

Biochar: A Multifaceted Prospect for Carbon Sequestration and Carbon Farming

Nahal Zahra

Research Scholar, Division of Environmental Sciences, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar 190 025, Srinagar, Jammu and Kashmir, India

Abstract—Biochar, a stable form of carbon produced through the pyrolysis of biomass, has garnered significant attention as a promising tool for carbon sequestration and sustainable agriculture. Its ability to retain carbon in soil for centuries offers a potential solution to mitigate climate change by reducing atmospheric CO₂ concentrations. Furthermore, biochar enhances soil fertility, improves water retention, and suppresses greenhouse gas emissions, contributing to carbon farming practices. This paper explores the multifaceted potential of biochar for carbon sequestration, its role in improving agricultural productivity, and its integration into carbon markets. Challenges in feedstock availability, variability in biochar quality, and socioeconomic barriers are also discussed. As biochar technology evolves, future research should focus on optimizing production processes, developing tailored biochar products, and integrating biochar into global climate policies. Ultimately, biochar represents a promising and scalable solution to climate change and agricultural sustainability, offering both environmental and economic benefits.

Keywords—biochar, carbon stability, carbon sequestration, carbon farming, green house emissions, environmental sustainability

I. INTRODUCTION

The escalating threats of climate change, driven primarily by anthropogenic greenhouse gas emissions, have prompted an urgent global search for sustainable mitigation strategies. Among the array of climate-smart solutions, biochar has emerged as a compelling candidate due to its dual capacity to sequester carbon and enhance soil health [1,2]. Derived from the pyrolysis of organic biomass under oxygen-limited conditions, biochar is a stable, carbon-rich material with a porous structure and high surface area, making it ideal for long-term carbon storage in soils [3]. Unlike conventional biomass decomposition, which releases carbon dioxide back into the atmosphere, pyrolysis transforms biomass into a more recalcitrant form of carbon, significantly slowing its return to the atmosphere.



Fig.1 Pictures showcasing biochar

Biochar's value proposition goes beyond carbon sequestration. When applied to agricultural soils, it improves soil fertility, water retention, microbial diversity, and nutrient cycling, thereby offering synergistic benefits for climate resilience and food security [4]. These qualities make it a pivotal tool in carbon farming—an emerging approach that

integrates agricultural productivity with atmospheric carbon removal. According to recent assessments, the global technical potential for biochar to offset CO₂ emissions could range from 1 to 2.6 gigatons per year, depending on feedstock availability and policy adoption [5].

Additionally, the increasing interest in biochar is reflected in corporate and policy frameworks. For instance, in early 2025, Google partnered with a biochar company to remove 100,000 tons of carbon from the atmosphere—highlighting biochar’s growing credibility in the voluntary carbon market [6]. Simultaneously, the International Biochar Initiative and other policy-oriented organizations are pushing for standardization in carbon accounting methodologies, which is crucial for integrating biochar into formal climate action plans.

Despite these advancements, the scalability of biochar technology faces several challenges, including variability in performance across ecosystems, economic feasibility in low-income regions, and the need for regulatory frameworks to certify and monetize carbon credits. Therefore, it is imperative to critically evaluate biochar’s current and future prospects as a tool for climate change mitigation and sustainable land management. This review seeks to synthesize recent findings, technological developments, and policy shifts to provide a comprehensive understanding of biochar’s multifaceted role in carbon sequestration and carbon farming.

II. BIOCHAR PRODUCTION AND PROPERTIES

2.1 Feedstock and Pyrolysis Technology :

Biochar is primarily produced through the pyrolysis of organic materials such as agricultural residues (e.g., straw, husks), forestry waste (e.g., wood chips, sawdust), municipal solid waste, and animal manure. Pyrolysis is a thermochemical decomposition process conducted in the absence or near-absence of oxygen, which results in three main products: biochar (solid), syngas (gas), and bio-oil (liquid) [3,4]. Among these, biochar is the most stable product, retaining up to 60% of the original carbon content of the feedstock, depending on pyrolysis conditions.

