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Biochar at the Core of Nature-Based Carbon Management: A Comparative Review Bridging Environmental Sustainability and Economic Feasibility

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ABSTRACT

Climate change continues to challenge both environmental stability and economic systems worldwide. Among available mitigation strategies, nature-based carbon management (NBCM) methods provide the dual advantage of reducing atmospheric carbon dioxide (CO_2) and restoring ecosystems. This review examines four main NBCM approaches, forest and grassland restoration, wetland and blue-carbon ecosystems, urban green spaces, and regenerative agriculture, to test the hypothesis that biochar-based regenerative agriculture is the most sustainable and practical pathway for long-term carbon sequestration. Confirming this hypothesis is essential because policy and investment decisions increasingly depend on identifying NBCM options that combine scientific effectiveness with economic feasibility. The study reviews papers, patents, and reports published between 2016 and 2024, integrating environmental, technological, and policy findings. The review reveals several key insights. Nature-based methods collectively offer significant global potential for carbon reduction, yet their success depends on ecological and socioeconomic conditions. Biochar-based regenerative systems stand out by showing persistent improvements in soil-organic-carbon storage, crop productivity, and greenhouse-gas mitigation, supported by numerous international case studies. The analysis also identifies the main constraints, production cost, infrastructure requirements, and limited awareness, that determine the pace of large-scale adoption. The contribution of this review lies in linking biochar's environmental durability with its socioeconomic applicability, providing a bridge between climate science, agriculture, and sustainable development policy. Future efforts should focus on field validation across climates, cost optimization for biomass-to-biochar chains, and supportive policy frameworks to encourage wider adoption. These findings present a clear pathway for scaling NBCM solutions, positioning biochar as a leading nature-based strategy for long-term climate mitigation.

1 | Introduction

Over recent decades, climate change has emerged as one of the most significant global challenges, due to rising concentration of greenhouse gases in the atmosphere, particularly CO_2, which stems from human activities such as fossil fuel combustion, deforestation, and unsustainable agricultural practices [1]. Figure 1 illustrates the long-term record from the Mauna Loa Observatory and projections by the UK Met Office for 2024, alongside the IPCC (2022) 1.5°C pathway scenario. The growing divergence between the observed CO_2 trajectory and the 1.5°C target pathway clearly demonstrates that the present mitigation pace is insufficient [2]. Therefore, carbon-management strategies aimed at both reducing emissions and enhancing long-term sequestration capacity have become critical to closing the emission–temperature gap [1, 3].

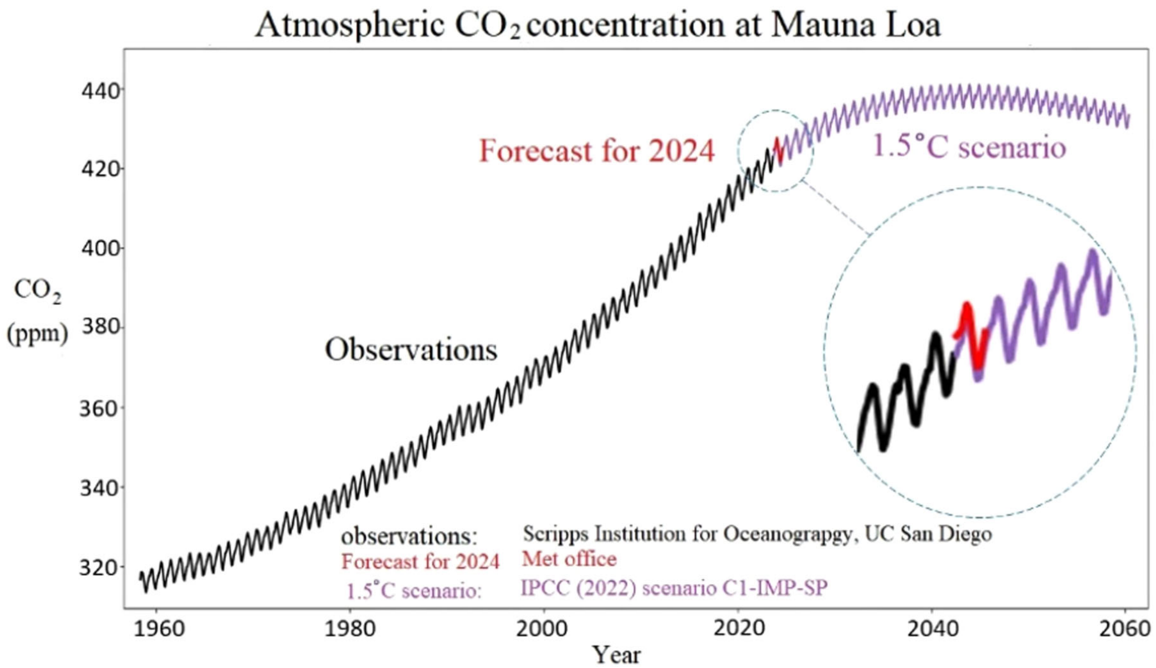

FIGURE 1 | Atmospheric CO_2 concentration and global average temperature from 1850 to 2020 [2].

TABLE 1 | Comparison of technological and NBCM approaches [4–6].

Features	Technological methods	Nature-Based methods
Cost	High	Moderate
Required Infrastructure	Complex (CO_2 processing infrastructure)	Simple (land-based; trees)
Scalability	High in regions with available land and policy support	Limited by high costs, energy intensity, and infrastructure requirements
Environmental impact	Sometimes negative (high energy use, potential local environmental burden)	Positive (ecosystem restoration, biodiversity gains, water regulation)
Additional benefits	Limited, mainly carbon removal	Biodiversity conservation, soil fertility, erosion control, improved water retention, etc.
Policy support needed	Large-scale R&D funding, carbon pricing, infrastructure development	Land-use planning, incentives for farmers, long-term maintenance programs

Carbon management strategies are commonly classified into two complementary pathways: technological and nature-based. These represent contrasting approaches for achieving net atmospheric CO_2 reduction, differing in cost, infrastructure intensity, scalability, and environmental side effects [4]. A comparison of these two approaches is provided in Table 1. Technological methods such as carbon capture and storage (CCS), direct air capture (DAC), and renewable-based CO_2 utilization can achieve capture efficiencies of up to 90% but typically involve high capital and energy requirements. In contrast, nature-based solutions harness existing ecosystems, forests, wetlands, grasslands, and regenerative agricultural systems, to remove CO_2 through biological processes at comparatively lower implementation costs. By leveraging natural capacities, these methods not only facilitate carbon capture and storage but also provide co-benefits such as improved soil fertility, water retention, biodiversity conservation, and climate resilience [5, 6]. While nature-based solutions are increasingly recognized for their ecological and social co-benefits, it is important to note that certain industrial carbon management pathways, particularly cement substitution using char-based materials, have also demonstrated high economic returns and strong mitigation potential. Techno-economic evaluations suggest that phosphate-enriched chars derived from waste refining or wastewater treatment can replace part of the cement in concrete, achieving notable reductions in both production cost and life-cycle CO_2 emissions [7, 8]. These findings emphasize that nature-based and industrial approaches should be viewed as complementary rather than competing strategies within a broader carbon management framework.

