



The Role of Biochar in Soil Remediation and Carbon Sequestration

Mohanadoss Ponraj ^{1*}, Athiappan Murugan ², Subbarayalu Alagendran ³

¹ Department of Biological Sciences, School of Mathematics and Natural Sciences, The Copperbelt University, Riverside, Kitwe 21692, Zambia

² Department of Microbiology, Periyar University, Salem 636011, India

³ Department of Biochemistry, Crop Management Division Dhanalakshmi Srinivasan Agriculture College, Perambalur (Affiliated to TNAU, Coimbatore), Perambalur – 621212, Tamil Nadu, India

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Abstract

Biochar, a carbon-rich material produced through the pyrolysis of biomass, has garnered significant attention for its dual role in soil remediation and carbon sequestration. This article explores the mechanisms by which biochar improves soil health, remediates contaminated soils, and contributes to long-term carbon storage. Recent studies highlight biochar's ability to enhance soil fertility, reduce greenhouse gas emissions, and immobilize heavy metals and organic pollutants. The chemical properties of biochar, including its high surface area, porosity, and cation exchange capacity, are critical to its effectiveness. This article also discusses the potential of biochar to mitigate climate change by sequestering carbon in soils for centuries. Challenges related to production, application, and long-term impacts require further research.

Keywords: Biochar, soil remediation, carbon sequestration, heavy metal immobilization, greenhouse gas reduction

1 Introduction

Soil degradation and climate change represent two of the most critical environmental crises of the modern era. Over 33% of the Earth's soils are currently degraded due to erosion, salinization, compaction, acidification, and chemical pollution, threatening global food security and ecosystem stability [1]. The Food and Agriculture Organization (FAO) estimates that soil degradation affects 1.5 billion people worldwide, with annual economic losses exceeding \$400 billion [2]. Concurrently, atmospheric carbon dioxide (CO₂) levels have surged to 420 ppm as of 2023 [3], amplifying global temperatures, altering precipitation patterns, and intensifying extreme weather events. Agriculture alone contributes approximately 25% of anthropogenic greenhouse gas (GHG) emissions, primarily through nitrous oxide (N₂O) from fertilizers, methane (CH₄) from livestock, and CO₂ from deforestation [4]. Addressing these intertwined challenges demands innovative, scalable solutions that restore soil health while mitigating climate change.

Biochar, a carbon-rich material produced via pyrolysis of organic biomass, has emerged as a multifaceted tool for sustainable environmental management. Pyrolysis—a thermochemical process conducted at 300–900°C under oxygen-limited conditions—converts agricultural residues, forestry waste, and other organic feedstocks into a stable form of carbon. Historically, indigenous practices in the Amazon Basin utilized charcoal-enriched soils (known as *terra preta*) to enhance fertility, demonstrating biochar's ancient roots [5]. Modern science has revitalized interest in biochar, recognizing its dual capacity to remediate contaminated soils and sequester atmospheric carbon for centuries [6].

The physicochemical properties of biochar—including high porosity, expansive surface area (10–400 m²/g), cation

exchange capacity (CEC), and alkaline pH—enable it to improve soil structure, retain nutrients, and immobilize pollutants [7]. For instance, biochar's porous matrix enhances water infiltration and microbial habitat, while its functional groups (e.g., carboxyl, hydroxyl) bind heavy metals and organic contaminants [8]. Simultaneously, biochar's recalcitrant aromatic carbon structure resists microbial decomposition, enabling long-term carbon storage [9]. The International Biochar Initiative estimates that global biochar deployment could sequester 2.6 billion metric tons of CO₂ annually by 2050, equivalent to 10% of current emissions [10].

Recent advancements have expanded biochar's applications. Engineered biochars, modified via chemical activation or mineral doping, exhibit enhanced pollutant adsorption and catalytic properties. For example, magnesium-impregnated biochar effectively immobilizes phosphate and ammonium in eutrophic waters [11], while iron-modified biochar degrades chlorinated solvents via Fenton-like reactions [12]. Moreover, biochar's role in climate-smart agriculture is gaining traction. Field trials in Kenya and Brazil demonstrate that biochar-amended soils increase crop yields by 15–25% while reducing N₂O emissions by 30–50% [13, 14]. These findings align with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 15 (Life on Land).

