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Biochar

REVIEW **Open Access**

Engineered biochar improves nitrogen use efficiency via stabilizing soil water-stable macroaggregates and enhancing nitrogen transformation

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Abstract

The use of inorganic nitrogen (N) fertilizers has increased drastically to meet the food requirements of the world's growing population. However, the excessive use of chemical nitrogen fertilizer has caused a series of soil and environmental problems, such as soil hardening, lower nitrogen use efficiency (NUE), nitrate pollution of water sources, nitrous oxide emissions, etc. In this review, we aimed to elaborate and discuss the role of engineered biochar in inducing the stability of water-stable macroaggregates, improving inorganic N transformation, and utilization efficiency to address the current uncertainties of nitrogen loss and maintaining soil and water quality. Firstly, we elucidated the characteristics of engineered biochar in improving biochar quality to work as a multifunctional player in the ecosystem and promote resource utilization, soil conservation, and ecosystem preservation. Secondly, we discussed how the engineered biochar modulates the stability of water-stable macroaggregates and soil inorganic nitrogen transformation to enhance plant response under various toxic or deficient nitrogen conditions in the soil. Thirdly, the role of engineered biochar in biological nitrogen fixation, mediating *nirK, nirS*, and *nosZ* genes to promote the conversion of N_2O to N_2, and decreasing denitrification and N_2O emission was reviewed. Altogether, we suggest that engineered biochar amendment to soil can regulate soil water-stable macroaggregates, reduce N input, improve nitrogen metabolism, and finally, NUE and crop growth. To the best of our knowledge, this is the first time to evaluate the combined interactions of "engineered biochar × soil × NUE × crop growth," providing advantages over the increasing N and water utilization and crop productivity separately with the aim of enhancing the stability of water-stable macroaggregates and NUE together on a sustainable basis.

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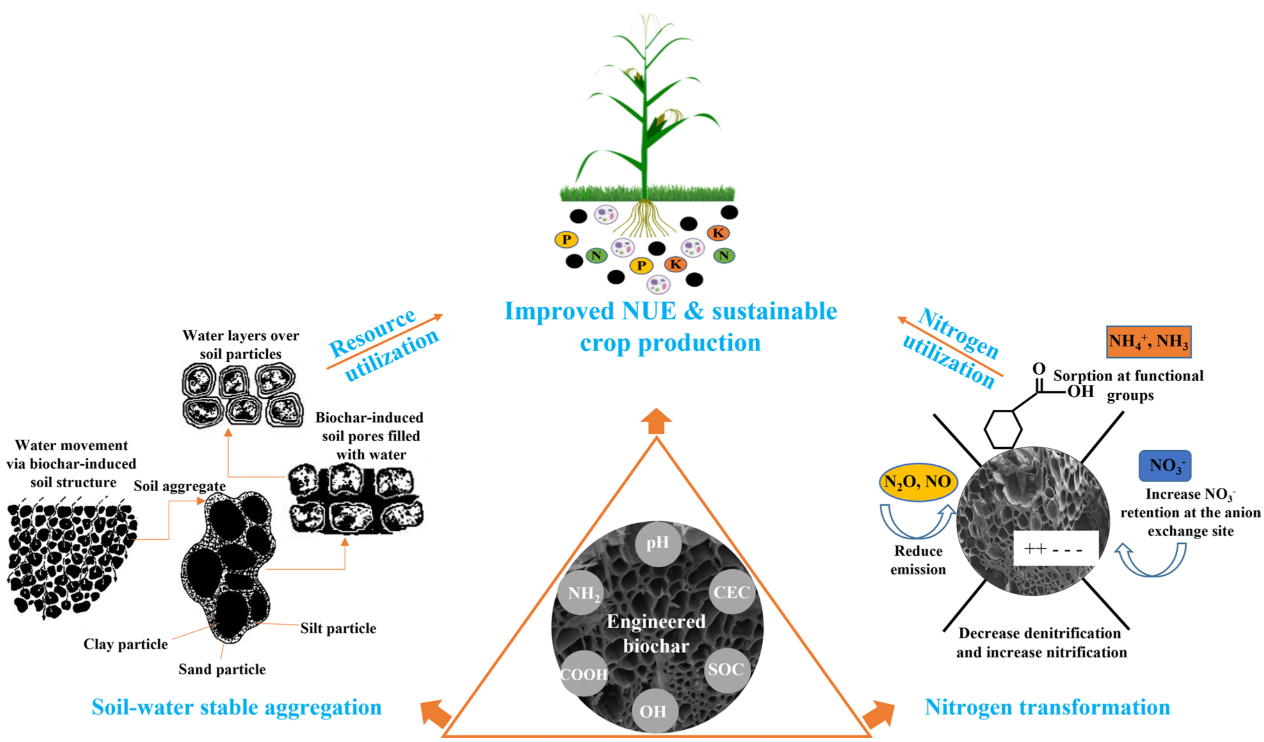
Highlights

- Excessive application of nitrogen (N) chemical fertilizers causes N loss and lower nitrogen use efficiency.
- Engineered biochar can build micro and macro soil structures and induce the stability of water-stable macroaggregates.
- Engineered biochar can improve biological nitrogen fixation, promote the conversion of N_2O to N_2, and decrease denitrification and N_2O emissions.
- Engineered biochar compensates for high and low N stress by regulating N metabolism, transformation, and remobilization in plants.
- Engineered biochar improves NUE by reducing N input and denitrification and enhancing soil water-stable macroaggregates and N transformation.

Keywords Nitrogen, Engineered biochar, Macroaggregates, Multifunctional player, Nitrogen use efficiency

Graphical abstract



1 Introduction

Nitrogen (N) fertilizers are vital for plant nutrition, but their application is an expensive agricultural input, and an excess or deficit of N lowers the NUE (Khan et al. 2021a) and is lost to the ecosystem posing severe threats to the environment and human health (Wang et al. 2016; Cao et al. 2019). The exponential increase in urbanization and industrialization has surged economic development while declining natural resource conservation and sustainable crop production. Globally, the availability of nitrogen (N) and water is considered the most limiting factor of crop growth and production (Quemada and Gabriel 2016). Considering the production demand and limited availability of arable land, farmers have been intensively using chemical fertilizers to increase crop production; however, the negative impacts of chemical fertilization on future agriculture and the ecosystem are not negligible. Conventional and chemical farming practices gradually degrade soil fertility, decrease NUE, pollute ground water, and decline crop production (Khan et al. 2021a). The use of N fertilizers in China was 25.74 megatons in 2020, equivalent to 22% of the world's N fertilizer usage (FAO 2021). Crop cultivation requires a massive number of nutrients that are applied as chemical fertilizers, and N is the most limited nutrient among them, although its application rate is higher than all the other nutrients. Generally, the uptake/absorption efficiency of added N (i.e., N uptake efficiency), and assimilation and remobilization efficiency (i.e., N utilization efficiency) combinedly represent NUE (Xu et al. 2012). Reliable, economical, and sustainable approaches are needed to recycle natural resources, relieve the hostile effects of mineral fertilizers on the soil ecosystem and improve the NUE of crops for future sustainable crop production.

N is a crucial and vital nutrient, and its effective utilization is critical to feed the world's growing population (Sylvester-Bradley and Kindred 2009). The preparation of mineral N fertilizers by the Haber–Bosch process has played a crucial role in present agriculture by achieving high yields (Bouchet et al. 2016). In addition, in the near past, to increase crop yields and meet the food requirements of the world's growing population, the use of inorganic fertilizers has increased drastically. Excessive application of N fertilizers reduces NUE via quick N losses through surface runoff, denitrification, and ammonia volatilization (Huang et al. 2018a, b). Water is the primary factor in the environmental issues brought on by excessive nitrogen consumption, such as nitrate pollution of water bodies or rising nitrous oxide emissions (Quemada and Gabriel 2016). In order to minimize nitrogen losses and sustain agricultural output, management strategies should focus on maximizing both nitrogen and water inputs simultaneously. Previous studies have suggested various management strategies for N fertilization, such as slow-release fertilization, optimal chemical fertilizers, and side-deep placement; however, these techniques are not significant due to high labor costs and lack of technology (Iqbal et al. 2019). In comparison, soil organic amendments, along with chemical fertilizers such as biochar, seem more sustainable, and have attained much importance due to their role in promoting the soil ecosystem, improving nutrients and water use efficiency simultaneously, and elevating crop productivity (Guo et al. 2017; Alotaibi and Schoenau 2019).

Gradual development in modernization and agricultural activities produces a tremendous amount of soil and organic waste. Resource and energy recovery from solid wastes in the form of biochar has emerged as a sustainable technique of biochar production to achieve circular bio-economy targets (Duan et al. 2020; Liu et al. 2021a, b, c). The application and benefits of biochar with scientific evidence date back to the 1850s, and biochar was recommended in various horticultural activities with documented research in 1915 (Lehmann and Joseph 2012a). Generally, biochar can act as a multifunctional player for agriculture, the energy sector, and the environment by performing several processes, such as carbon sequestration, water conservation, nutrient retention, and immobilization of heavy metals (Jindo et al. 2020). However, the benefits of raw biochar are significantly low due to its lower density, less adsorption capacity, and small particle size compared to modified biochar (Wang et al. 2017). Engineered biochar is an organic material obtained by pyrolysis of biomass in anaerobic conditions and further treated by numerous techniques to enhance its functionality and efficiency (Kazemi Shariat Panahi et al. 2020).

Engineered biochar after pyrolysis of biomass in anaerobic conditions is further treated by numerous techniques to enhance its functionality and efficiency and plays an important role as a soil conditioner, nutrient enhancer, and environment stabilizer. Recently, modified and engineered biochars have been deployed in various fields due to their prominent role and potential. Modifying the pyrolysis procedure by utilizing mixed feedstocks or different carrier gases at varied temperatures can be one of the easiest techniques to alter the biochar nature and produce a specific kind of engineered biochar (Kończak et al. 2019). Consequently, choosing particular feedstocks or altering the raw material through biological, chemical, physical, or mechanochemical approaches can affect the pore structure of the biochar to a certain extent that can modify soil structure to retain soil water and nitrogen (Wang et al. 2017). A well-managed soil structure can promote nutrient cycling and water availability (Piedallu et al. 2016), and various changes in soil structure are caused by aggregates, which are also essential for regulating and holding soil nutrients (Ma et al. 2022). Previously, it was found that exogenously added N enlarged soil macroaggregates, suggesting a positive effect of N supplement on the stability of the soil structure (Lu et al. 2021). Hence, adding biochar to soil can increase the stability of the soil aggregate and generate a strong association with the transformation and utilization of N dynamics. The co-limitation of the availability of N and water is the relationship link that governs plant biomass production (Sadras 2004); it indicates that methods to enhance plant development should assure the equal availability of both resources. Thus, the current review primarily focuses on investigating engineered biochars that can improve soil water and nitrogen utilization simultaneously rather than increasing N and water utilization separately.

There is an array of previous studies that investigated the raw biochar role in soil inorganic N transformation and utilization from a single or minor perspective in relation to soil improvement or plant growth regulation. Previously, various studies compiled the findings of soil inorganic N response under raw biochar addition (Nguyen et al. 2017; Liu et al. 2018b; Liu et al. 2019a, b), however; there is a research gap to determine whether engineered biochar induces soil water-stable macroaggregates regulating water use, soil inorganic N cycling, transformation, and remobilization in the plant through various pathways. Meanwhile, a brief and comprehensive overview is required to address the research gap related to the potential of engineered biochar as a multifunctional player in the regulation of ecosystems, soil conditions, and plant growth to enhance NUE. The main aim of this review is to elaborate and explore the role of a resilient approach of engineered biochar amendment to address the current concerns of nitrogen loss and sustain soil and water quality, NUE, and crop production. The specific objectives of this work are to clarify (i) the role of engineered biochar as a multifunctional player in resources and waste recycling and utilization; (ii) the impacts of engineered biochar on the modulation of soil–water stable macroaggregates and soil inorganic nitrogen dynamics, (iii) the role of engineered biochar in reducing N input, compensating N surplus or deficit conditions and improving NUE, plant growth, and production and (iv) recommendation for future studies to further highlight the new possible benefits of engineered biochar application for future sustainable agriculture. This will be the first study to evaluate the interactions between "engineered biochar, soil, NUE, and crop growth" with the goal of improving integratively the stability of water-stable macroaggregates, NUE, and crop growth. Thus offering advantages over separately increasing N and water utilization and crop productivity on a sustainable basis. This comprehensive review will provide new avenues of research on engineered biochar to help the researchers and organizations working on nitrogen fertilizers utilization to enhance NUE and sustainable crop production.

2 Methods

This review was conducted on the basis of an extensive literature search, which covered books, book chapters, conferences, scientific research articles, and review articles that were peer-reviewed. In order to find relevant articles, the terms "biochar," "engineered biochar," "char," “soil,” “nitrogen,” and "nitrogen use efficiency" were searched in the databases of Web of Science, Scopus, Wiley Blackwell, Google Scholar, and Springer Link. We explored the title and abstract of each publication to see if they contained unique and original data measured for the relevant responses, including soil nutrients, microbes, and plant growth. The material that emerged from this search was then further filtered to ensure that it adhered to the following standards: (i) the study examined how soil N cycle changed in response to the addition of biochar; (ii) biochar was made by anaerobically pyrolyzing organic materials, and (iii) control and biochar treatments were present in the study. We carefully reviewed the papers that fit these requirements, and without duplicating their conclusions, this review has thoroughly presented the most important results of these scientific papers. Furthermore, we gathered and analyzed data from peer-reviewed reports and research articles using OriginPro 9.1 and displayed them in tables and bar plots.

3 Biochar and engineered biochar's role as a multifunctional player in resource utilization

Biochar can be called the black gold of future agriculture, and it can be prepared using various feedstock biomass through pyrolysis in anaerobic conditions. Biochar production is an effortless and prominent technology for waste and resource utilization that is suitable worldwide (Kumar Awasthi et al. 2017). The production of biochar will recycle animal and plant wastes to reduce the amount of their disposal rate (Saletnik et al. 2019). Through pyrolysis, it is possible to generate energy in the form of biochar from biodegradable animal waste, agricultural biomass, and sewage sludge. Utilizing the waste materials listed above to produce biochar may also indirectly lower methane emissions from the land surface and lessen the need to find alternative waste management techniques. Biochar has unique properties and structure, which helps to improve soil status, water and nutrients conservation, and plant growth (Lehmann and Joseph 2012a). The biochar properties and functions can vary with variations in pyrolysis temperature and feedstock type. The pyrolysis temperature over 500 °C initiates the aromatization and graphitization processes, enhancing the aromatic C groups and intensity of hydrophobicity and consequently elevating nutrients absorption and retention (Xiao et al. 2018). Previously, Ahmad et al. (2014) reported that biochar prepared from plant and wood biomass has a larger surface area than biochar prepared from animal manure. Therefore, it is necessary to consider the pyrolysis temperature and feedstock type for biochar preparation according to the need and purpose of biochar application.

The biochar amendment increases the soil porosity to capture more water and adsorb nutrients to improve nutrient utilization and crop yield. Biochar works as an emerging resilient soil amendment and performs various

Fig. 1 Mechanized diagram highlighting the multifunctional role of biochar towards sustainable agriculture

profitable functions that benefit the soil–plant relationship in resource uptake and utilization (Khan et al. 2022b). In general, biochar amendment can help in carbon sequestration, water conservation, nutrient retention, and immobilization of heavy metals to play the role of a multifunctional player in the energy sector, the environment, and progress towards sustainable agriculture (Fig. 1).

3.1 Biochar as a sustainable multifunctional player

The use of biochar in the ecosystem can be related to diverse areas such as soil conservation, wastewater purification and waste management, energy production, combating climate change, cleaning up contaminated soils, and sustainable agricultural development, as illustrated in Fig. 1. The recognition of preta de Indio, or "Indian black earth" in the Amazon, which is renowned for its high carbon and nutritional content, sparked interest in biochar as a potential soil enhancer (Bezerra et al. 2019). Soil is a limited and vulnerable resource, and it requires extra care to maintain its health. Healthy soil preserves soil biodiversity, which enhances soil structure, conserves water, and establishes symbiotic relationships with plant roots to help in the recycling and supply of nutrients to promote plant growth. Biochar can achieve the goal of soil health by modulating soil characteristics. As evidenced by earlier studies, the soils were formed a few thousand years ago as a result of forest fires and other natural events, as well as soil enhancement by pre-Columbian people using charcoal (Medyńska-Juraszek 2016).