The temperature at which pyrolysis is conducted plays a critical role in determining the properties of biochar. Low-temperature pyrolysis (300–500°C) tends to produce biochar with higher yields and greater nutrient content, while high-temperature pyrolysis (500–700°C) results in biochar with greater aromaticity, surface area, and long-term stability in soils [1]. Furthermore, slow pyrolysis favours higher char yields and is commonly used for soil applications, whereas fast pyrolysis, which occurs at higher heating rates, is often aimed at maximizing bio-oil production.

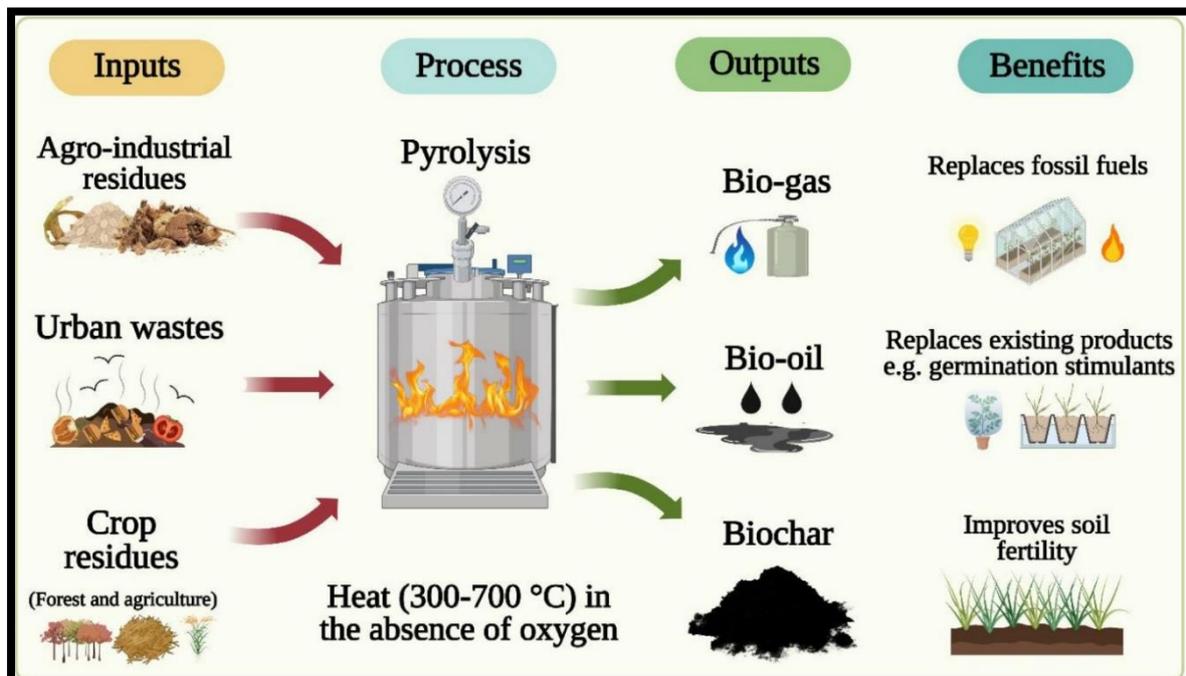


Fig 2. Overview of production of biochar by various materials

Recent innovations in torrefaction, hydrothermal carbonization, and gasification have expanded the scope of biochar production, enabling better control over product quality and making the process more

energy-efficient. Additionally, integrated bio-refineries are being developed to co-produce biochar along with other renewable products, increasing the

overall economic feasibility of biochar-based systems [5].

2.2 Physical and Chemical Properties:

Biochar's functional characteristics are largely governed by its morphology, elemental composition, surface area, pH, porosity, and the presence of functional groups such as carboxyl, hydroxyl, and carbonyl [4]. These properties influence its interactions with soil, water, nutrients, and microbial communities.

