Biofuel Research Journal 45 (2025) 2350-2372

Biofuel Research Journal

Journal homepage: www.biofueljournal.com

Review Paper

Can biomass-derived chars serve as a viable alternative to commercial inorganic fertilizers?

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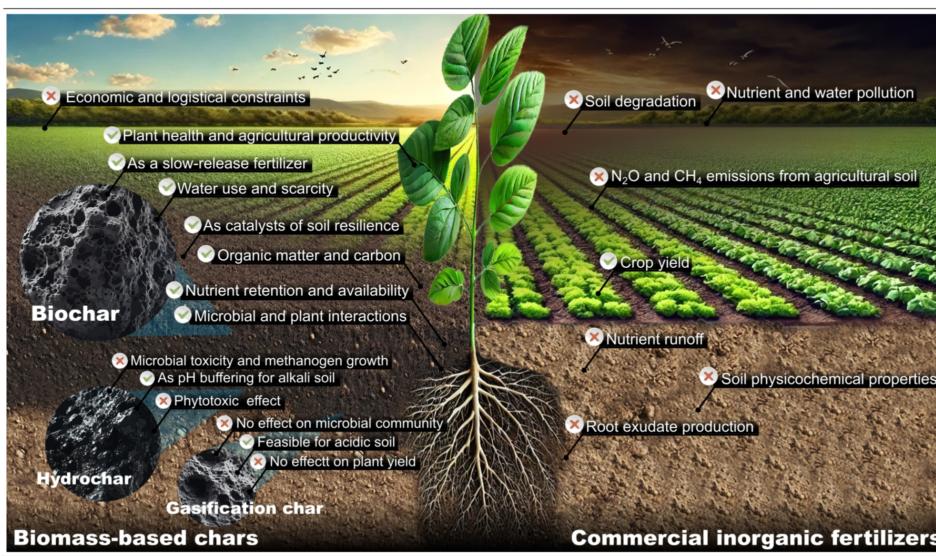
HIGHLIGHTS

- ➢Biomass-derived chars were assessed as alternatives to inorganic fertilizers.
- ➢Inorganic fertilizer use raises environmental concerns and market volatility.
- ➢Biochar offers the best balance of soil enhancement and carbon sequestration.
- ➢Biochar improves nutrient retention and reduces environmental impact.
- ➢Economic and regulatory factors limit large-scale biochar adoption.

GRAPHICAL ABSTRACT



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ARTICLE INFO

Article history:
Received 2 January 2025
Received in revised form 22 February 2025
Accepted 24 February 2025
Published 1 March 2025

Keywords:
Biomass-derived char
Biochar
Soil fertility
Inorganic fertilizer alternative
Sustainable agriculture
Nutrient management

ABSTRACT

The increasing reliance on commercial inorganic fertilizers has raised significant environmental and economic concerns, including soil degradation, nutrient leaching, water pollution, and greenhouse gas emissions. This review critically evaluates biomass-derived chars produced via thermochemical processes, i.e., pyrolysis, gasification, and hydrothermal carbonization, as potential alternatives to synthetic fertilizers. Among the three biomass-derived chars, biochar stands out as the most viable option for soil amendment due to its high stability, nutrient retention capacity, and long-term carbon sequestration benefits. Gasification char, despite its high porosity and adsorption capacity, often lacks bioavailable nutrients, whereas hydrochar, though rich in organic compounds, poses challenges related to stability and phytotoxicity. Biochar application has been shown to significantly reduce N_2O emissions, enhance soil water retention, and mitigate nutrient runoff, offering clear environmental advantages over conventional fertilizers. Moreover, biochar has transitioned from an experimental soil amendment to a commercially available product with increasing adoption in agriculture worldwide, further reinforcing its practical viability. However, large-scale implementation still faces economic and logistical constraints, including high production costs, transportation inefficiencies, and regulatory uncertainties. Addressing these challenges through policy incentives such as subsidies and carbon credits can enhance the economic feasibility of biochar production and application. Given these findings, this review focuses on biochar as the most practical and sustainable alternative to commercial inorganic fertilizers.

Contents

1. Introduction

The consumption of food and agricultural products has been increasing as a result of urbanization and population growth, making it a major global challenge (Ambikapathi et al., 2022). Food systems, especially at the food production stage, pose a major threat to planetary boundaries (Hu et al., 2020). The boundary for biogeochemical flow has already been exceeded, and those for climate change, freshwater use, land-system change, and ocean acidification could be reached shortly (Hu et al., 2020). Among biogeochemical flows, nitrogen (N) and phosphorus (P) have a significant impact on the environment and health. Fertilizer application is the primary human-driven factor disrupting both N and P cycles (Steffen et al., 2015).

The interplay between soil biota and soil hydrological functioning is essential in many biogeochemical cycles, including the water and carbon (C) cycles (Philippot et al., 2023). Of these, microorganisms dominate soil life and perform an array of vital soil functions by regulating nutrient cycling, decomposing organic matter, defining soil structure, suppressing plant diseases, and supporting plant productivity (Coban et al., 2022).

The Intergovernmental Panel on Climate Change (IPCC) has identified that substantial carbon dioxide removal (CDR) is required to limit global warming to 2 °C (IPCC, 2022). Climate change-induced disruptions, such as altered rainfall patterns, more frequent and severe droughts, and increased temperatures, directly impact agricultural productivity, biomass production, and rural poverty, intensifying food insecurity and economic vulnerability (Shafiee et al., 2023). One way to keep CO_2 out of the atmosphere is to put it back in the ground (Marris, 2006). To this end, the IPCC recognizes soil C management (IPCC, 2022), including biochar application as a promising CDR method. This approach also improves soil health, sustains agricultural productivity, and increases the resilience of ecosystem services (Weng et al., 2022).

Biochar, gasification char, and hydrochar, collectively referred to as biomass-derived chars, are stable forms of C produced through different thermochemical processes. Biochar is derived from medium-temperature pyrolysis, while gasification char results from high-temperature gasification of dry biomass in a low-oxygen environment (Lawrence et al., 2018). Hydrochar, conversely, is formed via hydrothermal carbonization (HTC) of biomass in an aqueous environment (Ischia and Fiori, 2020). Chars with enhanced C content can be buried or plowed into agricultural soils. Their increased stability, compared to non-carbonized organic material makes them more effective for long-term sequestration (Kopittke et al., 2022).

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Commercial inorganic fertilizers, such as N, P, and potassium (K), boost crop yield (Yousaf et al., 2017). However, these fertilizers alter the physicochemical properties of soil and root exudate production (Seitz et al., 2024), affecting the structure and diversity of crop microbiomes in most cases negatively (M. Wang et al., 2024). Depending on application rates, fertilizer inputs can increase microbial biomass but often reduce microbial diversity (Kracmarova et al., 2022), with distinct effects on soil- versus root-associated microbiomes (Kong et al., 2023). Soil acidification from fertilizers inhibits microbial growth, while plant-growth-promoting bacteria may become more abundant (Wei et al., 2024). However, excessive nutrient inputs diminish microbial benefits to plant growth (French et al., 2021).

The reliance on inorganic fertilizers in modern agriculture poses significant environmental and economic challenges, including soil degradation, water pollution (Bijay-Singh and Craswell, 2021), and greenhouse gas (GHG) emissions (Menegat et al., 2022). To address these issues, there is growing interest in biomass-derived char as a potential sustainable alternative to commercial inorganic fertilizers. However, while biochar has demonstrated agronomic and environmental benefits, critical questions remain regarding its viability as a large-scale fertilizer replacement. Can biochar consistently match or surpass the effectiveness of inorganic fertilizers in terms of crop yield and soil fertility? How does it compare in terms of water use efficiency, nutrient retention, and pollution mitigation? This review critically evaluates the current commercial market of inorganic fertilizer and biomass-derived char, as well as the potential of biomass-derived char as a sustainable alternative to commercial inorganic fertilizers. The effectiveness of biomass-derived char as an inorganic fertilizer replacement is assessed in terms of its impact on crop yields, soil fertility, water use efficiency, and nutrient runoff. Furthermore, the environmental implications, focusing on emissions of nitrous oxide (N_2O) and methane (CH_4), nutrient pollution, and below-ground microbial biodiversity loss were assessed. Economic considerations, including cost analysis and practical challenges to large-scale adoption, are also discussed to provide a comprehensive overview of char's feasibility in agricultural practices.

2. Global inorganic fertilizer dynamics: trends, patterns, and implications

Over the past few decades, the inorganic fertilizer sector has undergone significant transformations, driven by increasing global food demand, technological advancements, and growing environmental concerns (Shanmugavel et al., 2023). However, the dynamics of inorganic fertilizer production, distribution, and use are increasingly influenced by geopolitical events, economic shifts, and climate change. Global inorganic fertilizer consumption has increased significantly, as reported by the Food and Agriculture Organization (FAO). Developing regions have shown the most rapid growth due to their reliance on external inputs for agricultural intensification (FAO, 2024b).

Figure 1 provides an overview of temporal global inorganic fertilizer metrics, highlighting the trends in production, agricultural use, and application efficiency across croplands' area, per capita, and agricultural value over the last three decades. While a general upward trend in global inorganic fertilizer production and agricultural use is observed during the period, the data also reveals significant fluctuations driven by international events and economic factors.

The metrics experienced steady growth from the early 1990s until the late 1990s, reflecting increasing global agricultural intensification. However, the 1997–1998 Asian Financial Crisis temporarily curtailed investments in agriculture, reducing inorganic fertilizer production and use (Langley et al., 2000). A recovery phase in the early 2000s was interrupted by the 2007–2008 Global Food Crisis, which saw a surge in fertilizer demand and prices due to food shortages (Lin and Martin, 2010). This was quickly followed by the 2008–2009 Global Financial Crisis, causing a decline in fertilizer use and production as economic activity slowed (Lin and Martin, 2010).

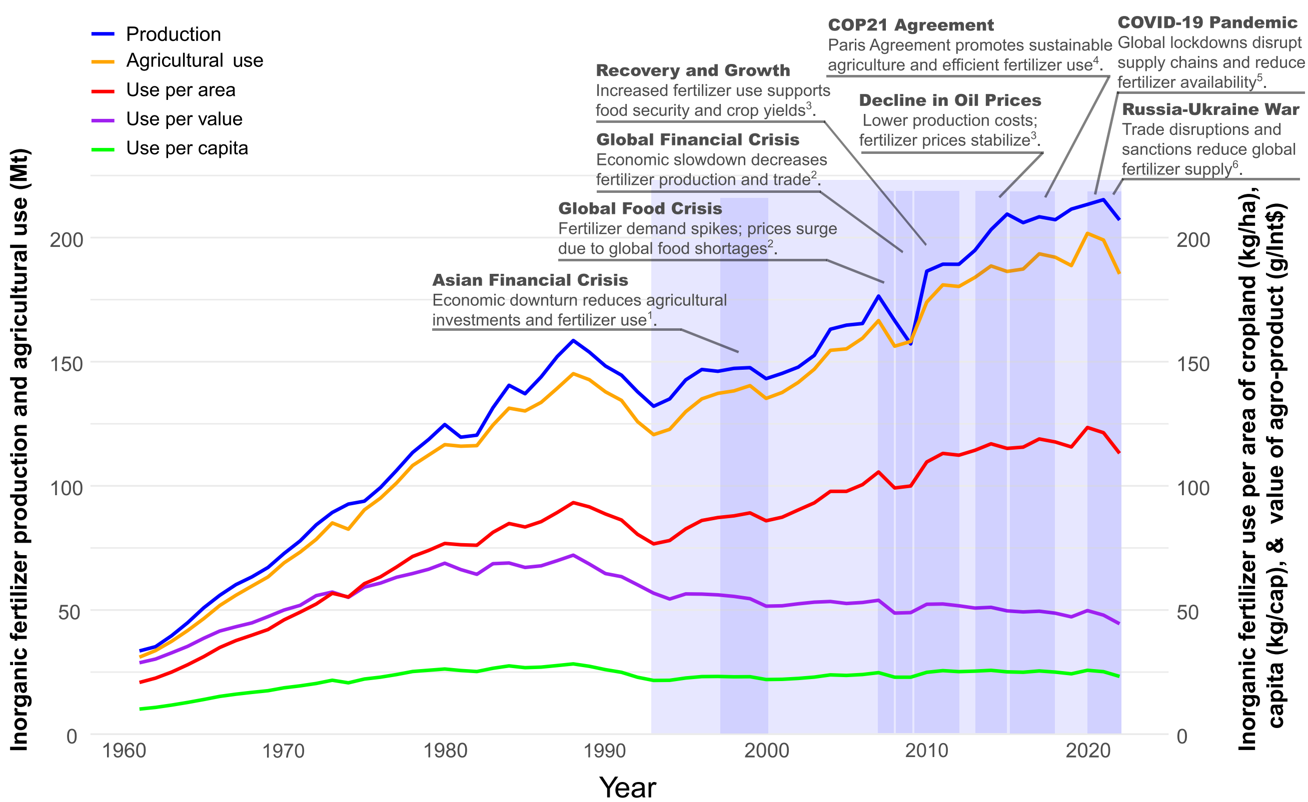

Fig. 1. Temporal trends in inorganic fertilizer metrics: A comprehensive view of global inorganic fertilizer production (blue, in Mt) and agricultural use (yellow, in Mt), alongside fertilizer application intensity per area of cropland (red, in kg/ha), per capita usage (green, in kg/cap), and usage per value of agricultural production (purple, in g per international dollar (g/Int$)). The numbers on the graph represent the original reference of the event: [1](Langley et al., 2000), [2](Lin and Martin, 2010), [3](FAO, 2015), [4](IEA, 2016), [5](IFA, 2020), [6](Hebebrand and Glauber, 2023). *Data source*: (FAO, 2024a).