The relatively stable C in biochar can be added directly to the soil and contribute to different soil organic carbon (SOC) pools, increasing the amount of carbon in the soil. SOC is a key indicator of soil health which helps in the regulation of crop production and mitigation of greenhouse gas balance to promote adaptation to climate change (Bai et al. 2019). In general, due to land conversion and cultivation, agricultural soils often contain far less SOC than soils with wild vegetation (Poeplau and Don 2015). The ratio of natural carbon emission to natural carbon absorption has significantly shifted as a result of recent increases in CO_2 emissions to the atmosphere (Saletnik et al. 2019). Carbon can be sequestered in soil as a SOC content through organic amendments, especially if they are applied over a long-term duration (Chen et al. 2018); however, their stability is dependent on the quality of the amendment because many of them only stay in the soil for a short period (Flavel and Murphy 2006). In fact, a thorough meta-analysis of 3049 measurements from 417 peer-reviewed articles showed that applying biochar was the most efficient way to raise SOC content by 39% compared to cover crops by 6% or conservation tillage by 5% (Bai et al. 2019). Being a greenhouse gas and the primary source of ozone-depleting at the moment, nitrous oxide (N_2O) concentrations in the troposphere are rising (0.26% year^{-1}), which is of great concern in relation to fertilizer loss and environment quality (Clough and Condron 2010a). If the capacity of biochar to reduce greenhouse gas emissions can be better understood and connected to GHG mitigation measures, it will further increase biochar's agronomic potential. Adding biochar into the soil under soybean and grass systems decreases N_2O emissions by 50–80%, attributed to improved soil aeration and soil carbon stabilization (Clough and Condron 2010a). As pH rises, the N_2O:N_2 ratio shifts in favor of N_2, and if alkaline biochar materials are used to raise soil pH, it may result in a reduction of N_2O emissions (Firestone 1980). Thus, urgent and reliable actions must be taken to maintain a balance in the ecosystem by capturing carbon and N_2O and converting N to utilizable form by plants utilizing biochar made from different kinds of biomass is one of the resilient ways to address this issue on a sustainable basis with evidence from past observations.

Soil and plant health is vulnerable to organic contaminants and pollutants due to their highly toxic, mutagenic, and carcinogenic effects. Due to their sorption capabilities, biochars can successfully immobilize contaminants from solid, liquid, and gaseous media. Several studies have found that biochar's highly aromatic nature, the abundance of surface functional groups, micro-porous surface, and high specific surface area make it an excellent choice for immobilizing organic pollutants in both soil and water (Zhang et al. 2013; Lian and Xing 2017; Khan et al. 2022a). Biochar can be applied as a resource-based renewable fuel at the application rate of 13.5 t ha^{-1} and can store carbon for almost two hundred years (Matovic 2011). In particular, it should be noted that biochars produced at higher temperatures have more effective sorption capabilities due to their larger specific surface area and increased porous structure. According to previous research studies, biochars can be employed as sorbents intended to immobilize contaminants and heavy metals from municipal sewage, aqueous solutions, and industrial wastewater (Tong et al. 2011; Regmi et al. 2012). These observations highlight that biochar can also play an ameliorative role in the reclamation of the environment, along with improving soil conservation and crop production.

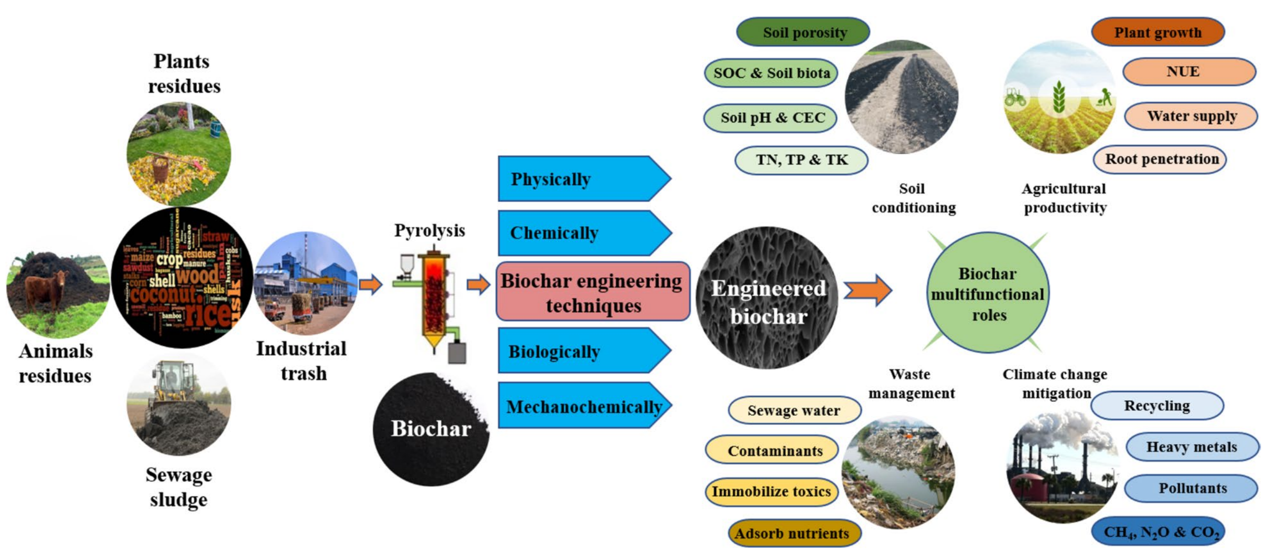


Fig. 2 A schematic diagram highlighting the sustainable methodology of recycling bioresources and utilization into engineered biochar production for multifunctional roles in the ecosystem

3.2 How to improve the quality of biochar

Overpopulation, industrialization, and economic development are continuously increasing solid organic wastes and deteriorating the quality of the environment. Thus, it is crucial to adopt a green and feasible approach to sustainably recycling resources and wastes and utilizing them for environmental and economic sustainability (Fig. 2). In general, the low surface functioning and the underdeveloped pore structure of pure biochar make it challenging to achieve high efficiency in practical applications (Awasthi 2022). In order to improve performance, biochar must typically be further processed, modified, or functionalized after it is produced through pyrolysis to adjust its surface qualities and customize its pore structure. The pore structural features, functional groups, and specific surface area play major roles in determining the functional capabilities of the modified biochars (Wang et al. 2017). Consequently, the development of various modified biochars that can enhance their use in agricultural applications has become the primary focus of the current research. Biochar engineering will further improve the nature and properties of biochar to facilitate resource utilization and organic waste recycling (Liu et al. 2021a, b, c). Several physical, chemical, and biological methods are reported to engineer the biochar properties, such as pore structure, surface area, and surface functional groups (Awasthi et al. 2018; Kazemi Shariat Panahi et al. 2020). All engineering methods are applied after raw biochar preparation and considered as post-modification techniques.

3.2.1 Biologically engineered biochar

Recently, various techniques have been used to bioengineer efficient, sustainable, and economic biochars for application in various fields of environment and agriculture. Various microbes are investigated that can engineer and enhance the characteristics of biochar by binding to biochar in direct and indirect ways (Dehhaghi et al. 2019; Liu et al. 2021a, b, c). Generally, microorganisms are applied as a surface coating for biochar to improve the adsorption capacity of biochar (Anae et al. 2021). Incorporating selected microbes can promote colonization, surface area, and biofilm of biochar (Liu et al. 2021a, b, c). The best method of biological engineering of biochar is converting organic waste to digestate, and biogas is anaerobic digestion in the presence of bacteria (Inyang et al. 2010; Wang et al. 2017). Biochar's zeta potential was significantly impacted by anaerobic digestion, showing abundant functional groups and negatively charged surfaces that may attract cations onto the biochar surfaces (Wang et al. 2017).

The biological modification of biochar aims to create designed biochar from biologically processed biomass feedstock via anaerobic digestion or bacterial conversion. In comparison to raw biochar, the digested biochar displayed greater pH, specific surface area, CEC, anion exchange capacity (AEC), hydrophobicity, and a larger negative surface charge as a result of the digesting process' ability to change the redox potential and pH levels of the feeding biomass (Inyang et al. 2010). The enhancement of CEC and AEC raises the prospect of employing biologically activated biochar as ion exchangers that might adsorb both positively and negatively charged ions from soil and water. During anaerobic digestion, treated biochar had negative zeta potential, indicating strongly negatively charged surfaces and functional groups that might increase the cation's attraction on the biochar surface (Wang et al. 2017).

3.2.2 Physically engineered biochar

Physical engineering is the simplest and most traditional method to modify biochar by regulating steam, gas, thermal, or plasma during biochar preparation. The most common physical modification techniques for biochar are microwave modification, steam activation, and magnetic modification. A relatively recent method of pyrolysis known as microwave pyrolysis offers many benefits over traditional methods, including the ability to properly regulate the process, utilize energy, and financial efficiency (Morgan et al. 2017; Wang et al. 2017). As a result, compared to biochar produced by traditional pyrolysis, biochar modified with microwaves could have more functional groups and a larger surface area (Wan et al. 2009). At lower pyrolysis temperatures (300 °C), microwave modification can prepare effective biochar to boost CEC and soil water holding capacity (WHC) (Mohamed et al. 2016), which can further enhance the stability of soil macroaggregates. The main effect of physical engineering is to alter biochar's physical properties, such as pore structure, volume and density, surface area, particle size, and ash content (Sajjadi et al. 2019). Increasing pyrolysis temperature, the gasification process slightly alters the carbon matrix in biochar, which is led by C–CO_2 or C–H_2O gaseous agents (Saletnik et al. 2019). The biochar pores during the physical engineering technique are linked to enlarging the pore sizes by eliminating the biochar carbon reactive fractions (Yang et al. 2019).

The surface area of biochar is correlated with its degree of pyrolysis; however, the surface porosity and interior surface area can be enhanced with the modification conditions. A different method of heating, such as microwave-assisted pyrolysis (MWAP), is another kind of physical engineering biochar that produces biochar with additional values (Shirvanimoghaddam et al. 2022). Microwave irradiation is another newly developed method of physical modification of biochar, improving its specific surface area and absorption capacity by hydraulic functional groups (Hafeez et al. 2022). The steam activation process of biochar is carried out by pyrolyzing biochar in the presence of water vapor, carbon dioxide, and air at a specific temperature (Wang et al. 2017). Biochar that had been steam activated almost doubled the surface area while losing polarity due to the degradation of the carboxyl and phenol functional groups (Shim et al. 2015). Compared to non-activated biochar, it was discovered that a technological steam activation of biochar expedites its favorable effects on plant nutrient uptake and retention (Borchard et al. 2012). Physical modification agents are hygienic, pure, low cost, and simple to manage; they improve pore structure, add oxygenic functional groups, and have advantages over chemical modification. Biochar's surface area was potentially expanded during steam activation by CO_2 modification, while N-containing molecules on the char surface were positively affected by NH_3 modification (Wang et al. 2017). Steam activation exhibits nearly twice the beneficial impacts of raw biochar in most situations, emerging as an intriguing alternative for future biochar modification and uses.

3.2.3 Chemically engineered biochar

Biochar modification with chemicals occurs by treating with specific acidic, alkaline, or metal solutions. The chemical engineering method is more complicated and advanced than the physical engineering technique. However, chemical activations are thought to be more efficient than physical activations because they generate high specific surface area and porosity with less energy consumption (Kambo and Dutta 2015; Awasthi 2022). Raw biochars are treated with chemical agents such as KOH, H_2SO_4, $ZnCl_2$, and H_3PO_4, and then again, biochars, after drying, are passed through inert gases in pyrolysis (Dong et al. 2017; Saletnik et al. 2019). These chemical agents eliminate carbonaceous fractions from the biochar matrix to accelerate the production of novel pores and volatile organic compounds (Liu et al. 2015). Despite the fact that chemical activation has a number of advantages, several disadvantages limit its usage to a certain extent, such as huge consumption of water, generation of pollutants, and chemical recycling (Kambo and Dutta 2015).

The application of various chemical treatments enhances the biochar's absorption capacity and promotes the function of functional groups. The performance of biochar as an adsorbent can be considerably impacted by nitric acid oxidation, which can significantly increase the concentration of acidic groups on the surface of biochar and improve its absorption capacity (Wang et al. 2017). The negatively charged carboxyl groups in biochar become more capable of interacting with positively charged metals after chemical treatment (Wang et al. 2015). To improve hydrochar's capacity to absorb ammonium and remove heavy metals from water, biochar was treated with H_2O_2, which increased the surface area and oxygen-containing functional groups (Huff and Lee 2016). The surface area, thermal stability, and CEC of hickory wood biochar were dramatically increased following slow pyrolysis and subsequent modification with NaOH (Ding et al. 2016). However, after the chemical treatment, it is necessary to wash out the chemicals and their salts, which consumes extra water (Awasthi 2022).

3.2.4 Mechanochemically engineered biochar

The new mechanochemical technique has been trending recently to fabricate the potential and efficiency of engineered biochars. It is typical to anticipate that adding reactive chemical and physical effects to materials for functionalization may greatly increase the effectiveness of the material's performance. Despite the known qualities of physical and chemical engineered biochars, some barriers exist, such as low catalytic efficiency, poor porosity, and surface area, which are improved with mechanochemical engineering/ball-milling technique (Kumar et al. 2020). Customizing biochars by a ball-milling process is more affordable, environmentally friendly, and repeatable. However, very few studies examined the use of ball-milling for modifying novel biochars with enhanced functional features (Naghdi et al. 2017).

In order to attain the improved mass transfer fluxes and active loading required for biochar to be employed as an energy storage medium, its porosity and surface area must be upgraded or customized. Generally, it is activated further through physical heating and adding particular chemical reagents ($ZnCl_2$, H_3PO_4, KOH) as activators (Zhou et al. 2022). Plasmas having non-thermal or low-temperature discharges and non-equilibrium features, such as high-density reactive species and electrons at low gas temperatures and energy, are beneficial for material processing (Neyts 2019; Zhou et al. 2022). Activating biochar with a mechanochemical technique promotes the biochar's effect by improving the surface area, oxygen-containing functional groups, and pore sizes (Naghdi et al. 2017; Lyu et al. 2018). Fabricating biochars by ball-milling methods is an economical, reproducible, and sustainable approach (Awasthi 2022). Biochar can be ground into a powder using a ball mill, which reduces the particle size and elevates the specific surface area of the material, boosting the possibility for organic and inorganic ions to bind to the material (Cai et al. 2016; Lyu et al. 2018). Optimizing milling settings in a planetary ball mill, the surface area of biochar made from corn-stover feedstock rose by a factor of 60 to 194 $m^2 g^{-1}$ (Peterson et al. 2012). However, the field of ball-milling/

mechanochemical engineering and biochar modification is new, and many investigations are needed to elaborate on its potential and output.

3.3 Summary

Altogether, the amendment of biochar had a significant positive role in conserving and utilizing natural resources and working as a multifunctional player in the ecosystem. To utilize the biochar in the best possible way as a multifunctional player in the ecosystem, it is recommended to quantify the characteristics and specifications of a locality or soil type before the application or selection of a biochar level and type for optimum resource utilization. Mostly, the action and mineralization of biochar take a long time, which can be activated through various techniques of biochar engineering. The elemental status of biochar will also change upon variation in materials types and preparation conditions; therefore, it is necessary to consider the characteristics of a field or locality and design a specific biochar to meet the requirements accordingly for the best outcomes.

4 Consequences of different conditions of inorganic nitrogen with and without biochar

N has been regarded as the most crucial, limited, and required nutrient for crop growth and productivity among basic essential macronutrients (N, P, and K) (Tamura et al. 2011). The application and amount of nitrogen in the soil are not rational, and plants often experience different concentrations of nitrogen in the soil that affect plant growth in various ways. We need to consider the consequences of deficient, toxic, and sufficient amounts of nitrogen on plant growth and its transformation from soil to plant and adapt feasible agronomic approaches to optimize the availability and uptake of soil nitrogen for plant utilization. Here we evaluated the effects of different nitrogen conditions on plant growth and explained the ameliorative role of biochar to compensate for such adverse conditions of inorganic nitrogen.