2.2.1 Surface area and porosity: Biochar exhibits a highly porous structure with substantial internal surface area, particularly when produced at higher pyrolysis temperatures. This enhances its ability to retain water and nutrients, which is especially beneficial in sandy or degraded soils.

2.2.2 pH and electrical conductivity (EC): Most biochars are alkaline, which makes them effective in ameliorating acidic soils and enhancing nutrient availability. However, pH can vary based on the feedstock used; for instance, manure-derived biochar often has higher pH and nutrient content than wood-based biochar [3].

2.2.3 Cation Exchange Capacity (CEC): The CEC of biochar improves over time due to the oxidation of its surface, facilitating the adsorption and slow release of nutrients, such as ammonium, potassium, and phosphorus [1].

2.2.4 Carbon stability: One of the most crucial attributes of biochar is its recalcitrance — the resistance to microbial decomposition. Biochar's polyaromatic carbon structure ensures *long-term carbon storage in soils*, potentially for hundreds to thousands of years [2].

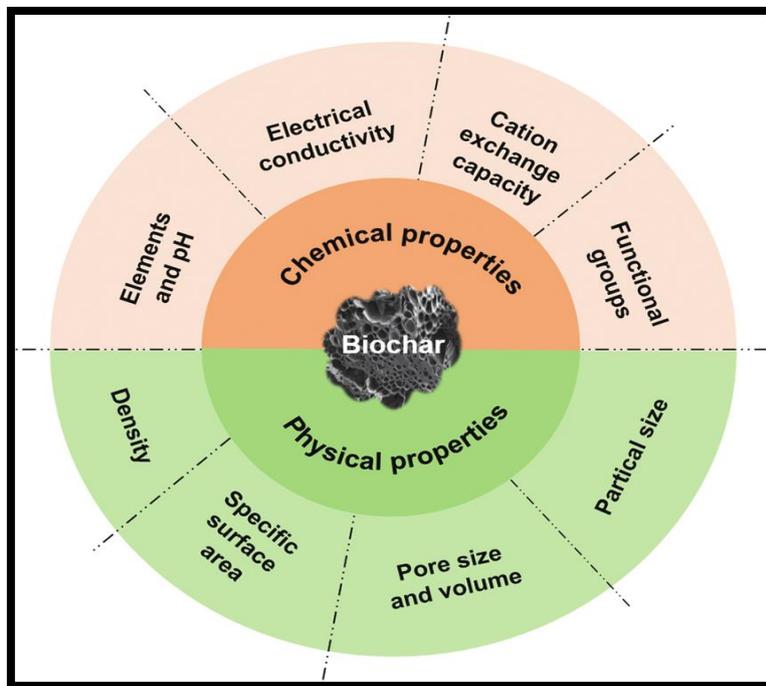


Fig 3. Chemical and physical properties of Biochar

2.3 Customization for Targeted Applications:

Recent research is focused on tailoring biochar properties for specific applications through techniques such as chemical activation, co-composting, and surface functionalization. For instance, magnesium-modified biochars have been used to improve phosphorus recovery, while iron-impregnated biochar enhances heavy metal immobilization in contaminated soils [7]. Furthermore, biochar-blended fertilizers are gaining popularity as they offer a slow-release mechanism, reduce nutrient leaching, and improve nutrient use efficiency.

Given this wide range of feedstocks, technologies, and post-treatment options, biochar can be designed with precision to meet the agronomic, environmental, or industrial needs of a specific region or soil type, making it a highly versatile tool in carbon farming systems.

III. ROLE OF BIOCHAR IN CARBON SEQUESTRATION AND MECHANISM

One of the most significant and scientifically validated advantages of biochar is its ability to act as a long-term carbon sink, effectively locking

atmospheric carbon dioxide (CO₂) into stable forms in soil systems. Unlike fresh organic matter, which decomposes rapidly and releases CO₂ and other greenhouse gases (GHGs) back into the atmosphere, biochar exhibits remarkable resistance to microbial breakdown, thereby allowing for millennial-scale carbon sequestration [2].