From 2010 to 2015, fertilizer metrics recovered, driven by increased focus on food security and the expansion of agricultural production in response to population growth. During this time, a drop in oil prices contributed to stable production costs, benefiting the global fertilizer market (FAO, 2015). The COP21 Paris Agreement (2015) was a critical moment in global climate policy, focusing on reducing GHG emissions and promoting sustainable practices, including in agriculture. While the direct impact on inorganic fertilizer metrics may not be immediate, the agreement influenced long-term trends by encouraging efficiency in fertilizer use and a shift towards sustainable agricultural practices. As such, it is valid and significant to annotate its influence on the graph, especially for its indirect effects on fertilizer demand and agricultural policy (IEA, 2016).

The COVID-19 pandemic in 2020 significantly disrupted global fertilizer supply chains, reducing availability and increasing prices (IFA, 2020). This was followed by the Russia-Ukraine War, which severely impacted global fertilizer trade due to supply disruptions and sanctions on major producers (Hebebrand and Glauber, 2023). These events have highlighted the vulnerability of the global inorganic fertilizer market to geopolitical and economic shocks.

Figure 2 illustrates a detailed geospatial analysis of global inorganic fertilizer dynamics in 2022, highlighting production, agricultural use, and trade flows across countries and regions. The heatmap reveals significant disparities in inorganic fertilizer usage. Countries such as China, India, and the United States show the highest agricultural use, driven by intensive farming systems and food security demands. In contrast, many countries in Africa and Oceania exhibit lower usage, reflecting challenges in accessibility and affordability, as emphasized in the FAO report (FAO, 2024a). The five leading producers, i.e. China, Russia, India, the United States, and Canada, dominate the global inorganic fertilizer landscape. The regional heatmap emphasizes Asia's preeminent role, producing over 102 million t (Mt) of inorganic fertilizers. Europe and North America also exhibit high production levels, aligning with developed agricultural systems. Africa and Oceania, with lower outputs, remain reliant on imports, raising concerns about supply chain vulnerabilities.

Trade flow arrows shed light on global supply chain dependencies. Import-heavy regions like South America often lack sufficient domestic production, heightening their exposure to market shocks. Major exporters such as Russia and Canada stabilize global supply and create geopolitical sensitivities. The graph reveals the interconnected nature of fertilizer production, use, and trade while highlighting critical areas for policy intervention to ensure sustainable agricultural practices and resilient food systems globally.

Inorganic fertilizer prices experienced a dramatic surge, rising nearly 30% in 2022 after an unprecedented 80% increase the previous year. This steep escalation was fueled by a convergence of global challenges, including soaring input costs, geopolitical tensions, and trade disruptions. Sanctions on major producers like Belarus and Russia, coupled with export restrictions from China, have significantly strained supply chains. Urea prices have surpassed their historic peaks from 2008, while prices for phosphates and potash are approaching similar record levels. These price hikes, compounded by the ongoing conflict in Ukraine, have intensified global concerns about fertilizer affordability and availability, posing critical challenges to agricultural sustainability and food security (Baffes and Koh, 2022).

Understanding these patterns is essential for addressing disparities in fertilizer availability, optimizing resource use, and balancing the dual objectives of enhancing food security and mitigating environmental degradation.

3. The significance of alternatives to commercial inorganic fertilizers

Efficient fertilizers are essential for achieving global food security (Lam et al., 2022). The growing global population and industrialization have led to an increased consumption of fertilizers. This increased use has resulted in significant environmental challenges, including soil degradation, water scarcity, and energy shortages (Avşar, 2024).

Simultaneously, environmental and social pressures are compelling developed nations to adopt sustainable practices. The '4R' principles (i.e. applying the right source of nutrients, at the right rate to optimize yields for specific crops, in the right place in the field, and at the right time when crops require them), have become critical in this transition (IFA, 2023). These principles aim to optimize yields, reduce environmental impact, and decarbonize synthetic fertilizer production, aligning with the United Nations' Sustainable Development Goals (SDGs). Notably, the production and use of inorganic fertilizers account for approximately 5% of global GHG emissions (Gao and Cabrera Serrenho, 2023). Fertilizer prices are highly volatile due to geopolitical tensions, trade restrictions, and supply disruptions from centralized trade systems. These risks highlight the need for sustainable

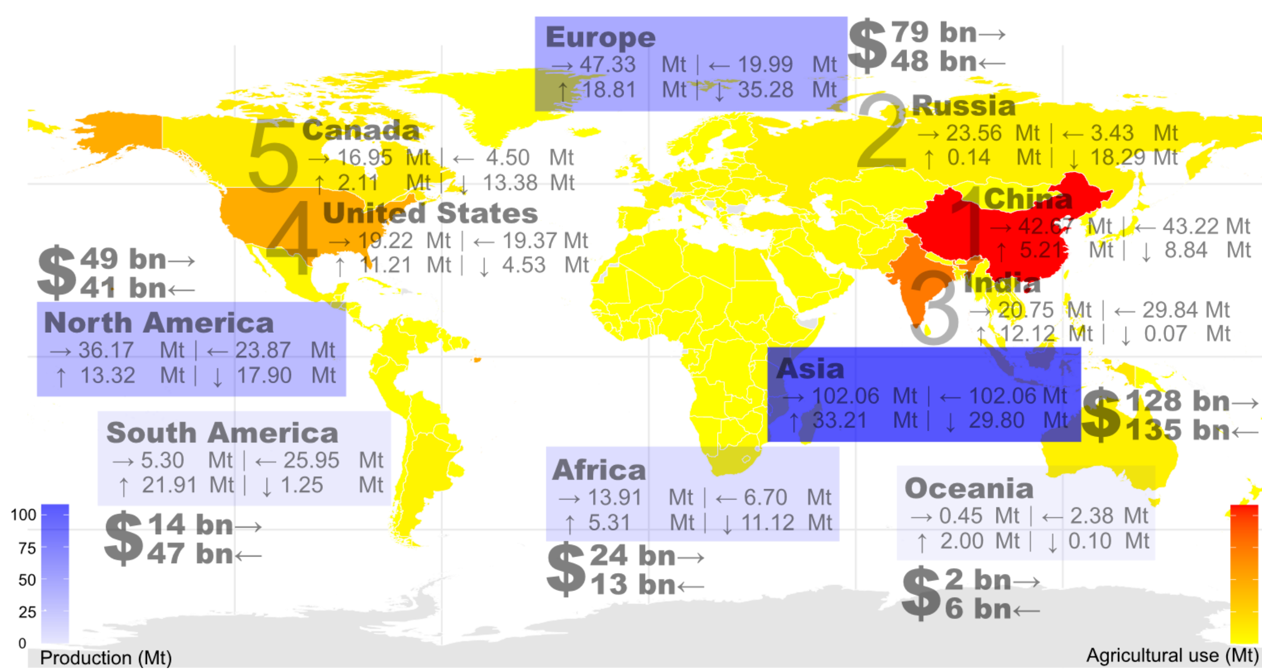

Fig. 2. Geospatial Analysis of Fertilizer Dynamics in 2022: A heatmap depicting fertilizer agricultural use (←) at the country level, highlighting the top five fertilizer-producing countries. Regional fertilizer production (→) is visualized across continents, with trade dynamics represented by imports (↑) and exports (↓). *Data source*: *(FAO, 2024a; IFA, 2024).*

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alternatives to ensure market stability and long-term agricultural resilience (IFC, 2023).

Agricultural soils are the largest anthropogenic source of N_2O, primarily due to the extensive use of synthetic N fertilizers and manure over the past century. N_2O is a potent GHG with 298 times the warming potential of CO_2 over 100 years and is a leading contributor to stratospheric ozone depletion. Without mitigation, rising agricultural fertilizer demands will drive further increases in N_2O emissions, posing significant challenges to climate and ozone recovery efforts. Enhanced-efficiency or slow-release fertilizers, such as char, offer effective solutions (Lawrence et al., 2021; Lyu et al., 2021; Khosravi et al., 2022; Marcińczyk and Oleszczuk, 2022). Produced through the thermochemical conversion of organic materials, char can enhance soil fertility, improve water retention, sequester C, and mitigate N_2O emissions, promoting sustainable agriculture (Avşar, 2024).

Circular economy models in agriculture, which emphasize recycling biowaste and byproducts, offer pathways to reduce reliance on non-renewable resources while fostering regenerative farming practices (Mulya et al., 2024). Moreover, soil management strategies, including organic amendments, such as adding wood, compost, and char, can greatly influence soil organic carbon (SOC) content (Valle et al., 2020). Furthermore, increasing SOC in agricultural systems is a primary nature-based option for mitigating climate change, improving soil fertility, and ensuring food security (Zhou et al., 2025). By integrating these innovative approaches, the global agricultural sector can address the dual challenge of meeting rising food demands while reducing environmental impacts. This transformation demands concerted efforts across research, policy, and practice to develop and implement more scalable and sustainable solutions.

4. A snapshot of the present market of the biomass-derived char industry

The industry of biomass-derived char has experienced significant growth in recent years, reflecting its increasing importance in sustainable agriculture and C sequestration efforts. In 2023, the global biochar market was valued at approximately USD 680.84 million and is projected to reach USD 2,097.72 million by 2032, exhibiting a compound annual growth rate (CAGR) of 13.47% during the forecast period (Fortune Business Insights, 2024).

The 2023 Global Biochar Market Report, a comprehensive analysis of the biochar industry's trajectory, employed a robust methodology combining an anonymous web-based survey with 11 in-depth interviews of industry experts. The survey garnered 1,007 responses from participants spanning 100 countries, providing a diverse and representative dataset (IBI and USBI, 2023). The findings, illustrated in **Figure 3**, reveal a significant expansion in global biochar production, with 2023 output reaching 3.66 times that of 2021. This corresponds to a compound annual growth rate (CAGR) of 91% over the two years, underscoring the industry's rapid development. Financially, the sector exhibited robust growth, with total revenue in 2023 increasing by a factor of 2.9 compared to 2021. This substantial rise reflects the escalating demand for biochar and its applications across various industries (IBI and USBI, 2023).

Regionally, Europe has demonstrated a strong commitment to biochar utilization, backed by substantial infrastructure growth and market maturity. According to the 2023/2024 European Biochar Market Report, Europe added 48 new biochar production plants in 2023 alone, bringing the cumulative total to 171 operational facilities. The forecast for 2024 predicts a further increase to over 220 installations, highlighting the rapid adoption of biochar technologies across the continent. In 2023, European biochar production capacity reached 75,000 t, representing a 41% year-over-year increase, with expectations to grow to 115,000 t by 2024 (EPI, 2024).