4.1 Low nitrogen deficiency

After applying nitrogen fertilizers, the fertilizers are utilized by plants instantly or stored as organic nitrogen by the soil's organic matter or lost through leaching and volatilization. Optimum fertilization of N is necessary because a deficiency can retard the development leading to low yield in various crops (Cao et al. 2009). It is common that nitrogen deficiency induces multiple biochemical and physiological changes in plants and disturbs the processes of photosynthesis and cell division (Jeppsson 1999). The deficiency of nitrogen increases ABA concentration in the plant and the accumulation of H_2O_2, attributing to the closure of stomata (Broadley et al. 2001; Mu and Chen 2021). Lack of N has been regarded as an abiotic stress increasing the accumulation of reactive oxygen species (ROS) and acts as a critical limiting factor for plant growth and development (Rubio-Wilhelmi et al. 2011). Under the low supply of N, cell wall decreases, causing a decline in rubisco activity and light-harvesting proteins, thus decreasing electron transport and carboxylation rate (Zhong et al. 2019). The physiological alterations due to nitrogen deficiency were observed in our previous study (Khan et al. 2021a), as shown in Fig. 3A–D.

4.2 High nitrogen toxicity

When the supply of N exceeds the demand, the extra nitrogen will leach out through runoff as nitrate, and the balance of soil nutrients will be disturbed. The application of high nitrogen will adversely affect the plant leaf cell, stomata, and thus plant growth, as evident in Fig. 3C, D. The addition of inorganic N at higher doses reduces nitrogen use efficiency and contaminates the environment in the form of ammonia volatilization, soil acidification, and water eutrophication (Guo et al. 2010; He et al. 2021). Excessive application of N fertilizers increases soil acidity and reduces soil pH, which results in high osmotic potential and aluminium accumulation which is toxic to soil microbial activities, and thus microbial C biomass will reduce (Vitousek et al. 1997). The excessive application of inorganic N fertilizers negatively affects chlorophyll inside the chloroplast, working as a machinery of photosynthesis (Khan et al. 2021a). Over-accumulation of these chemical fertilizers can cause toxicity problems to plants' health, as previously Jeppsson (1999) and Khan et al. (2021a) have found the toxic effects of high chemical fertilization on the growth of plants. The excess nitrogen loss in the form of nitrates to the environment negatively affects human health by consuming highly concentrated nitrate crops or contaminated water. Therefore, we should think about and adapt such agronomic approaches that could sustain our ecosystem and benefit our agricultural economy.

4.3 How biochar induces nitrogen metabolism from rhizosphere to plant

In dryland conditions, nitrate is the major form of inorganic nitrogen, while ammonium is the major form in flooded conditions. The plant roots release various organic acids, exudates, and oxygen, which can induce the soil redox potential and the activities and abundance of microbial communities involved in nitrogen cycling in the soil. In paddy soils, the rice roots produce hasty nitrification by releasing oxygen through aerenchyma and uptake N in the form of nitrate compared to the

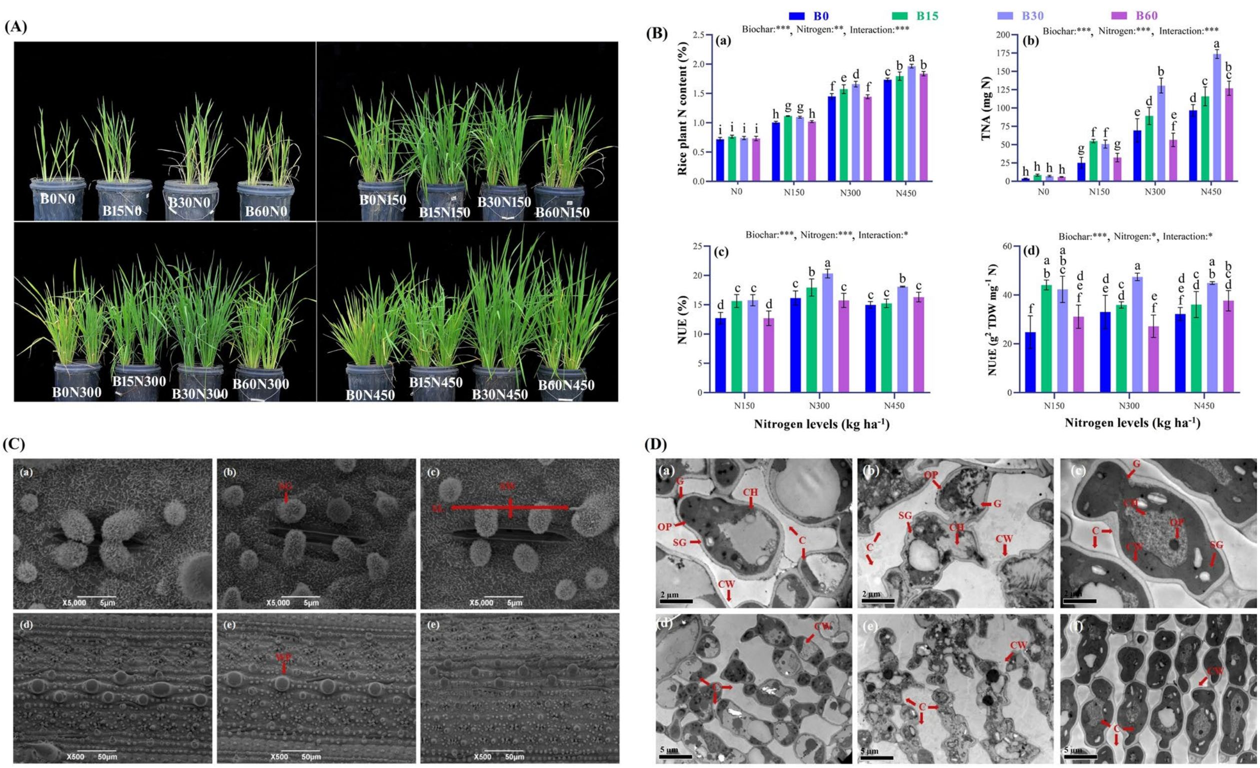


Fig. 3 The ameliorative effect of biochar on rice growth, nitrogen use efficiency, leaf cell ultrastructure, and stomatal morphology under high nitrogen application, findings from our previous study (Khan et al. 2021a), about biochar (0, 15, 30, and 60 t ha^{-1}) integration with different nitrogen levels (0, 150, 300, and 450 kg ha^{-1}). This figure illustrates how biochar can compensate for the deficient and toxic effects of low and high nitrogen addition and improve NUE. In the figure, figure (**A**) represents rice phenotypes of each treatment, figure (**B**) represents rice plant N content (**a**), total nitrogen accumulation TNA (**b**), NUE (**c**), and nitrogen utilization efficiency NUtE (**d**), figure (**C**) indicates the effects of N0B0: 0 kg ha^{-1} nitrogen and 0 t ha^{-1} biochar (**a**, **d**), N450 + B0: 450 kg ha^{-1} nitrogen and 0 t ha^{-1} biochar (**b**, **e**), and N450 + B30: 450 kg ha^{-1} nitrogen and 30 t ha^{-1} biochar (**c**, **f**) on rice leaf ultrastructure and figure (**D**) indicates the effects of N0B0: 0 kg ha^{-1} nitrogen and 0 t ha^{-1} biochar (**a**, **d**), N450 + B0: 450 kg ha^{-1} nitrogen and 0 t ha^{-1} biochar (**b**, **e**), and N450 + B30: 450 kg ha^{-1} nitrogen and 30 t ha^{-1} biochar (**c**, **f**) on rice leaf stomatal morphology

ammonium (Kirk and Kronzucker 2005; Xu et al. 2012). Plant rhizosphere alters ammonium or nitrate N uptake via acidification or alkalization through roots and induces the availability of inorganic soil N for plant uptake (Bloom et al. 2006). Continuously maintained soils with fertilizers like urea are possible hotspots for NH_3 generation, and the utility of biochar in such situations can be examined to keep NH_3-N in the soil reservoir. Biochar has the potential to retain N in soil and transform it via promoting ammonia and ammonium retention, reducing N_2O emission and NO_3^- leachate, enhancing biological N fixation and beneficial soil microbes for efficient plant utilization (Clough and Condron 2010a). Previously, Asada et al. (2002) noted the presence of acid functional groups with the help of electron spin resonance spectroscopy and demonstrated that NH_3 adsorption on biochar was linked with a decrease in acid functional groups by rising pyrolysis temperature. The adsorption capacity of a palm oil biochar produced at 500 °C and subjected to NH_3 at a concentration of just 6 µL L^{-1} was 0.70 mg g^{-1} at 23 °C, and 10% relative humidity (RH) and increased to 4 mg g^{-1} at µL L^{-1} and 73% RH acid functional groups were thought to be crucial for the biochar's capacity to adsorb NH_3 (Kastner et al. 2009).

It is well understood that biochar improves soil cation exchange capacity (CEC), nutrient availability, and retention. A previous study (Cheng et al. 2006) compared the abiotic versus biotic potentials for oxidizing biochar over a period of 4 months at two different temperatures (30 and 70 °C) and discovered that oxidation occurred more abiotically at 70 °C, with increases in CEC (53–538%) brought on by the formation of carboxylic functional groups. This rise in CEC over such a short period suggests that biochars properly weather over time and elevate their cations holding capacity, such as NH_4^+ and enhance soil fertility. The CEC of biochar depends on its surface area, and a review of the literature by Lehmann and Joseph (2012b) revealed that biochar needed to be produced at a temperature greater than 500 °C to affect an increased surface area when applied to the soil.

4.4 Biochar affects transformation and remobilization of nitrogen in plants

The translocation of nitrate to different areas of a plant over long distances can be easily managed by regulating and promoting the role and expression of the nitrogen transporters with the help of agronomic management techniques of biochar addition. The leaves act as a sink for nitrogen during the vegetative stage, and later this nitrogen is remobilized and reused in the developing seeds during the senescence stage, primarily as amino acids (Okumoto and Pilot 2011). Biochar's ability to release essential nutrients over time can save the ATPs used in the transportation and remobilization of nitrogen in different parts of the plant. Adding biochar to soil stores extra nitrogen and prevents its loss while releasing the stored nitrogen during nitrogen-deficient conditions (Khan et al. 2020).

The preferable forms of nitrogen for plant uptake are ammonium (NH_4^+-N) and nitrate-nitrogen (NO_3^--N). Plant roots contain absorption mechanisms for nitrate and ammonium with varying affinities to cope with the heterogeneity and dynamic fluctuations of nitrate and ammonium concentrations, ranging from 100 μM to more than 10 mM soil solutions (Xu et al. 2012). Constitutive and nitrate-inducible components make up each high-affinity and low-affinity nitrate transport mechanism (Miller et al. 2007). The strong adsorption effect of biochar due to lower acidic functional groups can adhere to the soil's nitrogen forms and promote plants' nitrogen utilization. N acquisition by roots is influenced by root architecture as well as the activities of ammonium and nitrate transporters (Garnett et al. 2009; Xu et al. 2012). Biochar addition alters the soil pore structure and increases aeration and moisture content, which can promote root morphology and, consequently, the functions of ammonium and nitrate transporters. Previously, the pronounced absorption of ammonium and nitrate ions on biochar surfaces has been observed to have increased CEC, less acidic functional groups, and high pyrolysis temperature (Clough and Condron 2010a).

4.5 Biochar compensates for abiotic stress of high or low nitrogen concentration

The lower or higher concentration of nitrogen in the soil can also pose the threat of abiotic stress to plants similar to other major abiotic stresses such as cold, salinity, heat, oxidative stress, and heavy metals in the ecosystem, reducing plant growth and production globally. Most of them are interconnected, resulting in highly adverse effects on crops as well as their surroundings. Several strategies have been proposed to overcome the negative effects of nitrogen stress, such as high-yielding verities, stress-tolerant species, and organic amendments. Several studies in the past have observed that biochar not only promotes crop growth and development in normal conditions but also enhances crop growth and yield under adverse situations such as drought, salinity, and heavy metals (Akhtar et al. 2014; Haider et al. 2015; Farhangi-Abriz and Torabian 2017; Zhang et al. 2022). The amendment of biochar is an old technique, but recently, it has received more attention due to its potential to increase soil fertility, mitigate climate change problems, water use efficiency, and crop production.

The amendment of biochar suppresses the vulnerability of plants to drought conditions by improving soil status, ion-binding capacity, and water retention (Kuzyakov et al. 2014). Moreover, Hafeez et al. (2017) reported that biochar addition under drought conditions improved the water-holding capacity of soil, which can be considered a sign of a rise in plant available water. Organic matter present in biochar absorbs more water for later use by the plant under drought and reduces the harmful effects of drought stress by regulating photosynthesis, stomatal traits, osmolytes, and antioxidant activities (Khan et al. 2021b). The amendment of soil with biochar enhances soil physiochemical conditions and soil water conservation that improves the processes of plant water potential, stomatal conductance, and photosynthesis (Hafeez et al. 2017), and it has been suggested as a sustainable drought stress mitigation approach for many plants (Batool et al. 2015).

Biochar can increase plant growth and yield and mitigate the abiotic stress caused by heavy metals and salts. Salinity stress has various adverse effects on plant growth and development, and salt accumulation in the soil can affect seed germination, seedling establishment, and ultimately poor plant growth and yield. The application of sugar cane residue-derived biochar reduced the bioavailability of Cd, Cu, and Pb and improved the soil microbial activities and plant growth (Nie et al. 2018). Previously, it has been observed that CEC and soil organic matter were increased with the help of the priming effect of biochar while soil pH and sodium contents were decreased (Wu et al. 2014). The addition of rice straw biochar alleviated the cadmium toxicity in soil and reduced its accumulation up to 35–81% in rice plants (Zheng et al. 2015). Comparing other conventional and technical approaches, the amendment of biochar is a sustainable and environment-friendly candidate to overcome the negative impacts of abiotic stresses. The biochar types and application rates may respond differently, e.g. high saline soil will prefer low pH biochar; therefore, proper biochar type should be selected for a specific area or locality.

4.6 Summary

The amount or concentration of inorganic nitrogen applied in the soil that affects nitrogen transportation and assimilation can't be neglected during biochar application. Biochar has the potential to decrease nitrogen deficiency by decomposing the organic nitrogen or reducing nitrogen toxicity with the action of adsorption to optimize the nitrogen balance in the soil. The proper levels of biochar are advised for application to the soil to adjust and compensate for the low or high amount of inorganic nitrogen in the soil and sustain the nitrogen uptake and utilization by the plant. Therefore, it is crucial to adopt such environment-friendly fertilization strategies to reduce N inputs, improve the NUE of crops, maintain high yields, and ensure sustainable agriculture in the future.

5 Interaction of engineered biochar with soil and inorganic nitrogen

The overall effect of biochar on the soil is related to its aromatic structures and functional groups; however, thethe effect of biochar on soil can be different due to the differences in raw materials and pyrolysis conditions that will alter the aromatization and functional groups on the biochar surface.

5.1 Effect of biochar on soil physiochemical properties

Biochar has the potential to improve the retention and utilization of macro and micronutrients in the soil in a mechanized and systematic way to promote the uptake of these nutrients by plants, as illustrated in Fig. 4. It can also interfere with various nutrient cycles of carbon and nitrogen by involving physiochemical processes like surface adsorption of different elements and interaction with microorganisms (Xu et al. 2018; Purakayastha et al. 2019). Biochar plays an important role in various nutrient processes such as surface complexation, ligand exchange reactions, and controlled-diffusion adsorption of elements, which consequently manage the dynamics of plant-available nutrients in soils (Mandal et al. 2016; Liu et al. 2013).

In addition to its direct impact on nutrient supply and availability, biochar influences soil nutrient dynamics with the help of various structural and chemical characteristics (Fig. 4). Biochar can induce changes in soil physical structure in terms of inter pores between biochar and soil particles due to porous shape and high surface area, promoting soil porosity, bulk density, and water holding capacity. Previously, various studies reported that biochar amendment reduced bulk density and improved soil porosity, moisture content, and hydraulic conductivity (Asai et al. 2009; Laird et al. 2010; Jeffery et al. 2011). The transformation of phosphorus (P) in the soil is influenced directly or indirectly by three different mechanisms due to biochar produced from various crop residues or feedstocks: (1) serves a direct source of soluble and exchangeable P, (2) improves soil pH and enrich various elements like Al^{3+}, Fe^{3+}, Ca^{2+}, and Mg^{2+} that makes complexes with P, and (3) serves as a source of carbon (C) and energy to enhance the activities of microbes and mineralization of P (DeLuca et al. 2012). Several physiochemical factors of soil could affect the solubility of K compounds in soil and the availability of biochar-derived K to plants (Jindo et al. 2020).