3.1 Structural Stability and Recalcitrance

The core mechanism behind biochar's sequestration potential lies in its highly aromatic and

polycondensed carbon structure, which makes it resistant to microbial and oxidative degradation. Studies using radiocarbon dating and spectroscopy techniques have shown that biochar can persist in soils for centuries to millennia, depending on environmental conditions and the pyrolysis process [1]. High-temperature biochars (>500°C) are particularly effective in ensuring long-term carbon stability due to greater aromatic condensation [3].

3.2 Indirect Carbon Sequestration

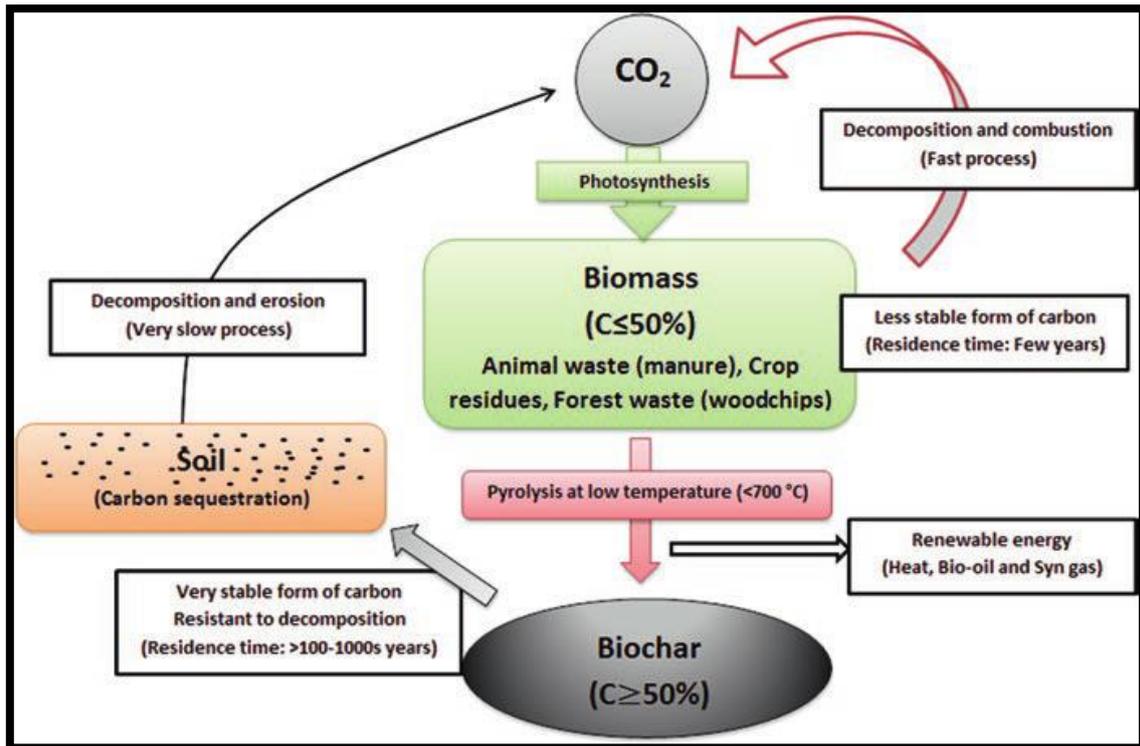


Fig 4. Mechanism of carbon sequestration by biochar

Beyond direct carbon stabilization, biochar also contributes to indirect carbon sequestration through several mechanisms:

3.2.1 Enhanced plant growth: Biochar-amended soils often show improved nutrient and water retention, leading to increased plant productivity. This additional biomass production can be harvested and re-pyrolyzed to create more biochar, establishing a *positive carbon feedback loop* [7].