However, challenges persist. Variability in feedstock composition, pyrolysis conditions, and soil types complicates standardization [15]. Over-application of biochar may elevate soil pH to levels unsuitable for certain crops or alter microbial communities [16]. Economic barriers, such as high production costs and limited farmer awareness, further hinder scalability [17]. Despite these hurdles, biochar's potential to reconcile agricultural productivity with environmental sustainability

*Corresponding author: Mohanadoss Ponraj, Department of Biological Sciences, School of Mathematics and Natural Sciences, The Copperbelt University, Riverside, Kitwe 21692, Zambia, Email: goldking1977@gmail.com

positions it as a cornerstone of the circular bioeconomy. This article synthesizes recent research on biochar's mechanisms in soil remediation and carbon sequestration, evaluates its global scalability, and identifies critical gaps for future innovation.

2 Biochar Production and Properties

Biochar production begins with selecting biomass feedstocks, which range from woody residues (e.g., pine, oak) to agricultural byproducts (e.g., rice husks, corn stover) and organic wastes (e.g., manure, sewage sludge). Feedstock choice directly influences biochar's chemical composition; lignocellulosic materials yield high-carbon biochars, while nitrogen-rich feedstocks produce biochars with elevated nutrient content [18]. The structural composition of the feedstock, particularly the lignin-to-cellulose ratio, determines the final biochar's stability, porosity, and surface chemistry. For example, hardwood-derived biochars typically exhibit a more condensed aromatic structure, contributing to higher recalcitrance and carbon sequestration potential. In contrast, biochars derived from manure or sludge contain a greater fraction of bioavailable nutrients, making them valuable for soil amendment but less effective for long-term carbon storage.

Pyrolysis temperature is another critical factor. Low-temperature pyrolysis (300–500°C) retains volatile organic compounds (VOCs) and functional groups, enhancing nutrient retention, whereas high-temperature pyrolysis (600–900°C) maximizes surface area and porosity, optimizing adsorption capacity [19]. Additionally, the temperature influences the degree of aromatic condensation and graphitization, affecting the biochar's electrical conductivity and electron exchange properties. High-temperature biochars tend to have lower hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios, enhancing their resistance to microbial degradation and improving their role in carbon sequestration. Moreover, temperature variations impact the release of biochar-associated bioavailable metals, with lower temperatures favoring greater retention of potassium and phosphorus, while higher temperatures increase the availability of silicon and aluminum oxides, which influence soil structure and water retention.

The thermochemical breakdown of biomass during pyrolysis involves three stages: dehydration (removal of moisture at <150°C), depolymerization (breakdown of biopolymers like cellulose at 200–400°C), and carbonization (formation of aromatic structures at >400°C). Each stage dictates the formation of intermediate volatile compounds and the structural rearrangement of biochar. The dehydration phase influences the initial weight loss of biomass, while depolymerization governs the release of bio-oil precursors such as furans and phenols. The carbonization stage leads to the formation of stable polycyclic aromatic hydrocarbons (PAHs), which enhance the recalcitrance of biochar. Gasification, a related process conducted at higher temperatures with limited oxygen, produces syngas (a mix of CO, H₂, and CH₄) alongside biochar. Compared to traditional pyrolysis, gasification results in a lower biochar yield but generates a higher energy-content gas phase, which can be used for energy recovery and industrial applications. Recent studies emphasize the importance of residence time; slow pyrolysis (hours) favors biochar yield, while fast pyrolysis (seconds) maximizes bio-oil production [20]. Residence time also affects the development of porosity, with prolonged retention allowing for greater surface oxidation and enhanced cation exchange capacity (CEC).

Biochar's physicochemical properties underpin its environmental applications. Its alkaline pH (7–10) neutralizes acidic soils, reducing aluminum toxicity and enhancing phosphorus availability. The ability of biochar to modify soil pH depends on its ash content and the presence of alkaline

metals such as calcium, potassium, and magnesium. In highly acidic soils, biochar amendments can improve root growth and microbial activity, facilitating nutrient cycling. The CEC (20–80 cmol/kg) enables nutrient retention, preventing leaching of potassium, calcium, and magnesium [21]. The negative surface charge of biochar enhances its interaction with cations, thereby improving the efficiency of fertilizers and reducing nutrient losses in agricultural systems. Additionally, the presence of surface oxygen-containing functional groups, such as carboxyl and hydroxyl groups, further contributes to nutrient retention and the immobilization of heavy metals.