Soils represent the largest terrestrial carbon pool, containing roughly twice as much carbon as the atmosphere and about three times more than all living vegetation combined [9–11]. Because of this magnitude, even modest changes in soil carbon storage can significantly influence atmospheric CO_2 concentrations. Conversion of native vegetation to cultivated systems has historically released substantial amounts of soil carbon to the atmosphere, primarily through microbial oxidation and erosion [9]. Given the pivotal role of soils in terrestrial carbon dynamics, enhancing their carbon storage capacity has become a central focus of land-based carbon dioxide removal strategies, among which biochar, a carbon-rich material produced through biomass conversion under oxygen-limited conditions, has gained recognition as one of the most promising and sustainable methods for long-term carbon sequestration and soil quality improvement [12, 13]. The scientific concept of biochar as a tool for climate change mitigation was first introduced in the 1990s, and research in this area has expanded rapidly over the past three decades [14]. Producing and applying biochar not only reduces greenhouse gas emissions associated with burning and decomposition of agricultural biomass but also improves soil quality. Furthermore, due to its stable structure, biochar can store carbon in the soil for centuries. It is noted that the carbon sequestration potential of biochar is strongly influenced by factors such as soil type, climatic conditions, and the physicochemical properties of the feedstock and pyrolysis process [15–17]. While the environmental potential of biochar and other NBCM solutions has been widely demonstrated, their large-scale deployment ultimately depends on economic feasibility. For all carbon management technologies to be implemented at scale, environmental benefits must align with economic incentives. Empirical evidence shows that investment behavior and profitability expectations strongly shape the adoption of sustainable technologies. Portfolio-based analyses reveal that investors increasingly prefer low-risk, stable, and sustainability-oriented sectors [18], while studies on private investment dynamics emphasize that financial confidence and supportive policy frameworks are key to long-term participation in emerging green industries [18, 19]. Ongoing advances in integrated waste-to-energy and biochar production technologies, however, suggest promising pathways for improving cost efficiency and profitability at industrial scale [20–23].

While earlier reviews have mainly concentrated on the economic feasibility and scalability barriers of biochar deployment, this study moves beyond that scope by integrating the latest environmental and techno-economic insights to provide a more holistic understanding of its role within NBCM strategies. This review systematically evaluates NBCM strategies, with a specific focus on biochar as a scientifically validated and scalable pathway for carbon sequestration. It quantifies biochar's contribution to soil carbon enhancement, its long-term stability in terrestrial storage, and its co-benefits for greenhouse-gas (GHG) reduction and soil resource efficiency. Beyond biochar, the analysis compares four principal NBCM categories: forest and grassland restoration, wetland and blue-carbon ecosystems, urban green spaces, and regenerative agriculture, using standardized criteria to assess their sequestration capacity, environmental co-benefits, implementation barriers, and policy integration potential. By synthesizing recent empirical evidence from 2016 to 2024, including studies from underrepresented regions such as the Middle East, South America, and South Asia, this review addresses a critical gap in the literature regarding the long-term environmental–economic performance of biochar and its adoption barriers in developing economies. This study is particularly timely, as achieving global climate targets requires carbon management solutions that are not only environmentally effective but also economically feasible. Addressing this environmental–economic nexus provides valuable insights for policymakers, researchers, and industrial stakeholders seeking scalable and profitable low-carbon strategies. The central hypothesis of this study is that biochar-based regenerative agriculture represents the most sustainable and economically viable pathway among NBCM options, combining high carbon permanence with measurable co-benefits. The literature selection was based on peer-reviewed sources indexed in Web of Science, Scopus, and ScienceDirect, filtered by relevance, methodological rigor, and use of keywords including "biochar," "nature-based solutions," "carbon sequestration," and "climate mitigation."

2 | Overview of Nature-Based Carbon Management Methods

Nature-based methods encompass a range of actions aimed at conserving, sustainably managing, and restoring natural and modified ecosystems. These approaches address societal challenges while providing significant benefits for both humans and the environment [24]. Recognized as a key tool for combating climate change, their global potential to reduce greenhouse gas emissions is estimated at 8–14 gigatons of carbon dioxide equivalent annually [25]. Beyond mitigating climate change, nature-based methods offer multiple co-benefits, including improved air and water quality, enhanced biodiversity, better human health, and sustainable livelihoods. Some strategies, such as wetland conservation, primarily prevent greenhouse gas emissions, while others, such as regenerative agriculture and the restoration of degraded forests, actively remove carbon dioxide from the atmosphere. These actions, often referred to as natural carbon removal solutions, generally receive greater public support compared to engineered approaches, such as direct air capture or bioenergy with carbon capture technologies, due to their inherently natural characteristics [26]. NBCM methods can be categorized into four main groups: forests and grasslands, soils and agriculture, wetlands and aquatic ecosystems, and urban green spaces and ecosystem restoration. This categorization and the associated carbon management practices within each group are illustrated in Figure 2 [27]. While each of these approaches contributes uniquely to carbon mitigation, their comparative performance varies significantly in terms of permanence, scalability, and economic feasibility. Understanding this diversity is essential for evaluating which nature-based strategies, particularly biochar-based regenerative systems, offer the most durable and cost-effective solutions for long-term climate mitigation. Globally, large-scale application of these methods has gained increasing attention and accounts for significant carbon sequestration potential. For instance, The Bonn Challenge [28], launched in 2011 as a global restoration initiative, has garnered commitments from over 70 countries to restore 350 million hectares of deforested and degraded land by 2030, with an estimated potential to remove approximately 1 Gt of CO_2 from the atmosphere each year. A global assessment by Bastin et al. [29] found that restoring 0.9 billion hectares of tree canopy in areas naturally suited to support forests could sequester up to 205 Gt of carbon, equivalent to nearly 25% of the atmospheric carbon pool. These estimates not only demonstrate the theoretical potential but also the growing real-world application and political commitment toward scaling nature-based carbon removal strategies.