A detailed analysis of end-use markets indicates that 70% of global biochar producers identified crops as the primary product application (IBI and USBI, 2023). This predominant focus on agriculture highlights biochar's efficacy in enhancing soil fertility, improving crop yields, and contributing to sustainable farming practices. Furthermore, producers have prioritized market development activities in the sectors of biochar-enhanced fertilizers (i.e., integrating biochar with fertilizers to improve nutrient efficiency and soil health), bulk soil amendment (utilizing biochar to enhance soil structure, water retention, and C sequestration), environmental remediation (applying biochar for the adsorption of pollutants and restoration of contaminated sites), compost/manure additive (incorporating biochar into compost and manure to reduce odors, GHG emissions, and nutrient leaching), and horticultural growing media (using biochar as a component in potting mixes to improve plant health and growth and to reduce the amount of peat) (IBI and USBI, 2023). These strategic priorities reflect the industry's commitment to expanding biochar's applications and its potential to address environmental challenges, promote sustainable horti- and agriculture, and contribute to climate change mitigation.

Europe is at the forefront of incorporating biochar into urban soil enhancement, previously pioneered in Sweden, and is now expanding to other countries such as Austria, Germany, and Switzerland. The European Union's Carbon Removal Certification Framework (CRCF), finalized in 2024, shows the inclusion of biochar in C farming, industrial removals, and C product units (EPI, 2024). This policy environment facilitates investments in biochar technology and strengthens its role in achieving net-zero emissions.

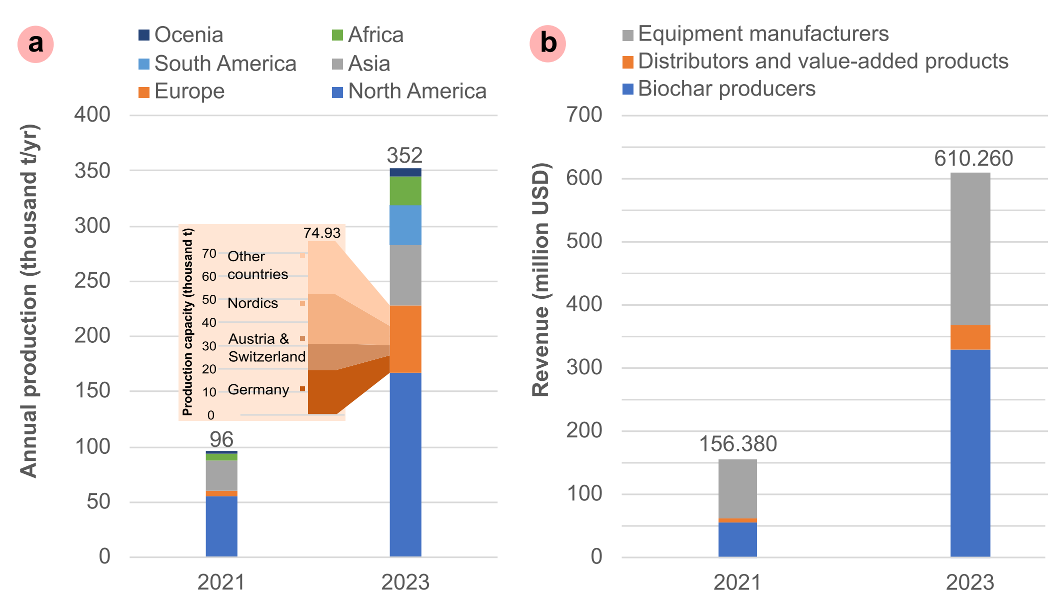

Fig. 3. Comparative analysis of the global biochar market (2021 vs. 2023): **a.** Annual production per continent (thousand t/yr). **b.** Economic valuation by industry sector (million USD). *Data Source: (IBI and USBI, 2023; EPI, 2024).*

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Furthermore, the U.S. and Canada Biochar Protocol by the Climate Action Reserve establishes a rigorous framework for quantifying and verifying GHG reductions and CDR from biochar projects (CAR, 2024). The protocol ensures that biochar projects achieve additional C sequestration beyond business-as-usual practices and requires regular monitoring, reporting, and verification (MRV) to maintain compliance. While its reliance on default permanence factors and stringent requirements may pose challenges for small-scale producers, the protocol enhances the credibility of biochar projects in C markets by integrating scientific rigor, environmental safeguards, and transparent accounting practices, promoting both climate mitigation and sustainable land management (CAR, 2024).

5. Thermochemical processes for biomass-derived char production

5.1. Processes, conditions, and key influencing factors

Biomass thermochemical conversion processes thermally transform biomass into value-added products, e.g. biofuels, soil amendment substrates, and biomaterials (Gheewala, 2023). This section covers the key technologies used for converting biomass, including direct combustion, gasification, pyrolysis, and HTC. The technology is chosen based on the final desired products. The overview of these four processes is shown in **Figure 4**, classified based on operational conditions, variations in end-product distribution, and end-product properties.

Direct combustion, as a common method, involves burning biomass, alone or co-fired with coal at a temperature range of 800 - 1500 °C in an oxygen-rich condition for power generation, heating, and cooking (Cheirsilp and Maneechote, 2022). The main product of this process is heat, while CO_2 and water vapor are co-products, together with other secondary hydrocarbon gaseous products (Goyal et al., 2008). This traditional method is conducted in either open fires, open cookstoves, or installed combustion systems. Direct combustion of biomass can however cause environmental issues and health risks (Castro et al., 2018). As combustion is aimed to produce heat (mainly for domestic or industrial use) or electricity (via a Rankine cycle in thermal plants) the process should be designed to guarantee the completion of oxidation reactions, thereby achieving higher thermal efficiency.

Gasification, on the other hand, partially oxidizes biomass at high temperatures (700 - 1000 °C) to convert biomass into a synthesis gas (syngas) composed of carbon monoxide (CO), hydrogen (H_2), CO_2, and CH_4, and minor quantities of other hydrocarbons (González et al., 2011; Sankaran et al., 2018). Syngas can be used for electricity generation, chemical synthesis, or other industrial uses. The gasification process is influenced by feedstock type, moisture content, gasifying agent, catalysts used, and reactor design (e.g., fluidized bed, downdraft, or updraft gasifiers) (González et al., 2011). Biomass with a moisture content of 10%-20% is recommended to use for gasification for producing syngas with a high heating value (Molino et al., 2018). After gasification, a solid residue containing varying amounts of fixed C and usually a high proportion of ash, depending on the operating conditions and feedstock, remains (González et al., 2008). Gasifiers in use today range from conventional designs like fixed-bed, fluidized-bed, entrained-flow, and rotary kiln gasifiers to advanced technologies such as plasma gasifiers, supercritical water gasifiers, and solar gasifiers, all of which influence gas composition, efficiency, char yield (by-product), and tar formation (undesired product) (F. Wang et al., 2024).

Pyrolysis operates in an oxygen-limited atmosphere at temperatures between 350 to 800 °C, producing biochar (also known as pyrochar), syngas, and bio-oil using biomass with less than 30% moisture content (Xiong et al., 2013). The process is carried out under controlled conditions to optimize the yield and product quality. Low moisture-content biomass is recommended for use to ensure efficient heat transfer and reaction kinetics, which is essential for achieving high-quality end products (Boutaieb et al., 2020). The two main factors, heating rate, and temperature, play a significant role in determining the distribution of products. Pyrolysis can be classified into four categories based on temperature, residence time, and heating rate: slow pyrolysis, intermediate pyrolysis (torrefaction), fast pyrolysis, and flash pyrolysis. Slow pyrolysis operated at a low-temperature range of 350-600 °C with a heating rate of 10-30 °C/min for hours to days favors biochar with high C content, while fast pyrolysis enhances bio-oil production (Sharma et al., 2024). Torrefaction, an intermediate pyrolysis with a heating rate of less than 50 °C/min, occurs at lower temperatures (200-350 °C) (Basu, 2013), partially decomposing biomass while retaining more of its original structure (H. Wang et al., 2020). Fast pyrolysis operated at a temperature of 500 °C, with a heating rate of > 500 °C/min for a residence time of less than 2 s produces more bio-oil than biochar (Sharma et al., 2024). Flash pyrolysis is operated at an extremely high temperature of more than 700 °C with a quick heating rate of > 1000 °C/minute for seconds to liquid or gaseous products (Manyà, 2012).

HTC is known as a wet pyrolysis or wet torrefaction that converts high-water content biomass into hydrochar at 180-250 °C under saturated vapor conditions (10-50 bars) over 1-12 h (Libra et al., 2011; Lucian and Fiori, 2017; A. Singh et al., 2024). The primary product of HTC is hydrochar, a coal-like material that is rich in carbon and can be used as a fuel, soil health enhancer, or as a renewable material used in wastewater treatment, construction, and energy storage. However, process water (PW), which is the water obtained after filtration of the slurry formed during the HTC reaction, contains acids and organic compounds that can be used for the recovery of valuable elements.

Temperature plays an important role in determining the product yield and composition across all thermochemical processes (Dang et al., 2024). The extent of its influence is also subjected to the action of other factors specific to each one (e.g., the presence of water, inertness of the system, oxidizing atmosphere). Biomass undergoes dehydration at lower temperatures, devolatilization within an intermediate range, and complete decomposition at higher temperatures (Kambo and Dutta, 2015). Residence time (or holding time) also affects the conversion efficiency, with a longer duration reducing the volatile content while increasing the yield of fixed C content (Wang et al., 2018). Pressure effects have been less studied but are known to influence biochar properties in pyrolysis by enhancing C content and modifying surface characteristics (Newalkar et al., 2014). Pressure effects in HTC are rarely studied because the process typically occurs in sealed autoclaves that naturally generate pressure. However, in this aspect, the reactor void volume (i.e., the volume of space that remains unoccupied after being filled with water and biomass) determines the real thermodynamic state of the water-biomass mixture, impacting degradation kinetics and system safety (Alvarez-Murillo et al., 2022). Machine learning has emerged as a valuable tool for optimizing biomass thermochemical conversion, enabling precise prediction of product yields and improving process efficiency (Li et al., 2023).

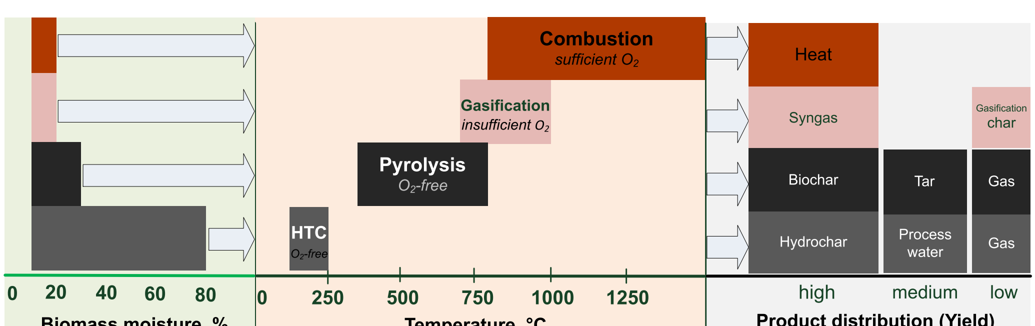

Fig. 4. Thermochemical conversion processes classified by biomass moisture (%), process temperature (°C) and oxygen supply, showing their product distributions. Adapted from Chen et al. (2021).

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5.2. Biomass sources for char production in agricultural application

Selecting the appropriate biomass for char production is a critical step in aligning with the sustainable development strategies for the local communities and local businesses (Homagain et al., 2016). This section discusses the suitable and unsuitable biomass sources for char production via thermochemical conversion, together with the environmental implications and practical aspects of using these biomass sources. First, the most appropriate biomass for char production is lignocellulosic (or plant-based) biomass, which is classified into four common groups: (1) agricultural/crop residues, (2) energy crops, (3) forest residues, and (4) industrial or municipal solid wastes (Liu et al., 2019). Second, IBI states that sustainable biochar is produced from biomass residue materials such as rice husks, corn stover, and non-commercial forestry residues (IBI and USBI, 2023). While a variety of biomass types are used for char production, hazardous or contaminated biomass should be avoided in thermochemical conversion due to the unclear chemical reactions at high temperatures. Contaminated feedstocks may produce harmful by-products or toxic compounds, posing environmental and health risks, especially if used in agriculture.