The stable carbon skeleton structures of biochar particles absorbed the water-insoluble portions of K and gradually released them during biochar aging (Liu et al. 2019a; b). The biochar surface contains oxygen functional groups, which can adhere to more water particles that improve the water holding capacity (WHC) and water use efficiency (WUE) of soil, consequently improving nutrient retention, soil fertility, and crop productivity (Rondon et al. 2007). The presence of organic matter, ash content, and other nutrients promotes SOC, soil pH, electrical conductivity, and CEC (Jeffery et al. 2011; Ur Rahim et al. 2020). The plant nutrient dynamics are related to soil pH, and biochar application can alter soil pH; thereby, biochar can modify the solubility and availability of plant nutrients (Purakayastha et al. 2019). The biochar amendment to soil helps mineralize soluble minerals and solubilize ions to affect the soil EC and soil salinity (He et al. 2021).

5.2 Effect of engineered biochar on soil microbial and enzymatic activities

Previously, researchers have mainly targeted the effect of biochar on soil chemical and physical properties, and biochar's impact on soil biota has rarely been investigated. Soil microbes represent the soil ecosystem, and they are vulnerable to any physical or chemical change in soil, thus presenting as a strong indicator of soil conditions. The soil microbes, in the form of various community groups, modify the soil conditions and nutrient transformation with the help of their biological activities and involvement in various nutrient cycles. Soil microorganisms directly influence soil ecosystem services through soil aggregation, C cycling, and nutrient transformations (Blanco-Canqui 2021). The role and functions of these microorganisms are dependent on the addition of organic matter, which alters various soil management factors and characteristics (Thies and Rillig 2012). Biochar amendment to soil can alter the biomass, community composition, and activities of soil microbes, which can further affect nutrient mineralization by decomposition of residues and nutrient transformation (DeLuca et al. 2012).

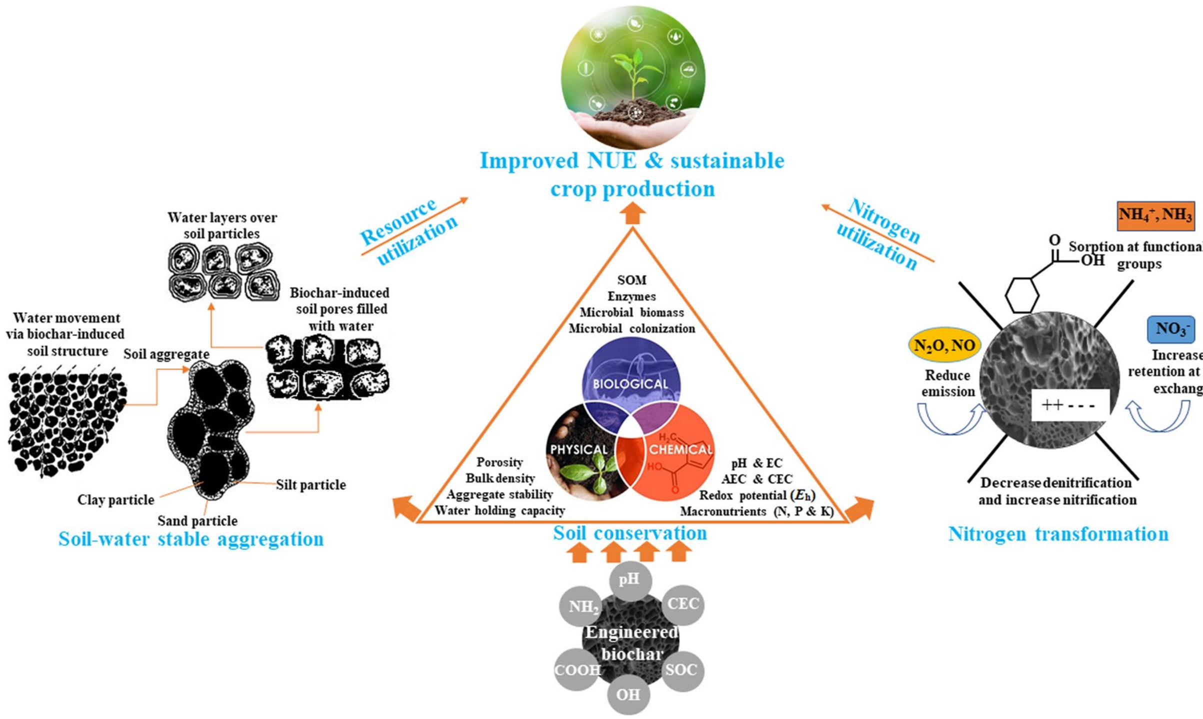


Fig. 4 Schematic diagram representing biochar's role in modulating soil properties and nitrogen transformation to promote sustainable crop production. Engineered biochar enhances soil physiochemical and biological properties to promote the formation of soil water-stable aggregates and resource utilization by the plant. Engineered biochar and the induced soil properties can increase nitrogen utilization and decrease nitrogen loss and emission by decreasing denitrification and increasing nitrification, ammonium, and nitrate retention to elevate NUE and sustainable crop production

Biochar particles provide shelter to microbes for colonization and enhance microbial processes in acidic soils by increasing micro pores and soil pH and reducing soil acidity (Gul et al. 2015). The biochar-induced interaction of bacteria, fungi, and nematodes with plants in the rhizosphere positively affects the ability of nutrient uptake by plant roots (Thies and Rillig 2012). However, if biochar contains toxic compounds, its application might adversely affect soil microbes (Cayuela et al. 2014); thus, it is recommended to quantify the biochar's nature and characteristics carefully prior to application to soil.

The activities of soil enzymes are closely related to biochar as biochar induces soil pH, organic matter, moisture content, and soil pore structure, which helps in the modulation of soil enzymatic activities. Soil enzymes work as catalysts to decompose SOM and alter various nutrient cycles, which is vital to regulate ecosystem responses to biotic and abiotic changes in soil properties after biochar addition (He et al. 2021). The characteristics of soil, such as SOM, water content, texture, temperature, and pH, can affect the activities of soil enzymes (Ouyang et al. 2014). The biochar addition induces soil quality in a positive direction to promote soil enzymatic activities by increasing soil pH, moisture content, and organic matter due to the presence of huge organic carbon and the retention ability of biochar (Ouyang et al. 2014).

These transformations in soil properties with biochar addition can significantly influence soil enzymes such as soil catalase, phosphatase, invertase, and urease. However, the soil enzymatic activities under biochar addition are inconsistent and varied, which might be positive or negative due to soil properties, enzymes, climate, and biochar type and dosage (Gul et al. 2015). In addition, the improvement and transformation of soil dynamics with biochar amendment can also alter the soil nitrogen utilization and its related enzymes, such as nitrate reductase, nitrite reductase, glutamine synthetase, and glutamate synthase that have a significant role and influence on nitrogen utilization for plant growth and development. Previously, Khan et al. (2022b) stated that biochar addition promoted the hydrolysis of inorganic nitrogen fertilizers by improving the activity of soil urease which is more beneficial due to its involvement in nitrogen cycling and availability for plant utilization.

5.3 Engineered biochar promotes soil water-stable macroaggregates

The productivity and sustainability of soil are largely dependent on soil aggregation stability. The fundamental building blocks of soil structure are known as soil aggregates, which are divided into three categories based on their diameter: macroaggregates (diameter > 250 mm), microaggregates (diameter 53–250 mm), and the silt–clay fraction (diameter 53 mm) (Lu et al. 2021). In addition to regulating soil physical and biological processes, soil water-stable aggregates can also determine the fertility and environmental status of the soil. A suitable soil structure can decrease soil erosion and CO_2 emissions while increasing biodiversity, nutrient cycling, water availability, and plant diversity (Piedallu et al. 2016). The majority of variations in soil structure are caused by aggregates, which are also crucial for stabilizing and retaining soil nutrients like carbon and nitrogen (Ma et al. 2022). Soil microbial biomass, plant roots, and SOC are a few variables that can have an impact on soil aggregates; however, it remains unclear how soil aggregates quality can be improved to contribute to nitrogen utilization. In a previous study, it was discovered that exogenously applied N enhanced the mean weight diameter of soil macroaggregates, indicating a favorable impact of N addition on the stability of the soil structure (Lu et al. 2021). Hence, an improvement in the soil aggregate structure with biochar addition can play a significant role in the transformation and utilization of soil inorganic nitrogen. Thus, it is strongly advised that appropriate fertilization amendments be adopted in order to maximize soil water-stable aggregates, nitrogen utilization, and agronomic performance.

High organic matter, unique functional groups, and porosity of engineered biochar have the potential to turn soil macro aggregates into soil water-stable aggregates and promote soil water and nutrient availability (Table 1). Zheng et al. (2018) demonstrated how oxidized carboxyl groups and minerals interacted in biochar, which may react with soil particles and composites to enhance the number of soil aggregates. Recently, the huge use of synthetic nitrogen fertilizers in agriculture has resulted in persistent changes in soil physiochemical conditions, ecology, and environment. Using chemical and organic fertilizers in agricultural production has expanded in recent decades, raising the dangers of soil structural degradation linked to inefficient resource management (Guo et al. 2019). One of the essential mechanisms of soil aggregation includes preserving SOC and promoting carbon sequestration that helps maintain soil fertility and physical structure (Abrar et al. 2020; Mustafa et al. 2020), which is why it had the biggest impact on the development of soil water-stable macroaggregates. The production of soil water-stable macroaggregates can be induced by biochar acidification, and the reason might be that biochar acidification can enhance the density of carboxyl and oxygen-containing functional groups on the biochar surface, making it easier for biochar to combine with soil particles and create soil aggregates (Chang

Table 1 Effect of biochar on the formation and stability improvement of soil water-stable macroaggregates

Soil texture	Biochar type	Biochar application rate	Soil water-stable macroaggregate stability/mean weight diameter of aggregates (mm)		Country	Reference
			MWD value/increased/no effect	Change (%)		
Clay	Rice husk	4%	1.07	16	China	Lu et al. (2014)
Clay	Straw	6%	0.57	21	China	Sun and Lu (2014)
Clay	Wheat straw	40 Mg ha^{-1}	Increased	38	China	Liu et al. (2014)
Silt loam	Sugarcane bagase	5%	24	179	China	Abdelhafez et al. (2014)
Clay loam	Wood	1%	53.6	21	China	Demisie et al. (2014)
Silt loam	Oat hull	20 Mg ha^{-1}	4.16	54	Chile	Curaqueo et al. (2014)
Sandy loam	Corn cob	9 Mg ha^{-1}	No effect	–	China	Zhang et al. (2015a; b)
Sand	Hay	50 Mg ha^{-1}	No effect	–	The Netherlands	Jeffery et al. (2015)
Clay	Wood	42 Mg ha^{-1}	Increased	–	Italy	Baiamonte et al. (2015)
Clay loam	Corn straw	8 Mg ha^{-1}	1.75	35	China	Ma et al. (2016)
Sandy loam	Rice husk	1%	0.83	19	Srilanka	Gamage et al. (2016)
Silt loam	Rice hull	5%	Increased	30–67	South Korea	Kim et al. (2016)
Sandy loam	Corn cob	4%	Increased	28–80	Zambia	Obia et al. (2016)
Sandy Loam	Straw	3%	Increased	92	Austria	Burrell et al. (2016)

et al. 2019). The porous and loose biochar structure induces soil's physical properties by reducing soil bulk density and increasing soil porosity and water-holding capacity to influence water-stable aggregates and facilitate the penetration of the roots for nutrient and water uptake and utilization. The differences in soil's aggregate structure due to biochar addition influence the tensile strength, hydrodynamics, and gas transport in soil, which might significantly affect soil biota (Lehmann et al. 2011; Ma et al. 2022). The strength of these impacts in soil aggregate depends on feedstock type and biochar production conditions, which jointly govern the structure of macro and micro biochar particles. When the tensile strength of biochar is lower than that of soil (for example, in soils high in clay), adding biochar can lower the soil's overall tensile strength (Lehmann et al. 2011). Therefore, a decrease in soil tensile strength with biochar addition can enhance the efficiency of nutrient mining by promoting microbial and root association to enhance nitrogen uptake and utilization.

Soil water-stable aggregates are the important components of soil systems that can contribute to both nutrient and water utilization, which are crucial inputs required by plants. The amount and type of plant inputs that induce soil characteristics will have a significant impact on the development and dispersion of soil aggregates as well as soil texture. Generally, when compared to inorganic amendments, organic amendments can greatly increase the water stability of soil aggregates (Liu et al. 2019a, b). A previous study showed that the addition of N without any organic amendment affected root characteristics and reduced large macro aggregation (2–8 mm) by reducing the mean weight diameter of soil (Chen et al. 2022), while porous biochar structure and high surface area can facilitate root penetration and thus soil macro aggregates. Previously, sugarcane bagasse and oat hull biochars enhanced the mean weight diameter of soil aggregates by 179% and 54%, respectively, which might be due to the high porosity and specific surface area of biochar (Abdelhafez et al. 2014; Curaqueo et al. 2014). The addition of biochar may encourage microbial processes that lead to the production of soil aggregates by causing microbial secretions to function as soil-particle bonding agents. In a previous study, it was demonstrated that acid-treated biochar with a lower pH might reduce the net negative surface charge, causing soil flocculation and dramatically increasing the hydraulic conductivity of soil compared to alkaline biochar (Kumari et al. 2016). Additionally, the hydrological characteristics of the soil are impacted by the size of the biochar particles, which interact specifically with the hydraulic conductivity and macroaggregates of the soil (Lu et al. 2019). In addition, it is crucial to investigate the connections between soil aggregates and NUE after adding biochar since soil aggregate stability is a crucial element that affects the concentration and transformation of water and nutrients in the soil. In light of these views, we hypothesize that adding modified biochar to the soil will result in an increase in soil hydraulic conductivity, macroaggregate stability, and NUE as compared to adding regular biochar, and it is credited to the unique features of the modified biochar (Fig. 4). In this review, we summarized various studies and found that biochar can positively affect soil water-stable macroaggregates to promote soil quality and nitrogen utilization (Table 1).

5.4 How engineered biochar induces soil inorganic nitrogen

Nitrogen is the most critical nutrient for a plant's growth and development and participates in various plant metabolic processes, such as the synthesis of proteins, nucleic acid, chlorophyll, enzymes, vitamins, and plant hormones affecting crop yield and quality (Liu et al. 2018a, b). The primary supply forms of N are NO_3^--N, NH_4^+-N, and amide-N, which are mainly absorbed and utilized by plants, while biochar contains an organic-N and a certain amount of inorganic-N, which includes NH_4^+-N, NO_2^--N and NO_3^--N (Liu et al. 2019a, b). Biochar amendment with an optimum level can benefit N uptake and plant growth; however, at higher levels, it can negatively affect plant growth with phytotoxic effects due to excessive salts (Mukherjee and Lal 2014).

The chemical and structural properties of biochar can help explain biochar's synergetic role in soil biological processes that can significantly interfere with nitrogen dynamics. The nitrogen in biomass converts and forms recalcitrant aromatic structures during biochar pyrolysis, and these aromatic structures can reduce the mineralization rate of carbon and nitrogen (Chen et al. 2014). The presence of weak van der Walls forces on the surface of biochar establishes connections between the positive charge of NH_4^+ and the negative charge of soil or organic matter to facilitate the adsorption of NH_4^+ (Hale et al. 2013). The overall effect of biochar on N transformation and soil denitrification might also depend on soil type, biochar application rate, and pyrolysis temperature during biochar production. Purakayastha et al. (2019) reported that biochar amendment produced from oak wood feedstock at 200–400 °C increased the N_20 emissions, while there was no significant increase in N_20 emissions when biochar was produced at 600 °C . Application of poultry litter and wheat straw biochar to a neutral Vertisol and acidic Aeronosol at the rate of 1–5 Mg ha^{-1} did not affect the soil total N; however, amendment of the same biochar at 5–10 Mg ha^{-1} to an alkaline Calcisol and acidic Ferrasol significantly enhanced the soil total N (Macdonald et al. 2014).