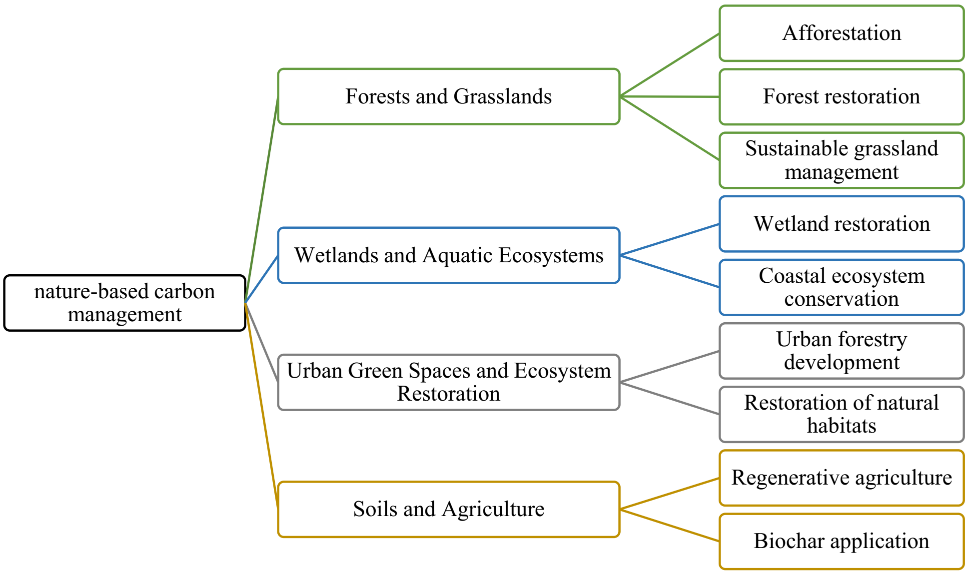

FIGURE 2 | Categorization of NBCM methods [27].

2.1 | Forests and Grasslands

NBCM in forests and grasslands is recognized as one of the key strategies for mitigating climate change. Forests and grasslands act as natural carbon reservoirs due to their high capacity to absorb CO_2 from the atmosphere, playing a significant role in maintaining global carbon balance [30]. In a study by Griscom et al. [31]. It was shown that conservation and restoration actions, such as afforestation, restoration of degraded grasslands, and prevention of deforestation, could provide approximately 37% of the emission reductions needed to achieve the goals of the Paris Agreement. In grassland management, strategies like improved livestock grazing practices, planting native vegetation, and smart water management can enhance carbon storage capacity. Similarly, in forests, practices such as sustainable afforestation, biodiversity conservation, and reducing ecosystem degradation can significantly improve carbon sustainability [32].

NBCM in forests and grasslands is rooted in ecological and biological cycles. It involves carbon uptake by plants through photosynthesis, storage in biomass such as trunks, roots, and leaves, and the transfer of carbon to soil. During photosynthesis, plants absorb atmospheric CO_2 and convert it into organic compounds (e.g., glucose). A significant portion of the absorbed carbon is stored in plant structures, including wood, leaves, and roots, and older forests can store large amounts of carbon for decades or even centuries. Dead plant matter, such as leaves and branches, falls to the ground and contributes to soil organic matter, where part of the carbon becomes stably sequestered in the soil over time [33, 34]. In grasslands, native vegetation and healthy plant cover facilitate the absorption of CO_2, transferring this carbon to the soil where it becomes locked into soil organic particles. Controlled grazing is another effective method, as it can stimulate plant growth and, in turn, increase carbon sequestration. Conversely, overgrazing leads to soil degradation and reduces carbon storage capacity [35]. This process, illustrated in Figure 3, depicts how forests and grasslands sequester atmospheric CO_2 by storing it in plant biomass and soils through organic matter inputs. It also highlights the contrasting effects of controlled grazing, which enhances soil carbon storage.

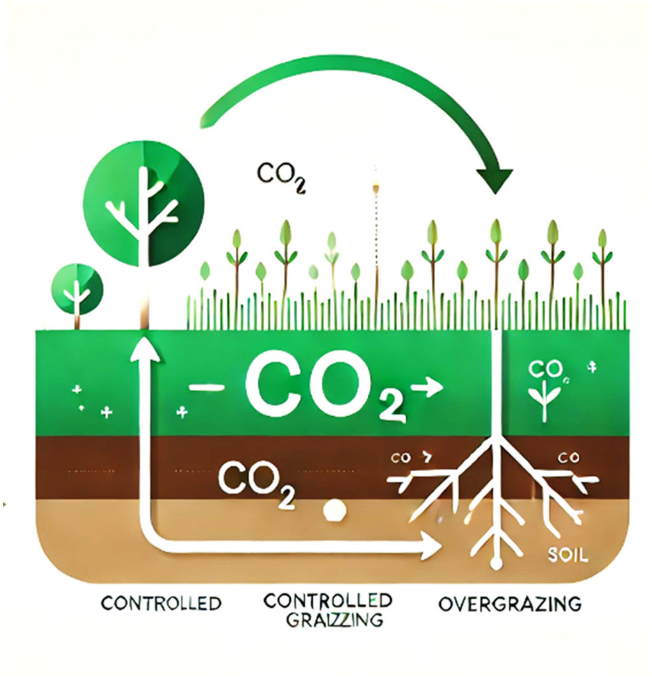

FIGURE 3 | Carbon sequestration pathways in forests and grasslands, showing CO_2 absorption into biomass and soil, with positive effects of controlled grazing and negative impacts of overgrazing.

2.2 | Wetlands and Aquatic Ecosystems

Aquatic ecosystems play a critical role in nature-based carbon management. These ecosystems, including coastal wetlands, mangrove forests, seagrass meadows, and rivers, function as natural carbon reservoirs and help mitigate the impacts of climate change [36]. Wetlands, due to their high accumulation of organic matter in both soil and water, are considered some of the largest carbon sinks in the world. The carbon stored in these ecosystems is referred to as blue carbon. Carbon in aquatic ecosystems is stored either in the form of dead organic matter or within living plants. Wetlands absorb CO_2 through photosynthesis, stabilizing it as biomass and organic matter in their soils [37]. Additionally, these ecosystems prevent the rapid decomposition of organic matter, which would otherwise release stored carbon back into the atmosphere. Studies have shown that saline wetlands (e.g., mangroves) and seagrass meadows can store significantly more carbon than terrestrial forests [38]. In contrast to forests, which primarily store carbon in above-ground biomass, wetlands sequester carbon mostly in anaerobic soils where decomposition of organic matter is significantly slower. This allows for long-term accumulation of soil organic carbon. According to Chmura et al. [39], coastal wetlands including salt marshes, mangroves, and seagrass beds sequester carbon at rates ranging from 18 to 171 gC/m^2. year, which is comparable to or exceeds many upland forest systems. Moreover, the anoxic conditions in wetland sediments protect organic carbon from microbial decay, enhancing long-term storage stability despite potential methane emissions. These findings reinforce the role of wetlands as highly effective yet often underappreciated components of global carbon management strategies.