3.2.2 Suppression of greenhouse gases: Numerous meta-analyses have reported that biochar application can suppress soil emissions of nitrous oxide (N₂O) and methane (CH₄)—both potent GHGs. This is primarily due to altered microbial activity and soil aeration dynamics [4].

3.2.3 Soil organic matter (SOM) protection: Biochar can protect native soil organic matter by adsorbing labile carbon fractions and stabilizing

microbial communities, reducing the mineralization of existing soil carbon—a phenomenon termed the negative priming effect [1].

3.3 Atmospheric CO₂ Capture

Recent groundbreaking studies suggest that biochar-amended soils may continue to adsorb atmospheric CO₂ post-application through abiotic and biotic interactions, such as carbonate precipitation and microbial carbon assimilation [2]. This “secondary” carbon capture function opens new avenues for biochar as a dynamic and ongoing sink for atmospheric carbon rather than a one-time sequestration input.

3.4 Integration with Global Carbon Accounting

To quantify biochar's contribution to climate mitigation, standardized methodologies for carbon

accounting are being developed by organizations such as the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC). These frameworks assess parameters such as carbon yield, stability, soil application rate, and residence time, helping to translate biochar's climate benefits into verifiable carbon credits for global markets [8].

In summary, biochar's ability to sequester carbon encompasses both direct stabilization of biomass carbon and indirect ecosystem-mediated mechanisms

that enhance carbon capture, reduce emissions, and improve soil carbon dynamics. These unique attributes position biochar as a scalable and scientifically sound negative emissions technology in the broader context of climate action and sustainable agriculture.