Biochar can significantly influence soil nutrients' retention, mineralization, and immobilization by exhibiting a high carbon sink, more pores, and a large surface area (Fig. 4). The amendment of biochar improves the decomposition of SOM through the priming effect to release nitrogen by increasing the activities of microorganisms due to the high C:N ratio in biochar particles (Blagodatskaya and Kuzyakov 2008). Single aromatic carbons and rich functional groups on biochar surfaces can improve cation and anion exchange capacities in soils, ultimately altering nitrogen retention (Clough and Condron 2010b). Several studies have reported that biochar improved soil N dynamics by elevating N mineralization, promoting nitrification, and reducing the volatilization of ammonia (Mandal et al. 2016; Clough and Condron 2010a, b; Khan et al. 2020). The amendment of biochar with high H/C ratios is necessary to improve N mineralization and the organic farming system challenged by insufficient nitrogen availability during plant growth and development (Pereira et al. 2015). The existence of an elevated amount of ammonia-oxidizing microorganisms and the transfer of electrons to denitrifying soil microbes are also counted in important mechanisms of biochar (Song et al. 2013). The synergetic effect of biochar promotes soil physical, chemical, and biological properties of soil to elevate the soil's microbial and enzymatic activities are the main drivers that improve nitrogen transformation and utilization.

5.5 Summary

Biochar incorporation promotes soil physiochemical properties, microbial activities, and soil water-stable aggregates to enhance soil resources and nitrogen utilization. Engineered biochar emerges as a renewable resource that can absorb NH_4^+-N and NO_3^--N to reduce greenhouse gas emissions, but it depends on many factors, such as pyrolysis temperature, dosage, biomass type, and soil characteristics. Thus, biochar can increase the availability of absorbed ammonium nitrogen to plants or microorganisms on a long-term basis while reducing the loss of nitrogen in soils and improving nitrogen utilization. It will be more advantageous to increase water and N use efficiency together than to maximize water and N inputs individually. The advantages brought about by the interplay of NUE and WUE are essential for boosting production in many agricultural systems while reducing environmental issues. Hence, new research and knowledge are required to evaluate the engineered biochar's role in promoting soil conditions, aggregate structures, and microbial activities concerning nutrient transformation and plant growth.

6 Mechanisms of biochar transforming soil inorganic N and modulating NUE

Fertilizers are essential for plant growth and are applied to soil to substitute the deficiency of various nutrients. It has been estimated that plants can only take up half of the applied fertilizers, and the other half is lost below the ground (Khan et al. 2021a). The main three processes that occur in the soil are denitrification, volatilization, and leaching, which cause the loss of fertilizers. Excess amounts of fertilizers that reach water sources through surface runoff can create nonpoint pollution and lead to adverse effects on aquatic animals and human health. Practicing conventional farming techniques increases crop yields but totally depends on chemical fertilizers, thus negatively affecting soil fertility and fertilizer use efficiency (Bitew and Alemayehu 2017). However, there is a predicted increase in demand for food as the world population is growing, and it is necessary to apply the best management practices to limit nitrate leaching without compromising yield.

Recently, researchers worldwide have been keen to improve the NUE of crops for future agriculture to alleviate the problems associated with chemical fertilization without compromising crop yield. The application of organic residues to the soil, such as manure, composts, and crop residues for carbon sequestration, encounters a faster degradation rate, which releases more carbon dioxide into the atmosphere and increases greenhouse gas emissions (Juriga and Šimanský 2018). Due to its unique and inert nature, biochar is often applied to soils in combination with organic or mineral fertilizers as well as with organic wastes such as sewage sludge (Kończak and Oleszczuk 2018), an emerging and sustainable technique to enhance the use efficiency of applied fertilizers (Asai et al. 2009; Laird et al. 2010). The plant's productivity is directly affected by nutrient availability, which is a product of nutrient dynamics in the soil environment (Marschner 1986). The central aspect of biochar supplementation is its sustainable effect on soil quality and plant productivity (Johannes Lehmann 2007).

Compared to the other fertilization management techniques such as deep placement, control release fertilizers, side dressing, or coated fertilizers, which require a lot of technical approaches and labor cost, the synergetic effect of biochar integration with inorganic fertilizers could be more prominent in terms of reliable application technique, reducing fertilizers lost, soil sustainability and crop productivity. The amendment of rice straw biochar to soil can influence the nitrogen cycle, directly and indirectly, in a systematic manner, as illustrated in Fig. 5. Therefore, integrating nitrogen with biochar is a sustainable approach that increases C sequestration and nutrient utilization and improves soil quality. Considering this

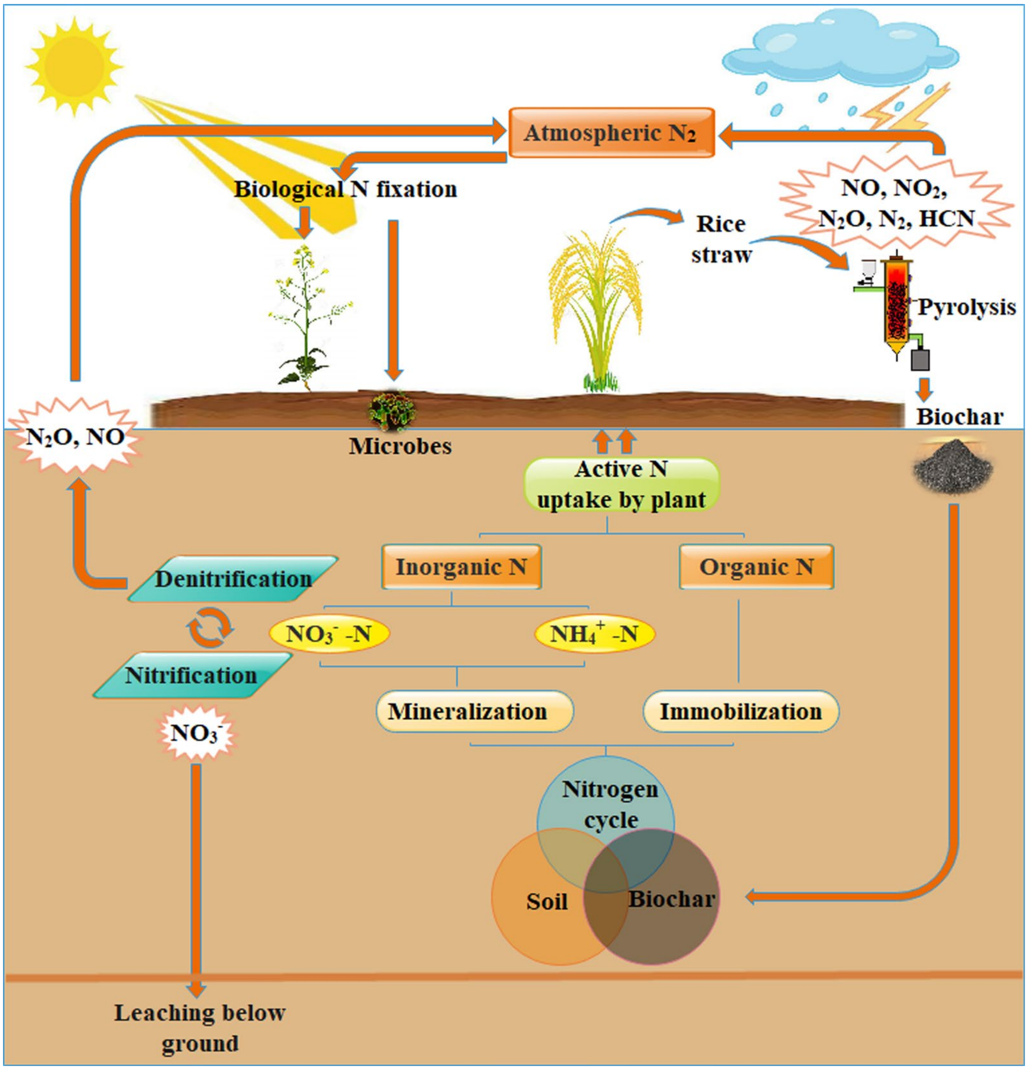


Fig. 5 A proposed diagram illustrating the impact of engineered biochar on the nitrogen cycle

huge impact of biochar, it is of great interest to elaborate on how biochar alters soil conditions and induces transformations and the availability of inorganic nitrogen for plant use.

6.1 Adsorption and desorption strategy of biochar

A major issue contributing to environmental pollution and eutrophication is nitrogen leaching from soils, especially in light-textured soils. Previously it has been reported that biochar could desorb the adsorbed nitrogen over a period of time for plant uptake (Kameyama et al. 2014). Recently, biochars made from various feedstocks under various pyrolysis conditions have been the subject of substantial research to reduce the leaching loss of N from soil (Jones et al. 2012; Zhu et al. 2012; Purakayastha et al. 2019). The negative and positive sites on the biochar surface can sorb ammonium and nitrate forms of nitrogen electrostatic attraction force (Joseph et al. 2010; Nelissen et al. 2015). Feedstock type and pyrolysis temperature can have variable effects on the sorption capacity of biochar. According to a previous study (Yao et al. 2012), Brazilian pepperwood produced the most potent biochar for NH_4^+-N adsorption up to 12% among various feedstocks, which included sugarcane bagasse, peanut hull, bamboo, and Brazilian pepperwood. Biochars have a negative charge and facilitate the absorption of NH_4^+-N through electrostatic attraction (Zheng 2010). A range of sandy silt soils was treated with bamboo charcoal (pyrolyzed at 600 °C) for 70 days, and the amount of NH4 N leaching loss was reduced by a total of 15% (Ding et al. 2010). Another study (Asada et al. 2002) found that bamboo biochar prepared at 500 °C adsorbs NH_3 more effectively than biochar prepared at > 700 °C. Generally, the adsorption of NO_3^--N could be less due to higher negative charges on biochar surfaces. However, the presence of base functional groups on the biochar surface, like chromenes, ketones, and pyrones, can facilitate the adsorption of NO_3^--N to the biochar surface (Montes-Morán et al. 2004). Moreover, the sorption of NO_3^--N might be enhanced gradually, and biochar turns hydrophilic with the aging of biochar (Biochar for Environmental Management 2012).

Biochar with a porous structure, high surface area, and various functional groups helps to retain the extra inorganic nitrogen and desorb it later, considering the plant requirements. Biochar can play a dual role in the application to soil to provide various nutrients for current uptake and retained nutrients for later utilization for efficient growth of plants (Khan et al. 2020). The chemisorption of soil inorganic nitrogen depends on the biochar functional groups (Lehmann and Joseph 2012a). Biochars produced from grasses contain a huge amount of carboxylic groups than biochars produced from woody feedstock, which favors the sorption of inorganic nitrogen in grassy biochars (Harvey et al. 2012). When the temperature is higher (> 600 °C), the oxygen-containing functional groups are lost, and acidic functional groups turn to basic or neutral aromatic groups (Mukherjee et al. 2011; Gai et al. 2014). Soil inorganic desorption capacity and ability of biochar are related to various factors of biochar, such as biochar amendment rate, feedstock type and pyrolysis temperature, anion and cation exchange capacity, climatic conditions, soil type, and nitrogen requirements of the plant (Taghizadeh-Toosi et al. 2012). However, Jones et al. (2012) found that the dissolved organic N (DON), NO_3-N, or NH_4^+-N levels in the soil were unaffected by commercially available biochars made from chipped trunks and large branches of copper beech and oak trees. Likewise, no long-term effects on N mineralization, NH_3 volatilization, denitrification, or NH4 sorption were seen after adding biochar, as well as minute effects on soil organic carbon and DON (Clough et al. 2013). In contrast, biochar promoted the available N content in alkaline sandy loam soil, while the impact was more for maize stover biochar than wheat straw biochar (Purakayastha et al. 2019).

6.2 N mineralization under biochar

Plants can readily absorb the ammonium or nitrate forms of inorganic nitrogen in the soil. Due to its anionic nature and water solubility, nitrate is prone to leach out of the soil system and does not form bonds with the negatively charged sorption sites of the soil, while ammonium can sorb onto negatively charged sites (Ahmad et al. 2021). The priming effect, which governs the mineralization of soil organic matter (SOM) upon adding new substances, might be induced by biochar addition (Zimmerman et al. 2011). The mineralization of native soil organic pools is impacted by applying biochar to the soil, which in turn affects the soil N cycling (Zimmerman et al. 2011). A previous study observed that adding maize biochar to soil increased gross N mineralization by 18–221% (Nelissen et al. 2012). The response of biochar to convert organic N to inorganic N via mineralization is variable, and it may change with different feedstock types, application rates, pyrolysis temperatures, and C:N ratio of biochar as the labile organic compounds in biochar is influenced by temperature and feedstock to induce the activity of the priming effect (Joseph et al. 2010; Zimmerman et al. 2011; Singh et al. 2012). Lower pyrolysis temperature (< 400 °C) enhances the mineralization rate of biochar by increasing the availability of easily decomposable organic carbon contents than biochar of higher pyrolysis temperature (> 525 °C) (Luo et al. 2011; Singh et al. 2012). Soil N mineralization tends to increase under manure-based biochar application compared to plant-based biochar due to the lower ratio of C:N (Singh et al. 2012).

The process of N mineralization responds to time, and the priming effect during N mineralization occurs for a very short duration of time (Zimmerman et al. 2011). Biochar promotes the priming effect at the initial stage of application by providing a new carbon source to stimulate soil microbes for the mineralization of labile organic compounds of biochar (Kuzyakov et al. 2014); however, in long-term biochar application, the mineralization process may decrease due to adsorption of organic matters on surfaces or pores of biochar and become less available to soil microbes (Zimmerman et al. 2011). In contrast to claims that adding biochar to soil would aid in the mineralization of organic soil N pools (Nelissen et al. 2012; Singh et al. 2012; Ahmad et al. 2021), several studies have found that applying biochar to soil either has no effect (Cheng et al. 2012) or has a negative influence on the transformation of soil N (Dempster et al. 2012; Zheng et al. 2012). The findings indicated that mean gross N mineralization was not impacted by biochar, and the lower rate of biochar amendment in this study was the primary cause of the non-significant effect of biochar in contrast to previous studies, where rates of biochar were more than 1% (Cheng et al. 2012). Keeping in view the facts about the N mineralization process under biochar addition, it is suggested to observe the conditions of micro-climate, micro-flora, and micro-fauna of the soil before designing a specific biochar for possible significant results.

6.3 Biochar induces N immobilization

Besides mineralization, biochar can also immobilize the soil N to prevent its availability and decrease plant N uptake rate. Biochar provides labile organic compounds to soil microbes as a nutrient source, increasing the immobilization rate. Different soil microorganisms can immobilize NH_4^+ and NO_3^- (Nelissen et al. 2012), and both can be attracted to negatively and positively charged spots on biochar surfaces by electrostatic forces (Joseph et al. 2010). NH_4^+ and NO_3^- concentrations decreased in a study due to high induced soil alkalinity and adsorption capability of biochar, where two forms of biochar were added to five different soil types (Mandal et al. 2016). The reduced availability of soil inorganic nitrogen and high microbial activities related to soil N cycling and CO_2 emissions are the evidence to observe N immobilization (Ippolito et al. 2012; Zhang et al. 2012). Nitrate reaction to biochar addition in the soil is comparably less constant than the ammonium response. A previous study (Clough and Condron 2010b) concluded that NO_3-ions are sorbed onto the anion exchange sites of biochar, which could decrease its availability during the nitrification process.

It is widely known that the main determinants of NH_4^+-N and NO_3^--N concentrations are the kind of feedstock, the pyrolysis temperature, and the type of soil. The sorption of NH_4 ions was dramatically increased by about 62–81% in hardwood biochar generated at 400 and 600 °C. On the other hand, NO_3^- sorption was not detected in biochar; nevertheless, activated biochar displayed NO_3^- sorption of 2–23% (Zhang et al. 2015a, b). Wood-based biochars induce N immobilization to some extent; however, it is uncertain as woody biochar is more intractable than others (Lehmann et al. 2011; DeLuca et al. 2012). Likewise, biochar created at 600–900 °C lowered NH_4^+ concentration at the start in soil compared to urea fertilized treatment, while NO_3^- concentration was also reduced with biochar application at the later stage of the study (Lan et al. 2018). Applying biochar to various soil types has produced conflicting results for the sorption of both NH_4^+ and NO_3^- ions. In contrast to acidic sandy soil, alkaline clay soil treated with olive pulp biochar had a reduced $NH_4{}^+$ content, whereas neither olive nor corncob biochar had an impact on NO_3^- concentration in either soil type (Wu et al. 2018a, b). The rates of N immobilization or mineralization also depend on C:N ratio of biochar, and C:N of 20 is the baseline; N immobilization occurs if the ratio is above 20, and N mineralization starts as the ratio goes below 20 (Lehmann and Joseph 2012a).

