Chapter

Biochar Synergy with Smart Agriculture and Environment: From Soil Amendment to Precision Regulation Systems

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Abstract

Biochar, a carbon-rich product of biomass pyrolysis, is undergoing a paradigm shift from a conventional soil amendment to a precision regulation tool within smart agricultural systems. This review examines the evolving applications of biochar, integrating nanotechnology, sensor systems, and artificial intelligence (AI) to facilitate precision management of carbon, water, and nutrient cycles. We investigate how the combination of biochar and intelligent technologies fosters closed-loop systems that enhance resource efficiency, mitigate climate change, and promote environmental sustainability. Key topics include the functional enhancement of biochar via nanosensor integration and its role in climate-smart agriculture. By synthesizing scientific evidence and case studies, we highlight biochar's potential to tackle global agricultural challenges while underscoring the necessity for collaborative governance and technological innovation.

Keywords: biosensor, nanotechnology, closed-loop management, climate-smart agriculture (CSA), precision environmental management

1. Introduction

Biochar's legacy traces back to the ancient Amazonian Terra Preta de Índio (Indian Black Soil), where its use transformed infertile tropical soils into enduringly fertile ecosystems, demonstrating prehistoric mastery of soil enhancement through carbon-rich amendments [1]. Modern science confirms biochar's multifaceted value: its porous structure (300–2000 m^2/g surface area) improves water retention by up to 39% and soil porosity by 15–35% [2–4]; oxygen-rich surface groups (carboxyl, hydroxyl) enhance cation exchange capacity (CEC), allowing for better retention of nutrients like NH_4^+ and K^+ [5, 6]; its alkalinity counters soil acidity [7]; and it sustains microbial habitats while sequestering carbon for centuries [1, 8–12].

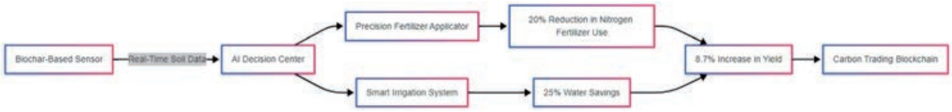

Figure 1.
The operational framework of the AI-biochar system in Jiangsu Province, China.

However, traditional applications face critical constraints: a passive "input-only" role, reliance on empirical field trials, narrow system boundaries, and non-optimized "one-size-fits-all" approaches [13]. These limitations collide with today's agricultural challenges, including the need to increase output by 60% by 2050 amid shrinking arable land [14], agriculture's 17–21% contribution to greenhouse gas emissions [12, 15], water scarcity (accounting for 70% of global usage), soil degradation, and pollution from agrochemicals [12, 14].

Intelligent technologies are now catalyzing a paradigm shift, transforming biochar from a basic amendment into a dynamic smart agriculture regulator [15]. This evolution hinges on three advances:

1. Functional innovation, where biochar becomes an "intelligent carrier" embedded with nanosensors (optical, electrochemical) or stimuli-responsive nanomaterials (e.g., pH/temperature-sensitive hydrogels) [16–18]. These engineered composites enable real-time soil monitoring (moisture, nutrients, pollutants) and adaptive responses—moving beyond static amendment to active "sense-and-respond" systems [19–25].

2. System integration, repositioning biochar as a hub for closed-loop resource management. It connects carbon loops (12–50% CO_2-equivalent reduction [15, 26]), water cycles (precision irrigation via enhanced retention [8]), and nutrient recycling (slow-release fertilizers from waste-derived biochar [2, 27, 28]), aligning with Climate-Smart Agriculture (CSA) goals [29].

3. AI-driven decision-making, where biochar-based sensors feed IoT networks. Machine learning algorithms then optimize variable-rate applications—reducing fertilizer use by 30% while maintaining yields [15, 30, 31].

This triad of advances converges in real-world systems like Jiangsu Province's AI-biochar project for rice-wheat rotations [32]. By integrating real-time soil and weather monitoring, AI-prescribed nitrogen management, and biochar's nutrient-retention capabilities, the project reduced fertilizer inputs by 20%, boosted yields by 8.7%, and curtailed N_2O emissions—showcasing scalable synergy between ecological function and digital precision (**Figure 1**).

Thus, biochar's technological metamorphosis—from ancestral soil enhancer to AI-augmented systems regulator—offers a pathway to reconcile food security, resource efficiency, and environmental resilience in the Anthropocene.