IV. ROLE OF BIOCHAR IN CARBON FARMING AND MECHANISM

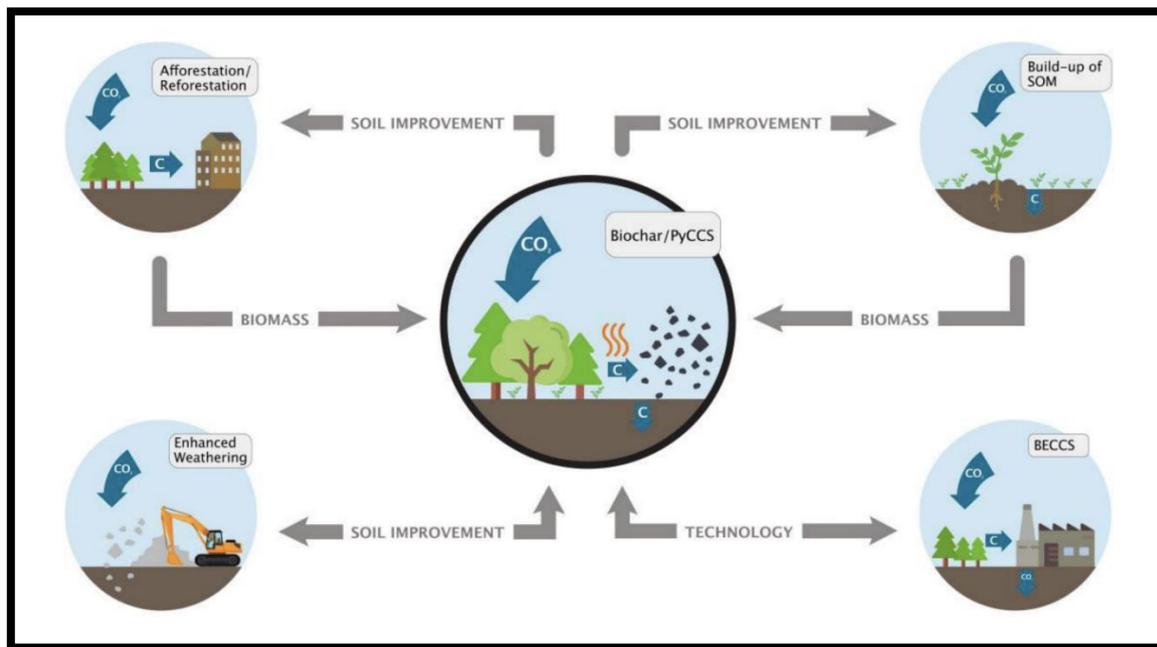


Fig 5. Overview of carbon farming by biochar

Carbon farming is an integrated land management approach that combines traditional agricultural practices with techniques aimed at enhancing carbon sequestration and reducing greenhouse gas emissions. Within this framework, biochar has emerged as a key instrument due to its multifunctionality—it not only stores carbon stably in the soil but also enhances crop productivity, soil health, and nutrient efficiency, aligning with both climate mitigation and sustainable agricultural development goals [2,5].

4.1 Enhancing Soil Fertility and Crop Productivity

One of the most direct pathways through which biochar contributes to carbon farming is by improving soil physical, chemical, and biological properties. Biochar's high porosity and surface area increase soil water-holding capacity, particularly beneficial in drought-prone and degraded soils [1]. Its alkaline nature can ameliorate acidic soils, enhancing the availability of essential nutrients like nitrogen, phosphorus, potassium, and magnesium.

Moreover, biochar retains nutrients by increasing the soil's cation exchange capacity (CEC), reducing leaching losses and enhancing fertilizer use efficiency. Recent studies also highlight biochar's role in modulating the rhizosphere microbial community, promoting beneficial microbes like nitrogen-fixers and phosphate solubilizers [7]. This leads to improved plant growth and biomass accumulation—an essential component of carbon cycling in carbon farming systems.

4.2 Reducing Greenhouse Gas Emissions

Biochar application has been shown to suppress soil emissions of major greenhouse gases. Specifically:

- N₂O emissions are reduced due to altered nitrogen transformation processes and microbial inhibition [4].
- CH₄ emissions from flooded paddy fields and wetlands decrease due to better aeration and shifts in methanogenic microbial populations [4].

By mitigating these emissions, biochar significantly contributes to reducing the overall climate footprint

of agriculture—often one of the largest emitters globally.

4.3 Improving Carbon Use Efficiency and Creating Circular Bioeconomies

Biochar integrates seamlessly into circular bioeconomy models, especially in regions with abundant agricultural or organic waste. Using crop residues, animal waste, or forestry biomass for biochar production not only provides a value-added use for waste but also prevents open burning, a major source of GHGs and air pollution in developing countries [3].

Additionally, the incorporation of biochar into composting processes (co-composting) has gained popularity. This not only reduces composting emissions but also enhances nutrient retention and compost maturity, creating high-value, carbon-rich soil amendments ideal for carbon farming applications.

4.4 Monetization through Carbon Credits and Policy Support

The emergence of carbon markets has opened new avenues for farmers and landowners to monetize their climate-positive practices. Verified biochar projects are now eligible for carbon credits under several protocols, including Puro. Earth, Verra, and the EBC C-sink program [8]. This provides direct economic incentives for biochar adoption, especially in low-income and agrarian regions.

Policymakers across Europe, North America, and parts of Asia are beginning to recognize biochar in their climate-smart agriculture frameworks, offering subsidies, research funding, and demonstration projects to scale up its implementation [9].

V. CHALLENGES IN BIOCHAR IMPLEMENTATION

While biochar holds great promise for carbon sequestration and sustainable agriculture, several challenges must be addressed to unlock its full potential. These challenges span economic, technical, environmental, and social dimensions, and overcoming them is crucial for scaling biochar's use in carbon farming and climate mitigation strategies.