6.4 Biochar effect on nitrification and denitrification

In the nitrogen (N) cycle, the ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) both play key roles in the initial and rate-limiting phase of nitrification, which is the oxidation of ammonia (Chen et al. 2008; Song et al. 2013). Biochar having a high surface area and porous structure may moderate soil temperature, aeration, and moisture content, and thus it can induce the activities of nitrifiers. Generally, the main nitrifiers, such as AOB and AOA, might be activated with biochar application (Thies and Rillig 2012). Previous research (Song et al. 2013) has demonstrated that the application of cotton stalk biochar considerably increased the amount of ammonia-oxidizing bacteria (AOB), indicating its capability to enhance nitrification. Biochar pores absorb water, decrease soil bulk density, and enhance soil porosity to promote the adsorption of nitrifiers inhibitors from soil and induce nitrification (Joseph et al. 2010; Mukherjee and Lal 2014). However, there is no positive effect of biochar application on AOA and AOB under water-saturated conditions (Harter et al. 2014), while in aerobic soil conditions, gene copy numbers of AOA and AOB increased by 1.5 and 1.7 times, respectively, under the combined application of biochar and NPK fertilizer, enhancing the overall nitrification rate in soil (Hosseini Bai et al. 2015).

The nature of biochar is mostly alkaline, which can favor the abundance and activities of nitrifiers in acidic soils. Nitrifiers are pH-dependent, and soil pH is directly or inversely proportional to biochar amendment. The amendment of biochar to forest soils has been found to boost nitrification rates and alter the composition of microbial communities (Ball et al. 2010). The authors hypothesized that the nitrification rates in the biochar treatment may initially be lower due to the presence of a nitrification-inhibiting component (α-pinene) in an unweathered biochar used to study biochar effects on N deposition to soil (Clough et al. 2010). Regarding N cycling studies using biochar, it is significantly important to evaluate the presence of microbially toxic or nitrification-inhibiting compounds and the degree of weathering or residence duration of the biochar in the soil. Nitrification in the soil starts when pH is above 6.0, while it halts when pH goes below 5.0 (Sahrawat 2008). The main factors contributing to alkalinity in biochar are oxygen-containing functional groups, minerals such as $CaCO_3$, and base cations formed during the biochar production process (Joseph et al. 2010; van Zwieten et al. 2010a, b). The amount and availability of $NH_4{}^+$ -N also alter the process of nitrification; hence ammonium-based fertilizers or organic fertilizers in integration with biochar promote the activities of nitrifiers (Sahrawat 2008). However, uncertainties regarding the application of biochar in alkaline soils raise the amount of the alkalinity and nitrification activity and hence nitrate leaching because increased nitrification rates typically lead to N leaching, thereby undermining the utilization of fertilization.

Biochar can reduce the denitrification process by decreasing nitrogen loss in the form of N_2O, which reduces the availability of NO_3^--N in the soil. Biochar decreases nitrous oxide emissions by up to 50% by affecting processes of denitrification (van Zwieten et al. 2010a, b; Clough and Condron 2010a, b). The functional groups such as Fe or Cu on the biochar surface attract N_2O and can be activated possibly for N–N or N–O scission, leading to a reduction in N_2O emission (Cayuela et al. 2014). Biochar can absorb organic carbon or inorganic nitrogen to decrease the substrate for microbes and thus reduce the N availability in soil, reducing the substrate for producing N_2O (Cayuela et al. 2014). It is well known that a higher surface area and porous structure of biochar can facilitate the reduction of substrate for microbes by absorbing more nitrogen and carbon. The denitrification processes can be reduced due to liming effect of biochar, as the higher pH can alter and regulate the activities of microbes and enzymes involved in denitrification.

The high CEC and negative charge on the biochar surface enhance its adsorption capacity to prevent nitrogen loss and decline in N_2O emission. Previously, it has been observed that biochar application decreases the N_2O emissions while the abundance of the (*nosZ*) gene increases, which is responsible for nitrous oxide reductase activity (Harter et al. 2014). In addition, *nirK* and *nirS* genes of nitrite reductase also increased up to 10% under the biochar application (Nguyen et al. 2017). Biochar application promotes the conversion of N_2O to N_2 during the last step of denitrification by mediating the *nosZ* gene and decreasing N_2O (van Zwieten et al. 2010a, b; Cayuela et al. 2014). It is important to note that biochar addition can trigger the expression of genes involved in nitrogen transformation to increase the nitrification rate and decrease denitrification. Future combined physiological and molecular studies will be remarkable to further elucidate the synergistic role of biochar. Numerous cast of bacterial, archaeal, and fungal candidates collaborate to catalyze the process of denitrification, which is the conversion of NO_3 to NO_2, nitric oxide (NO), N_2O, and finally N_2 (Hayatsu et al. 2008; Coskun et al. 2017). Thus we can assume that engineering biochar for specific kinds of microbes would be beneficial to facilitate the process of denitrification. The activities of these processes in denitrification could vary with properties of biochar, amendment rate, and nitrogen fertilizer forms.

6.5 Biochar promotes biological nitrogen fixation

Maintaining N inputs and outputs in many agricultural systems depends on biological nitrogen fixation (BNF), converting atmospheric nitrogen from its inert N_2 form to NH_3 by biological means. BNF is thought to contribute 17.2×107 Mg N to soils worldwide, with significant inputs coming from leguminous crops, approximately 21.5×106 Mg N (Mia et al. 2014). Several studies have evidenced the impact of biochar promoting the rate of BNF in soil (Anderson et al. 2011; Purakayastha et al. 2019; Ahmad et al. 2021). The high porous structure and surface area of biochar provide better habitat for soil microbes to promote the activities of nitrogen-fixing bacteria. Amendment of biochar influences nitrogen fixation by affecting free-living and symbiotic soil nitrogen-fixing bacteria, which helps to convert atmospheric N_2 to ammonia (NH_3) (Thies and Rillig 2012). It was hypothesized that adding biochar to soil enhanced the microenvironment for microbial growth (Horel et al. 2018), which might lessen the dependency of plants on mycorrhizae (Biederman and Stanley Harpole 2013). On the other hand, adsorption and immobilization of N on biochar surfaces decrease the N availability for plants and thus stimulate the activity of N fixation through nitrogen-fixing bacteria in root nodules. A previous study (Rondon et al. 2007) found that applying 90 g of biochar raised the amount of fixed nitrogen in common beans from 50% to 72%.

Biochar elevates the rate of N fixation by enhancing the nodulation and nitrogenizing activity in legumes to improve crop growth and yield (Clough and Condron 2010a, b; Thies and Rillig 2012; Xu et al. 2015). A previous study using an Oxisol discovered that BNF in *Phaseolus* spp. rose when biochar was added at moderate rates, probably because more Mo and B were available in the soil (Rondon et al. 2007). In a pot experiment, it was discovered that red clover (*Trifolium pratense* L.) had higher BNF when a low dose of plant-based biochar (10 t ha^{-1}) were applied as opposed to large doses (50 and 120 t ha^{-1}) (Mia et al. 2014). In contrast, high biochar application rates increase the contents of boron, molybdenum, potassium, phosphorus, and calcium, enhancing rhizobia nodulation (Rondon et al. 2007). The overall impact of biochar-inducing soil inorganic nitrogen dynamics is related to the above processes involved in nitrogen transformation. Biochars of different feedstocks, application levels, and pyrolysis conditions will have different adsorption and desorption capacity to induce the nitrogen transformation in soil. Two different maize straw biochars, including (i) slowly pyrolyzed at 600 °C and (ii) hydrothermally carbonized at 210 °C, were examined for their effects (Egamberdieva et al. 2019). Comparing hydrothermally carbonized biochar to slow pyrolyzed biochar, the latter showed improved soil biological activity and nitrogen fixation. Feedstock type may differentiate biochar pore size and habitation of microbes (Thies and Rillig 2012). For example, the diameter of bamboo biochar pores ranges from 0.001 to 1000 µm, while that of wood biochar pores is between 10 and 3000 µm, and thus different microbes can fit onto biochar pores because their sizes range from bacteria 0.3 to 3 µm, fungi 2 to 80 µm and protozoa 7 to 30 µm in size. Therefore, in future research, all the processes involved in nitrogen transformation should be studied under different types of biochar to draw guidelines for the sustainable use of biochar in improving nitrogen use efficiency.

6.6 Biochar modulates nitrogen use efficiency (NUE)

The ratio of total N uptake by plants (leaf, stem, grain, etc.) to total nitrogen input of soil (fertilizer, organic matter, and total soil nitrogen) is expressed as nitrogen use efficiency. Moll et al. (1982) defined NUE as the grain yield produced by utilizing per unit available nitrogen. NUE can be split into two parts: 1st is nitrogen uptake efficiency (NUpE) which measures the plant's ability to capture nitrogen from the soil, and 2nd is nitrogen utilization efficiency (NUtE), the ability of a plant to use the absorbed nitrogen to form seeds (Moll et al. 1982). The total N input of agricultural soils is mostly limited and less capable of supplying sufficient N forms, mainly due to the loss of N ions via conversion to gaseous forms (i.e., NH_3, N_2O, N_2, and NO) leaching below ground (Khan et al. 2022b). Plants can absorb N mostly in the form of ammonium and nitrate from N sources; however, they only make up 2% of the total soil N concentration, and their availability in soils is scarce (Hailegnaw et al. 2021). To achieve the high production demands, crop growers have gradually increased the use of inorganic fertilizers in inadequate amounts with less utilization efficiency and output rate (Fig. 6). Synthetic N fertilizers are applied to fulfill crop requirements; however, lower nutrient availability and recovery create environmental uncertainties like greenhouse gas emissions, eutrophication, and global warming (Abbruzzini et al. 2019). Nitrogenous fertilizers are widely applied to promote crop output in the agricultural sector around the world; however, all agriculture has decreased nitrogen (N) utilization efficiency due to nitrogen losses (Ahmed et al. 2019). The chemical fertilization of inorganic nitrogen is at its peak, as evident in Fig. 6B, which needs to be reduced and optimized while maintaining a higher grain yield is crucial to ensuring sustainable agriculture in the future. This challenge

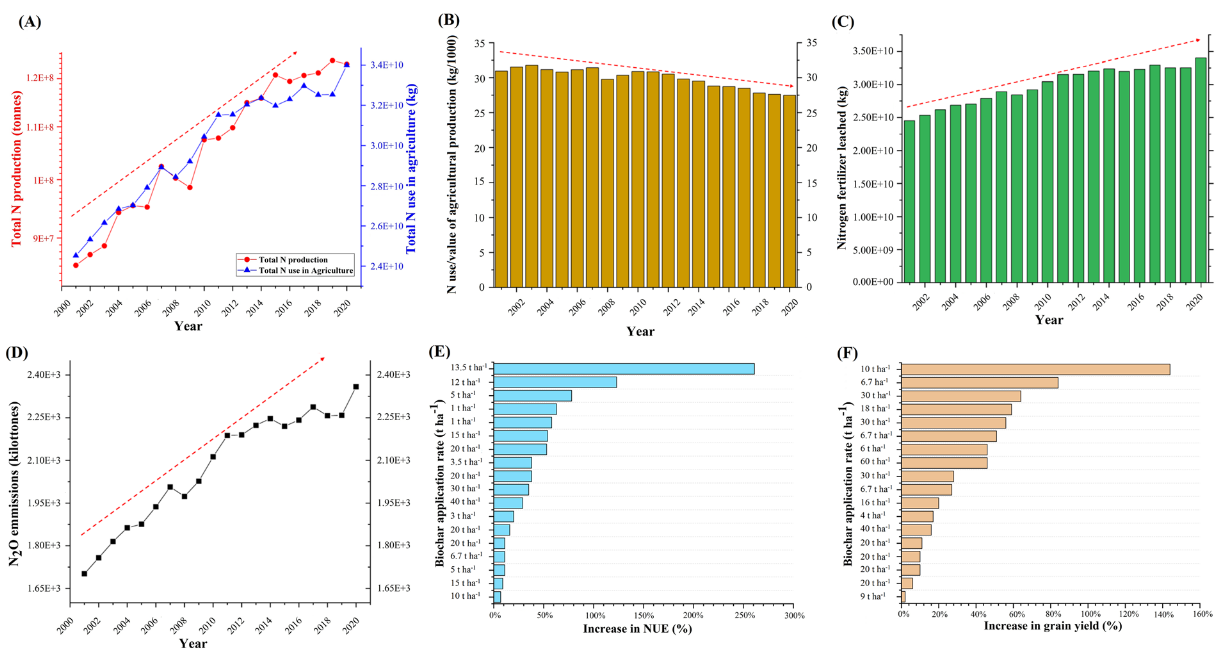


Fig. 6 Data of total N production and total N use in agriculture (**A**), N use/value of agricultural production (**B**), N fertilizer leachate (**C**), and N_2O emission (**D**) of the world (FAO 2021). Publications that used biochar amendment in field or pot studies were selected to evaluate the data of percent increase in NUE (**E**) and grain yield (**F**) by biochar. The total number of reviewed publications was 36. The total number of reviewed publications was 36. Based on these studies, we evaluated that biochar has the potential to decrease N fertilizer usage and improve its utilization, which will help to decrease N_2O emission and enhance NUE and crop yield on a sustainable basis. (Xiang et al. 2020; Khan et al. 2020; Omara et al. 2020; Hailegnaw et al. 2021; Huang et al. 2018a, b; Zhang et al. 2020; Sarfraz et al. 2017; Zhang et al. 2020; Khan et al. 2021c; Sun et al. 2019a, b; Tang et al. 2023; Kimani et al. 2021; Khan et al. 2022b; Liao et al. 2020; Kang et al. 2021; Chu et al. 2020; Oladele et al. 2019a, b; Cao et al. 2019; Liu et al. 2021a, b, c; Rondon et al. 2007; Oladele 2019; Yadav et al. 2019; Sun et al. 2014; Akhtar et al. 2014; Huang et al. 2018a, b; Baronti et al. 2014; Abbruzzini et al. 2019; Zhang et al. 2020; Khan et al. 2021a; Jing et al. 2020; Khan et al. 2022b; Bashir et al. 2020; Macdonald et al. 2014)

should be addressed by adapting various agronomic approaches to ensure the improvement of crop nitrogen use efficiency (NUE).

The higher application of inorganic nitrogen fertilizers can be lost from the soil and increase the soil acidity, further reducing the nitrogen use efficiency, plant growth, and grain yield. Previously, Khan et al. (2021a) observed that high application of sole nitrogen boosted nitrogen uptake without improving rice growth, biomass, or yield, resulting in a fall in NUE, while combining biochar with high nitrogen ameliorated the adversity of high or low nitrogen and enhanced NUE as shown in Fig. 4B. In addition, the synthesis of chemical fertilizers needs fossil fuel and energy, increasing fertilizer costs and greenhouse gas emissions. In this review, we analyzed the data of nitrogen dynamics for the last twenty years, from 2001 to 2020, to examine the N status in the environment (Fig. 6). This is a very alarming situation that worldwide, the total production and use of synthetic nitrogen fertilizers are increasing gradually with a decrease in N use per production due to the loss to the environment through leaching, which accelerates the greenhouse gas emissions and declines NUE (Fig. 6A–D). Interestingly, biochar amendment has proved to enhance NUE compared to unamended treatments, as evident in Fig. 6E and Table 2. A key part of the biochar amendment approach to decrease N fertilizer losses in agriculture will be to increase the NUE of the crop. A simple approach could be that plants can either increase the quantity of N they absorb from the soil or they can utilize the N they absorb more effectively, producing more with less to increase uptake and utilization efficiency, respectively (Garnett et al. 2009). Although it would be ideal if plants were developed with improvements in both features of nitrogen uptake and utilization, for the time being, improvements in either trait would be helpful, and biochar has the potential to promote both features of N. Thus reducing inorganic fertilizer rates and elevating NUE with an environment-friendly strategy is crucial to sustaining the natural resources and quality of the environment and promoting sustainable agriculture.