NBCM in blue carbon ecosystems involves protecting existing wetlands through the establishment of protected areas and strict regulations to prevent their degradation. Furthermore, restoration projects aim to rehabilitate degraded wetlands and restore their carbon sequestration capacities [37]. Examples of high-carbon-storage wetlands include mangrove forests in Southeast Asia, the Anzali Wetland in Iran, and the Everglades in Florida. These wetlands have a significant capacity for carbon storage and should be prioritized for conservation and further research [40]. The blue carbon cycle, illustrated in Figure 4, shows how coastal ecosystems, including mangroves, seagrasses, and salt marshes, capture atmospheric CO_2 through photosynthesis and store it in plant biomass and soils. Some carbon is buried in sediments for the long term, while some is exported as organic material to the deep ocean, serving as an additional carbon sink.

2.3 | Urban Green Spaces and Ecosystem Restoration

Urban green spaces and ecosystem restoration play a vital role in mitigating climate change by capturing and storing carbon. Plants in these spaces absorb CO_2 from the atmosphere and store it in biomass and soil. Studies have shown that urban forests significantly contribute to reducing air temperatures and improving air quality [41]. Additionally, the restoration of degraded ecosystems in urban areas, such as wetland rehabilitation and planting native trees, enhances biodiversity and improves ecosystem services. These measures not only facilitate carbon sequestration but also mitigate the urban heat island effect and promote mental and physical well-being among residents. A 2023 study highlighted that urban green spaces can effectively help reduce the impacts of climate change [42].

Investing in the development and maintenance of urban green spaces and ecosystem restoration is a sustainable strategy for combating climate change while enhancing quality of life in urban areas. Figure 5 illustrates the interaction between human activities and ecosystems, showing how urban areas emit CO_2 through fossil fuel use, agriculture, and industry, while urban green spaces and restored ecosystems help offset emissions and improve air quality [43].

2.4 | Soil and Agriculture

Soil, as one of the most vital natural resources, plays a key role in regulating the global carbon cycle, storing water, and

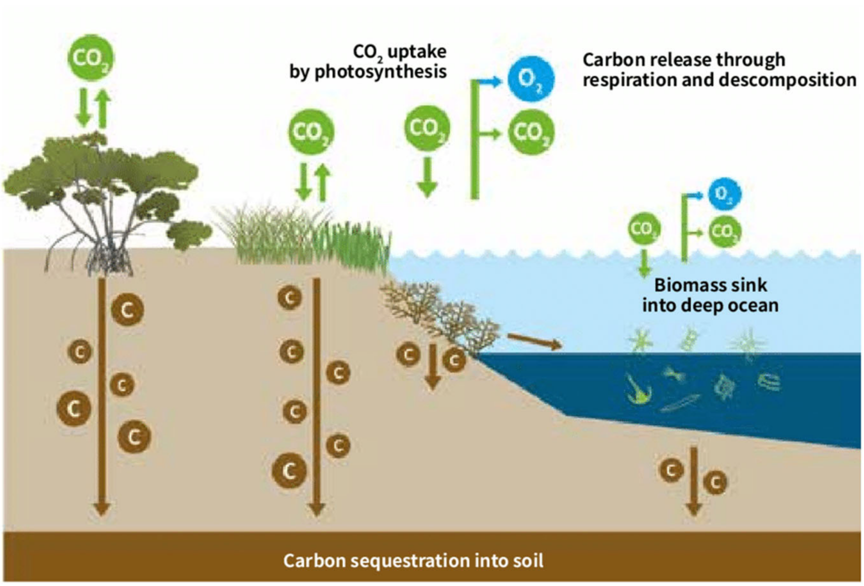

FIGURE 4 | The blue carbon cycle in coastal ecosystems. CO_2 is absorbed through photosynthesis, stored in plant biomass and soils, and partly transported to the deep ocean as a long-term carbon sink [40].

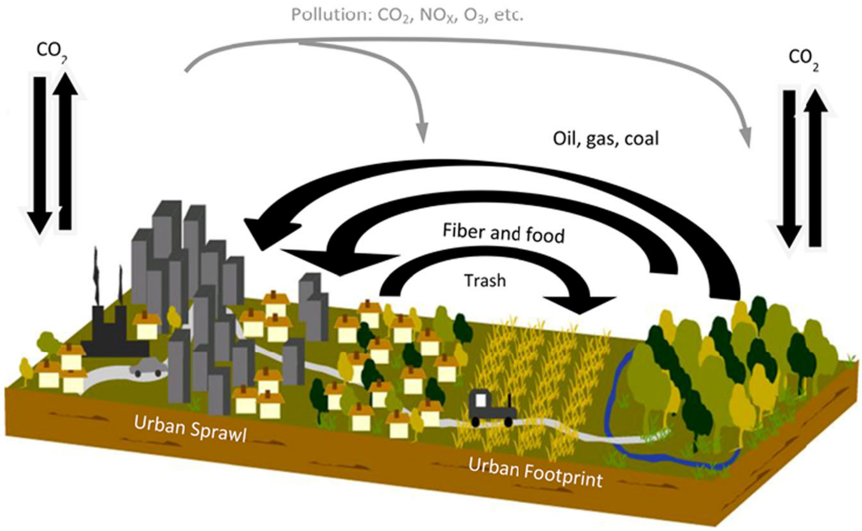

FIGURE 5 | The carbon cycle in urban spaces illustrating the role of green spaces and restored ecosystems in absorbing CO_2 [43].

supporting food production. However, human activities such as frequent tillage, excessive use of chemical fertilizers, and industrial agriculture have degraded soil structure, reduced organic matter, and increased greenhouse gas emissions [44]. The agricultural sector accounts for approximately 10–12% of total global greenhouse gas emissions, and the interaction between climate change and soil degradation has had detrimental effects on agricultural productivity. In this context, regenerative agriculture has emerged as a holistic and sustainable approach that not only focuses on food production but also aims to restore soil health, reduce greenhouse gas emissions, and increase carbon sequestration. This approach includes techniques such as reduced tillage, cover cropping, crop rotation, and the use of perennial plants, all of which improve soil structure and enhance its carbon storage capacity [45]. According to Rhodes [46], regenerative practices improve soil structure, making agricultural ecosystems more resilient to environmental stressors and climate change. This allows farmers to achieve sustainable and efficient production without relying on increased chemical inputs, instead harnessing the natural processes of the soil. Similar findings by Nunes et al. [47] confirm that regenerative agriculture reduces greenhouse gas emissions while improving soil sustainability and resilience. As a sustainable soil management strategy, regenerative agriculture plays a critical role in improving the carbon cycle. Soil with high organic matter content has a greater capacity to store carbon, and regenerative agriculture enhances this capacity by increasing organic matter levels. This allows the soil to naturally absorb and sequester more carbon, reducing greenhouse gas emissions and increasing carbon capture potential [48, 49]. Figure 6 illustrates the carbon cycle in regenerative agriculture, showing how practices like no-till farming, cover cropping, and crop rotation enhance soil carbon storage while reducing greenhouse gas emissions from agricultural activities.

