentary alfisol	Increase in activities of microorganisms in soil	Meier et al. (2017)
Corn straw (500 °C)	Sandy loam	Microbial biomass increased Increase in gram positive bacteria Increase in fungal population	Lu et al. (2014)
Cotton straw (450 °C)	Calcaric Fluvisol	Increase in enzyme activity, microbial activity, as well as microbial biomass	Liao et al. (2016)
Date palm waste (300 °C)	–	Sorption of heavy metals Increased the microbial biomass, soil respiration and soil organic matter	Al-Wabel et al. (2019)
Gliricidia sepium wood (300 °C, 900 °C)	Serpentine soil	Increased overall soil enzymatic activity Sorption of heavy metals	Bandara et al. (2017)
Gliricidia sepium wood (900 °C)	–	Microbial biomass increased Increase in bacterial and fungal count Increase in plant growth-promoting bacteria population Absorption of heavy metals	Herath et al. (2017)
Glucose	Forest and arable soil	Increase in gram positive bacteria	Steinbeiss et al. (2009)
Maize straw (400 °C)	Silt loam	Arbuscular mycorrhizal fungi/ saprotrophic fungi ratio affected	Luo et al. (2017)
Oak pellet (550 °C)	Clay Sandy loam	40–64% increase in phospholipid fatty acid biomass	Awad et al. (2018)
Pinus radiata	Silt-loam	Beneficial for phosphate solubilizing bacteria and carbon degrading bacteria	Anderson et al. (2011)
Pinus sp. Dairy + bull manure (500 °C)	Fertile Mollisol	Enhances the microbial biomass and microbial activity	Kolb et al. (2009)
Rice straw (550 °C)	Clay loam	Improved soil organic carbon mineralization Slight increase in microbial biomass	Pan et al. (2016)
Sawdust (550 °C)	Sandy loam	Increase soil organic matter Increase in phospholipid fatty acid biomass	Gomez et al. (2014)
Sugarcane bagasse (450 °C)	Sandy loam	Reduction the bioavailability of heavy metals Increase in Actinomycetes population (280%)	Nie et al. (2018)
Pine cone and vegetable waste (200 °C)	Sandy loam	Absorbed the heavy metals and increased microbial abundance	Igalavithana et al. (2017)

(continued)

Table 14.1 (continued)

Feedstock	Type of soil	Impact of biochar	References
Wheat straw (450 °C)	Anthrosol	Decreased the bioavailability of heavy metals Increase in fungal (370–930%) and Actinomycetes (19–38%) population	–
Willow leaves (470 °C)	Flinty clay loam	Nitrogen cycling is affected Bacteria +28% Actinobacteria +62% Gram-negative bacteria +27%	Prayogo et al. (2014)
Willow wood Swine manure (350 °C)	Temperature sandy loam	Microbial biomass increased Increase in gram-positive and gram-negative bacteria	Ameloot et al. (2013)
Yeast	Arable and forest soil	Nutrients levels enhanced Fungal population increased	Steinbeiss et al. (2009)

14.3 Biochar Colonization by Microorganisms

Decades of studies have been carried out to understand the physical and chemical processes involved in the colonization of different substrates by bacteria and the formation of biofilm on their surfaces but no general conclusion has been drawn because of the diversity of substrates as well as microorganisms (Rummel et al. 2017). Biochar contains pores that can be used by microorganisms as shelter houses. However, spatial heterogeneity exists between fungi and bacteria on internal and external pores of biochar (Quilliam et al. 2013a, b). The aging periods of biochar also determine the colonization of bacteria on surfaces and in pores. For instance, *Methanosarcina barkeri* and *Geobacter metallireducens* are attached to the surfaces of biochar within the first 20 days. Thus, adjustments in aging periods of biochar can help to improve the colonization of bacteria and fungi on the surfaces and pores of biochar (Quilliam et al. 2013b).

The negative charge surface, high pore volume, and large surface area help the biochar to sorb nutrients. Biochar itself is enriched with nutrients for example phosphorus, nitrogen, sodium, magnesium, and potassium. Cation exchange capacity of soil indicates the nutrients retaining ability of soil (Chen et al. 2012). Biochar improves the cation exchange capacity of soil and increases the nutrient holding capacity of soil and protects them from leaching. This provides an edge to the microorganisms especially the species inhabiting soils with low organic matter (Lehmann 2007). However, the sorption of nutrients mainly depends on the type of feedstock and the pyrolysis temperature used. For instance, the manure-derived biochar has higher ash content compared to wood-derived biochar which enables them to supply nutrients more efficaciously (Akhter et al. 2015). Similarly higher pyrolysis temperature favors the ash content in the manure- and crop-derived biochar (Xu and Chen 2013).

Biochar releases the nutrients in the soil at different rates. That's why biochar is regarded as a slow-release fertilizer. Such properties bring long-term advantages to soil fertility and microorganisms (Mukherjee and Zimmerman 2013). Biochar can also affect one microbial community by regulating the microbial functions of other species. For example, Fox et al. (2014) observed that biochar increased the population of rhizobacteria that could transform the organic phosphorous and sulfur into bioavailable forms. This indirectly promoted the growth of *Lolium perenne* and other microorganisms that could utilize inorganic phosphorous and sulfur. Biochar contains functional groups like oxygen-containing groups on its surface that sorb inorganic anions and nutrient cations and then supply nutrients to microorganisms (Chen et al. 2015).

The aromatic nature of biochar is the reason behind their defiant behavior towards microbial decomposition. Biochar contains higher carbon to nitrogen ratio, therefore, they have less carbon available for microbial degradation. As a result, the carbon sequestration of soil is improved after amendment with biochar (Demisie et al. 2014). Bacteria and fungi react and respond to the changes in pH, water conditions, and other environmental factors in their own way. Soil macro aggregates (>200) are better colonized by fungi compared to bacteria because fungi are favored in higher soil organic carbon and higher carbon to nitrogen ratio. In this way, fungi are favored over bacteria in biochars that promote macro aggregates formation (Ascough et al. 2010; Zhang et al. 2015).

14.4 Reduction in Toxicity of Contaminants to Microorganisms

Biochar has the potential to reduce the toxicity of soil contaminants for microbial communities. Koltowski et al. (2017) revealed that microbe mortality could be reduced by the use of willow biochar (700 °C) in soils contaminated with organic pollutants and heavy metals (Farooq et al. 2022; Ma et al. 2022a, b, c; Nawaz et al. 2022; Naz et al. 2024). It also enhanced the reproduction of *Folsomia candida* and reduced the leachate toxicity to *Vibrio fischeri*. The possible mechanism involved is the immobilization of organic pollutants and heavy metals (Zainab et al. 2021; Bibi et al. 2024; Saleem et al. 2022) like nickel, manganese, chromium, cobalt, cadmium and aluminum on the surface or pore of biochar. This mitigates the soil pollutants and provides favorable conditions for the growth of microorganisms as well as plants (Zielińska and Oleszczuk 2016).

Application of rice straw biochar reduced the concentration of zinc, lead, copper, and cadmium by up to 68%. This truncates the heavy metal stress from *Bradyrhizobium japonicum* i.e. N-fixing bacteria which in response fixes the nitrogen for plant growth (Seneviratne et al. 2017). Moreover, alleviating the stress of the heavy metal from microorganisms improves the interaction between soil microbial communities and biochar which have profound effects on the fertility of the soil.

14.5 Modification of Microbial Habitats

Biochar improves the physical properties of soil and thus modifies the microbial habitats indirectly. It controls the transport of microorganisms, enhances soil aeration, and reduces bulk density. Biochar increases water retention and improves the availability of nutrients to the microbial cells (Abit et al. 2012; Abel et al. 2013). In addition, it protects against dry-wet cycles occurring in the natural ecosystem which are detrimental to microbial activities (Liang et al. 2006). Biochar also modifies the pH of soil. Compared to chemical variables i.e. electrical conductivity, carbon and nitrogen content, a slight change in the pH (0.2–0.3 units) can affect the soil microbial community. Mitigation of heavy metals (for example aluminum) and increase in pH simultaneously increase the abundance of bacteria in soil (Qian et al. 2013).

Bacteria and fungi respond differently to different pH because bacteria are more sensitive to slight changes and can tolerate a narrow range of pH. So bacteria and fungi retort differently in biochar amended soils which may alter the structure of microbial communities in soil (Rousk et al. 2010). In North to South America, the population of Bacteroidetes, Actinobacteria, and Acidobacteria increased in soil when biochar bring the soil pH in the range of 3.2–9.0 (Lauber et al. 2009). Biochar pH has a direct relation with pyrolysis temperature i.e. increases with increasing pyrolysis temperature because of a reduction in volatile matter content and acidic functional groups. Thus biochar prepared at high temperature is more efficacious in improving the pH of the soil (Mukherjee et al. 2011).

14.6 Negative Impacts of Biochar on Microbial Diversities

Most investigations center around the effect of biochar on physiochemical characteristics of soil rather than biological properties. Soil microbial community is sensitive towards the environmental changes and their activities can stipulate the environmental changes before head. The amendment of soil with biochar can affect the diversity of soil microbial communities directly by changing the microbial community or indirectly by influencing the environmental factors (Sun and Lu 2014). The surface characteristics and highly aromatic hydrocarbon structure provides a habitat for specific bacteria, algae, and fungi and can resist the non-specific population of microorganisms.

Many studies have postulated the negative impacts of biochar on the microbial activities in the soil as shown in Table 14.2. The activity of large cockroaches is reduced by ~20–25% by the use of pine extract biochar (Bastos et al. 2014). Similarly, it also affects the diversity of microbial communities in the soil. In an experiment, Anderson et al. (2011) added biochar to contaminated water and observed a reduction in the microbial count of water, especially Micromonospora (7%) and Streptomyces (11%). Many studies have reported a potential drop in plant growth, crop yield, and availability of nutrients after the amendment of soil with

Table 14.2 Impact of various types of biochar on microbial communities

Feedstock	Soil	Effect	Impact of biochar	References
Apple tree (500 °C)	Paddy soil	–	Inhibition of photosynthetic microorganisms	Jia et al. (2018)
Corn Stover (600 °C)	Loamy temperate soil	0/−	It reduced the bacteria-to-fungi ratio and basal soil respiration. No change in microbial biomass	Domene et al. (2015)
Eucalyptus marginata Donn ex Sm. (600 °C)	Tensol Grey Orthic Sandy soil	–	Reduction in microbial mass, organic matter decomposition, and microbial community because of the decreased N mineralization by biochar addition	Dempster et al. (2012)
Maize corn cob rachis (450–500 °C)	Haploxerept Fluventic Sandy loam	–	No change in functional microbial diversity Depletion of microbial biomass	Andrés et al. (2019)
Maize straw (450 °C)	Fluco-aquic loamy soil	–	Decrease in microbial biomass G^+, G^-, fungi and bacterial content reduced	Wang et al. (2015)
Maize straw (450 °C)	Hapli-Ustic Cambiso	+	Reduced C mineralization Increased microbial biomass Increase in bacterial and fungal diversity	Chen et al. (2019)
Sawdust, Hickory and oak wood (500 °C)	Coarse-silty loam Aridisol	0	No change in enzyme activity, microbial biomass, diversity, and mycorrhizal fungal biomass	Elzobair et al. (2016)
Panicum virgatum L. (two-stage-pyrolysis)	Aridisol Fine	–	Crop shoot biomass is inversely proportional to biochar Affected microbial population Reduction in fungi to bacteria ratio	Kelly et al. (2015)
Quercus robur L., *Fagus sylvatica* L., and *Fraxinus excelsior* L. (480 °C)	Eutric Cambisol	0	The population of decomposing bacteria increased Fungal population declined	Jones et al. (2012)
Quercus robur L., *Fagus sylvatica* L., and *Fraxinus excelsior* L. (480 °C)	Eutric Cambisol	0	No long term effect on bacterial growth Initially decreased the fungal population which stabilizes later	Rousk et al. (2013)
Rice husk (>480 °C)	Pristine agricultural soil	+/−	Microbial biomass increased Fungal population declined Increased bacterial population	Anyanwu et al. (2018)
Rice straw (500 °C)	Hydromorphic paddy soil	+/−	Actinomyces increased by 20% Crop yield reduced *Fusarium oxysporum* and fungi decreased	Chen et al. (2018)

(continued)

Table 14.2 (continued)

Feedstock	Soil	Effect	Impact of biochar	References
Wheat straw (350–550 °C)	Anthrosol Hydroagric Paddy Stagnic	+/−	Microbial biomass increased Fungi to bacteria ratio declined	Liu et al. (2019)
Wheat straw (350–550 °C)	Hydragric Anthrosol Sandy loam	+/−	Decrease in *Glomeromycota, Ascomycota, Hydrogenophilaceae,* and *Methylophilaceae* Microbial biomass remains unaffected Bacterial population increased Fungal population declined	Chen et al. (2013)
Wheat straw (350–550 °C)	Hydragric Anthrosol Sandy loam	–	Increased α-bacterial diversity Reduced population of Basidiomycota (66%) and Ascomycota (11%) Declined fungal population	Zheng et al. (2016)
Switch grass (450–600 °C)	Sandy loam Calcined clay	–	Reduced the population of bacteria especially *E. coli* in soil	Gurtler et al. (2020)
Wheat straw (500 °C)	Planting soil	–	Population of *Fusarium* spp. declined significantly	Wang et al. (2020)

biochar. In one experiment, it reduced the yield of perennial ryegrass production, and in another reduced the wheat production by 46% and 70% (Baronti et al. 2010; Khan et al. 2022; Saini et al. 2022). Nie et al. (2018) observed a substantial reduction in the fungus population with the increase in biochar application.