The properties of biomass influence the characteristics of biomass-derived chars, along with the conditions of the conversion process. The increasing demand for high-quality biomass-derived chars, with enhanced capabilities and adaptability, has driven significant research in this area (Kwon et al., 2020). Many studies have investigated the influence of biomass variety on final biomass-derived chars. The biomass moisture content is the most crucial factor in selecting an appropriate thermochemical conversion method (Park et al., 2018). The ratio of lignin-cellulose in biomass is important to be considered, corresponding to the atomic ratios of H/C and O/C of derived chars. A high H/C ratio is more desired, making biomass-derived chars more stable and resistant to decomposition, leading to long-term C sequestration (Li and Tasnady, 2023). Apart from these properties, NPK content in biomass is interesting as a plant nutrient source which can be taken up through the plant roots. Inorganic fertilizer can be substituted by biomass-derived chars when these chars contain plant-available minerals (Glaser et al., 2015). According to quality requirements NY/T 3041-2016 of biochar-based fertilizer in China, major mineral nutrients of N, Phosphorus pentoxide (P_2O_5), and Potassium oxide (K_2O) are required to be higher than 20% (corresponding to 12.3% of N + P + K) (Rasse et al., 2022).

Figure 5 specifies eligible feedstocks and agricultural end uses, according to the U.S. and Canada Biochar Protocol by the Climate Action Reserve. Many of the eligible feedstocks, such as agricultural and forestry waste (Raghuram, 2022), food waste (Y. Wang et al., 2022), and production chain residues (Salcedo-Puerto et al., 2025), are commonly utilized through composting or as by-products of anaerobic digestion, like digestate (Herrmann et al., 2024), to support nutrient recycling. However, thermochemical conversion into biomass-derived chars offers additional benefits, as it enhances nutrient retention, reduces GHG emissions, and creates a more stable, long-lasting soil amendment (Nguyen et al., 2022). The protocol's recognition of these feedstocks highlights the potential of biochar to enhance both C sequestration and sustainable agricultural practices.

5.3. Change in properties of biomass-derived chars from different thermochemical processes

Due to its ability to support rapid crop growth, farmers prefer to use commercial inorganic fertilizers on their farms each season. However, excessive use of inorganic fertilizers can disturb the soil's natural nutrient balance, causing imbalances and degrading soil quality. Recently, biomass-derived chars have been effectively utilized as a soil amendment to enhance nutrient retention (Sun et al., 2017), promote soil C sequestration (Li et al., 2018), aid in soil remediation (Zhou et al., 2017), and mitigate GHG emissions (Feng et al., 2017). Poor agricultural practices cause nutrient leaching, particularly N, P, and K. These three important elements are highly required for plant growth and protein synthesis.

The specific thermochemical conversion method significantly influences the properties of biomass-derived chars. **Table 1** lists several key properties of biomass-derived chars that influence their suitability as soil amendments. The properties of hydrochars differ significantly from those of biochar and

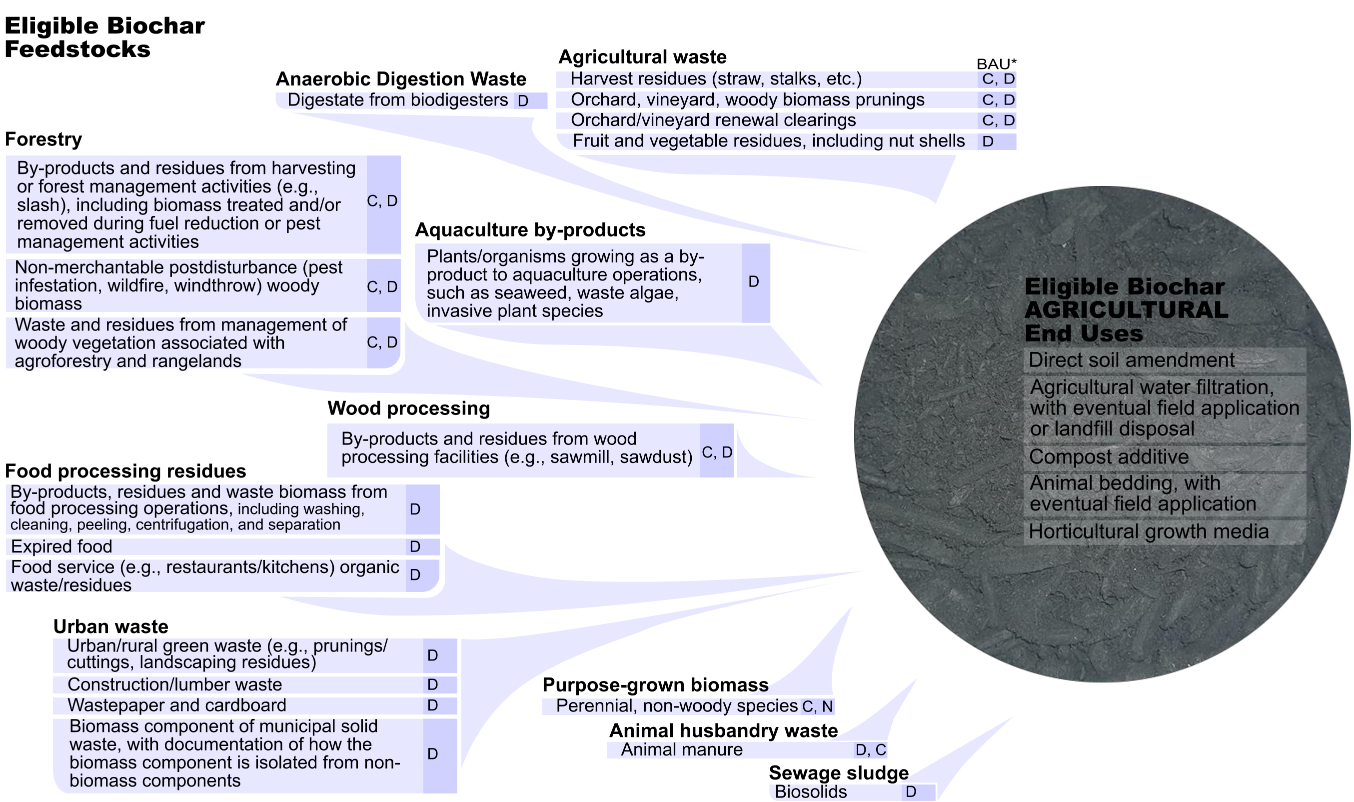

Fig. 5. Infographic of eligible biochar feedstocks, their current business-as-usual, and corresponding eligible biochar agricultural end uses, developed based on information from the U.S. and Canada Biochar Protocol by Climate Action Reserve (CAR, 2024). *Abbreviations*: BAU, business-as-usual; C, combustion; D, decomposition; N, no business-as-usual.

Table 1.
Comparative properties of biomass-derived chars from different thermochemical conversions, which potentially influence soil properties.

Thermochemical Conversion	Pyrolysis	Gasification	Hydrothermal Carbonization
Biomass-derived chars	Biochar	Gasification char/ash	Hydrochar
Solid yield (wt%-db)	30-50%[1]	5-15%[2]	40-70%[3]
Properties that make chars suitable for use in soil			
pH	8-10 (alkaline); Neutralize acidic soils[4]	9.0-11.6[5]; Alkaline due to high accumulation of metal salts and high ash content[6]	4.0–5.7 (acidic, except for high-pH feedstocks such as digestate that neutralize its pH); Neutralize alkaline soils[7]
H/Corg	0.38-0.44 efficient soil C sequestration[8]	Less than 0.4 (0.11-0.38)[9]	Relatively higher H/Corg ratio[10]
Porosity/Surface area	50-250 $m^2.g^{-1}$; moderately porous; improve soil water retention[11]	14-1362 $m^2.g^{-1}$; mostly highly porous[12]	20 $m^2.g^{-1}$; non-porous[13]
VOCs	Low amount; depending on biomass type and pyrolysis temperature	Low amount	High concentration, such as furanic and phenolic groups.
NPK	Low concentrations of N and K in biochar, due to volatility at high temperature	Strongly depends on feedstock type; may improve the bioavailability of P[14]	Hydrochar contains inorganic N (e.g., NO_3^--N, NH_4^+-N, and NO_2^- -N), organic N (e.g., proteins, amino sugars, and nucleic acids)[15]
Polyaromatichydrocarbons (PAHs) Highly toxic compounds to plant growth	12-355 μg/kg[16]	vary widely depending on the feedstock, operating conditions, and contact time of gas and char[17]; gasification char with a high surface area is more prone to higher PAH retention; 0.7-438 mg/kg[18]	2973-6222 μg/kg; exceeded agricultural use standard limits[19]
Functional performance of char in agricultural applications			
Plant yield	Neutral/positive effect[20]	No significant effect[21]	Controversial effect[22]
Soil pH buffering	Feasible for acidic soil[23]	Feasible for acidic soil[24]	Can act as pH buffering for alkali soil[25]
Microbial activity	Enhancing microbial activity, varying on climate conditions[26]	No/ inhibitory effect on microbial community in soil[27]	Controversial effect[28]

References: [1](Khater et al., 2024; Al-Rumaihi et al., 2022; Shahbaz et al., 2022); [2](Sharma et al., 2024); [3](Ischia and Fiori, 2020; Petrović et al., 2024); [4](Rodrigues et al., 2023); [5](Hansen et al., 2016; Zhang et al., 2020); [6](You et al., 2017); [7](Eibisch et al., 2013); [8](Bayabil et al., 2015); [9](Hernández et al., 2020; Romero Millán et al., 2021); [10](Kambo and Dutta, 2015); [11](González et al., 2009); [12](Bikbulatova et al., 2018; You et al., 2017; González et al., 2009); [13](Román et al., 2012); [14](Zhang et al., 2020); [15](de Jager and Giani, 2021); [16](J. Wang et al., 2019); [17](Rollinson, 2016); [18](Hansen et al., 2015; Llovet et al., 2021); [19](Liu et al., 2021); [20](Joseph et al., 2021; Backer et al., 2016); [21](Llovet et al., 2021); [22](Battipaglia et al., 2023; Bona et al., 2023; Puccini et al., 2018); [23](Bhattacharyya et al., 2024); [24](Deal et al., 2012); [25](Shen et al., 2024); [26](Kumar et al., 2025); [27](Marks et al., 2014; Marks et al., 2016); [28](M.A. Islam et al., 2021).

gasification chars, as the HTC process occurs at much lower temperatures under high-pressure water conditions. Similarly, but to a lesser extent, gasification chars differ markedly from pyrolysis-derived biochar due to the partially oxidative conditions in the gasifier, which alter their physicochemical and morphological characteristics. The suitability of a particular char for a specific soil type depends on its physicochemical properties. For instance, biochar with higher pH and liming potential is beneficial for acidic soils (Singh et al., 2022), while those with higher nutrient content are advantageous for nutrient-deficient soils (Syuhada et al., 2016). Due to unique properties, such as high pH and cation exchange capacity, biochar application becomes a sustainable soil remediation technology (Ahmad et al., 2014).

The hydrogen-to-organic C ratio (H/Corg) is a key factor in mitigating N_2O emissions from soil and reflects the physicochemical properties of char related to its stability (Budai et al., 2013; Cayuela et al., 2015). According to guidelines of European biochar certificates for sustainable production of biochar (EBC, 2024), H/Corg is limited to less than 0.7 when biochar is used in the agricultural sector, and a ratio below 0.4 indicates high biochar stability, enhanced C sequestration potential, and lower biochar degradation rates. Biochar from pyrolysis at high temperatures exhibits greater aromaticity and C stability, making it effective for long-term C sequestration (Tomczyk et al., 2020). Gasification chars also demonstrate high stability due to the severe processing conditions (Phounglamcheik et al., 2021). Hydrochar, while less stable than biochar and gasification char, still contribute to C sequestration and can be engineered for enhanced stability through post-processing treatments (Bahcivanji et al., 2020).

Compared to other types of chars, gasification char typically has higher nutrient content due to excessive C loss during the gasification process. However, most of these nutrients are non-bioavailable because the higher gasification temperatures often transform them into stable, inert forms (Zhang et al., 2020). On the other hand, residual char or ash of gasification has the potential to serve as a substitute for phosphate fertilizers. Insoluble phosphate in biochar can be converted into bioavailable phosphate through post-treatment processes, such as steam gasification (Laghari et al., 2021). Biochar generally retains more water-soluble nutrients than gasification char due to lower processing temperatures, making them suitable for enhancing soil fertility (Zhang et al., 2020). Compared to low-temperature biochars, higher pyrolysis temperatures result in an increased mineral content, including Ca, K, Mg, and other alkaline elements, due to a reduction in process yield (Rafiq et al., 2016). Besides, hydrochars can retain significant amounts of nutrients, depending on the feedstock and process conditions, and may be particularly useful in soils requiring immediate nutrient availability (Xiong et al., 2021; Volikov et al., 2024).