2. Biochar as an intelligent carrier: Nanotechnology and sensor integration

In the context of smart agriculture, biochar has emerged as an intelligent core carrier endowed with sensing, response, and regulatory capabilities through the application of nanotechnology and sensor integration. This evolution provides innovative tools for precision environmental management [33–36].

2.1 Precision regulation of biochar structure driven by nanotechnology

To optimize its performance as an intelligent carrier (loading capacity, targeting, response sensitivity), nano-scale structural design of biochar is imperative (**Table 1**).

2.1.1 Directed optimization of pore structure

Pyrolysis condition control: The temperature (300–700°C), heating rate, and residence time significantly influence pore development. Elevated temperatures (>500°C) facilitate micropore formation, while lower temperatures (300–500°C) help retain oxygen-containing functional groups [36].

Precursor selection: Lignocellulosic materials (such as wood and straw) yield abundant pores, whereas manured biochar tends to have a higher ash content and more complex pore structures [13].

Physical/chemical activation: The activation process using steam or KOH/$ZnCl_2$ expands pores and increases specific surface area (up to >3000 m^2/g), thus enhancing loading capacity [38].

2.1.2 Surface functionalization modification

a. Acid/base modification: Oxidation with HNO_3/H_2SO_4 increases carboxyl and hydroxyl groups; treatment with NaOH/KOH enhances negative charge and hydroxyl content [38, 39].

b. Metal (hydroxide) loading: Techniques such as impregnation-calcination or coprecipitation allow for the loading of Fe_3O_4, MgO, $Al(OH)_3$, and $La(OH)_3$, facilitating magnetic separation or selective phosphorus adsorption [40, 41].

Regulation strategies	Specific methods	Main objectives/effects	Key performance improvements
Pore optimization	High-temperature pyrolysis, steam activation, chemical activation (KOH, $ZnCl_2$)	Increase specific surface area, regulate pore size distribution (micro-/mesoporous ratio)	Loading capacity ↑, diffusion rate ↑, mass transfer efficiency ↑
Surface functionalization	Acid/base treatment, metal (hydroxide) loading, organic molecule grafting, heteroatom doping	Introduce/enhance specific functional groups (–COOH, –OH, $–NH_2$, quaternary ammonium, etc.)	Adsorption selectivity ↑, catalytic activity ↑, wettability control, electrochemical performance ↑
Nano-composite	Loading nZVI, composite with carbon nanotubes/graphene, embedding in hydrogels, composite with clay	Synergize multiple material advantages, construct multifunctional interfaces	Multifunctionality (adsorption + catalysis+ magnetic recovery + conductivity + water retention), stability ↑, responsiveness ↑

Table 1.
Main methods and effects of nanotechnology on biochar carrier performance [37].

c. Organic molecule grafting: The grafting of quaternary ammonium salts, amino groups, or hydrophobic groups modifies cation exchange capacity, metal chelation, or wettability [38, 39].

d. Heteroatom doping: The introduction of nitrogen, sulfur, or phosphorus alters the surface electronic structure, enhancing catalytic or adsorption properties [39, 42].

2.1.3 Advanced nano-composite strategies

a. Biochar-based nano-zero-valent iron (nZVI-BC): Biochar stabilizes nZVI nanoparticles, synergistically enhancing the reduction of heavy metals and organic pollutants [43].

b. Biochar-carbon nanotube/graphene composites: π-π stacking facilitates the formation of three-dimensional conductive networks, thereby improving electrochemical performance [44].

c. Biochar-clay mineral composites: The combination of adsorption and ion exchange capabilities enhances the removal of nutrients and heavy metals [45].

d. Biochar-hydrogel composites: The integration of biochar within hydrogels merges adsorption with water retention, offering intelligent management of water and fertilizers [46].

2.2 Principles, construction, and integration of biochar-based sensors

Functionalized nano-biochar, characterized by its unique physico-chemical properties—including conductivity, catalytic activity, large surface area, and abundant adsorption sites—serves as an ideal material for the development of high-performance, cost-effective sensors for in-situ agricultural environmental monitoring. The primary types of these sensors are outlined below (**Table 2**).

2.3 Application cases

See **Table 3**.