As biochar enhances the nutrients and water availability it reduces the need for mycorrhizal associations. In this way, biochar increases the phosphorous availability and reduces fungi abundance. Similarly, biochar can also affect microbial biomass in soil. Compared to the control, the soil amended with biochar faced a significant reduction in biomass of microorganisms as revealed by Dempster et al. (2012). In another field experiment by Castaldi et al. (2011) no change was prominent in microbial biomass even after 3–14 months of wood biochar addition.

14.7 Bactericidal and Anti-pathogenic Effects

Some types of biochar contain nitrification inhibitors which result in nitrification reduction. Biochar may be equipped with bactericidal or fungicidal compounds like α- and β-pinene, ethylene, pinecarveol, aldehydes, and acetaldehydes which can restrain the activities of microorganisms in the soil (Nguyen et al. 2017). The bactericidal activity of biochar depends upon the content of volatile organic compounds, pyrolysis temperature, and the type used for biochar (Clough et al. 2013). For instance, α-pinene retained in the *Pinus* biochar halts the population of Nitrosomonas (Ward et al. 1997).

Similarly, the denitrification process is also affected by biochar amendment. It reduces nitrous oxide emissions by up to 50%. Nitrous oxide may bind to the metal ions (Copper or Ferric) embedded in biochar leading to a reduction of nitrous oxide emission (Cayuela et al. 2014). Biochar reduces the substrate availability by absorbing carbon and nitrogen. In this way it reduces the accessibility of nitrogen and carbon into the soil which limits the activities of microorganisms in soil especially the population of denitrifying bacteria decreases drastically because biochar absorbs soil organic matter and distribute it into organo-mineral fractions (Joseph et al. 2010).

Biochar strengthens the structural and functional diversity of the rhizosphere which triggers a rivalry between natural soil biota and pathogens for food resources available in the soil. The exact mechanism of pathogen resistance is not clear yet. However, the complex interaction between pathogen, host plant, and soil environment could bring disease suppression mechanism (Debode et al. 2020; Al-Zaban et al. 2022; Solanki et al. 2022). Biochar has a diverse array of mechanisms to suppress the growth of pathogens (Metayi et al. 2022; Mehmood et al. 2021). They have pores in which they absorb the beneficial microorganisms and protect them from pathogens as shown in the Fig. 14.1. It may activate the plant defenses indirectly and resist pathogens in the rhizosphere (Amna et al. 2021).

Five mechanisms of pathogenic resistance were summarized while studying the 13 pathosystems. These mechanisms include changes in nutrient availability (Adnan et al. 2018a, b, 2019, 2020, 2022; Deepranjan et al. 2021; Guofu et al. 2021; Zafar et al. 2020a, b, 2021), and abiotic conditions (Ali et al. 2022d; Dola et al. 2022;

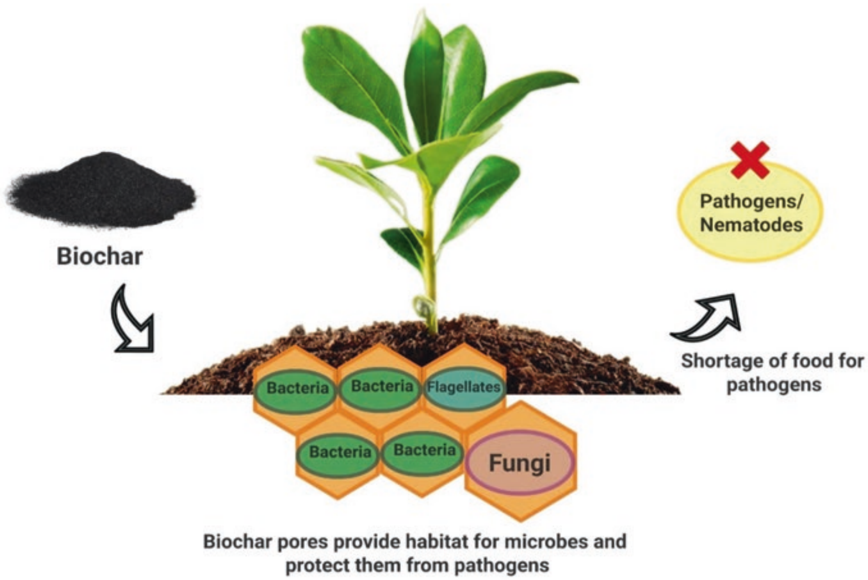

Fig. 14.1 Biochar contains pores that serve as a habitat for beneficial microorganisms and their population grows. This provokes competition between beneficial and pathogenic microorganisms

Faryal et al. 2022; Saeed et al. 2022; Wahab et al. 2022; Abdul et al. 2021a, b), increase in abundance of symbiotic microorganisms, strengthening of plant resistance, sorption of phytotoxic and allelopathic compounds that are hazardous to plants, or availability of fungi toxic compounds on the surface of biochar.

Many studies have been carried out to alleviate the pathogenic species from the rhizosphere of plants. Elmer and Pignatello (2011) used commercial quest biochar for the growth of *Asparagus sp.* which protected the plant against the *Fusarium* crown and root rot. Silva et al. (2020) used the biochar made from *Eucalyptus urophylla* and *Eucalyptus saligna* which reduced the *Fusarium* wilt in tomatoes. *Fusarium oxysporum* and *Fusarium asparagi* were also inhibited by coconut charcoal-carbonized Chaff biochar when applied on *Asparagus officinalis* (Matsubara et al. 2002).

Postma et al. (2013) used biochar made from pig bone to alleviate the disastrous effects of *Fusarium oxysporum* from *Lycocperisicon esculentum*. In *Zea mays* field poultry fecal waste biochar was used to inhibit *Fusarium verticilloides* (Akanmu et al. 2020). Citrus wood biochar could be against *Leveillula taurica* for *Capsium annum* plant species (Elad et al. 2010). Zwart and Kim (2012) used biochar produced from *Pinus ellioti, Pinus palustris, Pinus taeda*, and *Pinus echinata* to inhibit growth of *Phytophthora cactorum,* and *Phytophthora cinnamomi* in *Quercus rubra* and *Acer rubrum*. Postama et al. (2013) used pig bone biochar in fields of *Lycopersicon esculentum* to protect them from *Phytium aphanidermatum*. *Ocimum basilicum* and *Capsicum annuum* could be protected from *Pythium ultimum* using the spruce bark biochar. However, it did not affect the reduction of pathogenicity (Gravel et al. 2013).

In *Cucumis sativus*, biochar from eucalyptus wood chips could be used against *Pythium aphanidermatum* (Jaiswal et al. 2019). Harel et al. (2012) reported the effectiveness of biochar made from Citrus wood–crop wastes in *Fragaria ananassa* against *Podosphaera aphanis*. *Ralstonia solanacearum* in *Lycopersicon esculentum* can be resisted by biochar made from municipal waste and peanuts shells (Nerome et al. 2005). Moreover, Jaiswal et al. (2014) reported the positive impact of biochar produced by pyrolysis of greenhouse waste and Eucalyptus wood chips in *Phaseolus vulgaris* and *Crocus sativus* against *Rhizoctonia solani*.

14.8 Impact of Toxic Biochar Compounds

Biochar has the ability to alleviate the infertility of soil by mitigating various pollutants like polycyclic aromatic hydrocarbons, pesticide residues, polychlorinated biphenyls, and other potentially toxic metals (El-Naggar et al. 2019). However, biochar has also been reported as a source of dangerous organic compounds which might be hazardous to microorganisms in soil. For example, polychlorinated dibenzodioxins, and dibenzofurans produced during the pyrolysis of biochar can pose a threat to the microbial population (Lyu et al. 2016). Similarly in another study, Kookana et al. (2011) found that compounds like acrolein, formaldehyde, xylenols, cresols, and PAHs are hazardous to microorganisms as well as plants and soil. Volatile organic compounds are produced during the pyrolysis of biomass.

Volatile organic compounds include chemicals with low molecular weight (cresol, phenol, methylate phenol, methanol, propionic butyric, and acetic acid). All of these chemicals, individually or in a mixture, are toxic and carcinogenic for humans (Brtnicky et al. 2021). Volatile organic compounds are also produced by bacteria as signal molecules that recruit other microbial populations e.g. bacterial volatile organic compounds recruit rhizobacteria to promote plant growth (Ali et al., 2022a, b, c, d; Raza et al. 2021; Afridi et al. 2022). These volatile organic compounds can also alter the nitrogen cycling through inhibition of nitrification. So the presence of volatile organic compounds in biochar can also alter the diversity of microorganisms. They can halt the mycelial growth of fungi (Chen et al. 2013).

The polycyclic aromatic hydrocarbons concentration in biochar is usually defined by the method and conditions used for the biochar production. The polycyclic aromatic hydrocarbons concentration in biochar was analyzed by Brown et al. (2006). They indicated that pyrolysis temperature determines polycyclic aromatic hydrocarbons level. At low temperature, polycyclic aromatic hydrocarbons having low molecular weight were in abundance and at high pyrolysis temperature, polycyclic aromatic hydrocarbons with high molecular weight were in abundance. Wang et al. (2017) found that the speed of the pyrolysis process also determines polycyclic aromatic hydrocarbons content. Fast pyrolysis and short residence time resulted in high polycyclic aromatic hydrocarbons yield compared to slow pyrolysis and long residence time. Moreover, the facility used for biochar production also affects the polycyclic aromatic hydrocarbons content.

The use of traditional kilns in which tar oils and syngas is not eliminated results in a 10% increase in polycyclic aromatic hydrocarbons content in biochar (De la Rosa et al. 2016). Therefore, different threshold levels of polycyclic aromatic hydrocarbons have been assigned to the biochar. Various biochar products have various concentration of polycyclic aromatic hydrocarbons ranging from 0.1 to 10,000 mg/kg. That's why the intended properties of biochar to be used should be determined before exercising it in the agricultural soil (Wang et al. 2017).

14.9 Indirect Impact of Biochar on Microorganisms

Most of the literature highlights the benefits of biochar amendments, but there are also some limitations to these benefits. First and foremost, agricultural soil faces inhibitory effects because of biochar aging which increases the need for intermittent addition of fresh biomass to sustain a normal soil-water environment and nutrient cycling. For example, Anyanwu et al. (2018) revealed that the growth of fungi and earthworms was affected by the pernicious effects of biochar aging in soil. Moreover, the underground root biomass of *Solanum lycopersicum* and *Oryza sativa* were also reduced by biochar aging. In addition, the amendment of soil with specific biochar is limited to specific soil. Thus same biochar cannot be used for different types of soil and if used may have baneful effects on soil fertility and microbial populations (Zhu et al. 2015). Moreover, biochar amendment also boosts the growth of weeds which compete with plants and soil biota for nutrients and survival.