Microporous structures (<2 nm pore size) provide habitats for beneficial microbes, while mesopores (2–50 nm) trap organic pollutants. The hierarchical pore structure of biochar allows it to function as a microbial refuge, supporting populations of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi. These microbes contribute to enhanced nutrient cycling, decomposition of organic matter, and suppression of soil pathogens. In contaminated environments, biochar's sorptive properties aid in the immobilization of organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and pharmaceuticals. Advanced characterization techniques, such as X-ray photoelectron spectroscopy (XPS) and Fourier-transform infrared spectroscopy (FTIR), reveal surface functional groups responsible for redox reactions and metal complexation [22]. These functional groups influence biochar's ability to participate in electron transfer reactions, which are essential for the transformation and detoxification of environmental contaminants. For instance, quinone groups on biochar surfaces facilitate electron transfer, enabling the reduction of Cr(VI) to less toxic Cr(III) [23]. Additionally, biochar's interaction with dissolved organic matter (DOM) and soil minerals can further modulate its reactivity, influencing long-term stability and effectiveness in environmental remediation.

Overall, biochar's production conditions and physicochemical properties define its role in soil amendment, pollutant removal, and carbon sequestration. Its tunable nature allows for tailored applications in agriculture, environmental remediation, and industrial processes, making it a versatile tool for sustainable resource management. Table 1 summarizes the impact of feedstock selection, pyrolysis conditions, and physicochemical characteristics on biochar's functionality in soil amendment, pollutant remediation, and carbon sequestration.

3 Biochar in Soil Remediation

Soil contamination by heavy metals and organic pollutants poses severe risks to human and ecological health. Biochar's remediation mechanisms include adsorption, precipitation, and catalysis. The effectiveness of these mechanisms depends on the biochar's physicochemical properties, including surface area, porosity, functional groups, and mineral composition. Heavy metals like cadmium (Cd) and lead (Pb) bind to biochar's oxygen-containing functional groups through ion exchange and surface complexation [24]. The presence of carboxyl, hydroxyl, and phenolic groups enhances the chelation of metal cations, reducing their bioavailability and toxicity. For example, cadmium adsorption follows the Langmuir model, with maximum capacities exceeding 150 mg/g for optimized biochars [25]. The adsorption efficiency varies with factors such as pyrolysis temperature, feedstock type, and surface modifications, with engineered biochars often displaying superior metal-binding capacity due to functionalization with minerals such as manganese oxides, ferric oxides, or biochar-derived humic-like substances.

Table 1: Key Factors Influencing Biochar Production, Properties, and Applications