We postulated that adding biochar to the soil in conjunction with inorganic fertilizers could elevate NUE and encourage sustainable agriculture. Mostly, the plant prefers ammonium and nitrate nitrogen; however, soil inorganic nitrogen preference varies among different soil types and plants; i.e., NH_4^+-N is preferred by acidic soil while NO_3^--N is preferred by alkaline soil (Hahne and Schuch 2004). After the active uptake of NO_3^-, the activities of nitrate reductase (NR) and nitrite reductase (NIR) reduced it to nitrite (NO_2^-) and ammonium (NH_4^+), respectively. The glutamine synthetase (GS) and glutamate synthase GOGAT cycle convert ammonium generated from nitrate or directly from ammonium absorption by ammonium transporters (AMTs) into amino acids (Khan et al. 2022b). The soil acidity and toxicity related to aluminium are decreased with the liming effect of biochar to improve the condition of the root zone environment and promote the assimilation of soil inorganic nitrogen (Van Zwieten et al. 2010a, b). There is also an indirect effect of biochar on inorganic nitrogen by shifting and absorbing root exudates through biochar priming effects and thus influencing SOC dynamics (Nguyen et al. 2017). Smaller biochar particles have greater specific surface areas, which may result in more active sorption sites and greater inorganic ion adsorption capability (Tang et al. 2013). This can be achieved by biochar engineering to reduce the biochar particle size for pronounced prevention and adsorption of N to increase NUE. Biochar improves NUE by reducing soil nutrient leaching, increasing soil organic matter, and improving soil moisture content to facilitate the timely supply of resources to the plant.

The effects of biochar may not be consistent, and the final effect on NUE can vary due to certain characteristics of biochar, which need attention during the time of biochar selection and application. The pyrolysis temperature, type, application rate of biochar, and soil type are important factors affecting the soil inorganic N transformation and use efficiency. In this review, we examined the results from the previous studies and found that NUE can be increased with the addition of various types and doses of biochar (Fig. 6E). Moreover, biochar prepared under pyrolysis temperature 600–900 °C retained the NH_4^+ in the rhizosphere compared to sole urea treatment, and later on, NO_3^- was also retained in the soil (Lan et al. 2018). There are many studies with contradictory results on the role of biochar in NH_4^+ and NO_3^- sorption to promote NUE. Previously, Pereira et al. (2015) observed that NUE remained insignificant, and biochar promoted soil conditions, microbial activities, and nutrient transformation while reducing N_2O emissions. Amendment of rice straw biochar in anthrosols significantly increased $NH_4{}^+$ sorption by up to 68%; however, no NH_4^+ sorption was noted in ferrosols soil (Yang et al. 2015). Likewise, alkaline clay soil under olive pulp biochar showed a lower concentration of $NH_4{}^+$ than acidic sandy soil, while both soils did not influence NO_3^- concentration under olive and corncob biochar (Wu et al. 2018b). Likewise, Cao et al. (2019) stated that biochar improved NO_3^- carrying capacity, nitrate reductase, and NUE by reducing NO_3^- leaching, soil denitrification intensity, and soil nitrogen oxide fluxes. The application of biochar increased wheat growth, NUE, amino acid contents, and grain yield; however, the effect of biochar was negative above 20 t ha^{-1} (Sun et al. 2019b). Applying rice straw biochar at 30 t ha^{-1} under rapeseed cultivation significantly improved

Table 2 Summary of the selected recently published studies elaborating the role of biochar affecting soil status, plant growth, and nitrogen use efficiency

Test crop	Soil texture	Biochar application rate	Nitrogen use efficiency increase/decrease % or no effect	The main effect of biochar on NUE in relation to soil status or plant growth	Country	References
Rice	Clay loam	22.5 t ha^{-1}	No effect	↑ Rice biomass and yield and ↓ environmental pollution related to sole chemical fertilization	China	Dong et al. (2014)
Lettuce	Silt loam	10 t ha^{-1}	No effect	↑ Soil conditions, microbial activities, and nutrient transformation while ↓ N_2O emissions	California	Pereira et al. (2015)
Maize	Alkaline	1% w/w	+ 29	↑ Soil water-holding capacity, total organic carbon, stomatal conductance, nitrogen uptake, and NUE	Pakistan	Sarfraz et al. (2017)
Rice	Fulvisol	20 t ha^{-1}	+ 10, 11, and 7 in three seasons	↑ Soil fertility and NUE	China	Huang et al. (2018a, b)
Wheat	Saline	20 t ha^{-1}	+ 5–38	↑ Wheat growth, NUE, amino acid contents, and grain yield	China	Sun et al. (2019a)
Rice	–	12 t ha^{-1}	+ 123	↓ Soil nitrate (NO_3^-) leaching while ↑ soil pH, organic carbon, total nitrogen, available P and K contents, NUE, and rice growth	Nigeria	Oladele et al. (2019a)
Apple	Sandy clay loam	0–4% w/w	+ 261	↑ NO_3^- carrying capacity, nitrate reductase, and NUE by ↓ NO_3^- leaching, soil denitrification intensity, and soil nitrogen oxide fluxes	China	Cao et al. (2019)
Rice	Clay loam	10 t ha^{-1}	+ 7	↑ NUE by ↓ N_2O and CH_4 emission rates	China	Xiang et al. (2020)
Maize	Silty clay loam	5 t ha^{-1}	+ 11	↑ Nutrient cycling and ↑ NUE and maize growth	USA	Omara et al. (2020)
Rice	Anthrosol	1.5% w/w	+ 78	↑ Soil pH, NH_4^+-N content, root morphology, and rice NUE	China	Chu et al. (2020)
Rapeseed	–	1 t ha^{-1}	+ 58	↓ Denitrification and ↑ soil nitrification, nutrient cycling ability of microbes, and NUE of rapeseed	China	Liao et al. (2020)
Rapeseed	Clay sand mixture (2:1)	15 t ha^{-1}	+ 9	↑ Soil pH, soil organic matter, N uptake, and NUE of rapeseed	China	Khan et al. (2020)
Rice and wheat	Irragric Anthrosols	20–40 t ha^{-1}	+ 20–53	↑ Soil organic carbon, total nitrogen, aggregate stability, root growth, and, finally, NUE	China	Zhang et al. (2020)

Table 2 (continued)

Test crop	Soil texture	Biochar application rate	Nitrogen use efficiency increase/decrease % or no effect	The main effect of biochar on NUE in relation to soil status or plant growth	Country	References
Maize	Acidic cambisol	2% w/w	+11	↑ Soil conditions and optimum uptake of N, P, K, Ca, and Mg, maize biomass, and NUE	Czech Republic	Hailegnaw et al. (2021)
Chinese cabbage and rice	–	1 t ha^{-1}	+58 and 63	Biochar ↓ N_2O emissions in paddy soil and ↑ NUE of Chinese cabbage and rice	South Korea	Kang et al. (2021)
Rice	Clay sand mixture (2:1)	30 t ha^{-1}	+35	↓ The adverse effects of high single nitrogen on plant growth and ↑ nitrogen utilization and NUE	China	Khan et al. (2021a)
Rice	Inceptisol	20 t ha^{-1}	+54	↑ Soil pH, electrical conductivity (EC), total N, SOC, available phosphorus (AP), NUE, and rice growth	Japan	Kimani et al. (2021)
Rapeseed	Clay sand mixture (2:1)	15 t ha^{-1}	+16	↑ The activities of soil enzymes and plant nitrogen metabolism-related enzymes and NUE of rapeseed	China	Khan et al. (2022b)

Values of nitrogen use efficiency represented with "+" indicate an increase in nitrogen use efficiency percent and an upward arrow "↑" indicates an improvement, and a downward "↓" indicates a decline in mentioned indices

the plant growth and biomass; however, the NUE was high at 15 t ha^{-1}, suggesting that high biochar immobilized soil inorganic nitrogen decreased its availability for plant uptake (Khan et al. 2022b). Similarly, Sun et al. (2019a) observed that biochar addition of 5–20 t ha^{-1} significantly increased wheat biomass, and NUE and biochar more than 20 t ha^{-1} was excessive and decreased wheat NUE. Another study by Sarfraz et al. (2017) found out that biochar increased soil water-holding capacity, total organic carbon and stomatal conductance, and nitrogen uptake in plants and thus increased NUE. As we mentioned earlier, engineered biochar promoting the stability of water-stable macroaggregates can be crucial to improving the soil moisture content promoting N uptake, stomatal conuductance, plant grrowth and finally NUE.

As discussed earlier, biochar has the potential to manage and transform the soil N dynamics and improve its uptake and utilization by the plant due to its unique structure and functionality, which includes: (i) improving soil physiochemical and biological properties that regulate nutrients cycling, (ii) retaining nutrients due to a porous surface, high CEC and negative charge, and (iii) preventing N losses through emission and surface runoff. Generally, the negative and positive charge sites of biochar sorb and retain NH_4^+ and NO_3^- in soil by increasing the AEC and CEC of soil (Joseph et al. 2010). The applied N fertilizers in managed systems where N exceeds plant demands could be bound with biochar in either the NH_4^+ or NH_3, thereby effectively reducing the inorganic-N pool available for subsequent nitrification and denitrification-induced losses of N_2O-N and thus improving NUE (Ahmad et al. 2021). It is vital to understand the underlying regulatory networks controlling N uptake, assimilation, and redistribution within the plant while modifying N uptake efficiency to enhance total NUE. Earlier, Khan et al. (2022b) found out that biochar triggered the activities of soil and plant nitrogen metabolism-related enzymes, which significantly promoted the N transformation from soil to plant and improved the NUE of rapeseed. The biochar's neutralization and redox potential capacity regulate and transform N from N_2O to N_2 to reduce N losses and promote NUE (Khan et al. 2021a). More oxygen-containing functional groups and fatty chains are present in nano-engineered biochar, which improves excellent dynamic stability and reactivity capabilities. By interacting with anions, these properties could boost the anion adsorption capacity. In order to limit the loss of soil water and nutrients, Vithanage et al. (2015) discovered that acidification of biochar increased the amount of oxygen-containing functional groups, specific surface area, and surface structure and altered the surface structure features. Previously, the characteristics of biochar were altered by Mahdi et al. (2019) using various acids. They discovered that acidification of biochar eliminated contaminants like metals and added new acidic functional groups to the biochar's surface to enhance its porosity structure. Thus biochar modification can improve the biochar surface and porosity to promote soil macroaggregates and simultaneously enhance soil water and nutrient conservation and, thus, water use and nitrogen use efficiencies. On the basis of the previous studies that elucidated the potential and role of biochar inducing soil inorganic nitrogen and improving nitrogen use efficiency (Table 2 and Fig. 6), it is suggested to use biochar as an organic amendment to sustain soil quality, environmental stability, and crop productivity.

6.7 Integration of engineered biochar with inorganic fertilizers inducing plant growth and yield

The synthetic fertilizers are often applied in huge amounts to attain high production. Still, without organic amendments, the nutrient supply and utilization rate of inorganic fertilizers is very low, which needs to be compensated to prevent fertilizer loss, environmental degradation, and maintain agricultural sustainability. The role of biochar in improving plant growth by the action of soil and plant nitrogen transformation in a possible mechanized way is illustrated in Fig. 7. Integration of biochar with composts or inorganic fertilizers can enhance crop growth and production through main important factors such as increments in soil-specific surface area, total porosity, water holding capacity (WHC), cation exchange capacity (CEC), and liming effects (Rajkovich et al. 2012). Organic amendment coupled with chemical fertilizer has been approved previously as a better strategy to conserve

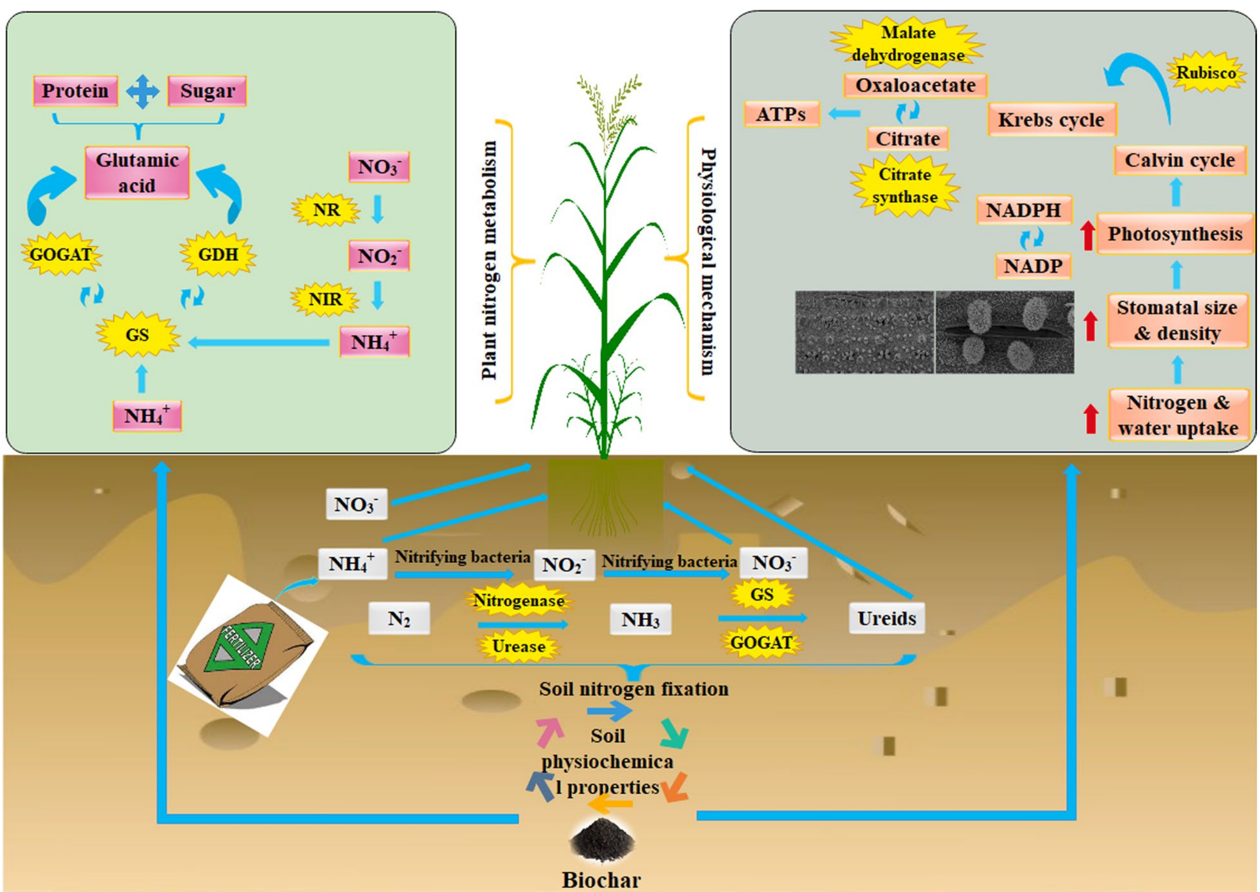


Fig. 7 A conceptual diagram illustrating biochar effects on plant growth in relation to nitrogen metabolism in soil and plant modulating plant physiological mechanism to promote crop production

and improve soil fertility and crop productivity than the sole application of chemical or organic amendments (Fischer and Glaser 2009; Bandyopadhyay et al. 2010).

The effect of biochar is not always positive or consistent, and it varies with application rate and duration of time, which can differentially affect plant growth. The addition of biochar at the rate of 16 to 20 t ha^{-1} under lower N fertilizer application, a reduction in chlorophyll was observed, indicating that biochar in N-deficient soils may decrease grain yield unless the addition of N fertilizer is not integrated (Asai et al. 2009; Semida et al. 2019). Application of inorganic fertilizers, along with rice straw biochar, improved rice crop growth and yield; however, the effect of biochar was not only positive but also negative upon sole application of biochar, reducing rice biomass and yield (Khan et al. 2021a). The integration of chemical fertilizer and rice husk biochar positively enhanced the growth and yield attributes of lowland rice (Munda et al. 2016). Bera et al. (2014) observed that rice straw biochar prepared at 400 ℃ applied at 2.25 g kg^{-1} equivalent to 5 t ha^{-1} combined with compound NPK fertilizer improved rice yield by 24.3% and 31.3% in two different soils. Previously, Mau and Utami (2014) added biochar in combination with *Arbuscular mycorrhiza* (AM) fungal spores and obtained significant increases in the availability and uptake of P, while the sole application of biochar did not enhance P uptake or maize growth. Biochar application rate should be kept optimum as it can positively or negatively affect crop growth by inhibiting nutrient availability in high biochar doses or reducing nutrient supply in lower biochar doses. Previously, it has been reported that biochar integration with inorganic fertilizer has both positive and negative effects on rice and rapeseed production (Khan et al. 2021a, 2022). Modifications and alterations in the characteristics of biochar and the implications of such changes on crop growth and yield are crucial factors in the majority of biochar applications. An increase or decrease in biochar's particle size can have variable effects on plant growth e.g. the impact of biochar particle size on the capacity of soil water-retention has been inconsistent, with some research finding greater values for tiny particles (Zhang et al. 2010) and others finding the opposite (Chen et al. 2017). Previously, when the growth responses of several species to different sizes of biochar particles were tested, the growth response of one specie was stronger to large particles, while a second demonstrated a higher growth response to small particles (Liao and Thomas 2019).