The porosity and surface area of the char influence soil aeration and water retention and provide a habitat for soil microbes, which are critical factors for plant growth (Blanco-Canqui, 2017). During the oxidation stage of the gasification process, the oxidizing agent removes a significant portion of C from the biomass, resulting in highly porous char formation compared to pyrolysis. The enhanced porosity and increased specific surface area of gasification chars underscore their potential to improve essential soil quality parameters, including soil structure, nutrient retention, and water-holding capacity (Hansen et al., 2015). While gasification char may serve as a potential habitat for microorganisms, its recalcitrant structure lacks essential substrates required for microbial growth and activity. Therefore, its influence on microbial communities is often minimal or limited (Imparato et al., 2016). Additionally, high surface area and porosity enable gasification chars and biochars to remediate soils contaminated with heavy metals and organic pollutants by facilitating adsorption (Trinh et al., 2017).

Beyond porosity, the surface chemistry of the char also has a strong influence on its performance. Several factors contribute to this influence: (a) the surface point of zero charges (PZC) affects the H+/OH- exchange between char and soil, thereby modifying soil pH (Román et al., 2020); (b) the presence of specific chemical compounds, such as phenols or furans, on the char surface, may cause phytotoxic effects (Al-Naqeb et al., 2022); (c) various functional groups facilitate the retention and transport of nutrients within the soil.

While this review initially examines various biomass-derived chars, the subsequent sections primarily focus on biochar. This emphasis is justified by its superior stability, agronomic benefits, and commercial scalability compared to gasification char and hydrochar. Biochar exhibits greater long-term C sequestration potential due to its high aromatic C content, making it significantly more resistant to microbial decomposition than hydrochar (Schmidt et al., 2021), which is more labile. Additionally, biochar with high C stability and less toxicity (Ferraz et al., 2020; Fan et al., 2023) has demonstrated greater effectiveness in improving soil fertility, nutrient retention, and water-holding capacity compared to gasification char (Singh et al., 2022), which lacks bioavailable nutrients. Beyond its environmental advantages, biochar has transitioned from experimental studies into practical agricultural applications and carbon credit markets, further supporting its feasibility as a large-scale alternative to inorganic fertilizers (Pierson et al., 2024). Given these advantages, the following sections provide an in-depth evaluation of biochar's production, functionality, environmental impact, and economic feasibility.

6. Biochar's multifaceted role in soil and plant systems

Biochar has emerged as a system for addressing critical challenges related to soil fertility, plant health, and environmental sustainability. As illustrated in **Figure 6**, biochar operates through intricate mechanisms that influence nutrient dynamics, soil structure, microbial activity, and plant growth. Biochar improves soil fertility by influencing physical, chemical, and biological soil properties (Singh et al., 2022). It increases water retention, nutrient availability, and pH buffering capacity, especially in sandy or acidic soils, making it a beneficial soil amendment in marginal lands (Bhattacharyya et al., 2024). Studies report average crop yield increases of 10-42%, particularly in nutrient-deficient soils where biochar enhances nutrient retention and reduces leaching losses (Joseph et al., 2021). However, biochar's effects can vary; in some cases, it has neutral effects on crop yields, especially in fertile soils with a balanced texture and a neutral pH (Vijay et al., 2021). A Canadian study (Backer et al., 2016) on acidic soils found a 14.2 % increase of corn yield after the biochar application of 20 t/ha on a loamy sand, while no significant effect was found on the finer textured sandy clay loam. For buckwheat yield in a semi-arid climate on neutral to slightly alkaline soils, an 11.23% - 22.82% increase was found after biochar addition of 20 - 60 t/ha in sandy loam soil, while for the silt loam, the yield increase was 7.36% to 14.87% (Zhou et al., 2024). Further studies have shown that the application of biochar has a positive effect on vegetable yields. Significant increases were found for tomatoes (Rehman et al., 2021), radish (Garcia-Perez et al., 2022), and cucumber (Mbah *et al.*, 2017), for the latter on slightly acidic, sandy loam by up to 47%, depending on the amount of biochar applied. Additionally, biochar fosters favorable rhizosphere conditions, such as increased microbial diversity, improved microbial activity (Kracmarova-Farren et al., 2024) and reduced phytotoxins, promoting root development, seed germination (Pandey et al., 2022), and plant resilience under abiotic stress (Hasnain et al., 2023). All these effects depend on the biochar feedstock, the biochar production process, the application rate, the used soil, and the plant species.

6.1. Stabilizing organic matter and soil carbon

Biochar products contain both labile and stable fractions, the proportions of which are influenced by the source material and the production conditions. These factors determine their recalcitrance to biodegradation in the soil (Busch and Glaser, 2015). The stable fraction interacts with organic substrates in the soil (Organic uptake in **Fig. 6a**) through electrostatic attraction or repulsion, polar attraction (hydrophobic interactions), and non-polar attraction (dipole interactions). These processes stabilize labile organic matter, preventing its rapid decomposition and promoting long-term C sequestration (Ernest et al., 2024), enhancing SOC stocks (Sun et al., 2023). The labile fraction is decomposed over time, but serves as food for the soil organisms and thus leads to an increase in microbial biomass in the soil (Lee et al., 2023).

The ability of biochar to adsorb organic molecules, including plant root exudates and secondary metabolites, plays a crucial role in rhizosphere interactions. By enhancing the bioavailability of these compounds, biochar promotes microbial interaction and root-microbe symbiosis (Kracmarova-Farren et al., 2024), which are essential for nutrient cycling and plant health (Valle et al., 2020).

6.2. Enhancing nutrient retention and availability

One of biochar's defining features is its porous architecture, which provides extensive reactive surfaces for nutrient retention and exchange (Inorganic uptake in **Fig. 6b**). Adding biochar to the soil enhances its ion exchange capacity, facilitating the retention of both positively and negatively charged ions. This dual functionality is critical in nutrient-deficient soils, where nutrient loss through leaching is a major challenge (Joseph et al., 2021). The high capacity for the adsorption of essential nutrients such as ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), and K^+, is mitigating nutrient leaching and improving nutrient availability to plants (Joseph et al., 2021). Changes of biochar application on cation exchange capacity (CEC) range from -27% to +904%, depending on the biochar's source material, production temperature, application rate, ash content and the properties of the receiving soil (Mukherjee et al., 2014; Domingues et al., 2020; Garcia-Perez et al., 2022; Antonangelo et al., 2024). On weathered soils with low initial CEC the largest improvements after biochar application were reported (Martinsen et al., 2015). Another study (Mukherjee et al., 2014) found an increase of CEC in the soil over 15 months after biochar application. The authors also found this aging effect on the anion exchange capacity (AEC). Particularly in acidic soils, the liming effect of biochar increases soil CEC even further by increasing soil pH (Chintala et al., 2014; Adekiya et al., 2024). Nutrient-enriched biochar or biochar consisting of larger fractions of labile C leads to the slow release of additional nutrients into the system.

Building upon the established benefits of biochar in enhancing nutrient retention and availability, its role in mitigating metal toxicity in soils is equally significant. Biochar's high surface area and porous structure enable the adsorption of heavy metals, thereby reducing their bioavailability and toxicity to plants (Fan et al., 2023). This adsorption capacity is particularly beneficial in acidic soils, where metals such as aluminum (Al) can reach toxic levels, inhibiting root growth and function. By immobilizing these metals, biochar creates a more conducive environment for root development and overall plant health (Shetty and Prakash, 2020).

Similarly, biochar amendments have been shown to decrease the mobility of cadmium and lead in contaminated soils. Research indicates that biochar can effectively reduce the uptake of these metals by plants, thereby decreasing heavy metal transfer to edible plant parts (Sarraf et al., 2024). In addition to its metal-adsorbing properties, biochar's liming effect contributes to the amelioration of soil acidity, further mitigating metal toxicity (Fan et al., 2023). The increase in soil pH following biochar application precipitates metals like Al into less soluble forms, reducing their availability to plants (Sarraf et al., 2024). This dual mechanism, direct adsorption, and pH-induced precipitation highlight biochar's multifaceted role in enhancing soil health. However, considering the fact that biochar is partly biodegradable, attention needs to be taken to the fate of non-biodegradable contaminants in biochar-amended soils.

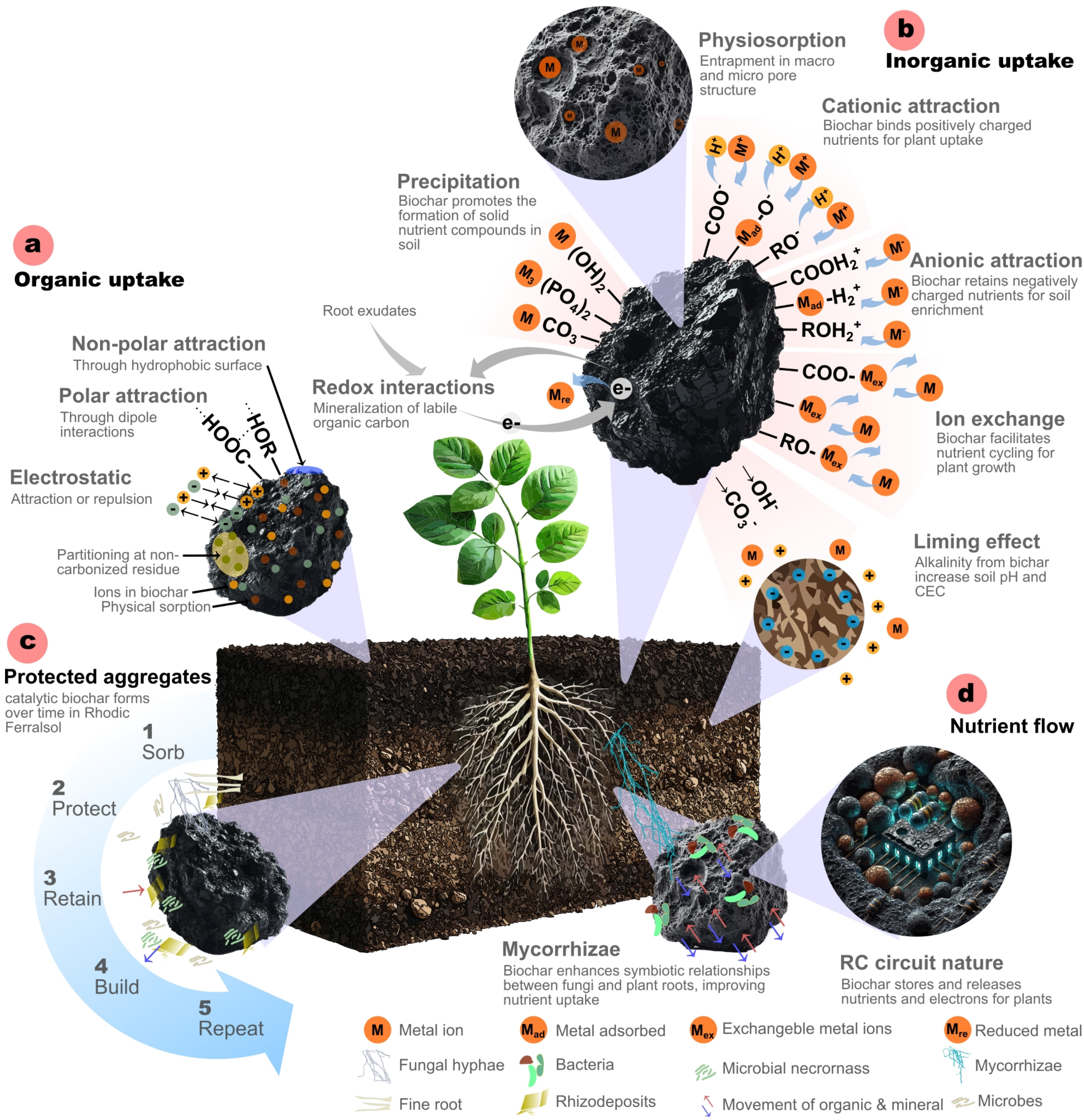

Fig. 6. Mechanisms of biochar interactions within soil and plants: **a**. uptake of organic substrates, **b**. uptake of inorganic substrates, **c**. conceptual illustration of protected aggregate formation on catalytic biochar surfaces over time in soil, and **d**. overview of key processes triggered by biochar application, including reactive surface development and interactions with plant roots (Adapted from Oliveira et al., 2017; Chew et al., 2020; Valle et al., 2020; Joseph et al., 2021; Weng et al., 2022). *Abbreviations*: CEC, cation exchange capacity; RC, resistor-capacitor parallel circuit.