Factor	Description	Influence on Biochar Properties	Key Applications
Feedstock Type	Woody residues (e.g., pine, oak), agricultural byproducts (e.g., rice husks, corn stover), organic wastes (e.g., manure, sewage sludge)	- Lignocellulosic materials → High-carbon biochar, stable for sequestration - Nitrogen-rich feedstocks → Higher nutrient content	Soil amendment, carbon sequestration, nutrient recycling
Lignin-to-Cellulose Ratio	Determines biochar stability, porosity, and surface chemistry	- Hardwood biochars → Aromatic structure, high recalcitrance - Manure/sludge biochars → More bioavailable nutrients, lower long-term stability	Soil fertility improvement, short-term nutrient supply
Pyrolysis Temperature	Low (300–500°C) vs. High (600–900°C)	- Low: Retains VOCs, enhances nutrient retention - High: Increases porosity, surface area, adsorption capacity	Contaminant sorption, carbon sequestration, microbial support
Hydrogen-to-Carbon (H/C) and Oxygen-to-Carbon (O/C) Ratios	Indicators of aromatic condensation and microbial degradation resistance	- Low ratios → Increased stability, reduced microbial degradation	Long-term carbon storage, soil amendment
Pyrolysis Stages	Dehydration (<150°C), Depolymerization (200–400°C), Carbonization (>400°C)	- Dehydration → Weight loss - Depolymerization → Bio-oil precursor release - Carbonization → Stable aromatic structures (PAHs)	Energy production, pollutant degradation
Gasification vs. Pyrolysis	Higher temperature, limited oxygen gasification vs. traditional pyrolysis	- Gasification → Lower biochar yield, more syngas - Pyrolysis → Higher biochar yield, optimized properties	Energy recovery, soil amendment
Residence Time	Slow pyrolysis (hours) vs. Fast pyrolysis (seconds)	- Slow: Higher biochar yield, improved porosity - Fast: Maximizes bio-oil production	Adsorption processes, microbial support
pH (7–10) and Alkalinity	Influences soil pH, neutralizes acidity	- Reduces aluminum toxicity - Enhances phosphorus availability	Soil remediation, plant growth enhancement
Cation Exchange Capacity (CEC)	20–80 cmol/kg	- Retains essential nutrients (K, Ca, Mg) - Reduces leaching losses	Fertilizer efficiency, nutrient retention
Pore Size Distribution	Micropores (<2 nm) vs. Mesopores (2–50 nm)	- Micropores: Habitat for microbes - Mesopores: Adsorption of organic pollutants	Microbial refuge, pollutant removal
Surface Functional Groups	Carboxyl, hydroxyl, quinone	- Supports metal complexation, redox reactions - Enhances electron transfer	Heavy metal immobilization, redox reactions
Advanced Characterization	XPS, FTIR	- Identifies functional groups - Determines biochar reactivity	Environmental remediation, contaminant detoxification

Precipitation occurs when biochar's alkaline properties elevate soil pH, triggering the formation of insoluble metal hydroxides or carbonates. This mechanism is particularly relevant in acidic soils where biochar amendments shift the pH to a range that reduces metal solubility. In arsenic (As)-contaminated soils, biochar loaded with iron oxides promotes the conversion of mobile arsenite (As^{3+}) to stable arsenate (As^{5+}), reducing bioavailability by 40–60% [26]. The iron oxide–biochar composite acts as a redox mediator, facilitating electron transfer that drives the oxidation of arsenite, which is more toxic and mobile, into arsenate, which is less bioavailable and more readily adsorbed by soil minerals. Similarly, biochars impregnated with calcium or magnesium enhance the precipitation of heavy metals by forming stable carbonate complexes, further restricting their mobility in the environment.

Organic pollutants, including polycyclic aromatic hydrocarbons (PAHs) and pesticides, are immobilized via hydrophobic interactions and π - π electron donor-acceptor mechanisms. The aromatic structure of biochar, which resembles activated carbon, allows it to adsorb hydrophobic organic contaminants with high efficiency. Biochar's graphitic domains adsorb PAHs like pyrene, while hydroxyl radicals

generated from biochar-activated persulfate degrade chlorinated herbicides [27]. Advanced oxidation processes (AOPs) involving biochar catalysis have gained attention for their ability to degrade persistent organic pollutants through the generation of reactive oxygen species (ROS). A 2022 study demonstrated that walnut shell biochar degraded 89% of atrazine within 24 hours via peroxymonosulfate activation [28]. The efficiency of this process depends on the biochar's redox-active sites, which can be enhanced by doping with transition metals such as cobalt or iron.

Biochar also enhances microbial degradation by serving as a biofilm substrate. Its porous structure provides a protective habitat for microbial communities, shielding them from environmental stressors while facilitating the degradation of organic pollutants. *Pseudomonas* and *Bacillus* species, enriched in biochar-amended soils, metabolize PAHs into less toxic intermediates [29]. The microbial consortia associated with biochar also participate in co-metabolic pathways, where primary microbial metabolism indirectly contributes to the breakdown of recalcitrant contaminants. Additionally, biochar can act as an electron shuttle, accelerating microbial electron transfer processes involved in the degradation of chlorinated

solvents, petroleum hydrocarbons, and pharmaceutical residues.