In a study carried out by Safaei Khorram et al. (2018), an increase of 200% in weed growth was evident after application of 15 t/ha, and repeated application of biochar was suggested to worsen the condition. In another experiment, Vaccari et al. (2015) found that after the application of biochar on targeted parts of plants only the vegetative growth increased but the fruit yield remained unchanged. It could also delay the flowering of plants (Hol et al. 2017). Biochars came up as a solution to mitigate pollutants in the soil which could help microorganisms to develop better communities in the soil but this attribute of biochar is very selective. For example, biochar amendment could not help with the mitigation of di-chloro diphenyl tri-chloro ethane (DDT) (Denyes et al. 2016).

Another drawback of biochar is that it has a very high content of ash if it is produced at a very high temperature. This may produce a noxious effect on plant growth and soil microbial community (Butnan et al. 2015). In many cases, biochar also absorbs the available nitrogen and traps essential nutrients which are required for the growth of plants and the sustainability of microbial populations. It may act as a competitor by reacting with soil nutrients instead of ensuring their availability for plants and microorganisms (Joseph et al. 2018). For example, phosphate is absorbed by the biochar when phosphorus fertilizer is applied with biochar for synergistic benefits. This sorption results in the unavailability of phosphorus for plants and microorganisms (Xu et al. 2016).

14.10 Conclusion

Biochar has come forward as a solution to alleviate the infertility of soils. It can ameliorate the soil's physiochemical as well as biological properties directly or indirectly because of its structure and properties. Soils amended with biochar have improved phosphorous and nitrogen availability, pH, SOM, water-holding capacity, and nutrient availability. These advantages of biochar help specific microorganisms in their survival and growth. Microorganisms colonize the biochar because of its porosity and biochar protects them from pathogens. It serves as a storehouse of nutrients and water, alleviates the toxic heavy metals from the soil, and modifies the habitat for microorganisms in degraded and sandy soils. However, the benefits of biochar are limited by the type of feedstock used, pyrolysis temperature, pyrolysis speed, and the aging of biochar. It may have no or negative effects on the abundance of microorganisms. It may contain bactericidal, fungicidal (α- and β-pinene, ethylene, pinecarveol, aldehydes, and acetaldehydes) or toxic compounds) that are detrimental to microbial populations. In the review of the discussed pros and cons of biochar, it seems to be a valuable supplement if its effects and properties are tested before amendments in agricultural fields. Further studies are needed to address the negative effects to improve the efficacy of biochar in favor of microorganisms, plants, and soil.

Acknowledgments Not applicable

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Chapter 15
Biochar and Arbuscular Mycorrhizae Fungi to Improve Soil Organic Matter and Fertility

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Abstract Increasing feeding mouths are the vital element of increased food production and demand. The required resources (i.e. land, water and nutrients) to produce food are limited and decreasing with the passage of time. Moreover, intensive farming and poor soil management are depleting the soil organic matter and hence the maintenance of soil fertility status is a critical issue for the scientists. In brief, soil fertility and health are directly linked with farm profitability. In this scenario, the biochar (BC) and arbuscular mycorrhizae fungi (AMF) have the tremendous ability to sustain soil fertility and productivity. In addition, the application of both BC and AMF not only increases the production per unit area but also improves soil health for future generations. Here we reviewed that biochar improved the soil

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porosity and stability, soil structure, soil aggregation, tensile strength, soil infiltration, soil penetration resistance, nutrient cycling, water holding capacity, and reduce the runoff and erosion. Moreover, BC is attracting global scientists to promote sustainable and environmentally friendly agriculture because it may help to decrease fertilizer requirements and reduce carbon emissions. The synergism effect of BC and AMF was noted. Reviewed literature indicated that combined application of BC and AMF resulted in significant increase in AMF spore number, microbial biomass, and soil enzyme activities both in the fertile and non-fertile soils. Moreover, they also promote growth, physiological petameters, root architecture and morphology.

Keywords Arbuscular mycorrhizae fungi · Soil organic carbon · Biochar · Microbial activities · Soil productivity

15.1 Introduction

Soil plays an important role in ecosystem services, landscape production, human development, agriculture production, and climate change mitigation (He et al. 2021). Soil health plays an important role in the growth of the plant in a natural environment. In the past years, ecological and environmental issues such as soil degradation, soil contamination, water shortages, climate change, and fertility loss have decreased crop yield, increased the abiotic and biotic stresses, and posed serious risks to food security (Murtaza et al. 2021; Abdul et al. 2021a, b; Abdi et al. 2021; Adnan et al. 2018a, b, 2019, 2020; Deepranjan et al. 2021).

It is mandatory to consider the quality parameters of soil, they do not always respond similarly to organic matter and microbial Inoculation. And plant efficiency responses depend on experimental conditions, which consist of the choice of organic matter, type of plant and species, experimental conditions, type of experiment (studies of field or pot), and nutrient ratios (Vahedi et al. 2021). Greenhouse gas

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emission, organic matter mineralization, nutrient cycling, and decomposition processes can be controlled and highly influenced by micro-biome in soil. Microbes in soil have great importance for soil function.

The activity of soil microbes regulates almost 80% of the functions in soil. Using microbial biomass in the soil can indicate the soil and activities of microbes. Further, we can monitor all the changes which occurred in the soil after the addition of several amendments like soil pollution and management practices (Oladele et al. 2019). Biochar applications can enhance the physical health of the soil, consisting of texture, air, structure, density, water temperature, etc. Biochar amendments in the soil enhance the firmness of soil aggregates, especially in (sandy clay). Eventually, it is efficient for improving drought conditions by water holding capacity in soil (Das et al. 2020). The specific surface area stands for an expressed as per unit of mass and it represents the surface area of each particle in the sample. A larger surface area promotes additional colonization of native Microorganisms, and all biological activities are affected by specific surface area in soil. After increasing specific surface area and applying biochar amendments, water retention can increase in soil (Barna et al. 2020).

For soil nutrients, soil organic matter is the main source in soil. Soil organic matter is useful for enhancing the microbial activities in soil and for, increasing nitrogen absorption and reducing the loss of nitrogen through volatilization (Mandal et al. 2021). The formation stability of aggregates in the soil is influenced by biotic and abiotic factors, consisting of soil moisture, community structure, soil organic matter, plant species, fertilization, microbiome, tillage, and activity of soil fauna (Barna et al. 2020). Furthermore, soil organic matter can improve the structure's growth in soil, crop development, and physical properties (Tan et al. 2017). Soil dissolved organic matter is a major source of carbon in the soil for the microbial community. Microbes interact with terrace metals in soil, influencing their fate, bioavailability, and transportation. In soil, dissolved organic matter consists of biologically obtained materials like polysaccharides, humic substances with low molecular mass, and proteins (Yang et al. 2019). Carbon in soil occurs in two forms such as soil organic carbon and soil inorganic carbon. Soil organic carbon is an important tool to control the behaviour of organic and inorganic soil pollutants (Khalid et al. 2020).

Different important soil components like microbial biomass dissolved organic matter and light fraction organic matter can be influenced by Active organic matter in the soil. Active soil organic matter improves the soil quality and impacts the soil material cycle. Moreover, active soil organic matter is good for maintenance and stabilizes the granular structure in the soil. Furthermore, they provide phosphorus, nitrogen, potassium, and some essential micro-nutrients in the soil, which are required for plants. But the concentration of active soil organic matter is impacted by temperature, cation exchange capacity, water content, pH and soil physical properties (Tan et al. 2017). Organic carbon in the soil is obtained from the carbon inputs in a plant through roots, arbuscular mycorrhizal fungi, and shoots (Huang et al. 2021). Soil stability is known as the sensitivity of soil to artificial and natural disturbances. In addition, soil quality indicators are considered several biological properties like microbial biomass, amino acids, activities of earthworms, respiration, and soil enzymes (Mandal et al. 2021).

Modification with several organic waste materials like manure, straw, compost, and crop residues can create the soil organic matter in the degraded soil, which plays a major role in restoring chemical, ecological, biological, and physical functionality. If soil organic increases, it can directly affect the structure of the microbial community, mineralization of nutrients, biomass turnover, and soil microclimate (Amoah-Antwi et al. 2020). However, it was seen that the any increased concentration of salt can affect the ability of the plant to absorb water and thus, it disturbs the osmotic balance, guard cell activities, hydraulic conductivity, metabolic processes, nutrient absorbances, net photosynthetic rate, stomatal conductance, and intercellular carbon dioxide concentration. These all factors have adverse effects on the ability of plant development and growth (Elhindi et al. 2017).

15.2 Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi are an important component of a sustainable plant system in plants among the other microorganism that live in the rhizosphere of plants. Arbuscular mycorrhizal fungi are an essential, integral part of the soil-plant system, which forms a symbiotic relationship with land plants. The word "mycorrhiza" is known as fungus roots (Upadhyay 2015). Mycorrhiza has a symbiotic relationship with the endophytic root fungi and plants. It is known as one of the earliest and worldwide interactions considered most important for plant biomass production. In an ecosystem between other functions, mycorrhizal fungi provide mineral nutrients to their host plants, and In return, they get photosynthetically derived carbohydrates (Hammer et al. 2015). In terrestrial ecosystems, arbuscular mycorrhizal fungi are present worldwide. Arbuscular mycorrhizal fungi allow nutrient uptake in plants and improve the regulation of carbon dynamics in soil. It consists of more than 200,000 species and present in grasses, trees, hornworts, and herbs habitat. They represent greater than 80% of plant species in the terrestrial ecosystem (Wei et al. 2019). Nutrient uptake and root colonization of plants increase due to arbuscular mycorrhizal fungi hyphal networks, which grow in the outer depletion zone of roots (Fig. 15.1). Compared to other weed agronomic species, "velvetleaf" is considered a strong arbuscular mycorrhizal fungi host with greater colonization rates. When arbuscular mycorrhizal fungi colonization increased in the field, both nutrient shoot tissue, and biomass has been increased. Another study indicated that fungal Inoculation could increase the (Cu, P, K, Mn, and Mn) in both roots and shoots of chicory (Zhao et al. 2021).

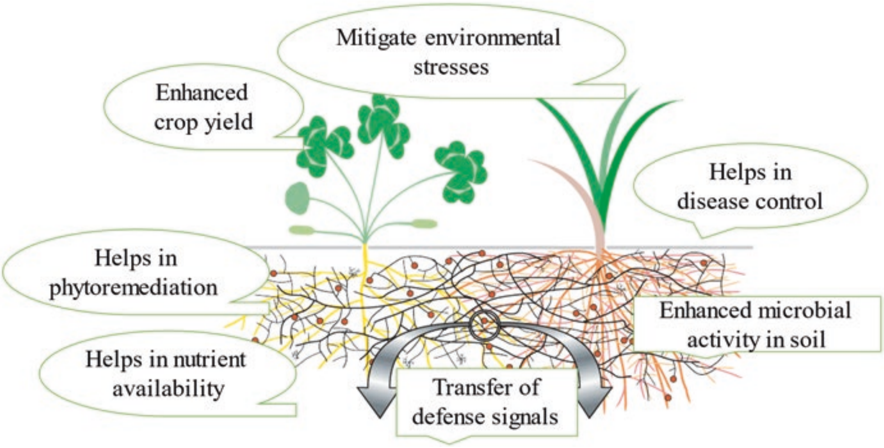

Fig. 15.1 Role of arbuscular mycorrhizal fungi is the soil ecosystem

15.3 Classification of Arbuscular Mycorrhizal Fungi

- Vesicular-arbuscular mycorrhizae: It is a member of zygomycetes fungi and derived from the 'arbuscular' characteristic structure. That occurs in vesicular and cortical cells.
- Ectomycorrhiza: They are from basidiomycetes. Around roots, they form a mantel, and between root cells. They form a Hartig net.
- Orchid mycorrhizae: They are linked with orchid roots and create hyphal coils inside roots and stems.
- Ericoid Mycorrhiza: This is a type of plant that members of Ericales like tea, kiwi fruit, rhododendron, persimmon, blueberry, azalea, and cranberry. They produce hyphal coils of root hair in epidermal cells. Arbuscular mycorrhizal fungi are among the most popular and oldest symbiosis among all of them. According to an estimate, it evolved 400 million years in the form of first land plants (Upadhyay 2015).