5.1 Feedstock Availability and Cost

The selection of appropriate feedstocks is one of the major hurdles in biochar production. While agricultural residues and biomass waste are ideal

feedstocks, their availability and seasonal variability can impact the economic viability of biochar production [3]. Additionally, transportation costs can become prohibitive when feedstocks need to be sourced from distant locations. For biochar to be economically feasible at a large scale, it is critical to establish local supply chains and value-added production technologies that optimize the cost-effectiveness of feedstock collection and conversion.

5.2 Variability in Biochar Quality and Performance

Another significant challenge is the variability in biochar quality, which is influenced by factors such as feedstock type, pyrolysis temperature, and the specific technology used [2]. This variability can lead to inconsistent performance in soil applications, especially regarding nutrient release, pH adjustment, and microbial interactions. A standardized system for biochar quality assurance and certification is needed to guarantee the reliability of biochar products, particularly in commercial agricultural settings.

5.3 Environmental Concerns and Sustainability

Despite biochar's environmental benefits, its production and widespread use must be carefully managed to prevent potential environmental degradation. Pyrolysis, while efficient, is an energy-intensive process that can generate emissions if not properly controlled. Furthermore, large-scale biochar production may place additional pressure on already limited land and water resources if feedstock extraction is not managed sustainably [1]. Addressing these issues will require integrated life cycle assessments (LCAs) to evaluate the overall environmental impact of biochar systems and ensure they do not inadvertently cause more harm than good.

5.4 Socioeconomic and Policy Barriers

The adoption of biochar in developing countries, where agriculture is heavily reliant on smallholder farming, faces social and policy barriers. These include the lack of awareness, limited access to capital, and the absence of policy incentives that would support biochar adoption [5]. Additionally, regulatory frameworks for carbon credit markets are still evolving, and farmers may be reluctant to adopt biochar technologies without clear financial incentives or guaranteed market access for carbon credits.

VI. FUTURE DIRECTIONS IN BIOCHAR RESEARCH

Given the evolving nature of climate change science and agricultural sustainability, biochar research is at a critical juncture. Future research must focus on addressing current knowledge gaps, enhancing biochar's properties for specific applications, and developing comprehensive systems for biochar implementation at scale.

6.1 Advances in Biochar Production Technologies

Ongoing innovations in pyrolysis technologies, such as fluidized bed reactors, hydrothermal carbonization, and microwave-assisted pyrolysis, promise to improve biochar yields, reduce energy consumption, and lower production costs [7]. The use of renewable energy sources to power pyrolysis units could further enhance the sustainability of biochar production, making it more economically viable for large-scale applications. Additionally, more research is needed on integrated biochar production systems, which could simultaneously produce bioenergy (syngas or bio-oil) alongside biochar, thus increasing the overall efficiency of the process [1].

6.2 Targeted Biochar Design and Customization

As the field of biochar expands, there is increasing interest in tailored biochar products that cater to specific agricultural or environmental needs. For instance, biochar doped with nutrients or minerals like nitrogen, phosphorus, or iron is being explored to boost soil fertility and address nutrient deficiencies in specific soil types [4]. Similarly, biochar functionalized with nanoparticles or biochar composites could be optimized for applications such as heavy metal remediation or water purification, thereby broadening its scope in environmental cleanup.

6.3 Integration with Climate Policies and Carbon Markets

As biochar proves its effectiveness in sequestering carbon and improving soil health, it is essential that global climate policies integrate biochar more comprehensively. Future research should focus on developing carbon accounting frameworks that accurately quantify biochar's long-term sequestration potential, considering factors like feedstock type, pyrolysis temperature, and soil conditions. More sophisticated models are needed to predict biochar's effects on carbon cycling in diverse ecosystems and its climate impact over extended periods [8].

In addition, as carbon markets continue to evolve, biochar should be incorporated into voluntary and

compliance carbon trading systems, offering farmers and landowners opportunities to participate in climate mitigation efforts and generate revenue through carbon credits.