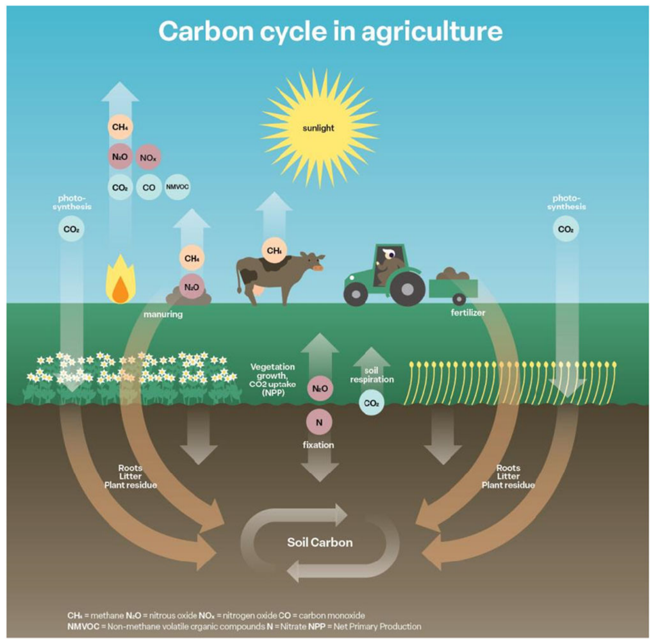

FIGURE 6 | The carbon cycle in regenerative agriculture, highlighting practices such as no-till farming, crop rotation, and cover cropping [50].

One key method within regenerative agriculture is no-till farming, which protects soil from erosion and organic matter depletion while maintaining a permanent vegetation cover to improve soil quality and retain moisture [48]. No-till farming involves leaving the soil undisturbed, which preserves its natural structure and prevents the oxidation of organic matter [51]. This method reduces direct CO_2 emissions caused by the breakdown of organic matter due to tillage, thereby increasing carbon storage in the soil. Additionally, no-till farming enhances soil stability and water retention capacity, making it more resistant to erosion and drought [52]. Reduced mechanical farming activities associated with no-till farming also directly lower CO_2 emissions [49]. Another critical aspect of regenerative agriculture is crop rotation, which involves planting crops with varying nutrient requirements. This practice enhances biodiversity within the soil and makes agricultural systems more resistant to pests and diseases, thereby reducing the reliance on chemical pesticides [53, 54]. Quanjou et al. [55] confirmed through their studies that crop rotation increases soil carbon storage and reduces greenhouse gas emissions. Perennial crops, due to their ability to grow without frequent replanting, also contribute to reducing greenhouse gas emissions. These crops, which remain on the land year-round, protect soil from erosion while their roots and residues add organic matter to the soil, increasing carbon content [56]. Additionally, the deep root systems of perennial plants enhance organic matter stabilization in the soil, contributing to long-term carbon storage [57].

Vegetation cover can enhance the carbon cycle and reduce CO_2 emissions, as soils with vegetation retain higher amounts of carbon [58]. One of the most significant innovations in sustainable carbon management in soils is the use of biochar, a product derived from the pyrolysis of biomass (heating in low-oxygen conditions). Due to its stable, carbon-rich structure, biochar can be stored in soils for the long term, preventing the conversion of carbon into greenhouse gases [59]. Historically, biochar was primarily produced as a solid biofuel and soil conditioner, serving both energy and agricultural purposes [60, 61]. However, its unique physicochemical stability and high carbon content have shifted recent research and policy attention toward its role in long-term carbon sequestration and soil enhancement. Beyond environmental applications, biochar also holds value across industrial domains, as a solid fuel, a material for civil engineering (e.g., concrete additives and composites), and a feedstock for gasification and refining processes that yield energy and valuable by-products. Unlike the simple return of crop residues such as straw to the field, biochar systems involve the thermochemical conversion of biomass through pyrolysis under limited oxygen conditions, resulting in a highly stable form of carbon with a significantly longer residence time, often one to two orders of magnitude greater than that of the original biomass [17]. Under natural conditions, changes in soil organic carbon (SOC) are typically slow and occur over decadal timescales. However, biochar amendment can significantly accelerate SOC accumulation. A recent meta-analysis of 981 observations reported an average SOC increase of 36.2% after more than 2 years of biochar application, with sustained crop yield benefits observed even beyond 6 years [62]. This transformation produces a chemically stable form of carbon that resists microbial decomposition and contributes to long-term soil carbon retention. A recent global meta-analysis by Xu et al. [63] reported that biochar application alone increased soil organic carbon by approximately 33%, while simultaneously enhancing crop yield by 15% and reducing global warming potential (GWP) by 27% on average. These findings underscore the multifunctional value of biochar as a climate-smart soil amendment, though its effectiveness strongly depends on factors such as biochar C:N ratio and soil pH. From an economic standpoint, to increase the profitability of biochar application, recent research has emphasized synergistic systems that combine biochar with nutrient recovery, waste-to-energy processes, or biochar-based fertilizers to enhance cost efficiency and adoption [64–66]. In other words, beyond its role in carbon storage, biochar improves soil structure, enhances water and nutrient retention, reduces the need for chemical fertilizers, and increases resource efficiency [67]. Studies show that agricultural systems incorporating biochar can sequester up to 30% more carbon compared to conventional systems [45]. Additionally, producing biochar from agricultural residues prevents greenhouse gas emissions caused by the burning or decomposition of biomass, contributing to a sustainable carbon management cycle [68]. In summary, regenerative agriculture and biochar use, as complementary strategies, not only mitigate climate change but also enhance soil quality, biodiversity, and the sustainability of agricultural ecosystems. Developing supportive policies, investing in biochar production technologies, and educating farmers on regenerative methods are critical steps for scaling these solutions [43].