15.4 Symbiosis of Arbuscular Mycorrhizal Fungi with Plants

A symbiotic relationship between arbuscular mycorrhizal fungi and roots benefits the soil structure formation, such as pore structure, wetting rates, and aggregate stability. Moreover, Arbuscular mycorrhizal fungi promote tolerance of stress in plants under severe drought, heavy metals, salinity and nutritional stress (Guo et al. 2013). Arbuscular mycorrhizal fungi are a primary biotic soil component and comprise the number of obligate biotrophs roots which exchange 80% benefits of the mutual plant and consider a natural biofertilizer because they provide nutrients, pathogen protection, interchange for photosynthetic products, and water to their host. Its appearance coexists with the emergence of plants on land, which are ancient root symbionts. If it is not present in an adequate amount in the soil ecosystem, it can decrease the functioning of the efficient ecosystem. Many factors like inoculation timing, compatibility of species with another target environment, the extent of spatial competition in a target niche with other organisms affected the success of the inoculation process, and arbuscular mycorrhizal fungi persistence in soil (Berruti et al. 2016). The changes in arbuscular mycorrhizal fungi community diversity and composition reflect some nutrients demanded in agricultural soil (Zhu et al. 2016). Moreover, arbuscular mycorrhizal fungi globally claimed that they can aid in the mitigation of nutrition and water stress in plants (Cheng et al. 2021).

For more than 30 years, arbuscular mycorrhizal fungi has been used to restore mine areas due to their obligate root symbionts nature, and they can improve the establishment and survival of the plant (Ohsowski et al. 2018). However, there is a huge difference between the colonized plant of arbuscular mycorrhizal fungi and plants that are non-colonized. Under nutritional stress, mycorrhiza improve the absorption of phosphorus, calcium, and potash. Moreover, in sever soil stresses, the balance between different ionic concentration such as Ca/Na and K/Na is improved due to arbuscular mycorrhizal fungi (Elhindi et al. 2017).

The efficiency of arbuscular mycorrhizal fungi is improved along the application of biochar in all type of soil systems. In the presence of biochar, arbuscular mycorrhizal fungi increases the root colonization and hence improved the root architecture (Wang et al. 2020). In addition, the increase in colonization is linked with the characteristics of biochar in the existence of some organic matter in soil (Atkinson et al. 2010). Moreover, microorganisms in soil like arbuscular mycorrhizal fungi represent an essential link between mineral nutrients in soil and plant. They can ensure the availability of nutrients from the soil and act as natural fertilizers (Begum et al. 2019). The arbuscular mycorrhizal fungi mycelium belongs to the root system (Diagne et al. 2020). From the volume of soil, they obtain nutrients that are unavailable to roots. Moreover, fungal hyphae are thinner than roots, and because of that, it penetrates the smaller pores (Jiang et al. 2021).

Mineral nutrients and carbohydrates can exchange inside the roots over the interface between fungus and plants (Berruti et al. 2016). Arbuscular mycorrhizal fungi colonize the root cortex and shape the structure of branches inside the cell, for example, “arbuscules,” which is known as a functional site for nutrient exchange. It has been observed that arbuscular mycorrhizal fungi control and regulated the nitrogen dioxide emission by improving plant nitrogen uptake and assimilation (Nanjundappa et al. 2019). Consequently, it reduces soluble nitrogen in the soil and causes a limitation of denitrification. Because of anthropogenic activities, if it is not present in sufficient quantity in the soil, it can reduce the functioning of an efficient ecosystem (Berruti et al. 2016). The presence of arbuscular mycorrhizal fungi can stimulate the activities of microbes in soil and promote the activity of soil microbial biomass and phosphates (Vahedi et al. 2021). The availability of phosphorus can interrupt the symbiotic interaction of arbuscular mycorrhizal. Arbuscular mycorrhizal fungi positively affect plant production in an open field and under controlled conditions, which add some nutritional benefits to host plants due to soil fungal symbionts (Atkinson et al. 2010).

Arbuscular mycorrhizal fungi have been considered good for promoting growth in stressful conditions. The working of fungi is started along with formation of colonization that improve nutritional, physiological, and morphological changes to enhance the vigour and plant growth by improving the water and nutrients access through slight modification of the root architecture. However, in some cases, it was seen that it improve the photosynthesis rate in the host plant by changing the physiological status and enhancing the phosphorus content in the leaf area (Hashem et al. 2019). Consequently, aggregate formation is affected by secreted exudates. Glomalin, known as glycoprotein, acts as a glue in soil aggregation. Arbuscular mycorrhizal fungi secreted hyphae and become an important part of soil organic matter fraction called glomalin soil protein (Liu et al. 2020). Due to microbial degradation, resistance, and insolubility in water, glomalin becomes extremely stable. There is a close relationship between extraradical hyphae, intraradical arbuscular mycorrhizal fungi colonization, and macroaggregate of water-stable content in the soil (Barna et al. 2020). Arbuscular mycorrhizal fungus interaction includes the alteration in the signalling process of mycorrhizal fungi changing in soil physicochemical properties. Biochar work as a refuge for arbuscular mycorrhizal fungi (Han et al. 2016).

Around 95% of plants in the terrestrial ecosystem characteristically belong to mycorrhizal families, which means arbuscular mycorrhizal fungi symbiosis happens in most habitats (Liang et al. 2009). Arbuscular mycorrhizal fungi occur as a community in roots and soil, so they collectively contributed to nutrient uptake such as phosphorus. Reconstructed communities of Arbuscular mycorrhizal fungi increase the plant growth in soil (Wang et al. 2007). It was noted that arbuscular mycorrhizal fungi contribute mainly to soil organic matter by generating demand for the sink as plant carbon and distributing it to underground biomass of hyphal. In addition, arbuscular mycorrhizal fungi impacted the soil carbon by affecting the rate of decomposition of soil organic matter by interacting with other biotas in the soil (Bi et al. 2020). However, arbuscular mycorrhizal fungi do not directly influence the decomposition of organic matter (Ren et al. 2021). But it depends on saprophytic microbes which decompose the complex carbon sources for nitrogen availability. Interaction between microbes and arbuscular mycorrhizal fungi can be because by rhizodeposition of hyphal exudates (Parihar et al. 2020).

15.5 Biochar as Soil Amendment

Biochar is a recalcitrant organic residues produced to improve the soil carbon accretion through biomass degradation thermally under anaerobic conditions (Lustosa Carvalho et al. 2020). Pyrolysis is a thermal decomposition of biomass that produce biochar as a product. Biochar has become important due to its sustainable use in soil management practices and global climate change issues (Namgay et al. 2010). Global biochar production differs from 0.05 to 0.3 GT C year^{-1}. On the other side, the net worldwide production of the plants is about 60 GT C year^{-1} (Atkinson et al. 2010). After applying biochar, it becomes better to retain moisture in the soil. Biochar improves overall soil quality through many energy sources, mineral nutrition, and carbon for the reproduction and development of microbes (Tan et al. 2017; Ashfaq et al. 2021; Atif et al. 2021; Fahad et al. 2015, 2016; Ibad et al. 2022; Hesham and Fahad 2020; Irfan et al. 2021; Khadim et al. 2021a, b; Khan et al. 2021; Khatun et al. 2021; Muhammad et al. 2022; Subhan et al. 2020; Tariq et al. 2018; Wiqar et al. 2022; Wu et al. 2019, 2020; Xue et al. 2022).

Biochar preparation includes some methods, including carbonization, pyrolysis, flash carbonization, laser, hydrothermal, gasification, microwave carbonization, torrefaction, and plasma cracking. The most common methods for preparing biochar are hydrothermal carbonization, pyrolysis, and gasification (Anae et al. 2021). Biochar includes several types of biomasses as source material, for example, animal manure, crop residues, and woodchips which instantly increase the temperature of pyrolytic sugar cane straw manufacture (Puga et al. 2015). The presence of aromatic sheets on the surface of biochar makes it more amphoteric for adsorbates and enables strong non-linear adsorption. The presence and absence of soil fauna are important factors for stability of biochar in soil (Sashidhar et al. 2020). Biochar consists of extreme stability, a larger surface area, abundant nutrients, a high level of carbon, high porosity, and rich functional groups (Sun et al. 2021). The nature of the feedstock and operational conditions determined the nutrient content in biochar (Pathy et al. 2020).

15.6 Biochar and Soil Physiochemical Properties

Biochar addition improves the soil quality and sequestration of carbon dioxide. Some studies indicate that biochar can change soil pH, bulk density, cation exchange capacity, and physicochemical properties (Zhao et al. 2014). Biochar works as a carbon-rich residue, a relatively charred organic material to improve soil nutrient status. It can change the physicochemical properties of soil by directly releasing nutrients and indirectly changing the concentration of plant-available nutrients (Ohsowski et al. 2018). Biochar can also produce through a straw for the improvement of soil properties. When biochar is added to sandy loam soil, it reduces the soil bulk density and increases the water holding capacity (Li et al. 2021a). However, application of biochar in agricultural coarse texture soil can improve the water holding capacity of soil so plants can get more water and soil porosity (Zhou et al. 2019).

The applications of biochar in the soil have the potential to increase the microbial community, soil fertility, carbon storage capacity, and soil structure and immobilize the toxic metals in the soil (He et al. 2021). Microorganisms are essential for the ecosystem and services in soil. For example, for maintenance of soil health and quality, suppressing pathogens, maintaining soil health and quality, and driving biogeochemical cycles (Palansooriya et al. 2019). Moreover, the application of biochar in the soil can increase the diversity, abundance, and microbial activities in soil. In addition, provision of good substrates and microbial habitats to their metabolic activities can improve the microbial activities by promoting ecological functions, for example, element cycling, plant productivity, enzyme activities, and polluted soil decontamination (Palansooriya et al. 2019). Thus, manure-based biochar is a source of nitrogen for plants. Applying manure-based biochar in the soil can increase the nitrogen mineralization due to release of high nitrogen contents in to the soil system (Dong et al. 2020). After applying manure-based biochar to soil, C: N ratio becomes important due to nitrogen mineralization and immobilization (Puga et al. 2020).

After stimulation of microorganisms, the C:N ratio and pH of organic amendments are also important for nitrogen mineralization (Ameloot et al. 2015). In addition, biochar is considered an ideal carrier for favourable microbes in the soil ecosystem. Due to the presence of volatile organic compounds, minerals, and free radicals in biochar, it can increase soil enzyme activity, microbial niches, and biogeochemical catalysis (Pokharel et al. 2020). However, it has the potential to reshape the microbial diversity which presents in soil. Due to surface area, negative surface charge, and high pore volume, biochar increases the nutrients availability in the soil-to-soil organisms. Biochar material is rich in releasable minerals like nitrogen, phosphorus, potassium, magnesium, calcium and sulfur, essential for microbial growth (Buss et al. 2022). Due to high cation exchange capacity, Biochar can retain cations for a longer time. The application of biochar can reduce nutrient loss in soil, increasing microbial metabolism and increasing their growth (Piash et al. 2021).

Biochar consists of aromatic and aliphatic carbons, which directly influence the characteristics and structure of dissolved organic matter in soil. The dissolved organic matter released from the biochar matrix can chemically alter the nature of nutrients in the soil (Feng et al. 2021). Biochar change encourages microbial activities, alters soil properties, and increases the sorption of organic and inorganic compounds. However, biochar stability depends on the O:C molar ratio. Furthermore, smaller organic particles and minerals can store in these pores (Gliniak et al. 2019). Previous studies proved that biochar application could affect the soil organic carbon pool. The contents of soil organic carbon usually govern soil processes for example reduction, oxidation, desorption, and reduction. This process can affect soil chemistry by changing cation ion exchange capacity, buffering capacity, pH, and redox status of the soil. Consequently, it can alter the pesticide desorption and sorption in soil (Khalid et al. 2020). Previous literature has proved that biochar amendments on have the potential to increase nutrient efficiency and crop yield and decrease the nitrogen dioxide emission in soil. Amendment of biochar ensures the environmental and agronomic benefits (Santos and Pires 2018; El-Naggar et al. 2019; Guo et al. 2020; Hossain et al. 2020).