6.3. Aggregates as catalysts of soil resilience

Biochar serves as a catalyst for soil resilience by promoting the formation and stabilization of soil aggregates (**Fig. 6c**). Acting as nucleation sites, biochar particles facilitate the binding of fine soil particles and organic matter into stable aggregates through sorption and microbial interactions (M.U. Islam et al., 2021; Sun et al., 2023). Over time, these aggregates protect SOC from microbial mineralization, thereby enhancing soil fertility and resilience (Zhao et al., 2023). Additionally, aggregate formation improves soil physical properties, such as porosity and water retention (Ramírez et al., 2023), which are particularly beneficial in drought-prone regions (Sharma et al., 2021). Other mechanisms for an improved water retention are (i) the additional internal porosity of the biochar and (ii) the creation of a higher variety of grain sizes in sandy soils, which leads to a broader pore size distribution. Biochar significantly increased available water for plants by 45% for coarse-textured soils (Razzaghi et al., 2020).

Biochar-amended soils additionally exhibit reduced erosion, contributing to overall soil sustainability (Valle et al., 2020). Furthermore, the continuous cycle of aggregate formation highlights the long-term structural benefits of biochar.

During this cycle, biochar adsorbs root-derived C, or rhizodeposits, onto its surface, preventing their immediate microbial decomposition (**Fig. 6c**). These rhizodeposits form organic layers on the biochar, as well as organo-mineral layers with fine soil minerals, aiding in the retention and protection of organic matter. Over time, microbial necromass also adheres to the biochar, integrating into similar protective layers. This cyclical process leads to the progressive formation of organic and organo-mineral coatings on the biochar surface, ultimately contributing to the stabilization and long-term accumulation of SOC (Weng et al., 2022).

6.4. Catalyzing microbial and plant interactions

Biochar-amended soils showed a pronounced shift in microbial communities, particularly promoting N-fixing and biocontrol bacterial genera (R.P. Singh et al., 2024). This change is not merely a quantitative increase in microbial diversity but a qualitative enhancement that aligns microbial function with crop nutrient and health demands, reflecting biochar's potential as a biostimulant (De Tender et al., 2016).

Biochar's reactive surfaces and electron-conducting properties (**Fig. 6a**) enhance nutrient cycling and microbial activity in the rhizosphere. As an electron shuttle, biochar facilitates redox reactions that influence nutrient availability, including reducing metal ions and the oxidation of organic matter (Kappler et al., 2014). These redox interactions are critical in nutrient-limited soils, where biochar bridges microbial metabolism and soil nutrient pools (Joseph et al., 2021).

In addition to nutrient cycling, biochar fosters symbiotic relationships between plant roots and mycorrhizal fungi. Mycorrhizal colonization on biochar surfaces, as depicted in **Figure 6d**, enhances nutrient uptake and improves plant resilience to abiotic stressors, including drought and salt stress (Neuberger et al., 2024). The porous structure of biochar provides a habitat for beneficial microbes, enhancing microbial activity and diversity in the rhizosphere. This microbial proliferation facilitates the decomposition of organic matter, leading to the release of plant-available nutrients (Kracmarova-Farren et al., 2024). Moreover, biochar can adsorb root exudates and other organic compounds, promoting microbial communication and symbiotic relationships between roots and microbes. These interactions are essential for nutrient cycling, disease suppression, and overall plant vitality. For example, a study (Yan et al., 2022) found that biochar application increased the production of root exudates, providing nutrients and energy for microbial metabolism and growth, which altered the relationship between rhizosphere microorganisms and plants. In addition, the change in microbial community can result in a higher abundance of potential biocontrol agents and an increased immunity of the plant, which eventually results in an increase in plant health upon infection (De Tender et al., 2021).

The alteration in root membrane potential can enhance nutrient uptake as needed by the plant, modeled as a Resistor-Capacitor (RC) parallel circuit (**Fig. 6d**) (Chew et al., 2020). Biochar facilitates electron transfer both directly, by serving as an electron shuttle, and indirectly, by promoting the transition of electrons from the valence band to the conduction band in Iron (Fe) minerals (Joseph et al., 2021). This process generates electron-hole pairs, leading to reactive oxygen species formation through Fenton and Fenton-like reactions (Yu and Kuzyakov, 2021).

6.5. Biochar as a slow-release fertilizer

As seen in *Section 5.2*, different biomass-based char products such as biochar or hydrochar have different stabilities. While biochar has a high proportion of stable C and along with a long residence time in the soil, hydrochar is less stable, less porous, and has a higher biodegradability. The fertilizing effect of biochar primarily depends on its nutrient enrichment before being incorporated into the soil. Without this enrichment, biochar's strong adsorption properties may cause it to absorb dissolved nutrients from the soil, reducing their availability to plants (Joseph et al., 2018). The fertilizing effect of hydrochar, on the other hand, is derived from the slow decomposition of the degradable part of the charcoal and the associated release of nutrients (Khosravi et al., 2022). The addition of hydrochar to the soil results in a higher CO_2 release into the atmosphere than in the case of biochar, but also the greater build-up of microbial biomass, because the decomposed organic material is food for the soil organisms (Li et al., 2020).

Biochar research is more advanced than hydrochar research, and issues such as nutrient depletion after applying fresh char to soil have been recognized and addressed. In contrast, hydrochar still presents challenges due to phenols, furans, and organic acids, which can have phytotoxic effects. Solutions are being explored, including washing, aging, composting (Dang et al., 2024), or hydrothermal humification to transform these compounds into artificial humic acids (AHAs) and artificial fulvic acids (AFAs) (Ghaslani et al., 2024).

7. Functional performance viability of biomass-derived chars as an inorganic fertilizer replacement

Biomass-based chars, traditionally valued as soil amendments for enhancing soil structure and fertility, are now gaining recognition for their potential as slow-release fertilizers (Palansooriya et al., 2025; Wang et al., 2025). With its exceptional ability such as retaining nutrients, minimizing leaching and water runoff, supplying essential nutrients, and enhancing soil microbial activity, biomass-based chars serve as an effective fertilizer for sustainable agriculture. Biomass chars can be applied on soil solely or combined with organic, inorganic, or microbial fertilizer to maximize their effectiveness. In most cases, the application of chars as a fertilizer requires enrichment with N, P, and K through direct, pre-, or post-treatment (Karim et al., 2019; Vimal et al., 2022). Direct treatment involves producing biochar from nutrient-rich biomass, such as manure, algae, or nutrient-enriched plant residues or a mixture of these biomasses that are rich in individual nutrients. Nutrient-enriched biochars can also be produced by pre-treating biomass with nutrient-rich minerals, inorganic fertilizers, or wastes with high mineral content prior to pyrolysis. Additionally, post-treatment involves co-application with fertilizers, which is not limited to inorganic fertilizers (Bi et al., 2024) but also includes organic fertilizers (Zhang et al., 2024) and microbial fertilizers (Gu et al., 2022). Considering the environmental aspect, notably, the co-application of biochar with chemical fertilizers has shown promising results, offering an alternative to reducing the intensive use of chemical fertilizers (An et al., 2022).

7.1. Impact on agricultural productivity

Biomass-derived char has been shown to enhance agricultural productivity by improving soil properties such as water retention (Kabir et al., 2023; Khan et al., 2024), cation exchange capacity (CEC) (Kabir et al., 2023), and nutrient availability (Batista et al., 2018). A meta-analysis of biochar applications has reported increases in crop yields, particularly in degraded or nutrient-poor soils (Xu et al., 2025). The enhancement in crop yields resulting from biochar application can be attributed to several key mechanisms, including improved nutrient retention (Hagemann et al., 2017) and regulation of soil pH (Shetty and Prakash, 2020), both of which contribute to enhanced soil fertility and plant growth. Biochar's porous structure and high surface area enhance the adsorption of essential nutrients such as N and P, reducing nutrient losses through leaching (Gelardi et al., 2021; Lu et al., 2022). In acidic soils, char acts as a liming agent, raising pH and improving nutrient availability to plants (Bolan et al., 2023). However, in alkaline soils, its effects can be neutral or slightly inhibitory, depending on the char type (Qayyum et al., 2021).

Moreover, biochar and organic fertilizer applications significantly increase the abundances of soil microbial functional taxa related to C, N, P, and sulfur cycles, thereby sustaining soil quality and promoting sustainable crop production (Hu et al., 2024). While biochar can increase productivity, its effectiveness depends on the feedstock, production conditions, and application rates (Jindo et al., 2020). Excessive biochar application or poorly tailored formulations may lead to nutrient immobilization, reducing short-term crop yields (Knoblauch et al., 2021).

Achieving the expected benefit from biochar is closely linked to its application to the soil at the desired rate and time, using suitable agricultural machinery. Depending on the soil's bulk density and organic matter content, it can be changed widely ranging from 5 to 30 t/ha or 5 to 25% by volume, particularly for container-grown or tree-planting holes (Brassard et al., 2018; Leppäkoski et al., 2021; Schmidt et al., 2021; Aller et al., 2023). The common equipment that can be used to apply biochar includes compost/manure spreaders, lime spreaders, broadcast seeders, seed drills, and liquid injection depending on the plant's or land's requirements. The most time and labor-efficient and cost-effective way to apply biochar is through the use of compost/manure spreaders, lime spreaders, or broadcasters with a large volume hopper. This significantly decreases the unit costs associated with labor and loading time (Sorensen and Lamb, 2018; Ejack et al., 2021).

Spring is the most common time to apply biochar, but a more effective time is often after harvest, along with a cover crop. This provides time for the biochar to equilibrate in the soil (Aller et al., 2023). However, the actual biochar application should be quantified using a standardized procedure, such as ASABE Standard S573 (Ejack et al., 2021).

Being small particles, biochar is sensitive to wind losses during handling, transportation, and application. However, the losses can be decreased by moistening, mixing with compost/manure, and/or granulation (Ejack et al., 2021; Leppäkoski et al., 2021; Aller et al., 2023; Grafmüller et al., 2024). Moreover, biochar that has become too wet may be difficult to spread depending on the equipment used. Pelletizing biochar with chicken litter, hay or another appropriate binder makes application easier with existing equipment. The denser pellets minimize potential loss when biochar is top-dressed (Mohammadi, 2021). A biochar-compost mixture provides greater flexibility for agronomic use, as it can be broadcast and incorporated into the soil or applied as a top dressing without incorporation. In contrast, manure-biochar mixture should be incorporated as soon as possible after spreading to minimize ammonia volatilization (Whalen et al., 2019). Furthermore, this flexibility allows farmers to save time and reduce cost, while lowering the risk of erosion losses (Aller et al., 2023).

7.2. Influence on water use and scarcity

Water scarcity is a critical global challenge, particularly in arid and semi-arid regions (Dolan et al., 2021). Biochar's ability to enhance soil water-holding capacity can contribute significantly to water conservation. Biochar's porous structure facilitates water absorption and retention, which is especially beneficial in sandy soils with low water-holding capacity (Li et al., 2021). Biochar amendments have been shown to significantly enhance soil water retention and improve crop growth under water-limited conditions. Research has demonstrated that biochar application can increase the growth and yield of quinoa in drought-prone soils, highlighting its potential as a water-saving strategy in agriculture (Condori-Ataupillco et al., 2025).

However, the extent of biochar's impact varies with soil type and biochar characteristics. For example, wood-derived chars tend to have greater water-retention capacity compared to agricultural biomass-derived chars (Ndede et al., 2022). Additionally, in clay-rich soils, char may exacerbate water logging due to reduced drainage (Wong et al., 2022). These findings highlight the need for site-specific studies before biochar is widely adopted for water conservation.

7.3. Impact on nutrient runoff

Nutrient runoff, particularly Nand P, is a major environmental concern due to its role in water pollution and eutrophication. Excessive nutrients in water bodies can lead to harmful algal blooms, oxygen depletion, and significant ecological and economic impacts (EPA, 2025). Biochar demonstrates significant potential in mitigating nutrient losses. Biochar's high adsorption capacity binds nutrients, reducing their mobility and leaching into water bodies. Studies have shown a 26–35% reduction in nitrate leaching (Grafmüller et al., 2024) and a 22-78% reduction in ammonium (Gelardi et al., 2021) loss following biochar application. Additionally, biochar application decreased P leaching from manured soil due to the sorption of both orthophosphate and organic P (Gupta et al., 2024). Moreover, biochar enhances nutrient cycling by serving as a slow-release nutrient carrier when combined with organic fertilizers, reducing the risk of nutrient overloading during rainfall events (C. Wang et al., 2022).