3 | Comparative Evaluation of Nature-Based Carbon Management Methods

As discussed in Section 2, NBCM encompasses a wide range of approaches and practices aimed at reducing greenhouse gas emissions and sustainably sequestering carbon in natural ecosystems. These methods not only mitigate the effects of climate change but also contribute to improved soil quality, enhanced biodiversity, and better environmental health. However, the effectiveness and feasibility of these methods depend on factors such as ecosystem type, available resources, and climatic conditions [5]. To better understand the differences and relative benefits of these methods, Table 2 compares their key features and environmental impacts. This comparative analysis aims to derive generalizable insights and guide both research and policy directions. It should be noted that this table provides a structured qualitative comparison based on published peer-reviewed sources. While quantitative metrics vary regionally, the included indicators represent a synthesis of commonly reported advantages and limitations for each method.

Based on the data presented in the table, the following conclusions can be drawn:

1. Carbon Storage Potential: Forests and grasslands are among the most powerful carbon storage methods due to their high capacity to absorb CO_2 from the atmosphere and store it in biomass and soil. Similarly, wetlands and aquatic ecosystems, particularly saline wetlands and seagrass meadows, exhibit comparable potential. However, this capacity is often restricted to specific geographic areas. In contrast, urban green spaces have moderate carbon storage potential due to limitations in planting areas and vegetation cover. Regenerative agriculture, particularly with the use of biochar, demonstrates the highest carbon storage potential. This is because, in addition to directly storing carbon in the soil, it also reduces greenhouse gas emissions from agricultural activities.
2. Carbon Storage Longevity: The longevity of carbon storage in forests and wetlands depends on the stability of these ecosystems; mature forests and saline wetlands can store carbon for decades or even centuries. However, this longevity is reduced in cases of ecosystem degradation or land-use change. Urban green spaces, due to their reliance on short-term and seasonal vegetation, have a shorter carbon storage duration. Biochar, used in regenerative agriculture, has a highly stable structure that can sequester carbon in soil for hundreds of years, making it the most sustainable method of carbon storage.

TABLE 2 | Comparative evaluation of NBCM methods based on qualitative indicators from recent literature [5, 43, 45, 79–84].

Features	Forests and grasslands	Wetlands and aquatic ecosystems	Urban green spaces	Urban green spaces	Regenerative agriculture
Carbon storage potential	High (CO_2 absorption by trees) [5]	High (blue carbon storage) [80]	Moderate (limited to urban areas) [83]	Moderate (limited to urban areas) [83]	High (carbon storage in soil and biomass) [45]
Longevity of carbon storage	Long-term (in mature forests) [79]	Long-term (in saline wetlands) [81]	Short-term (dependent on urban vegetation) [82]	Short-term (dependent on urban vegetation) [82]	Very long-term (stable biochar structure in soil) [43]
Environmental impacts	Biodiversity conservation, soil erosion reduction [5]	Protection of aquatic ecosystems [80]	Improved air quality, urban cooling [83]	Improved air quality, urban cooling [83]	Improved soil quality, increased biodiversity, reduced greenhouse gases [45]
Practical applications	Limited to forest and grassland areas	Limited to specific wetland regions	Restricted to urban areas	Restricted to urban areas	Widely applicable in agriculture, suitable for most regions [85]
Challenges	Deforestation risks, restoration costs [79]	Degradation from human development [81]	Lack of space, need for urban planning [82]	Lack of space, need for urban planning [82]	Initial biochar production costs, need for farmer training [43]

3. Environmental Impacts: Forests and wetlands have extensive environmental impacts, including biodiversity conservation and the reduction of soil erosion and sedimentation in waterways. Urban green spaces primarily focus on localized benefits, such as reducing urban temperatures, improving air quality, and creating livable environments for urban residents. Regenerative agriculture and biochar, on the other hand, provide multifaceted environmental benefits, such as improving soil quality, enhancing biodiversity, and reducing the need for chemical fertilizers. These impacts not only reduce greenhouse gas emissions but also improve agricultural productivity.
4. Practical Applications: Forests and wetlands, as well as urban green spaces, are often limited to specific environmental and climatic conditions. Urban green spaces also require precise urban planning and adequate planting spaces, restricting their application to urban areas. In contrast, regenerative agriculture and biochar offer high flexibility, making them suitable for implementation across a wide range of regions and climatic conditions. This makes them practical options for both developed and developing countries.
5. Challenges: Forests face threats from deforestation and human pressures, while wetlands are at risk of degradation due to human development and land-use change. Challenges for urban green spaces are primarily related to space limitations and implementation costs. Regenerative agriculture, while widely applicable, faces key challenges such as the initial cost of biochar production and distribution, as well as the need to educate farmers. However, these challenges can be addressed through supportive policies and investments in biochar production technologies.
6. Based on the analysis, regenerative agriculture, with a particular focus on biochar, emerges as an effective method among NBCM approaches. This method stands out due to its high sustainability, extensive environmental benefits, and significant carbon storage potential and longevity. In addition to mitigating climate change, regenerative agriculture plays a critical role in enhancing agricultural productivity and sustainability.

Overall, this comparative perspective demonstrates not only the diversity of NBCM options but also the conceptual differences identified across the reviewed literature, thereby reinforcing the analytical rather than descriptive orientation of this review.

4 | Global Adoption Patterns of Biochar

Despite its high potential for mitigating climate change, improving soil quality, and promoting sustainable carbon management, biochar is not yet widely adopted in many countries. The reasons for this limitation can be summarized into four key factors:

1. Production Costs and Required Technology: The production of biochar, especially on an industrial scale, requires advanced technologies such as pyrolysis, which depend on

expensive infrastructure and energy resources. In low-income or developing countries, insufficient financial resources and inadequate infrastructure are major obstacles to the development of this technology [45].

2. Low Awareness: Many farmers, policymakers, and even members of the scientific community are insufficiently informed about the benefits and applications of biochar. This lack of awareness has resulted in limited adoption of the technology in agriculture and natural resource management [59].
3. Lack of Supportive Policies: In many countries, the absence of supportive policies and financial incentives for the production and use of biochar has hindered its expansion. For instance, in developing countries, decarbonization policies often focus on renewable energy, leaving biochar as a lower priority [67].
4. Implementation Challenges: Producing biochar from biomass residues requires an efficient supply chain for the collection, transportation, and processing of raw materials. In rural or remote areas, the lack of adequate systems poses a significant challenge to the development of this technology [69].
5. Need for Long-Term Studies: Despite positive scientific evidence, many decision-makers require long-term data on the environmental and economic impacts of biochar. The lack of sufficient studies, especially under specific climatic and geographic conditions, is a key barrier to its acceptance [68].