15.7 Factors Affecting the Properties of Biochar

The biochar produced from different materials could improves the energy, mineral nutrients, and carbon, which increases the physical quality of soil and maintains the soil quality (Vahedi et al. 2021). Biochar produced from Conocarpus plants reduces the infiltration rate and saturated hydraulic conductivity improves the wet aggregate firmness and water holding capacity in soil (sandy loam) (Khajavi-Shojaei et al. 2020). Similarly, addition of biochar from pine wood shows the zero increase in carbon dioxide respiration but on the other hand biochar from grass materials increase the rate of carbon dioxide respiration (Das et al. 2020). During incubation of fresh pyrolyzed biochar, it was noticed that different enzyme behaviour was enhanced (Yadav et al. 2019). The production of biochar at low temperature can reduce the native organic matter via decomposition by aggregation. In addition, it can reduce the potential of biochar for clogging and cementing soil pores (Du et al. 2017). Moreover, the low temperature production biochar had the ability to slow down the release of minerals but provide a constant supply of nitrate, ammonia, and phosphate when applied to improve soil fertility through chemical fertilizers. In the end, nutrient content in biochar from diverse feedstock can result in the availability of nutrients in the soil and reduce the need for chemical fertilizers application (Murtaza et al. 2021).

The sensitivity of biochar at higher temperature pyrolysis can be reduced. So, the uncooperative impact of biochar on the aggregation of soil is associated with greater sensitivity of biochar which bring disturbance in changing conditions of moisture that causes changes in intensive and frequent leaching events (Teutscherova et al. 2020). The previous studies indicated that the feedstock is usually based on wood-produced biochar with the highest surface area (Shaheen et al. 2019; Zhu et al. 2019; Leng et al. 2021; Cao et al. 2022) and straw-based feedstock produces the highest cation exchange capacity (Chandra and Bhattacharya 2019; Luo et al. 2019; Bonga et al. 2020; Singh et al. 2020). That is why, mostly biochar produced from such materials which is alkaline with the capacity of acid-neutralizing till (33%) of agricultural lime because of its hydroxide and carbonate oxide nature. Hence, it reduces the redox potential of soil (Joseph et al. 2021). So, the application of such biochar increases the total average of nitrogen content in the soil. Additionally, biochar with higher calcium contents in their structure, which have the ability to improve nutrient retention, improve moisture, and control release in soil for longer period (Mandal et al. 2021). Biochar which is derived from wood having a 2–80 μm pore diameter, can be beneficial for the activities of mycorrhizal fungi. Moreover, woody biochar from Pinus radiate can increase the bacterial and fungal abundance and enhance the phosphorus solubilizing bacteria. It is demonstrated that fungal hyphae can penetrate inert materials pore (Thompson 2021). For example, inoculation vermiculite is used to prepare arbuscular mycorrhizal fungi (Kumsao and Youpensuk 2021). Some time, arbuscular mycorrhizal fungi inside clay cavities form the spores on clay particle surfaces (Morris et al. 2019).

15.8 Arbuscular Mycorrhizal Fungi and Biochar Interaction

The combination of mycorrhizal fungi and biochar approaches the objective of sustainable plant growth in a viable soil environment (Gliniak et al. 2019). In addition both arbuscular mycorrhizal fungi and biochar enhance soil carbon storage (Agnihotri et al. 2022) rather than the sole application of biochar (Fig. 15.2). Although biochar is rich source of carbon but its functionality was improved along with arbuscular mycorrhizal fungi or inherited availability of mycorrhizal fungi. Initially, it may increase carbon dioxide emission by improving microbial activity for a short duration. Moreover, the carbon emission effect could be significantly reduce through the application of arbuscular mycorrhizal fungi into the soil before the application of biochar (Parihar et al. 2020). It was noted that inoculation of arbuscular mycorrhizal fungi in dry agricultural land improves the light fraction of organic carbon and soil particulate organic carbon mostly due to the increase in glomalin content and mycelia length (Li and Cai 2021; Li et al. 2021b). However, the strong symbiosis between arbuscular mycorrhizal fungi and biochar are seen in all kind of stress environment with the naturally occurring mycorrhizal fungi community (Mickan et al. 2016).

No harmful effect on crop growth and development of arbuscular mycorrhizal fungi and biochar was noted. But still, many research questions need answer about the biochar and plant-promoting mycorrhizal fungi on the soil microbial activities (Hammer et al. 2015). Moreover, biochar applications interact with arbuscular mycorrhizal fungi in different ways with respect to different soil properties and hence, they affect the modification of soil pH and their feedback on the availability of nutrients and structure of microbial communities, which alter the nutrient release, immobilization, or retention, capacity of water retention change and provision of shelter in opposed to fungivore grazing (Wen et al. 2022). Some eternal factor such as intense grazing of animals can decrease the total hyphae in the soil matrix leading to an increase in viable

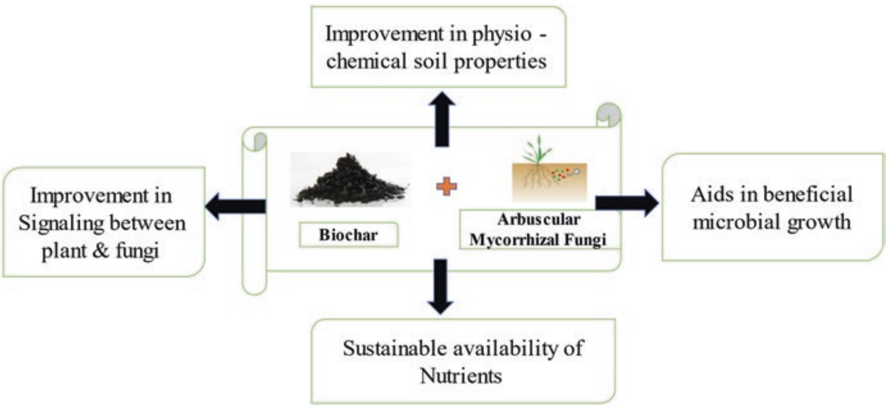

Fig. 15.2 Effects of the interaction of biochar and arbuscular mycorrhizal fungi on soil properties

hyphae that interact with biochar (Gujre et al. 2021). So, this is known that arbuscular mycorrhizal fungi increase the nutrient-rich patches in (inorganic and organic). In addition, arbuscular mycorrhizal fungi uptake nutrients through the external mycelium active part especially from the tips of the growing hyphal (Jabborova et al. 2021).

The presence of long hyphae is necessary to increase uptake of nutrients from larger surface area, mainly for lower mobility ions like phosphate. Moreover, particles of biochar consist of fertile microsites and a high concentration of phosphorus in smaller pores which are unreachable for the direct contact of phosphorus, nitrate, nitrite and other immobilizing minerals (Cheng et al. 2021). In addition, fertile microsites can benefit plants due to their association with arbuscular mycorrhizal fungi that can associate the roots to the surface of charged biochar. The association of arbuscular mycorrhizal fungi is directly correlated with rate of loss of nutrients like ammonium and phosphate from rhizosphere and hence improve the cycling process of nutrients. Biochar rich in cations that could enhance the efficiency of arbuscular mycorrhizal fungi leading to better productivity and efficiency (Xin et al. 2022). For example, a higher amount of phosphorus is transferred and absorbed by plants (Li and Cai 2021). The presence of mycorrhizal fungi in soil or application with biochar can approach the adsorbed nutrients and then available to the plants (Hammer et al. 2014).

Arbuscular mycorrhizal fungi have an associated relationship with all kind of terrestrial plants but its species may vary with respect to different kind of environmental conditions. It will improve the nutrients uptake such as potassium, phosphorus, nitrogen, magnesium, and calcium after its inoculation with the plants or inherent present of mycorrhiza into the soil. Additionally, they increase the carotenoid and chlorophyll content and increase the antioxidant enzymes, such as dismutase, peroxides, superoxide, ascorbate peroxides, and catalase (Nahuelcura et al. 2022; Wang et al. 2022). Moreover, the addition of mycorrhiza improves crop vegetative, and enhance the branching of root systems in plants (Ren et al. 2019). Although sole application of biochar significantly improves the morphological traits of root and plant growth and has positive effects on soil enzymatic activities but its combination with arbuscular mycorrhizal fungi promoted the growth and increase the spinach yield at much higher rate (Jabborova et al. 2021). They also improved the nutritional values.

Biochar can be affected arbuscular mycorrhizal fungi by in four possible ways:

1. Biochar can alter the availability and nutrients level (phosphorus, nitrogen, potash, and carbon) through changes in the physicochemical parameters of soil such as water holding capacity, pH, and cation ion exchange capacity, that affect host plant and fungus.
2. Biochar can change the microbiome of the rhizosphere, which promotes the growth of plants i.e., phosphate mobilizing bacteria and mycorrhizal helper bacteria.
3. Biochar can change the process of arbuscular mycorrhizal fungi signalling in plants (concentration and transport of signal molecules) when allelochemicals are absorbed, they alter the arbuscular mycorrhizal fungi root colonization.
4. Biochar serves as a shelter and microrefugia for hyphae consumers.

15.9 Dynamics of Arbuscular Mycorrhizal Fungi in Response to Biochar

The favourable soil conditions for activities and growth of arbuscular mycorrhizal fungi should be ensured throughout the management of mycorrhizas in the soil of agriculture (Benami et al. 2020). Such favourable conditions will be provided through the application of biochar into the soil at the time of application of fungi (Dos Santos Trentin et al. 2022). The growth of arbuscular mycorrhizal fungi could be inhibited in sever soil and climatic conditions. Under the suitable condition, the arbuscular mycorrhizal fungi abundance increased in the plant root system. The optimal amount of biochar is applied, it increases the availability of microhabitats in topsoil with lower clay content. This contributed to mycorrhizal benefits, for example, enhancing the phosphorus acquisition through plants (Jabborova et al. 2021; Jiang et al. 2021). However, degraded soil can require more biochar, but it also depend on nutrient status or organic matter of the soil. The significance of biochar particle size is rarely considered in association of arbuscular mycorrhizal fungi with plant benefits and changes in soil (Jaafar 2014).

Application of biochar in the soil can increase or decrease susceptibility of the host to symbiotic relations. However, the adsorptive properties of biochar and their high surface area and porosity will promote arbuscular mycorrhizal fungi activity by providing them with suitable habitats (Gujre et al. 2021). The effect of glomalin and arbuscular mycorrhizal fungi root colonization was improved due to cumulative indirect and direct effect of biochar. In addition, biochar provides the nutrients for arbuscular mycorrhizal fungi and mitigate the nutrients stress on the plant root system (Langeroodia et al. 2022) but the effects of this interaction between biological and physiochemical parameters are not clear (Barna et al. 2020). The addition of carbonous materials like biochar or compost in soil along with arbuscular mycorrhizal fungi in the root zone increases the biological activities in soil and soil quality parameters that improve the environment of rhizosphere (Abbaspour and Asghari 2019). Moreover, arbuscular mycorrhizal fungi inoculation and compost amendment increase the microbial biomass, microbial phosphorus biomasses, and organic carbon and amendment of biochar have the same effects on mycorrhizal colonization of root similar to the addition of compost (El Amerany et al. 2020) (Fig. 15.3).