Various studies reported the significant or non-significant effects of engineered biochar on crop growth traits (Table 3), and the possible mechanisms in soil and plant growth governed by biochar are illustrated in Fig. 7. Considering the structural morphology and unique characteristics of biochar, it can positively improve resource availability and supply by inducing root growth to promote the plant's physiological traits. The overall increase in plant-available moisture content can be directly correlated to the increment in the water-holding capacity of soil with biochar amendment (Liu et al. 2016). The improvement in plant growth by enhancing soil–plant water relation was observed in both normal water and drought stress conditions under the application of biochar (Haider et al. 2015). According to a prior study (Thomas 2021), engineered biochar considerably boosted average plant growth responses by 14% over those noted under raw biochar. An earlier study found that adding exogenous N improved the mean weight diameter of soil macroaggregates, suggesting that N addition can promote soil structural stability. Therefore, a significant transformation and consumption of soil inorganic nitrogen to attain optimum plant growth can greatly benefit from an improvement in the aggregate structure of the soil. As we mentioned earlier, biochar can promote the morphology of soil macroaggregates and, consequently, nitrogen utilization, as evident in Fig. 4; thus, using engineered biochar is strongly suggested to increase soil water-stable macroaggregates, nitrogen uptake and plant growth.

Biochar addition turns the soil color dark, increasing soil temperature to promote seed germination and crop yield. The amendment of biochar at 3% and 5% (w/w) in pots increased the rates of photosynthetic processes, chlorophyll contents, and lycopene, while amino acids and sugars were reduced (Younis et al. 2015); on the other hand Asai et al. (2009) reported that chlorophyll content in rice leaf was reduced which was grown on poor nutritive soil under biochar amendment. Previously, Khan et al. (2021a) concluded that biochar application at 30 t ha^{-1} reduced the adversity of higher single nitrogen application and improved the leaf stomatal indices and leaf cell ultrastructure. Moreover, amendment of wood biochar at 3 kg m^{-2} soil under the cultivation of *Abutilon theophrasti*, observed increments of threefold in photosynthesis, 1.7-fold in stomatal conductance, and 5% in chlorophyll fluorescence compared with untreated plants (Seehausen et al. 2017). The density of different functional groups on the surface of biochar can be increased using a chemical engineering process called biochar acidification, which makes it simpler for biochar to interact with soil particles and form soil aggregates (Chang et al. 2019). Soil aggregates are primarily responsible for changes in soil structure and are also essential for regulating and maintaining nutrients in the soil for plant uptake (Ma et al. 2022). Thus, a particular type of designed biochar can improve soil porosity and water-holding capacity to affect water-stable aggregates and

Table 3 Summary of recently published articles investigating the beneficial effects of biochar application on soil conditions and plant growth, enhancing crop yield

Test crop	Soil texture	Biochar application rate	Yield increase / decrease % or no effect	The main effect of biochar on crop yield in relation to soil status or plant growth	Country	References
Bean	Clay loam	60 t ha^{-1}	+46	↑ N fixation, high availability of B, Mo. K, Ca, and P, soil pH, bean growth, and high yield	Colombia	Rondon et al. (2007)
Wheat	Silty	30 t ha^{-1}	+28	↓ Loss of carbon, the tensile strength of mineral soils, ↑ soil organic carbon, and biomass and yield of wheat	Italy	Vaccari et al. (2011)
Maize	Sandy clay loam	25 t ha^{-1}	No effect	↓ Maize growth, dissolved organic C (DOC), soil NO_3 or NH_4, or N mineralization but only ↑ microbial community	UK	Jones et al. (2012)
Tomato	sandy loam	5% w/w	+13–20	↑ Soil moisture content and high water use efficiency, leaf relative water content, membrane stability index, and high fruit yield	China	Akhtar et al. (2014)
Wheat	Acidic ferrasol	10 t ha^{-1}	+144	↑ Soil conditions, SOC, TN, and ↓ aluminium toxicity to achieve better wheat yield	Germany	Macdonald et al. (2014)
Oat	Acidic sandy loam	20 t ha^{-1}	11% in the second year	↑ Soil pH, microbial communities, nutrient uptake, and oat yield	Denmark	Sun et al. (2014)
Wheat	–	25 t ha^{-1}	No effect	↑ Soil chemical properties and carbon sequestration; however, the wheat yield was not improved	Australia	Farrell et al. (2014)
Rice	Fluvisol	20 t ha^{-1}	+6 in the sixth season	↑ Nitrogen fertilizer transformations, NUE, and higher rice yield	China	Huang et al. (2018a; b)
Wheat	Typic Quartzipsamment	1.9% w/w	+27	↓ N_2O emission and nitrogen losses to ↑ N mineralization and utilization and thus grain yield	USA	Abbruzzini et al. (2019)
Rice	Alfisol	3–6 t ha^{-1}	+46	↑ Rhizospheric exudates secretion, soil enzymatic activities, and soil moisture content led to higher rice yield	Nigeria	Oladele (2019a; b,)
Geranium	Sandy loam	4 t ha^{-1}	+17	↓ Losses of nitrogen and phosphorus and high nutrient use efficiencies led to high crop production	India	Yadav et al. (2019)
Rice	Clay	20 t ha^{-1}	+4–10	↑ Soil physical and chemical characteristics to attain high yield	China	Huang et al. (2019)
Rice	Alfisol	6 t ha^{-1}	+311	↑ Soil pH, SOC, TN, AP, and K while ↓ soil nitrate leachate and ↑ rice yield	Nigeria	Oladele et al. (2019a)
Rice and wheat	Silty clay loam	20–40 t ha^{-1}	+10–16	↓ N stock in roots and ↑in SOC, TN, NUE, phosphorus use efficiency, and root biomass tend to enhance rice and wheat yield	China	Zhang et al. (2020)

Table 3 (continued)

Test crop	Soil texture	Biochar application rate	Yield increase / decrease % or no effect	The main effect of biochar on crop yield in relation to soil status or plant growth	Country	References
Rice	–	2% w/w	+51	↑ SOC, TN, available phosphorus, and soil enzymatic activities and rice yield	China	(Jing et al. 2020)
Hot pepper	–	18 t ha^{-1}	+59	↑ Soil pH, AP, carbon content, and fertilizer use efficiency, leading to high yield	Ethiopia	(Melaku et al. 2020)
Wheat	–	2% w/w	+84	↑ Soil pH and ↓ oxidative stress due to cadmium and drought conditions and ↑ chlorophyll content, growth, and wheat yield	Pakistan	(Bashir et al. 2020)
Wheat and maize	Chromic Cambisol	3.2 Mg ha^{-1}	No effect	↑ Mineral N, ↓ N_2O emission, and ↑ denitrification despite a significant effect on yield	China	Wei et al. (2020)
Rice	Anthropogenic alluvium	9 t ha^{-1}	+2	↓ Bulk density, N leaching, and ↑ SOC, N, P, and K promoted rice root growth and yield	China	Liu et al. (2021a; b, c)

Values of yield represented with "+" indicate an increase in yield percent, an upward arrow "↑" indicates an improvement, and a downward "↓" indicates a decline in mentioned indices

allow root penetration for nutrient and water uptake to enhance plant growth.

The increment in crop yield by advancing NUE with an economical and environment-friendly approach is the main driver toward sustainable crop production. Lack of water in the crop results in decreased N uptake, decreased yield, and decreased biomass (Quemada and Gabriel 2016), while a balanced N nutritional status increases crop drought resistance and increases water use efficiency (Cossani et al. 2012). The co-limitation of the availability of nitrogen and water availability is the determinant link that governs plant biomass production (Sadras 2004); consequently, it suggests that sustainable approaches are needed to guarantee the equal availability of both resources to enhance plant development. In addition, water limits the amount of nitrogen transportation in soil and absorption by roots (Quemada and Gabriel 2016); therefore, it is better to concurrently optimize N and water availability. A healthy and managed soil structure can increase water availability and nutrient cycling (Piedallu et al. 2016), and soil aggregates significantly affect soil structure, which is also crucial for retaining soil nutrients and water content (Ma et al. 2022). Thus, adding biochar to soil can strengthen the stability of the soil aggregate to conserve water content and establish a strong association with the transformation and utilization of N dynamics, as described in Fig. 4.

As we discussed earlier, synthetic fertilizers are used to gain higher yields; however, the approach is not environmentally healthy and wastes resources; thus, we need to add biochar to achieve sustainable yields. However, biochar's positive, negative, or neutral effect on crop yield depends on soil type, differences in feedstock, and pyrolysis conditions of biochar preparation. The crucial and important factors, such as soil type, soil pH, coupling fertilizers, biochar type, application rate, and crop species, were responsible for improving crop yield (Jeffery et al. 2011). An increment in pyrolysis temperature enhanced crop growth (Rajkovich et al. 2012); however, the opposite trend was also observed, and inorganic N content was decreased in biochar due to reduced plant nitrogen volatilization during combustion at lower pyrolysis temperatures compared to high temperatures (Makoto et al. 2011). Biochar prepared from food waste and paper mill under lower pyrolysis temperatures (300–400 ℃) negatively affected corn growth, while increasing the pyrolysis temperature, the corn growth was significantly improved (Rajkovich et al. 2012). Generally, biochar prepared under pyrolysis temperature (of 500 ℃) exhibited improved crop growth than others produced at 300–400 ℃ (Khan et al. 2020). Various studies, particularly on nutrient-poor soils, have estimated a robust synergetic effect of biochar addition in enhancing crop yields (Van Zwieten et al. 2010a, b; Zhang et al. 2012; Jin et al. 2019).

In this review, we found that there has been a huge increase in the production and use of synthetic nitrogen fertilizers for the last twenty years; however, their nutrient conversion into biomass rate is gradually decreasing (Fig. 6F). To overcome this, we must supply inorganic fertilizers along with biochar to prevent their loss and improve their conversion rate into biomass and increase crop yield. We analyzed the data of previous studies and found that biochar can significantly increase crop yield as compared to the sole applications of other organic or inorganic fertilizers (Fig. 6F). Research studies observed that the positive reflections of soil and crop productivity with biochar addition not only depend on soil type and pyrolysis conditions, but crop types, the application rate of biochar, and elemental compositions of biochar could also affect the biochar response (Purakayastha et al. 2019). Applying biochar at 10 t ha^{-1} linearly increased the wheat biomass while decreasing it at 20 and 50 t ha^{-1}; however, biochar application at a high rate in acidic soil did not decrease the radish growth (van Zwieten et al. 2010a, b). The biomass and grain yield of wheat were improved with biochar amendment; however, grain N content was not improved (Vaccari et al. 2011). We examined the role of biochar responsible for neutral, positive, or negative effects inducing soil conditions and nutrient transformation to affect crop yield in previous research studies (Table 3) and assumed that the performance of biochar can be unified and improved with certain modification techniques to reduce the uncertainties in biochar application and obtain the desired outputs.

6.8 Summary

Biochar has a very strong and significant effect on soil chemical, physical and biological properties, as discussed previously, to induce the soil inorganic N transformation and alter NUE. The root morphology and activity are most important in terms of water and nutrient uptake and engineered biochar addition due to porous surface and high functional groups increasing root penetration to promote soil macroaggregates, high N uptake, and increased NUE. Recently, farmers often use synthetic inorganic fertilizers to promote crop yield alongside deteriorating soil health and the environment. On the other hand, biochar addition to soil is one of the prominent approaches that increase crop yield, enhance soil conditions and decrease environmental pollution. However, soil organic amendments have a low ability to release nutrients to meet the nutrient demands of a specific crop; thus, the sole application of soil organic amendment could not meet the nutrient requirements of crop production, and therefore the integrated application of biochar with inorganic fertilizers can promote the soil conditions, nutrient utilization, and sustainable crop production. We discussed the varied effects of biochar on N dynamics and soil conditions and assumed that applying different biochar engineering techniques would be beneficial to unify the biochar effect. Thus, it is necessary to select and design the proper engineered biochar type and application rate for specific soil conditions to attain positive effects on improving NUE, plant growth, and yield.

7 Conclusions and future perspectives

7.1 Conclusions

The use of engineered biochar has the potential to sustain the quality of soil, reduce fertilizer use and loss, enhance nutrient utilization, and promote crop growth, owing to the numerous views and findings of biochar discussed in this review. We found out that engineering biochar promotes the quality and nature of raw biochar and helps in the recycling of natural resources and wastes in a useful way to improve the sustainability of soil, the utility of fertilizers, and the productivity of crops. The facts and figures of this review described the interaction of engineered biochar and soil conditions that induced the transformation and utilization of inorganic nitrogen to have significant effects on improving NUE and crop production. Overall, this review provides a thorough understanding of how different aspects of engineered biochar regulates the soil water-stable macroaggregates, N transformation from rhizosphere to plant, and N metabolism and remobilization in the plant to increase NUE. Conclusively, this factual and useful information establishes a strong foundation for the prospective of engineered biochar potential that enhances soil N utilization while reducing negative side effects on the ecosystem and crop growth, promoting sustainable crop production in the future. However, it should be noted that this does not mean that adding biochar to a field randomly anywhere in the world would always result positively, as the other factors must be considered, such as climate conditions, soil type, biochar type, biochar engineering technique, application rates, etc. Another concern is about the nature and quality of biochar, which may not influence every crop and soil condition equally; thus, we should engineer raw biochar on a priority basis to address the specific requirements and achieve the best outcomes. Hence, it is critical to conduct further multi locations studies focused on elucidating different biochar engineering techniques, feedstock types, and application rates under different crops to achieve resilient-based solutions for future sustainable crop production.

7.2 Future perspectives

The use of Engineered biochar has sparked a surge in research recently as a promising approach to enhancing soil health and NUE; however, the final effect is largely dependent on the land's intrinsic soil qualities, fertility status, and fertilization history of certain land. The variable effects of biochar on soil conditions, nutrient transformation, and crop production necessitate further research and analysis in a broader sense to determine the new information and suggest possible solutions to address the current problems associated with fertilizer loss and reduced NUE.

(i) Mostly the role of engineered biochar is evaluated in laboratory studies, short-term field trials, or glasshouse studies. When biochar is applied to soil, it undergoes a gradual decomposition and aging process. It is critical to fill the knowledge gaps of biochar persistence in research areas such as long-term engineered biochar effects on soil conditioning, nutrient retention and release capability, and crop productivity under long-term studies.

(ii) Currently, few investigations have compared the role of biochar application on fertilizer use efficiency and crop yield in multi-location studies; therefore it needs mechanistic and causative approaches to highlight the impacts of engineered biochar on soil functions, environmental factors, nitrogen utilization, and crop production for a possible implementation of biochar policy at any scale and area.

(iii) In previous studies, biochar has proven the activation of enzymes related to nitrogen metabolism, however; further research is needed to combine the soil and agronomic indices with the expression of various genes of ammonium transporters (AMTs) and nitrate transporters (NRTs) on a molecular basis to reveal the systematic role of engineered biochar in nitrogen transformation.

(iv) Biochar is well-known for its capacity to boost microbial activities in the soil; however, microbial modification research is still uncommon, which involves the inoculation of bacteria with engineered biochar before addition to the soil, which can improve soil quality, nutrient cycling, and environmental stability.

(v) More experiments and research are needed to investigate the engineered biochar's role in the interaction of soil water-stable macroaggregates with microbial activities, water use efficiency, and nitrogen use efficiency under various conditions of fertilizations.

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Author contributions
ZK, FUY and HS designed the research idea. YX-J collected the data. ZK wrote the manuscript. SJ, IA, MNK and MAK revised the manuscript.

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Declarations

Competing interests
The authors have no competing interests or no financial interests to declare relevant to this article's content.

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