8. Environmental viability of biomass-derived chars as an inorganic fertilizer replacement

The environmental viability of substituting commercial inorganic fertilizers with biochar is a complex subject, encompassing its effects on GHG emissions (Tisserant et al., 2023), soil degradation (Khan et al., 2024), nutrient pollution (Patro et al., 2024), water quality (Ayaz et al., 2025), biodiversity (Gao et al., 2022), and overall environmental footprint. A comprehensive evaluation of these aspects is essential to determine the sustainability of biochar as a fertilizer alternative.

8.1. Impact on N_2O and CH_4 emissions from agricultural soil

Biochar application has been widely studied for its potential to mitigate N_2O and CH_4 emissions. Both are potent GHGs with significantly higher global warming potentials than CO_2. An average 18% reduction in N_2O emissions following biochar application was reported (Ayaz et al., 2025). Biochar reduces N_2O emissions by adsorbing ammonium (NH_4^+), limiting its conversion to nitrate (NO_3^-) during nitrification, a key step in N_2O production (Dawar et al., 2021). It also improves soil aeration, promoting complete nitrification and reducing anaerobic conditions that drive denitrification, further decreasing N_2O emissions (Cayuela et al., 2013). Additionally, biochar's alkalinity increases soil pH, altering microbial activity and suppressing denitrification pathways responsible for N_2O formation (Cayuela et al., 2013).

The effect of biochar on CH_4 emissions varies. Some studies show reductions (Wu et al., 2019; Awad et al., 2018; Nan et al., 2020), while others report neutral or increased emissions, influenced by soil type, moisture levels, and biochar properties (C. Wang et al., 2019; Nan et al., 2020). Biochar modifies soil microbial communities, reducing methanogen populations while enhancing methanotrophs, leading to lower CH_4 emissions (Nan et al., 2021). Improved soil aeration also suppresses methanogenesis (Kim et al., 2017), and biochar's high surface area may directly adsorb CH_4, limiting its release (Ko et al., 2023). Additionally, enhanced plant growth from biochar increases root oxygenation, further suppressing methanogenic activity, and thereby reducing CH_4 emissions (Lee et al., 2023).

Some studies have reported increased CH_4 emissions following biochar application. This discrepancy may be attributed to several factors: the type of biomass used to produce biochar and the conditions under which it is pyrolyzed can influence its properties; for instance, biochar produced at lower temperatures may contain more labile organic compounds, which can serve as substrates for methanogenic archaea, potentially increasing CH_4 emissions (Ko et al., 2023). In anaerobic soils, such as flooded paddy fields, biochar can create microsites that favor methanogenesis; the addition of biochar may enhance soil organic carbon, providing additional substrates for methanogens, leading to increased CH_4 emissions (Nan et al., 2020). Higher rates of biochar application have been associated with increased CH_4 emissions in some studies; excessive biochar can alter soil physical properties, such as porosity and water retention, creating conditions conducive to methanogenesis (C. Wang et al., 2019).

Given these varying effects, biochar's mitigation efficiency depends on feedstock type, pyrolysis conditions (Qi et al., 2023), soil characteristics, and application methods (Lee et al., 2023). Higher-temperature biochars typically have greater adsorption capacity, influencing their effects on microbial communities and nutrient cycling. Soil texture, pH, and organic matter content further modulate biochar's impact on GHG emissions (Nan et al., 2020).

In summary, biochar effectively reduces N_2O emissions through nitrogen retention, improved aeration, and pH modulation. Its influence on CH_4 emissions is more variable, dependent on microbial shifts, aeration, and biochar properties. Optimizing biochar application is crucial for maximizing its GHG mitigation potential.

8.2. Impact on soil degradation

Soil degradation, characterized by the decline in soil quality and soil health due to factors such as erosion, compaction, and nutrient depletion, poses a significant threat to agricultural productivity and environmental sustainability. Biochar application has emerged as a promising strategy to mitigate soil degradation through various mechanisms.

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Biochar inclusion improves soil physical properties in both the short and long term. In the short term, biochar's porous structure decreases soil bulk density, thereby reducing compaction. This improvement enhances root penetration and water infiltration, promoting healthier plant growth. Studies have demonstrated that biochar application can reduce soil compaction by more than 10% (Khan et al., 2024). Additionally, in the long term, biochar facilitates the formation of stable soil aggregates by enhancing soil structure and increasing organic matter content. Stable aggregates improve soil aeration, water retention, and resistance to erosion, contributing to sustained improvements in soil health over time. Research indicates that biochar application significantly reduces soil loss by enhancing soil stability and promoting the formation of stable soil aggregates (Sharma, 2024).

Moreover, biochar enhances the soil's chemical properties. In the short term, biochar's high cation exchange capacity enables it to retain essential nutrients, reducing leaching losses and enhancing nutrient availability to plants. This property is particularly valuable in degraded soils lacking fertility. Over the long term, biochar, rich in stable C compounds, contributes to the long-term sequestration of C in soils. This increase in SOC enhances soil fertility and structure. A systematic review highlighted that biochar with high C content can significantly boost SOC levels, which is especially beneficial in poor soils (Qi et al., 2024). Furthermore, biochar contributes to the mitigation of soil erosion through the reduction of runoff and soil loss. Short-term benefits include increased water infiltration rates and improved soil aggregation, leading to a reduction in surface runoff. Long-term improvements result from continuous soil structure stabilization, making the soil more resistant to erosion over multiple cropping cycles (Sharma, 2024).

Lastly, biochar has a tremendous effect on the soil microbial community. In the short term, it can boost microbial abundance and increase microbial activity which results in a higher nitrification rate among others (Kerner et al., 2023). Over time, this eventually leads to healthier soil, which can increase soil nutrient cycling and plant performance over successive growing seasons. In summary, biochar application addresses key aspects of soil degradation through both immediate and long-term mechanisms. Short-term benefits include reduced compaction, enhanced nutrient retention, and increased microbial activity, while long-term effects involve stable carbon sequestration, improved soil aggregation, and sustained soil health restoration. These benefits highlight biochar's potential as a sustainable amendment for restoring and maintaining soil health in degraded agricultural systems.

8.3. Impact on nutrient and water pollution

Agricultural activities contribute significantly to water pollution through nutrient leaching, pesticide runoff, and heavy metal contamination, all of which threaten water quality and ecosystem health. Biochar has been explored as a potential mitigation strategy due to its ability to retain pollutants, enhance nutrient use efficiency, and improve soil structure (He et al., 2022).

Biochar plays a crucial role in reducing nitrogen N and P pollution by adsorbing key nutrients and limiting their mobility. Its porous structure and surface functional groups retain NH_4^+, NO_3^-, and PO_4^{3-}, reducing leaching losses and enhancing nutrient availability for plants (Lu et al., 2022). Additionally, biochar influences microbial communities, improving nitrogen cycling and enzymatic activities, which further mitigate nitrogen losses (Khan et al., 2022). Depending on its composition, biochar may act as a slow-release nutrient source, but the nutrient dynamics must align with soil-plant system requirements to prevent excessive accumulation (Lu et al., 2022).

Beyond nutrient retention, biochar is effective in mitigating water pollution by reducing runoff and adsorbing contaminants. Its high surface area facilitates the immobilization of pesticides, restricting their movement and lowering the risk of water resource contamination (Blanco-Canqui, 2019). Moreover, biochar binds heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), and arsenic (As^{3+}), decreasing their bioavailability and preventing groundwater contamination (Gao et al., 2022). By enhancing soil aggregation, biochar promotes water infiltration and reduces surface runoff, thereby mitigating sediment transport and pollutant discharge into aquatic ecosystems (He et al., 2022).

Next to nutrient retention and heavy metal adsorption, biochar has demonstrated potential in mitigating microplastic pollution within soil ecosystems. Microplastics, defined as plastic particles smaller than 5 mm, pose emerging environmental challenges due to their persistence, potential toxicity, and capacity to act as carriers for other pollutants. Research indicates that biochar can influence the fate of microplastics in soils through several mechanisms. First, biochar's porous structure and high surface area enhance the adsorption of microplastics (Wang et al., 2020), effectively trapping them within the soil matrix and preventing their leaching into groundwater or uptake by plants (Li et al., 2024). Second, biochar can alter soil microbial communities by providing habitats for microorganisms capable of breaking down plastic polymers. This microbial stimulation has been linked to the acceleration of microplastic decomposition within the soil environment (Ren et al., 2021). Third, as microplastics act as carriers for heavy metals and organic contaminants, biochar effectively adsorbs these co-contaminants, thereby mitigating their mobility and reducing their bioavailability (Miao et al., 2023).

Although biochar has gained attention for its promising short-term benefits, primarily due to its high nutrient content, its application presents potential environmental risks. These risks include the accumulation of heavy metals in soil, the persistence of hazardous compounds such as per- and polyfluoroalkyl substances (PFAS), and the potential emission of NOx and SOx during application or degradation (Patel et al., 2020).

The effectiveness of biochar in pollution control is influenced by feedstock type, pyrolysis conditions, and soil properties. Unmodified biochar may exhibit limited P retention unless engineered for enhanced sorption capacity. However, as a whole, biochar presents a promising strategy for improving nutrient retention, reducing contaminant leaching, and enhancing soil structure, ultimately mitigating agricultural water pollution.

9. Economic viability and practical considerations

Integrating biochar into agriculture requires a comprehensive evaluation of its economic viability compared to commercial inorganic fertilizers. This includes assessing potential subsidies, cost-sharing mechanisms, and practical challenges in large-scale adoption to promote stakeholder engagement.

9.1. Comparative cost analysis: Biochar and commercial inorganic fertilizers

The economic feasibility of biochar depends on production, transportation, and application costs (Campbell et al., 2018). Biochar production involves pyrolyzing biomass, which can be capital-intensive due to specialized equipment and energy requirements. Costs are significantly influenced by feedstock availability and type, pyrolysis technology, and operational scale. Feedstock procurement can account for 45% to 75% of total production expenses, with agricultural and forestry residues estimated at 63 to 82 USD/t (Amonette et al., 2021). Fast pyrolysis may offer better financial returns than slow pyrolysis due to higher bio-oil yields, providing an additional revenue stream (Brown et al., 2011).

Biochar's low bulk density leads to higher transportation costs per unit compared to conventional fertilizers. Densification methods, such as pelletizing, can improve transport efficiency but add to production costs. A study by the USDA Forest Service considered a transportation distance of 50 km for biochar pellets, highlighting the need to balance logistics with production site selection (Sahoo et al., 2021).

Application costs depend on incorporation methods and required rates. Biochar application rates of 2.5 to 20 t/ha are suggested to significantly improve plant yields (Joseph et al., 2013). However, high biochar costs, ranging from 600 to 700 USD/t in developed countries (UNIDO, 2021), can be prohibitive for large-scale applications. In contrast, chemical fertilizers are generally less expensive and have established supply chains, making them more accessible to farmers. Commercial inorganic fertilizers benefit from established production and distribution infrastructures, often resulting in lower costs. However, their long-term environmental costs, such as soil degradation and water pollution, are externalities not typically reflected in market prices.

Despite higher initial costs, biochar offers long-term agronomic benefits, including improved soil fertility, water retention, and C sequestration, which can generate revenue through carbon credit markets. A cost-benefit analysis in cereal agriculture indicated that biochar could be economically viable in the long term, especially considering its environmental benefits and potential for C credits monetization (Keske et al., 2020).

In 2024, biochar carbon credits were priced at an average of 176 USD/t, making it one of the more affordable CDR methods. In contrast, other CDR techniques such as direct air carbon capture and storage (DACCS) and mineralization had prices ranging from 227 to 827 USD/t, highlighting biochar's competitive cost in the CDR market (CDR.fyi, 2025). Major corporations are increasingly investing in biochar CDR credits. In December 2023, Microsoft signed an agreement to purchase 32,000 t of biochar CDR credits from the Exomad Green Concepcion project in Bolivia. Additionally, in March 2024, Microsoft entered into a six-year purchase agreement with The Next 150, securing 95,000 t of biochar CDR credits (Carbonfuture, 2023; The next 150, 2024). These real-world examples demonstrate how biochar projects are successfully monetizing carbon sequestration, enhancing their economic viability.