Combining the addition of sufficient amount of biochar amendment with arbuscular mycorrhizal fungi inoculation enhances the quality and quality of biological activities in nutrient stress condition (Dos Santos Trentin et al. 2022). Both biochar and arbuscular mycorrhizal fungi inoculation could be alterative to costly chemical fertilizer (Vahedi et al. 2021). It was noted the biochar has been successfully enhance the spore germination of mycorrhizal fungus and this improvement was because of better chemical and physical characteristics via increased availability of nutrients (Das et al. 2020). It is observed that the addition of biochar and arbuscular mycorrhizal fungi could interact and affect the nitrogen uptake, plant growth, greenhouse gas emission, and soil nitrogen availability from the ecosystem (Li et al. 2019). Improvement in the availability of soil nutrients improves the performance of host

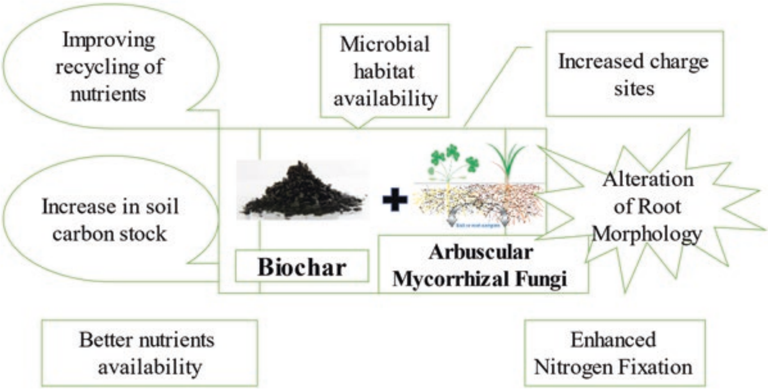

Fig. 15.3 Benefits of combining biochar and arbuscular mycorrhizal fungi

plant and arbuscular mycorrhizal fungi. It elevates the concentration of tissue nutrients and a high colonization rate for host plant roots through arbuscular mycorrhizal fungi (Warnock et al. 2007). Biochar is a suitable habitat for arbuscular mycorrhizal fungi that may include these three possible mechanisms.

1. Arbuscular mycorrhizal fungi improve the availability of nutrients.
2. Secreting metabolites of bacteria helps the arbuscular mycorrhizal fungi to grow.
3. Biochar serves as a shelter for colonizing bacteria and fungi from stressful conditions and predators (Madiba et al. 2016).

The combine effect of arbuscular mycorrhizal fungi and biochar are much stronger as compared to a single effect of them, and it also caused significant stimulation in attributes of photosynthesis, for example, stomatal density, photosynthetic rate, and stomatal pore aperture in controlling seedling of chickpea under stress condition (Hashem et al. 2019). The synergetic effect of biochar and arbuscular mycorrhizal fungi in the soil biological system are;

1. Biochar provides a suitable shelter or habitat for microorganisms in soil which save them from predators.
2. After the addition of biochar, mycorrhizas can influence the growth of plant and soil conditions by altering the properties of physicochemical in soil, such as water and pH in the soil.
3. The interaction of arbuscular mycorrhizal fungi with soil microorganisms can decrease the production of harmful compounds or stimulate the manufacture of the signalling compound.

Amazingly, arbuscular mycorrhizal fungi improve the soil enzyme activities along with increase in microbial communities and microbial attachment on the plant root system with the help of biochar (Xu et al. 2019). In addition, biochar increase the colonization of mycorrhizal and sporulation (Gujre et al. 2021). At the same time, measurement of phosphorus availability in soil and plants is used to indicate the effectiveness of arbuscular mycorrhizal fungi indirectly. Due to extensive hyphal networks, fungal hyphae can dominate the surface of biochar. Compared to the internal surface, differences in the growth form of hyphal are observed on the external surface of the charcoal (Li and Cai 2021). Moreover, the surface of biochar is slowly degraded through chemical processes and soil microbes. It can become a microbial habitat due to the coated organic material. Some forms of biochar can retain the moisture and absorb the cations, which indirectly influence the microbial activities in soil on the surface of biochar. Including hyphae of arbuscular mycorrhizal fungi, some pores with 1–4 μm and 2–64 μm diameter can be approachable to fungal and bacterial hyphae in soil (Basiru et al. 2020). Physical and chemical changes in biochar surface can occur when incorporated into the soil along with activated arbuscular mycorrhizal fungi (Cheng et al. 2021).

Arbuscular mycorrhizal fungi provide mineral nutrients to their host plants, and in return, they receive carbohydrates photosynthetically derived (Saia et al. 2020). So, higher content of nutrients in the soil system resulted into the better plant height and yield of dry shoot matter. Inoculation of Arbuscular mycorrhizal fungi improves the yield of dry shoot matter (Yusif et al. 2016). Moreover, soil amelioration with biochar in the degraded landscape can potentially improve the production of grassland plants, enrich the microbial population in soil and stimulate the arbuscular mycorrhizal persistence (El-Naggar et al. 2019). It has been noted that the sole application of biochar attracts the arbuscular mycorrhizal fungi through the mineral nutrients adsorbed on its surface (Liu et al. 2017). However, without fixed carbon (simple sugars/carbohydrates) from their host plants, arbuscular mycorrhizal fungi cannot complete their life cycle. So, the concentration of carbon in the soil, provided by biochar, influences the abundance of arbuscular mycorrhizal fungi in the soil environment (Warnock et al. 2007). Research indicated that biochar and arbuscular mycorrhizal fungi have three types of mechanisms;

1. Soil quality enhancement.
2. From fungal grazer providing shelter
3. Between plants and arbuscular mycorrhizal fungi improving the signalling mechanism

Arbuscular mycorrhizal fungi enhance the functions of the soil system and balance the nutrient level in the soil. It reproduces spores that are asexual and small multinucleate and significantly increases the numbers of mycelia. Moreover, productivity, biodiversity, and ecosystem variability can balance with arbuscular mycorrhizal fungi diversity (Wen et al. 2022). About 85% of plant families globally colonized through mycorrhizae (Soudzilovskaia et al. 2020). Arbuscular mycorrhizal fungi and biochar are the most popular, and challenging research areas posed through alternative energy production, non-sustainable modern agriculture practices, and global warming. Arbuscular mycorrhizal fungi among other soil microbiota (fungi, archaea, protozoa, invertebrates, algae, bacteria, nematodes, and arthropods) are regulators for soil productivity (Meena et al. 2020). Under extreme nutritional stress conditions, biochar acts as a buffer to provide a safe habitat for arbuscular mycorrhizal fungi, increasing the number of mycelia, arbuscules, spores, and cysts (Begum et al. 2019). Due to the deterioration in soil quality, environmental challenges and food scarcity issues are increasing. The process of green restoration by the combine using of arbuscular mycorrhizal fungi and biochar is a suitable option (Gujre et al. 2021).

15.10 Conclusion

This chapter has shown the arbuscular mycorrhizal fungi and biochar interaction toward sol organic stabilization. The presence of organic matter in the soil directly influences the structure of the microbial community, mineralization of nutrients, biomass turnover, and soil microclimate. Arbuscular mycorrhizal fungi are considering a primary biotic soil component. If it is not present in an adequate amount, it can decrease the functioning of the efficient ecosystem. The addition of biochar improves the soil quality and sequestration of atmospheric carbon sequestration (Fig. 15.4).

Application of both arbuscular mycorrhizal fungi and biochar in the soil can increase the diversity, abundance, and microbial activities in soil. Hence, both mycorrhizal fungi and biochar combination approach would ensure the food security by protecting the environment. In addition, the adsorptive properties of biochar and their high surface area and porosity promote arbuscular mycorrhizal fungi activity by providing them with suitable habitats. In near future, arbuscular mycorrhizal fungi may be recommended as a biofertilizer. Therefore, arbuscular mycorrhizal fungi and biochar may sustain the productivity of agricultural sector by improving the nitrogen uptake, plant growth, reducing the greenhouse gases emission, and increasing the soil nitrogen availability from the ecosystem of plant soil.

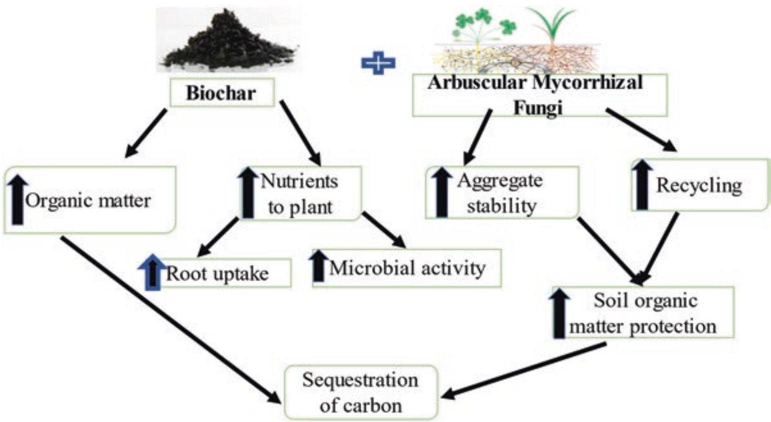

Fig. 15.4 Soil organic matter stabilization by biochar and arbuscular mycorrhizal fungi

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Chapter 16
Biochar Feedstocks, Synthesis and Interaction with Soil Microorganisms

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Abstract Biochar application to soils allows to enhance soil quality and fertility by improving soil structure and replenishment of nutrients. Biochar properties can be tuned by the type of feedstock used to synthesize biochar, and by the synthesis conditions. Biochar application also changes the soil microbial community, and, in turn, the decomposition rate of biochar and nutrient release. Here we review biochar with focus on synthetic methods, feedstocks, interactions with soil microbes.

Keywords Biochar application · Microbe-biochar interaction · Microbial response · Microbial community · Soil amendment

16.1 Introduction

Soil is a complex medium, comprising of soil partials and gravels of varying sizes, mineral nutrients, organic matter, water, air and microbial communities. All these fractions together in variable composition determines the soil physical and chemical

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properties i.e. soil texture, structure, porosity, pH, cation exchange capacity, water holding capacity which ultimately effects water and air movement in soil (Baghdadi and Zribi 2016; Maddela et al. 2017). All properties of soil are amendable by using multiple tools in which biochar application is one of the most promising technique employed now a days.

Biochar standard definition devised by international biochar initiative (IBI) is a "solid material usually carbon (C) enriched obtained from thermochemical conversion of organic residues/biomass/feedstock under deprived oxygen condition". This conversion ensures the active bioavailability of nutrients contained by organic residues/biomass with increased porosity and hence the water holding capacity of biochar. This amendment in the physiochemical architecture of biomass, making it an excellent absorbent for pollutants and hence a promising biological tool to treat non- productive and polluted soils now a days (Ahmad et al. 2014; Aller and technology 2016; Fahad et al. 2015, 2016; Atif et al. 2021). A vast variety of biomasses/feedstock is available in nature which could be employed to produce biochar, this includes animal waste, agricultural waste, plant residues, sewage and municipal waste (Li et al. 2019; Sánchez et al. 2015; Xu et al. 2012). The biochar produced itself had its own physio-chemical properties e.g. surface area, porosity, micro-macro mineral nutrients, cation exchange capacity, pH, organic matter, C/H ratio, C/O ratio, carbon and ash contents, heavy metal load, which determines its potential applications (Fryda and Visser 2015; Igalavithana et al. 2017; Libra et al. 2011).

In multiple studies, biochar with its unique physio-chemical architecture exhibited the potential to amend the soil physiochemical properties with least environmental hazards, quality threats and risk management by reducing foul emissions from greenhouse gases and methane (CH_4) into air (Li et al. 2019; Sánchez et al. 2015; Xu et al. 2012). Biochar's usually increase aromatic carbon contents into soil which is more stable than carbon present in organic matter (Sohi et al. 2010), lowers soil compactness by adding organic matter into soil (Liang et al. 2010), hence improving soil water holding capacity and also nutrients availability to plant by emending pH profile (Van Zwieten et al. 2010), reduce emission of carbon dioxide (CO_2) and ammonia (Cabeza et al. 2018), enhanced heavy metal sorption and microbial (bacteria and fungi) activity in rhizosphere, which in turns promotes plant growth and development under stressful situation (Compant et al. 2010).

Soil physio-chemical amendments induce heterogeneous responses of microbial-community structure which consequently alters the soil nutrient bioavailability, cycling and function (Biederman and Harpole 2013). The components of biochar including minerals, free radicals, volatile organic compounds (VOCs) directly influence the microbial activities and enzymatic activities and hence reshape the microbial community structure (Paz-Ferreiro et al. 2014). Microbial functional activities and structure are the two most promising parameters in the assessment of biochar impact on soil biological properties.