6.4 Socioeconomic Implications and Farmer Education

For biochar to be effectively adopted worldwide, particularly in developing regions, future research should also address the socioeconomic aspects of biochar use. This includes examining the cost-benefit analysis of biochar application for smallholder farmers, particularly in regions with limited access to resources. Educational programs focused on the benefits of biochar for both soil health and climate resilience will be essential in driving adoption [9]. Additionally, providing policy incentives for biochar implementation, such as subsidies or tax breaks, could help overcome economic barriers in low-income regions.

6.5 Collaborative, Multidisciplinary Research

Finally, biochar research will benefit from collaborative, interdisciplinary approaches that integrate agriculture, environmental science, engineering, and economics. This will facilitate the development of comprehensive, sustainable biochar systems that are tailored to the unique needs of different regions and agricultural systems. Such collaborative efforts can also help identify barriers to adoption and develop innovative solutions for scaling biochar use in diverse global contexts [1,2].

VII. CONCLUSION

In conclusion, biochar emerges as a versatile and effective tool for both carbon sequestration and enhanced agricultural productivity. Its role in capturing atmospheric carbon and improving soil health places it at the forefront of climate-smart agriculture strategies. Despite significant promise, challenges such as feedstock availability, cost-effectiveness, and regulatory frameworks remain critical obstacles to its widespread adoption. However, with advancements in production technologies, targeted biochar design, and integrated policy support, these challenges can be overcome. The future of biochar lies in multidisciplinary research that not only improves its efficacy but also ensures its accessibility to farmers worldwide. Biochar's integration into carbon markets and climate policies could facilitate a global transition

toward more sustainable agricultural practices and contribute significantly to global efforts to combat climate change. As the scientific community continues to explore and refine its applications, biochar has the potential to become a cornerstone of climate change mitigation and carbon farming strategies worldwide.

sequestration-opportunities-challenges-and-the-way-forward-by-david-kesner).

- [9] Ynfante, R. S., Falkowski, T. B., Stricker, E., & Céspedes, B. (2024). Biochar production in northern New Mexico: Identifying challenges and opportunities. *Journal of Environmental Management*, 367, 122072.

REFERENCES

- [1] Bekchanova, M., Kuppens, T., Cuypers, A., Jozefczak, M., & Malina, R. (2024). Biochar's effect on the soil carbon cycle: a rapid review and meta-analysis. *Biochar*, 6(1), 1-19. (<https://link.springer.com/article/10.1007/s42773-024-00381-8>)
- [2] Gui, X., Xu, X., Zhang, Z., Hu, L., Huang, W., Zhao, L., & Cao, X. (2025). Biochar-amended soil can further sorb atmospheric CO₂ for more carbon sequestration. *Communications Earth & Environment*, 6(1), 5. (<https://www.nature.com/articles/s43247-024-01985-5>)
- [3] Nepal, J., Ahmad, W., Munsif, F., Khan, A., & Zou, Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science*, 11, 1114752.
- [4] Elkhilifi, Z., et al. (2023). Potential role of biochar on capturing soil nutrients, carbon sequestration, and managing environmental challenges: A review. *Sustainability*, 15(3), 2527. MDPI
- [5] Karan, S. K., Woolf, D., Azzi, E. S., Sundberg, C., & Wood, S. A. (2023). Potential for biochar carbon sequestration from crop residues: A global spatially explicit assessment. *GCB Bioenergy*, 15(12), 1424-1436.
- [6] Axios. (2025). *Google partners with startup to cut 100,000 tons of carbon*. (<https://www.axios.com/2025/01/16/google-carbon-removal-charm-industrial-biochar>)
- [7] Nogués, I., Miritana, V. M., Passatore, L., Zacchini, M., Peruzzi, E., Carloni, S., ... & Marinari, S. (2023). Biochar soil amendment as carbon farming practice in a Mediterranean environment. *Geoderma Regional*, 33.
- [8] Kesner, D. (2023). Biochar-based carbon sequestration: Opportunities, challenges, and the way forward. *CIEEM*. (<https://cieem.net/biochar-based-carbon->