Given these challenges, the adoption of biochar across countries depends on factors such as technological development, supportive policies, public awareness, and financial resources. These differences highlight the critical role that economic, social, and environmental conditions play in the level of acceptance and expansion of this technology. Based on these factors, countries can be categorized into three main groups: developed countries, developing countries, and low-income countries. This article examines the characteristics of each category and provides case studies of successful projects or challenges faced in implementing this technology. Such analysis helps us understand why some countries are leaders in biochar adoption and how this technology can be expanded in nations facing greater barriers.

4.1 | Developed Countries

Developed countries leverage advanced technologies to produce biochar at an industrial scale. Controlled pyrolysis technology enables these nations to utilize diverse feedstocks, such as agricultural residues and wood waste, to produce high-quality, long-lasting biochar [70]. In the United States [69], woody forest residues in the forests of Oregon and Washington have been used to produce biochar. The main objectives of these projects were to reduce carbon emissions from forestry waste burning and to improve agricultural soil quality. The study showed that this technology can store carbon in the soil and help reduce greenhouse gas emissions. In this project, soil carbon storage increased by up to 2.5 tons per hectare, and dependence on chemical fertilizers in agricultural lands was reduced by 30%. In Canada [71], regional policies in Alberta have provided incentives for biochar producers, making it an important tool for waste management and sustainable agriculture. In this project, biochar was produced from agricultural residues, such as wheat straw, and applied to dairy farms to reduce methane emissions. This project was part of Canada's agricultural decarbonization policies. The results indicated a reduction of up to 25% in methane emissions from livestock waste management and a 15% increase in soil organic matter. In Germany, research projects such as REFERTIL [72] have focused on the application of biochar in organic agriculture. In this project, biochar produced from biomass residues, such as almond shells, was added to organic farming soils. The results demonstrated that the use of biochar can enhance the water retention capacity of soil and accelerate soil quality improvement. Economic assessments in Central Europe have further confirmed that the large-scale deployment of biochar remains sensitive to production costs and policy incentives. Studies by Vochozka and Maroušková [73, 74] highlight that long-term feasibility depends on cost reduction strategies and integration of biochar within broader carbon management systems, such as sewage sludge treatment and waste valorization pathways. Ensuring a year-round and consistent-quality feedstock supply, such as digestate, sewage sludge, spoiled wood, or fermentation residues, has also been identified as a key prerequisite for the techno-economic optimization of biochar systems, particularly when processing fees and energy recovery are integrated [75, 76].

These studies indicate that biochar in developed countries is successfully used as a solution for waste management, greenhouse gas emission reduction, and soil quality improvement. The outcomes of these projects highlight the potential of biochar to reduce the environmental impacts of agriculture and support sustainable farming. Moreover, supportive policies and technological advancements in these countries have been the key to successful implementation of biochar projects.

4.2 | Developing Countries

In developing countries, the use of biochar is mostly limited to small-scale and experimental projects. These projects typically utilize agricultural and forestry residues for biochar production, with the primary objectives of improving soil fertility, reducing greenhouse gas emissions, and managing biomass waste. Financial constraints, low farmer awareness, and inadequate infrastructure have hindered the widespread adoption of this technology on a larger scale [45, 68, 69]. In Kerala, India [77], a pilot project processed rice husks into biochar through controlled pyrolysis before application to paddy fields. This post-processed biochar improved soil water retention capacity by up to 20% and reduced methane emissions from flooded fields by up to 20%. In Brazil [13], biochar produced from sugarcane residues was used to restore degraded soils in the Amazon rainforest. This project increased soil organic matter by 18%, reduced soil erosion, and helped restore native vegetation. Such efforts are particularly significant in rebuilding sensitive ecosystems and mitigating the impacts of deforestation. In China [78], the application of biochar in vegetable farming has shown remarkable results. In Guangdong Province, biochar produced from wood residues and corn stalks increased agricultural productivity by up to 25% and reduced reliance on chemical fertilizers by 30%. These case studies highlight that, despite challenges, biochar has significant potential to improve agriculture and mitigate environmental impacts in developing countries.

4.3 | Low-Income Countries

As discussed at the beginning of Section 4 low-income countries, barriers such as financial constraints, insufficient infrastructure, and low levels of farmer awareness have hindered the widespread adoption of biochar. Despite these challenges, biochar holds significant potential as a sustainable solution for carbon management and soil quality improvement, especially due to the abundance of agricultural and forestry residues globally. Expanding international support, investing in technology development, and implementing effective educational programs can play a crucial role in promoting the use of this technology. While some countries have made progress in utilizing biochar, broader adoption on a global scale requires the formulation of comprehensive policies and a stronger focus on education and capacity-building [45].

5 | Key Insights and Future Directions

This study reviewed the effectiveness of NBCM methods, with a particular focus on biochar, in mitigating greenhouse gas emissions and improving ecosystem health. The findings highlight that nature-based methods, such as regenerative agriculture, forest and grassland management, and aquatic ecosystem conservation, effectively reduce atmospheric carbon levels while offering co-benefits such as biodiversity conservation, soil quality improvement, and erosion prevention. The analysis in this article demonstrates that among these methods, regenerative agriculture, with a particular emphasis on biochar, emerges as one of the most promising strategies. Biochar stands out as one of the most effective solutions for sustainable carbon management. It not only enhances the soil's carbon storage capacity but also significantly reduces greenhouse gas emissions from agricultural activities. Its stable structure allows for carbon sequestration over centuries, while simultaneously improving soil quality and reducing dependency on chemical fertilizers. However, challenges such as high production costs, insufficient infrastructure, and low public awareness limit its broader adoption. A broader synthesis of the mechanisms, advantages, challenges, opportunities, and typical applications of all four nature-based approaches is summarized in Table 3, providing a comprehensive perspective for policy and practice.

Based on the findings of Section 4, the global status of biochar adoption and utilization varies significantly across developed, developing, and low-income countries. A summary of these findings is presented in Table 4, which outlines the applications, benefits, and key challenges in each category of countries. The findings reveal a clear divide in biochar adoption between developed, developing, and low-income countries. Developed

TABLE 3 | Comparative Summary of NBCM Approaches: Mechanisms, Benefits, Challenges, and Applications.