Microbial activities are usually determined by basal respiration, N_2 fixation and mineralization, enzymatic activates (dehydrogenase) and functional groups activities (Paz-Ferreiro and Fu 2016). Community structure and compositions is determined by polymerase chain reaction, denaturation gradient (DGGE) versus temperature gradient gel electrophoresis (TGGE) and contents of phospholipid fatty acid (PLFA) in soil (Nannipieri et al. 2003). Several reports are available reporting the positive role of microbe-biochar induced amendment in soil structure and composition. This is together proved to be an effective strategy in soil contamination degradation (García-Delgado et al. 2015), immobilization of pollutants and heavy metals (Fang et al. 2014b; Yang et al. 2016), detoxification of environmental pollutant (Dong et al. 2014). However, specific mechanism of microbe-biochar of interaction is still unclear. The nature, types of biochar produced depending upon the feedstock and production processes, biochar interaction with soil which collectively modulates and regulates the soil microbial community structure and compositions, collectively made the microbe- biochar interaction unpredictable and complex.

The objective of this chapter is to provide comprehended overview of factors effecting physio-chemical properties of biochar and its characterization, how structure of biochar effects physio-chemical properties of soil and finally the role of biochar in soil amendment projects particularly by regulating microbial activity in the rhizosphere.

16.2 Factors Affecting Quality Standards of Biochar

Biochar properties are determined by two major factor, one is the type of feedstock used for generation of biochar and second the procedure/technique used and conditions set to synthesize product.

16.2.1 Physiochemical Characteristics of Biochar Feedstock

Feedstock used for the production of biochar is generally divided into two discrete groups i.e. lignocellulosic (wood) and non lignocellulosic (Non woody). Lignocellulosic feedstock belongs to plant origin which includes agricultural waste, organic waste from household activities and green yard waste, forest land wastes, waste from agricultural commodity processing industries e.g. sugar industry, juice manufacturing, processed fruit and vegetable industries, and biofuel/bioenergy crops. Non lignocellulosic group includes animal manure, microalgae from sea surface and municipal sewage sludge (Filiberto and Gaunt 2013; Kumar et al. 2017; Nartey and Zhao 2014). The composition of feedstock determines the characteristics of biochar during thermal decomposition i.e. proximate analysis (moisture contents and ash), cation exchange capacity, pH, carbon contents, percentage of volatile compounds (Angın 2013), cellulose, hemicellulose, lignin (Shivaram et al. 2013), inorganic compounds, particle size and porosity of decomposed matter, water holding capacity and optimal concentrations of micro and macro elements (calcium, iron, zinc, copper, sodium, potassium, magnesium etc.) (Yang et al. 2013; Zhou et al. 2013).

This is due to the fact that each feedstock exhibit unique thermal and biochemical properties and hence differential response to oxygen deficit thermal decomposition. In general, high lignin content oriented feedstock produce more biochar with enhanced porosity which ultimately promotes water retention properties upon application to soil amendment projects (Yang et al. 2013). Pore size further influenced by the vascular bundle containing feedstock which upon decomposition exhibit large pore size along with increased surface area, which act as an additive to soil improvement by providing space for microbial symbiotic relationships (Thies and Rillig 2009). High biodegradable property of biochar with increased surface area and surface functional groups imparts positive effect on porosity too (Hernandez-Mena et al. 2014).

Moisture content in biomass has significant effect on biochar production. Moisture exist in multiple forms within a biomass i.e. as free liquid, water vapor and chemically bound water (Vassilev et al. 2013). Moisture content is directly associated with heat energy, time and process required for biochar production. This over all determines the physio-chemical properties of biochar produced. Usually low moisture content is advisable due to reduction in steps, time and energy required for pyrolysis process and to make the process economically feasible (Tripathi et al. 2016). Carbon and ash contents depends on cellulose, hemicellulose and lignin contents of biomass. Cellulose helps in the formation of tar (a mixture of organic liquid, aldehydes, ketones and char) while lignin favors char production during biochar production process (Tripathi et al. 2016; Yu et al. 2014).

Practical examples exist elaborating the effect of biomass type on physiochemical properties of biochar. In a study in which sugarcane bagasse and rice husk were considered for biochar production. Sugarcane bagasse biomass is enriched with cellulose, hemicellulose and moisture contents while rice husk with lignin and ash contents. Both produced the biochar with different ration of carbon, ash and surface functional groups (El-Gamal et al. 2017). Cellulose and hemicellulose are comprised of sugar monomers which have lower molecular weight compared to lignin, hence decompose at lower temperature and release fractional molecules easily and quickly. Lignin is high molecular weight biomolecule with aromatic functional groups and hence resistant to thermal degradation and required high temperature. Inorganic constituents are also important in to determine the physio-chemical properties of biochar (Lee et al. 2013).

Biochar produced from animal manure and litter exhibited reduced surface area compared to woody and crop residues, even at high temperature (Lu et al. 2012). This variation may be attributed to contents of H/C, O/C ratios and their cross linkages, volatile organic matter and carbon contents and variable inorganic constituents of both types of biomass (Bourke et al. 2007; Tag et al. 2016; Wang et al. 2015). Porosity of biochar depends upon the release of volatile matter (Shaaban et al. 2014), which may be blocked by inorganic material. However, decomposition of cellulose and hemicellulose add into surface area significantly (Ahmad et al. 2012).

16.2.2 Technologies for Biochar Production

In general, four thermochemical routes are adopted to produce biochar which are pyrolysis, torrefaction, hydrothermal carbonization and gasification. The structure of carbon is highly temperature dependent, determines the stability of biochar produced (Lehmann et al. 2011). The transitory structures of carbon includes (1) transition biochar raised from crystalline type of feedstock used for synthesis, (2) Amorphous carbon obtained from the mixture of feedstock with varying thermal properties preserved at low temperature, (3) Graphite/composite carbon obtained from the fixation of graphite stacks in their amorphous phase, poorly structured, and (4) Turbostratic biochar produced at high temperature dominated by solid graphite crystals (Keiluweit et al. 2010; Zhou et al. 2013). Production of biochar with prophesied properties requires the selection of appropriate technique along with suitable conditions and through knowledge of influencing factors both quantitatively and qualitatively (Weber and Quicker 2018; Zhang et al. 2019).

16.2.3 Pyrolysis

Thermal decomposition of feedstock in the absence of oxygen is called pyrolysis. The products of pyrolysis includes a liquid (bio-oil, usually the mixture of hydrocarbon), non-condensable synthetic gas and biochar. The yield proportion of products depends on the type of pyrolysis process i.e. slow, fast and flash pyrolysis, all exhibiting varying reaction temperature, heating rate and time, pressure and feedstock holding time (Cheah et al. 2016). In slow pyrolysis process, longer retention time of feedstock with slow to medium heating rate opted in order to produce more yield of biochar. However, when the target is to achieve high yield of biofuel, the fast pyrolysis procedure is the methods of choice with high temperature and short residence time of feedstock (Daful and Chandraratne 2018). Yuan et al. (2020) reported that high percentage of biochar obtained from the walnut shell under slow pyrolysis technique irrespective of the temperature range used during the process, which confirms the effectiveness of slow pyrolysis towards biochar production.

Pre-pyrolysis treatment is conditional depending upon the type of feedstock selected for biochar production. In case of liquid or semi liquid biomass of feedstock, pre-pyrolysis reaction is carried out to remove water from the biomass by evaporation. Pre-pyrolysis reaction is followed by primary reaction and finally the secondary reaction in order to attain biochar successfully. Primary reaction is conditioned with de-volatilization by following dehydration, de-carboxylation and dehydrogenation. During primary decomposition, temperature is set low to medium. Secondary reaction is characterized with high temperature for successful cracking in heavy organic compounds e.g. lignin as well as re-polymerization and condensation, in order to produce biochar as final product along with non-condensed synthetic gases e.g. methane (CH_4), methylene (CH_2), carbon mono oxide (CO) and carbon dioxide (CO_2) (Foong et al. 2020; Kan et al. 2016; Rashidi and Yusup 2020; Tripathi et al. 2016).

High temperature of pyrolysis thermally crack the pore blocking substances and hence increasing the externally available surface area along with pore size and volume of biochar (Rafiq et al. 2016; Zhao et al. 2017). Volatile compounds produced during pyrolysis at high temperature also contribute to porosity positively and significantly (Shaaban et al. 2014). Increase in pyrolysis temperature results in the increase in the aromatic properties of the biochar products produced which resist to microbial decomposition (Xie et al. 2016). Mechanism of containment removal by biochar produced at high temperature is adsorption and sorption produced at low temperature (Chen et al. 2008) due to variability in the arrangement of surface function groups at both temperature extremes which ultimately effect cation exchange capacity (Ghani et al. 2013; Mia et al. 2017). Surface functional groups act as electron donors/acceptors and hence mediates surface area and its properties which ranged from acidic to basic. Variation in pH ultimately imparts specific hydrophilic and hydrophobic properties to biochar which changes cation exchange capacity (Ahmad et al. 2014; Yao et al. 2012). Biochar produced at high temperature exhibit less cation exchange capacity due to least active functional groups on the surface (Yao et al. 2012). However, contradicting reports are also available in which biochar produced at high temperature exhibited increased cation exchange capacity (Banik et al. 2018; Kasozi et al. 2010). The contradictions in results may be attributed to variation in feedstock, the functional groups present on surface and their specific response towards temperature fluctuation and rate of volatilization of different compounds (Banik et al. 2018; Cely et al. 2015; Kasozi et al. 2010; Mia et al. 2017).

16.2.4 Torrefaction

Torrefaction (also referred as mild pyrolysis) is a physiochemical conversion of biomass at mild temperature (200–300 °C) and inert atmospheric pressure for a time period half an hour to 2 h (Chen et al. 2018; Daful and Chandraratne 2018). However, torrefaction is not considered a promising technique for production of biochar due to the fact that; (1) the conditions set for torrefcation are not suitable enough to convert the physiochemical properties of biomass completely, hence biomass remain in transitory phase, in between the raw biomass and final processed biochar. (2) Significant amount of volatile compounds found in biochar produced in this process as like raw biomass. (3) Partial or no re-polymerization of heavy organic components of biomass occurred. Quality of biochar obtained after the completion of torrefaction process is more similar to pre-treatment in pyrolysis. Hence torrefcation is recommended to be used in combination with pyrolysis process for the production of biochar. It could be used to remove biomass moisture, densification and improve biomass properties or initial processing of biomass for final conversion into biochar (Abdullah et al. 2017; Chen et al. 2017; Zeng et al. 2019; Zhu et al. 2019).

16.2.5 Hydrothermal Carbonization

Hydrothermal carbonization also termed as wet pyrolysis. The process of wet pyrolysis is initiated under water-biomass solutions at high temperature (180–250 °C) and pressure at longer period of time (Gan et al. 2018; Zhang et al. 2019). The products of wet pyrolysis are also wet biochar (called hydrochar), biofuel and gas product which is mainly CO_2 (Saqib et al. 2019). Both dry as well as wet pyrolysis have their own advantages and success stories based on the objective and type of biomass selected for biochar preparation. The main advantages of hydro-thermal carbonization is it required wet environment for the initiation of process. This requirement reduces the need of pre-pyrolysis steps required for moisture removal, hence time and energy requirement pf procedure are lesser than dry pyrolysis. Water present in biomass act as solvent, reactant, catalyst and medium for energy and mass transfer during the reaction hence, facilitating hydrolysis, decarboxylation, dehydration, de-polymerization and ultimately enhance the speed of decomposition process (Guiotoku et al. 2011; Krylova and Zaitchenko 2018; Xu et al. 2018).

It is reported that cellulose, hemicellulose and lignin also decomposed more successfully in wet pyrolysis (Jeguirim and Limousy 2019; Wiedner et al. 2013). However, Hydro-char produced through hydro thermal carbonization showed less contents of ash and carbon contents compared to bio char. Furthermore, the surface area of hydrochar, low porosity and presence of noxious chemicals/products (phenolic compounds etc.), all collectively reduces the efficacy of hydro-char compared to biochar in soil ameliorating projects (Garlapalli et al. 2016). This variation in product appears mainly due to variable C/H ratio and O/C ratio during wet pyrolysis compared to dry pyrolysis (Jeguirim and Limousy 2019; Wiedner et al. 2013). However, maximum benefit of biochar with high quality could be achieved by combining both dry pyrolysis technique with hydro-thermal carbonization.