Beyond pollution mitigation, biochar improves soil fertility and water retention. By modifying soil structure and enhancing aggregation, biochar increases porosity and aeration, which are critical for root development and microbial activity. In sandy soils, biochar increases water-holding capacity by 20–30%, mitigating drought stress [30]. The microporous network of biochar acts as a sponge, retaining moisture and gradually releasing it to plants, thereby improving water-use efficiency. In clayey soils, biochar prevents compaction and enhances drainage, reducing the risk of waterlogging and root suffocation.

Nutrient retention is another major benefit of biochar amendments. Its high cation exchange capacity (CEC) prevents nutrient leaching, particularly in coarse-textured soils with low organic matter content. A meta-analysis of 371 studies found that biochar application elevated crop yields by 13% in nutrient-poor soils, driven by improved nitrogen use efficiency (NUE) and phosphorus mobilization [31]. By adsorbing ammonium (NH_4^+) and nitrate (NO_3^-), biochar reduces nitrogen losses due to volatilization and leaching, thereby enhancing fertilizer efficiency and reducing greenhouse gas emissions from agricultural systems. Additionally, biochar's interaction with soil microbial communities promotes nutrient mineralization and organic matter decomposition, further improving soil fertility.

Overall, biochar's multifunctional properties make it a promising tool for remediating contaminated environments while simultaneously improving soil health and agricultural productivity. By fine-tuning its physicochemical characteristics through feedstock selection, pyrolysis conditions, and surface modifications, biochar can be tailored for specific environmental applications, enhancing its role in sustainable waste management and climate change mitigation.

4 Biochar in Carbon Sequestration

Biochar's carbon sequestration potential stems from its resistance to microbial decay. Unlike fresh biomass, which decomposes within years, biochar's polycyclic aromatic hydrocarbons (PAHs) persist for centuries [32]. The structural stability of biochar arises from its high aromaticity and condensed carbon forms, which limit microbial accessibility and enzymatic degradation. These properties make biochar an effective long-term carbon sink in soil environments. The carbon stability factor (CSF), calculated via hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios, predicts biochar longevity. Biochars with H/C < 0.4 and O/C < 0.2 exhibit half-lives exceeding 1,000 years [33]. The degree of carbonization also influences the sequestration efficiency, with higher pyrolysis temperatures (above 600°C) yielding biochars with lower H/C and O/C ratios, thereby enhancing long-term stability.

Life cycle assessments (LCAs) estimate that converting 1 ton of crop residue into biochar sequesters 0.3–0.8 tons of CO_2 equivalents, offsetting emissions from feedstock transport and pyrolysis [34]. These estimates consider not only the direct carbon content retained in biochar but also the avoided emissions from decomposition, which would otherwise release CO_2 and CH_4 into the atmosphere. The sequestration potential varies with feedstock type, pyrolysis conditions, and post-application management practices. At scale, biochar could sequester 1.8–3.3 Gt CO_2 annually by 2100, equivalent to 5–10% of current emissions [35]. This potential highlights biochar's role in global carbon management strategies, particularly in agriculture and land restoration projects where

biochar-amended soils enhance productivity while acting as a carbon sink.

Additionally, biochar reduces GHG emissions from soils. By adsorbing NH_4^+ and NO_3^- , biochar curtails nitrification and denitrification pathways, lowering N_2O emissions by 30–70% [36]. The suppression of N_2O emissions is attributed to biochar's ability to alter microbial community structures, particularly reducing the abundance of denitrifying bacteria. Furthermore, biochar's porous structure enhances soil aeration, which favors complete nitrification and reduces anaerobic denitrification, a primary source of N_2O . In flooded rice paddies, biochar-induced methanotroph activity reduces CH_4 emissions by 20–40% [37]. The adsorption of organic carbon substrates on biochar surfaces limits methanogen activity, thereby decreasing CH_4 production. Additionally, the increased availability of oxygen in biochar-amended soils promotes methane oxidation by methanotrophic bacteria, further mitigating emissions. These combined mechanisms position biochar as a multifunctional tool for both carbon sequestration and greenhouse gas mitigation.

Beyond its immediate impacts on carbon storage and emissions reduction, biochar exhibits synergistic benefits when integrated with other carbon sequestration strategies. Its ability to enhance soil organic matter stability complements afforestation, regenerative agriculture, and enhanced weathering techniques. Moreover, biochar-amended soils exhibit increased cation exchange capacity (CEC) and water retention, which contribute to long-term soil carbon storage by stabilizing organic matter and reducing mineralization rates. The application of biochar in degraded soils can also foster microbial communities that facilitate carbon stabilization, further extending its sequestration potential.