	Mechanism	Advantages	Challenges	Opportunities & applications
Forests & grasslands	Photosynthetic CO_2 uptake; carbon storage in biomass and soils	High sequestration potential; biodiversity conservation; soil and water regulation	Deforestation risks; long maturation periods	Afforestation/reforestation; restoration of degraded ecosystems
Wetlands & blue carbon	Anaerobic carbon burial in soils and sediments of wetlands, mangroves, and seagrasses	Long-term stable storage; high density; flood control; fisheries support	Vulnerability to sea-level rise and salinity changes	Coastal wetland and mangrove restoration; blue carbon credit schemes
Urban green spaces	CO_2 absorption by urban vegetation and microclimate cooling	Improved air quality; urban heat mitigation; health and social co-benefits	Limited space; maintenance requirements	Green roofs, urban parks, street trees
Regenerative agriculture & biochar	Soil carbon enhancement through organic inputs, improved practices, and biochar's recalcitrant carbon	Long-term soil carbon storage; improved soil health and fertility; reduced fertilizer dependency; waste utilization	High biochar production costs; variable effects by soil type	On-farm biochar application; sustainable land management

TABLE 4 | Summary of biochar adoption trends by country category based on Section 4 of this article.

Country category	Example countries	Applications	Observed benefits	Key challenges
Developed	USA, Canada, Germany	Waste management, soil improvement	Stored up to 2.5 tons of carbon/ha; reduced fertilizer use by 30%; methane emissions cut by 25%	High costs; advanced infrastructure required
Developing	India, Brazil, China	Agricultural productivity, soil health	Productivity gains (20–25%); increased soil organic matter (18%)	Financial barriers; limited awareness
Low-Income	Sub-Saharan Africa	Biomass residue management	Significant potential due to abundant residues	Poor infrastructure; inadequate training

nations have successfully implemented biochar on a large scale, driven by advanced technologies and strong policy support. Countries like Canada and Germany illustrate how government incentives and technological innovation can play a crucial role in expanding biochar usage. On the other hand, developing countries face significant hurdles, including financial constraints and a lack of awareness among farmers and policymakers, despite their potential for adopting biochar. These barriers highlight the importance of targeted investments and education programs to bridge the gap. In low-income countries, the challenges are even more pronounced, with poor infrastructure and limited access to biochar production technologies significantly hindering progress. Addressing these issues will require international cooperation, increased funding, and a focus on building local capacity to ensure biochar becomes a viable solution for climate and agricultural challenges in these regions.

To promote global adoption of these solutions, supportive policies, cost-reduction strategies for biochar production, and comprehensive educational initiatives for farmers and policymakers are crucial. Particularly in developing and low-income countries, international investments and local policy frameworks will play a critical role in overcoming barriers and scaling the adoption of biochar technology.

For future research, it is recommended to conduct studies on reducing biochar production costs and developing affordable technologies for use in developing countries. Additionally, long-term evaluations of the environmental and economic impacts of biochar under diverse climatic and geographic conditions can enhance its adoption. Developing integrated carbon management models that combine biochar, regenerative agriculture, and other nature-based methods could also provide a more comprehensive framework for addressing climate change challenges.

6 | Conclusion

NBCM methods are emerging as indispensable strategies for addressing the dual challenge of climate change mitigation and ecosystem restoration. This review has aimed to synthesize the latest evidence on their environmental performance, practical feasibility, and economic relevance, particularly emphasizing biochar as a scientifically validated and scalable pathway for carbon sequestration. By critically comparing four major NBCM approaches, forests and grasslands, wetlands and blue carbon ecosystems, urban green spaces, and regenerative agriculture with biochar, this study has provided an integrated evaluation of their mechanisms, co-benefits, and barriers within diverse ecological and socioeconomic contexts. A new synthesis was presented by linking environmental efficiency with economic and policy dimensions, offering insights that extend beyond descriptive reviews. It highlights that while traditional literature has focused mainly on the ecological effectiveness of NBCM, this review identifies the industrial, financial, and policy mechanisms that determine large-scale feasibility. The main research gap addressed here concerns the long-term environmental–economic performance of biochar and its adoption potential across developing economies.

Findings indicate that all NBCM methods deliver meaningful climate and ecosystem benefits, yet their success varies by regional conditions. Among them, biochar-based regenerative agriculture demonstrates the highest potential for long-term carbon storage, soil fertility improvement, and waste valorization. The combination of biochar's physicochemical stability and its integration into agricultural practices allows for multi-century carbon retention and measurable gains in crop yield, nutrient cycling, and greenhouse-gas mitigation. From a techno-economic standpoint, although biochar production remains cost-sensitive, synergies with nutrient recovery, waste management, and fertilizer production can significantly improve profitability. This integrated approach supports circular economy principles and enhances industrial scalability. At a global level, the hypothesis proposed in this review, that biochar represents the most sustainable and economically viable NBCM pathway, is largely confirmed. The synthesis of empirical and techno-economic evidence suggests that biochar systems can be environmentally and economically sustainable when supported by proper feedstock management, technological innovation, and policy incentives. Developed countries demonstrate this through successful industrial applications integrated with waste valorization and emission reduction programs. In developing regions, where economic barriers persist, targeted investments in technology transfer and farmer education could unlock similar outcomes.

These findings underline that the future of NBCM depends not on a single universal method but on regionally adaptive portfolios that balance environmental gains with financial feasibility. Industrial adoption of biochar, particularly when linked to renewable energy systems or wastewater treatment, offers a realistic route to large-scale decarbonization. To further expand the frontiers of knowledge, future research should focus on (i) developing cost-reduction and scalability frameworks for biochar systems, (ii) integrating NBCM with digital monitoring tools for carbon accounting, and (iii) quantifying cross-sectoral co-benefits across agriculture, energy, and waste management.

In conclusion, this synthesis reinforces that biochar is not merely an agricultural amendment but a transformative climate technology. When combined with regenerative practices and circular economic models, it has the potential to become a cornerstone of sustainable carbon management, bridging environmental ambition with industrial practicality.

Nomenclature

CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DAC	Direct Air Capture
GHG	Greenhouse Gas
Gt	Gigaton
IPCC	Intergovernmental Panel on Climate Change
NBCM	Nature-Based Carbon Management
R&D	Research and Development
SOC	soil organic carbon

Author Contributions

Negin Mirzaei: conceptualization, methodology, software, visualization, writing – original draft, writing – review and editing. **Ahmad Hajinezhad:** conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, validation, writing – review and editing. **Hossein Yousefi:** conceptualization, formal analysis, investigation, methodology, project administration, resources, software, visualization, writing – review and editing. **Seyed Farhan Moosavian:** conceptualization, formal analysis, investigation, methodology, resources, visualization, writing – review and editing. **Reza Fattahi:** data curation, formal analysis, investigation, methodology, resources, software, visualization, writing – review and editing.

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Data available on request from the authors.

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