16.2.6 Gasification

Gasification process preferably utilized when objective is to produce synthetic gasses mainly CO_2, CO, CH_2, CH_4 and H. this process is carried out in the presence of gasses preferable the O_2. CO_2, and other gasses could also be utilized alone or in combination. Temperature ranges from 600 to 1200 °C, with residence time 10–20 s at heating rate 50–100 °C/Min (Daful and Chandraratne 2018). However, gasification is not adopted as preferred method of biochar production. Reason behind this avoidance is the products of pyrolysis remains same however the percentage of products vary greatly with reduced product quality. The contents of biochar are very low and biochar also not of good quality enough to be employed successfully in soil ameliorating projects. Biochar produced accompany with several noxious elements and heavy metals which instead of reclamation, add toxicity to soil (Sohi 2020;

Yang et al. 2019; Zhang et al. 2019) hence less attention is paid to standardization of gasification process in terms of biochar production.

16.3 Characterization of Biochar

Biochar and its application in soil amendment projects depends upon its stability which is determined by physiochemical properties. These properties directly depends on the type of feedstock (plant origin, animal origin etc.) process adopted for biochar production (dry or wet pyrolysis, gasification) and conditions set for biochar production (residence time, temperature of reaction, pressure, carrier gas, heating rate and time). Each factor has its own value in characterization of biochar. Characterization is compulsory step after biochar production, as it defines the rate of various biochar quality parameters (pH, cation exchange capacity, porosity, surface area, water holding capacity, ash and moisture contents etc.), macro and micro nutrients specificity and availability rate, heavy metal load and synthetic gasses produced and their rate. The combination of all these parameters overall defines the eco-toxicology of biochar produced. Standardization of quality parameters of biochar helps to determine dose rate for application of biochar and its suitability to a particular soil and hence their performance and success rate could be predicted (Fryda and Visser 2015; Igalavithana et al. 2017; Libra et al. 2011; Muhammad et al. 2022; Subhan et al. 2020; Tariq et al. 2018; Wiqar et al. 2022; Wu et al. 2019, 2020; Xue et al. 2022).

16.4 Effect of Biochar on Soil Physio-Chemical and Biological Properties

Thermal decomposition of feedstock brings physical changes in the structure of biomass. Physical alterations along with the rate of decomposition of biomass determines the chemical properties (pH, cation exchange capacity) and water holding capacity of biochar (Shaaban et al. 2014; Yang et al. 2015; Yuan et al. 2011). Usually feedstock with high contents of ash produce biochar with high cation exchange capacity (increased oxygenated functional groups) and acidity (Yang et al. 2015). Feedstock with more alkali groups and their derivatives produce more ash contents, thus biochar produced from animal based biomass have higher cation exchange capacity than plant based biomass (Tag et al. 2016; Yang et al. 2015). The activity of surface functional groups (oxygenated surface functional groups) to determine cation exchange capacity which further determine the pH of biochar, directly dependent on temperature and ultimate rate of decomposition of biomass (Fryda and Visser 2015; Igalavithana et al. 2017). pH of biochar is usually basic. Variation in pH is due to non-pyrolyzed inorganic matter and rate of decomposition of cellulose, hemicellulose and lignin contents in biomass (García-Jaramillo et al. 2015; Yuan et al. 2011).

Positive agronomic effects of biochar in soil amendment and hence crop production depends upon the stability and site specific dose rate of biochar. As biochar interact with soil molecular fractions in a very specific way with the exact properties being devised by type of biomass and biochar production conditions. Hence unwise and ill-defined use may leads towards negative effect (Janus et al. 2015). Applications of biochar into soil may include the amendment in the status of water holding capacity (Revell et al. 2012) and cation exchange capacity (Alburquerque et al. 2014), organic matter and other soil particles i.e. sand, silt, clay which occur through hydrophobic interactions and wander wall forces (Xueyong et al. 2018). These interactions devise the influence of biochar on soil physio-chemical properties by designing the specific cation, anion flow and interaction with organic and inorganic constituents of soil (Zhu et al. 2017).

Stability of biochar into soil relies on the residence time of carbon which vary greatly depending upon the type of feedstock (Singh et al. 2012). The bonding pattern of carbon in feedstock determine its release and functional activity (based on functional groups on the surface) into the soil. Biochar reduced the emission of greenhouse gasses (CO_2, CH_4) and N_2O from the soil (Sun et al. 2018; Woolf et al. 2010). Biochar are also add into the soil enrichment with micro and macro nutrients required for plant growth. Addition of biochar to soil results in the agglutination of biochar with soil mineral and particulate matter, change their dissociation energies that results reduction in the loss of volatile material from soil surface (Ding et al. 2016; Guo et al. 2012; Jha et al. 2010; Saletnik et al. 2016) reported that biochar enriched soil usually exhibit high cation exchange capacity which expectedly increase nutrient retention into soil by reducing leaching and volatilization losses through changing surface charge energies and organic matter contents into soil. Overall increase in mineral content, organic carbon and cation exchange capacity influence the pH of soil greatly (Rutkowska et al. 2014).

High cation exchange capacity mainly attributed to oxidation of aromatic carbon and release of carboxyl groups into soil (Glaser et al. 2002). The formation of functional groups into soils mechanize two different processes into soils (1) promotes surface oxidation of biochar itself, (2) enhance adsorption of organic matter onto the surface of biochar (Lehmann et al. 2005). The activation of said processes into soils promotes the increase in specific surface area which ultimately improves the porosity of soils particularly the rate of macro pores (Lei and Zhang 2013; Nair et al. 2017). Increased specific surface area with enhanced sorption capacity of organic matter, in long run facilitates in water holding properties of soils (Duong et al. 2017). Particularly the hygroscopic moisture contents of soils are improved which is the great modification for dry and degraded soils (Cybulak et al. 2016). Overall humification, carbon sequestration processes depends highly on the temperature of biochar production process. Usually more benefits achieved from the biochar synthesized at low temperature compared to high temperature (Joseph et al. 2010). High temperature biochar have lesser reactivity into soils than low temperature

(350–500 °C) due to high recovery of nutrients and carbon which is lost gradually with the increase in temperature (Keiluweit et al. 2010).

16.5 Interaction of the Soil Microbial Community with Biochar

Humified soils exhibit high water holding capacity, reduced soil temperature, larger pore size and nutrient enriched (micro and macro nutrients) so act as ideal habitat for microbial growth and development (Briones 2014; Compant et al. 2010; Ibad et al. 2022; Irfan et al. 2021; Khadim et al. 2021a, b; Khan et al. 2021; Khatun et al. 2021;). Amendments in soil physio-chemical properties reshape the soil microbial community by modifying bacteria vs. fungi and other microflora ratio along their habitat and hence the enzymatic activity (depends upon microflora activity and biomass) within soil (Ahmad et al. 2016; Mackie et al. 2015).

The whole mechanism of biochar interaction with microbe and modulation in effects divided into seven discrete categories. (1) Biochar induced variation in soil physio-chemical properties (water holding, cation exchange capacity, pH) modify the microbial habitat and hence directly effects the establishment, growth and development of microbes within soil. (2) Increased soil porosity promotes aeration and humification process in soil, both factors determine the conduciveness of growth conditions for microbial community and shelter under unfavorable conditions (Quilliam et al. 2013). (3) Decomposition of organic feedstock release macro and micro nutrients into soil which act as food reservoirs for microbes. Different types of feedstocks provide different profile of nutrients. Hence, based on nutrients availability, differential microbial communities (multiple community structure) develop under different biochar application conditions (Joseph et al. 2013). (4) Each microbial strain release specific type of enzyme during decomposition process of biochar. The success of biochar in soil amendment projects after pyrolysis and its conditions, further depends upon soil condition and microbial community structure. Both factors are crucial in determining the biochar further decomposition, release, sorption, adsorption and leaching of nutrients. Enzymatic activity is determined by microbial community structure. Multiple enzyme combinations are found with multiple microbial community structure (Lehmann et al. 2011; Yuan et al. 2016). (5) Biochar type determines the inter and intra microbial interaction via a combination of signaling molecules released by microbes and their compatibility for each other (Gao et al. 2016). (6) Biochar also act as a source to provide toxicity free environment for microbial growth. Free radicals (functional group) on biochar surface act as sorption/adsorption surface for toxic contaminants present with soil. Hence, biochar act as soil purifier against heavy metals toxicity (Qin et al. 2013; Stefaniuk and Oleszczuk 2016). (7) Microbes as natural decomposing agents establish compatibility and stability of biochar to soil and reduce leaching and runoff losses of nutrients from soil (Fang et al. 2014a).

Differential spatial and temporal pattern of microbial colonization and fungal hyphae growth observed on surface of biochar and within pore of biochar. Spatial differential pattern can be argued by the phenomenon; (1) natural soil is more nutrient enriched than inside of biochar pore. (2) Biochar may be enrich with toxic material and (3) Biochar pore may be blocked by organic material of soil (Quilliam et al. 2013; Kasozi et al. 2010). Aging of biochar and pyrolysis conditions may explain the temporal variation in colonization response of microbes (Quilliam et al. 2013). Aromaticity (elemental composition) of biochar is responsible for its recalcitrant nature against microbial decomposition. Meanwhile some fraction of biochar act as source of carbon for microbes which is determined by C/N ratio (Demisie et al. 2014). Biochar usually exhibit higher ratio of C/N than their feedstock. Higher C/N ratio restrict the use of biochar by microbes by lowering availability of carbon and lack of N (Yanardağ et al. 2015).

Bacteria and fungi, due to different morphological growth habit and habitat, have different preference for carbon source. Hence tolerance to different soil environmental conditions is also variable among both major type of soil micro flora (Zhang et al. 2015). Fungi compared to bacteria are considered more resistant and beneficial microbial agents under deprived carbon condition due to their body morphology. Fungi can survive on soil macro aggregation which exhibit higher C/N ratio. Hyphal growth supports the fungi under adverse condition by modulating the water and nutrient availability through hyphae network, enabling fungi to colonize on carbon poor soils (Ascough et al. 2010; Zhang et al. 2015). Hence, biochar which promotes soil macro aggregation, favors fungus growth than bacteria. H/C and O/C ratios both decrease by increasing the pyrolysis temperature and retention time of biochar, resulting in the production of intense aromatic biochar (Xiao et al. 2016).

There is a range of compounds called volatile organic compounds (VOCs), released during organic solvent extraction of biochar and dominant product of pyrolysis, act as microbial inhibitors in soils. VOCs vary greatly depending upon the type of feedstock (Ghidotti et al. 2017; Graber et al. 2010; Spokas et al. 2011). Diversity of VOCs sorbed on biochar can be the main contributing factor to variable response of microbial life to biochar. However, contradictory reports also found which report that VOCs support growth of certain bacteria (Sun et al. 2015). VOCs preferable alter the enzymatic reactions of microbial life in soil by modulating the surface functional groups. Free radicals induce oxidative stress in living forms of soil and destabilize their plasma membrane integrity. As microbes are the living forms, damage to membrane lead towards organism death and hence colony lapse due to oxidative stress (Liao et al. 2014; Reed et al. 2015; Yang et al. 2015). However, further investigations are required to explore the toxicity of biochar to soil microorganism and role of free radicals in shaping the soil microbial communities.

16.6 Conclusion

This chapter has shown the heterogeneity in biochar depending on the type of feedstock and biochar synthesis conditions. Both are most influential factors determining the biochar properties which includes biochar texture, structure, surface functional group, elemental compositions, elemental cycling, redox capacity, cation exchange capacity, conductivity, pH and volatile organic compounds. This heterogeneous nature of biochar presents a complex combination with soil microbial flora and soil conditions on spatial and temporal level. Biochar is strongly recommended organic product in soil amendment projects as it modulates the soil physio-chemical properties and ameliorates the soil toxic contaminants. However, its interaction with soil microbes may be positive or negative depending upon the microbial community structure (bacteria, fungi, their abundance, composition, enzymatic reactions).

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Index

S. Fahad et al. (eds.), *Sustainable Agriculture Reviews 61*, Sustainable Agriculture Reviews 61, https://doi.org/10.1007/978-3-031-26983-7