5 Challenges and Future Directions

Despite its promise, biochar's adoption faces barriers that span economic, logistical, and scientific challenges. One major constraint is feedstock availability, which competes with other biomass-based industries such as bioenergy production, composting, and livestock bedding. The risk of unsustainable biomass harvesting arises when demand exceeds supply, leading to deforestation and resource depletion, particularly in regions with limited agricultural residues [38]. Efficient feedstock management strategies, such as utilizing waste biomass from forestry and municipal sources, could mitigate these concerns while reducing environmental trade-offs.

Economic viability remains a pivotal factor in large-scale biochar deployment. The production cost of biochar varies based on feedstock type, pyrolysis technology, and regional energy prices. At a carbon price of \$50/ton CO_2 , biochar becomes profitable for approximately 30% of agricultural regions, primarily those with high carbon sequestration potential and favorable policy support [39]. However, in regions where carbon pricing mechanisms are absent or undervalued, biochar remains financially unfeasible without subsidies or market incentives. Scaling up biochar production would require investments in decentralized pyrolysis facilities, reducing transportation costs and making biochar more accessible to farmers. Additionally, biochar's long-term economic benefits, such as improved soil fertility and reduced fertilizer dependency, need further quantification to enhance farmer adoption.

Another significant challenge is the lack of long-term field trials assessing biochar's performance under diverse soil and climatic conditions. Most studies have focused on temperate agricultural systems, leaving knowledge gaps in arid and tropical regions, where soil degradation and carbon sequestration needs are high [40]. Biochar's interaction with

local soil characteristics, water availability, and crop types requires site-specific optimization. Moreover, the variability in biochar properties due to different feedstocks and pyrolysis conditions complicates standardized recommendations for its use. Future research should focus on large-scale, multi-year experiments that capture seasonal fluctuations and long-term soil health impacts.

Biochar's effect on soil biota remains another contested issue. While some studies suggest that biochar application enhances microbial diversity and promotes beneficial microbial communities involved in nitrogen cycling and organic matter decomposition, others report inhibitory effects due to shifts in soil pH, altered nutrient dynamics, and potential toxic compounds, such as residual polycyclic aromatic hydrocarbons (PAHs) [41]. The influence of biochar on soil microbial communities is highly dependent on application rate, feedstock type, and environmental conditions. Engineered biochars with tailored surface modifications could help mitigate negative impacts and enhance soil microbial symbiosis.

To accelerate biochar adoption, policy interventions and integrated waste management strategies must be prioritized. Policy frameworks, such as carbon credits, subsidies, and inclusion in emissions trading schemes, could provide financial incentives for farmers and industries to invest in biochar production. Governments could also support research and development initiatives that focus on optimizing biochar production efficiency and evaluating its long-term environmental benefits.

Integrating biochar with other waste valorization processes, such as anaerobic digestion or composting, could further enhance circularity. Co-application of biochar with digestate or compost has been shown to improve nutrient retention and organic matter stability, reducing greenhouse gas emissions from waste management systems. The "BIOCASCADES" EU project exemplifies how biochar can be incorporated into cascading biomass utilization strategies, demonstrating its potential in sustainable agriculture and waste valorization [42]. Developing holistic frameworks that integrate biochar with regenerative agricultural practices, bioenergy production, and soil restoration projects will be essential for maximizing its environmental and economic benefits on a global scale.

6 Conclusion

Biochar bridges soil restoration and climate action, offering a scalable solution to global sustainability challenges. By immobilizing pollutants, enhancing fertility, and locking away carbon, biochar aligns ecological and agricultural objectives. Collaborative innovation across science, policy, and industry will unlock its full potential, ensuring a resilient future for both soils and the climate.

Ethical issue

Authors are aware of and comply with, best practices in publication ethics specifically about authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language.

Competing interests

The authors declare that no conflict of interest would prejudice the impartiality of this scientific work.

Authors' contribution

All authors of this study have a complete contribution to data collection, data analyses, and manuscript writing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to enhance the manuscript writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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