Figure 7 highlights the interconnected economic and operational factors influencing biochar feasibility. Production costs are highly dependent on feedstock selection, process efficiency, and post-treatment modifications, all of which impact market competitiveness. Slow pyrolysis maximizes biochar yield but is energy-intensive, whereas fast pyrolysis prioritizes bio-oil, creating trade-offs in economic returns. Gasification, while efficient for energy recovery, produces minimal biochar, limiting its agricultural viability.

Logistics and scalability present additional challenges. Biochar's low bulk density inflates transport costs, making decentralized production near biomass sources a cost-effective strategy. Densification techniques improve transport efficiency but require added investment. The figure also indicates the role of post-treatment enhancements, such as chemical activation, which can improve product value but must align with high-value markets like C sequestration or industrial applications to justify costs.

Ultimately, biochar's viability hinges on cost-optimization across the entire supply chain, from efficient feedstock utilization to transport logistics and targeted product applications. Successful large-scale adoption depends on balancing economic feasibility, technological efficiency, and market-driven demand to compete with commercial inorganic fertilizers while maximizing long-term agronomic and environmental benefits.

9.2. Economic feasibility assessments

Integrating biochar as a substitute for commercial inorganic fertilizers presents both promising opportunities and notable economic challenges. A critical examination of these factors is essential to determine the viability of large-scale biochar adoption in agricultural practices.

- Economic Challenges in Biochar Adoption

The primary economic impediment to widespread biochar utilization is production cost. Factors such as feedstock availability, thermochemical technology, and scale of operations significantly influence these costs (Anokye, 2024). For instance, small-scale production often suffers from diseconomies of scale, leading to higher per-unit costs. The profitability of using biochars in soil amendment using black spruce forests by slow pyrolysis using techno-economic analyses. Their field experiment's results revealed an improvement in potato and beet growing (Keske et al., 2020) in Canada. Moreover, a positive feasibility output was also obtained in assessing the effect of cassava stem, rice husk, and corn cob biochars on cassava plant growth (Fru et al., 2018).

Additionally, the initial capital investment for pyrolysis equipment can be substantial, deterring individual farmers from adopting this technology. Operational costs, including labor, maintenance, and energy consumption, further exacerbate the financial burden. Consequently, without external financial support, the cost of biochar may outweigh the immediate economic benefits perceived by farmers.

- Role of Subsidies in Enhancing Economic Feasibility

Governmental financial incentives are vital in offsetting the high initial costs associated with biochar production and application. Mechanisms such as C credits, renewable energy credits, tax credits, and loan guarantees can provide the necessary financial support to enhance the economic viability of biochar projects. For instance, the U.S. Department of Agriculture administers programs offering financial assistance to biochar producers, aiming to reduce capital and operating costs. The monetization of environmental benefits through C credits is particularly significant. Biochar's ability to sequester C has led to its inclusion in C markets, where producers can earn credits for the CO2 removed from the atmosphere (Pierson et al., 2024). The biochar carbon credit market analysis report highlights that sustaining high carbon prices or implementing subsidies to decrease feedstock costs are essential strategies for establishing a robust biochar market (Elias et al., 2022).

Recent market analyses indicate the growing financial potential of biochar. The global biochar market was valued at USD 763.48 million in 2024 and is projected to grow to USD 2,097.72 million by 2032, exhibiting a compound annual growth rate (CAGR) of 13.60% during this period (Fortune Business Insights, 2024). This growth is driven by increasing

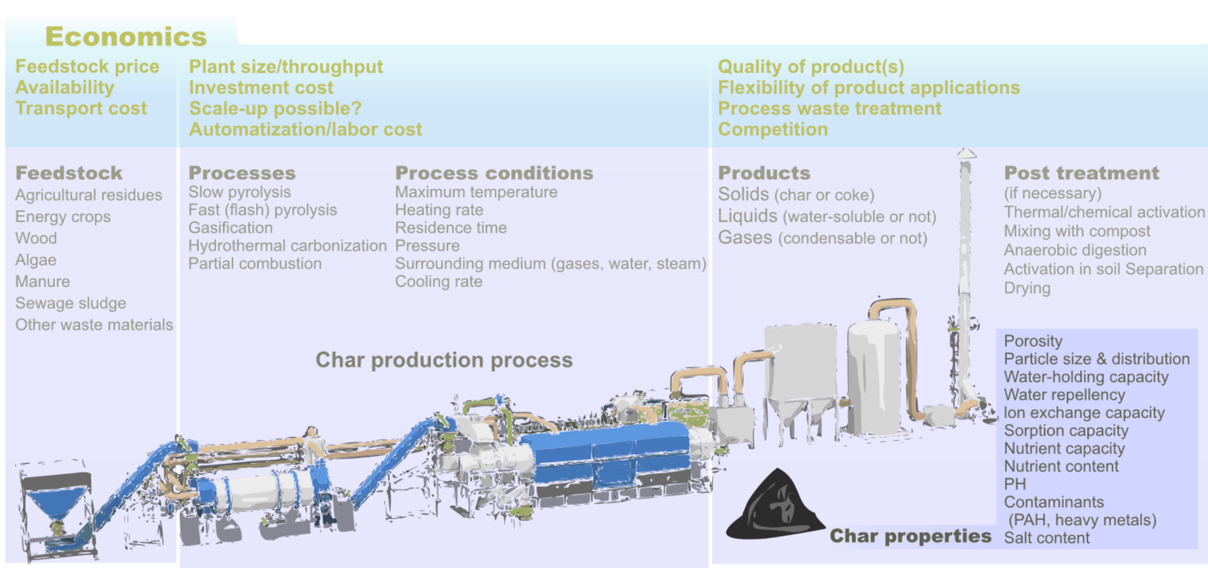

Fig. 7. Char production system outlining key economic and operational variables affecting biochar feasibility. The schematic illustrates how feedstock selection, thermochemical conversion processes, and post-treatment methods dictate production costs, scalability, and product marketability (Adapted from Libra et al. (2011), with the process line sketched from the BST-50 Model developed by BESTON, China, https://www.bestongroup.com/pyrolysis-plant/).

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recognition of biochar's environmental benefits and its role in sustainable agriculture.

- Cost-sharing mechanisms as a collaborative approach

Collaborative cost-sharing mechanisms offer an alternative strategy to distribute the financial burden of biochar production. Cooperative models, where multiple stakeholders, such as farmers, local governments, and private investors, share the costs and benefits, can lead to more sustainable adoption. For example, community-owned pyrolysis facilities can achieve economies of scale, reducing per-unit production costs. Additionally, public-private partnerships can leverage resources from various sectors to fund biochar projects, thereby diluting individual financial risks. Such collaborative approaches make biochar production more economically feasible, and foster community engagement and shared responsibility in sustainable agricultural practices. The profits from selling biochar often exceed the agricultural and environmental benefits; however, the exact value depends on commodity prices and emission costs (Kung et al., 2022).

- Challenges and considerations

Despite the potential benefits of financial incentives and cost-sharing mechanisms, several challenges persist. The availability and accessibility of subsidies can vary significantly across regions, leading to disparities in biochar adoption rates. Additionally, the process of quantifying and verifying C sequestration for C credits can be complex and resource-intensive, potentially deterring smaller producers. Moreover, the long-term sustainability of financial incentives is uncertain, as policy priorities may shift over time.

Furthermore, the development of transparent biomass supply chains is critical. Collaborations with entities like the U.S. Forest Service and large private landowners can help establish reliable sources of feedstock, ensuring consistent biochar production. Clear agreements regarding the timing, cost, quantity, and location of biomass generation are essential to maintain supply chain integrity (Elias et al., 2022).

10. Conclusions and future directions

The reliance on commercial inorganic fertilizers has raised serious environmental and economic concerns, driving the search for sustainable alternatives. This review assessed biomass-derived chars as potential substitutes. Compared to other biomass-derived chars, i.e. hydrochar and gasification char, biochar emerged as the most viable option, demonstrating superior nutrient retention (26–78% increase in nitrogen and P availability), enhanced water-holding capacity (45% improvement in coarse soils), and significant GHG mitigation (18% reduction in N_2O emissions). Unlike gasification char, which lacks bioavailable nutrients (except for P) and organic substrate for microbial growth, or hydrochar, which faces stability and phytotoxicity challenges, biochar offers long-term stability in soil. However, large-scale adoption of biochar remains hindered by high production costs (600–700 USD/t of biochar), transportation inefficiencies due to low bulk density, and regulatory inconsistencies across regions. While certification frameworks like the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI) set guidelines for biochar use, they lack global standardization and legal enforcement. This regulatory disparity leads to variability in composition, quality control, and application, limiting biochar's integration into agriculture and C markets.

On a global scale, biochar is increasingly recognized for C sequestration and soil restoration, established in the frameworks of several policies like the EU Carbon Removal Certification Framework (CRCF) and the U.S. and Canada Biochar Protocol incorporating biochar into carbon markets. The biochar market, valued at USD 763.48 million in 2024, is projected to reach USD 2.1 billion by 2032, indicating substantial expansion in the coming years in both private and public sector interest. However, scaling biochar adoption requires overcoming production inefficiencies, economic constraints, and regulatory gaps.

Future research should refine feedstock selection and thermochemical processes to optimize biochar properties for specific soil conditions while addressing safety concerns. These include the potential accumulation of heavy metals, the presence of polycyclic aromatic hydrocarbons (PAHs), and unintended soil ecotoxicity as well as soil physicochemical properties over time, all of which must be carefully evaluated to ensure safe agricultural application. Although biochar derived from nutrient-rich biomass is a promising sustainable alternative to slow-release fertilizers, the potential accumulation of heavy metals must be carefully evaluated to prevent soil contamination and ensure safe agricultural application. Standardized production protocols and certification frameworks are crucial for ensuring consistent quality across applications. Additionally, integrating biochar into circular economy models, such as co-application with organic and microbial fertilizers, could enhance its agronomic effectiveness and reduce reliance on synthetic fertilizers.

To improve economic viability, cost reduction strategies should be explored, including the development of decentralized pyrolysis facilities. Specifically, slow pyrolysis, which prioritizes biochar production while generating bio-oil as a co-product, offers a scalable approach to reduce costs. Additionally, optimizing intermediate pyrolysis to balance biochar and bio-oil yields could enhance economic feasibility and increase market adoption. Expanding carbon credit incentives, subsidies, and farmer compensation programs could further drive adoption. Large-scale field trials and long-term monitoring will be necessary to validate biochar's effectiveness across diverse soil and climate conditions.

Ultimately, the successful integration of biochar into mainstream agriculture requires a multidisciplinary approach, combining soil science, agronomy, economics, and policy-making. Key challenges that must be addressed include economic barriers such as high production and transportation costs, regulatory inconsistencies across regions, and the need for standardized certification frameworks to ensure biochar quality and safety for agricultural applications. Overcoming these obstacles will enable biochar to serve as a viable, sustainable alternative to commercial inorganic fertilizers while contributing to climate change mitigation and long-term soil health.

Acknowledgments

P.M. and C.D.T. would like to acknowledge the scholarship of the Mama Magda Aquaculture Fund (MMAF) of Ghent University, which was dedicated to P.M. for the completion of his joint PhD program between Universiti Malaysia Terengganu (UMT) and Ghent University (UGent, Belgium). The work was conducted under the umbrella of the collaborative consortium, the WASTE4CHAR project, funded by the Southeast Asia – Europe Joint Funding Scheme (JFS) 2023 for Science, Technology, and Innovation.

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Please cite this article as: Mohammadi P., Dang C.H., Román S., Duman G., Akdeniz R.C., Kömekçi F., Nik Ghazali N.N., De Tender C., Kulli B. Can biomass-derived chars serve as a viable alternative to commercial inorganic fertilizers? Biofuel Research Journal 45 (2025) 2350-2372. DOI: 10.18331/BRJ2025.12.1.5.

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Please cite this article as: Mohammadi P., Dang C.H., Román S., Duman G., Akdeniz R.C., Kömekçi F., Nik Ghazali N.N., De Tender C., Kulli B. Can biomass-derived chars serve as a viable alternative to commercial inorganic fertilizers? Biofuel Research Journal 45 (2025) 2350-2372. DOI: 10.18331/BRJ2025.12.1.5.