2.4 Challenges and future directions

a. Stability and reliability of sensing performance: Complex agricultural environments (soil texture, organic matter, pH, microbial activity) may interfere with sensor performance. There is a need for the development of robust sensing interfaces, anti-pollution/self-cleaning materials, and in-situ calibration methods.

b. Long-term stability and service life: Ensuring long-term (months to years) field stability of biochar-based sensors remains a challenge, necessitating research into material aging mechanisms and self-repairing systems.

c. Scalable production and cost control: Simplification and standardization of functionalized nano-biochar and sensor fabrication are essential for cost reduction and practical implementation.

Sensor type	**Core principle**	**Typical detection targets**	**Role of biochar**	**Agricultural environmental application examples**
Electrochemical sensors [47]	Current/potential/impedance changes	NO_3^-, NH_4^+, PO_4^{3-}, K^+, H^+, heavy metals (Cd^{2+}, Pb^{2+}), pesticides	Acts as an electrode modification material, providing a conductive substrate, (electro) catalytic activity, and high adsorption enrichment	Real-time monitoring of soil/irrigation water nutrients, rapid pollutant screening
Fluorescent sensors [48]	Fluorescence intensity change/wavelength shift	Heavy metals (Hg^{2+}, Cu^{2}), pesticides, H_2O_2 (stress marker)	Functions as a fluorescent carrier/quencher or participates in recognition reactions	Detection of trace pollutants in water/soil, early diagnosis of plant stress
Colorimetric sensors [49]	Solution/test strip color change	pH, heavy metals, pesticides, H_2O_2, glucose	Serves as a color reaction catalyst (nanozyme), color substance carrier, and adsorption enhancer	On-site rapid visual detection using test strips/microfluidics
Resistance/capacitance sensors [50]	Resistance/capacitance change with environmental parameters (humidity, gas)	Soil volumetric water content (VWC), NH_3, H_2S	Sensitive material, with dielectric/resistive properties that change with the environment	Precision irrigation control, environmental monitoring in livestock sheds, soil aeration assessment
Integrated sense-release system [51–53]	Sensing signal triggers carrier release/activation	Nutrient concentration thresholds, rhizosphere signaling molecules, pollutant levels	Combines sensing and responsive release functions	On-demand precision fertilization/pesticide application, *in situ* soil remediation, intelligent rhizosphere regulation

Table 2.
Main types of biochar-based sensors, principles, and agricultural environmental applications [47–53].

Case scenario	Integration of decision-making and execution	Advantages
In situ monitoring and simultaneous remediation of farmland heavy metal pollution [54]	Electrochemical or colorimetric sensor networks utilizing nZVI-BC composites monitor dynamic changes in Cd, As, etc., in soil pore water/leachate. When sensor-detected heavy metal concentrations exceed safety thresholds, the system automatically alarms and triggers enhanced adsorption/reduction of heavy metals through nZVI-BC repair materials deployed in the same area.	Integrated monitoring and remediation, dynamic evaluation of repair effects, precise and on-demand repair, and cost reduction.
Closed-loop system for precision water-fertilizer management [51, 52, 55]	Distributed biochar-based electrochemical/capacitive sensor networks monitor NO_3^-, NH_4^+, K^+, PO_4^{3-} content and volumetric water content (VWC) at various soil depths. Monitoring data is transmitted *via* IoT to cloud AI platforms, which generate optimal water-fertilizer decisions (irrigation volume, fertilization formula, timing) by integrating crop models, growth stages, and weather forecasts. Continuous monitoring of soil conditions following water-fertilizer application forms a closed-loop feedback system, continuously optimizing decisions.	Enhances efficiency in water-fertilizer management, leading to improved crop yield and resource utilization.
Intelligent control of protected agricultural environment [56]	Biochar-based sensors integrated into greenhouses or plant factories monitor air temperature/humidity, CO_2 concentration, substrate nutrients/water, and potential NH_3/H_2S gases. Data-driven environmental control systems (ventilation, humidification, CO_2 supplementation, irrigation fertilization) operate automatically to maintain optimal crop growth conditions.	Creates highly controllable environments, maximizes resource use efficiency, and achieves consistent high-quality, standardized production.

Table 3.
Implementation scenarios in smart agriculture and environmental monitoring [51, 52, 54–56].

d. Multi-parameter integration and selectivity enhancement: The development of miniaturized, integrated biochar sensor probes for simultaneous in-situ monitoring of multiple parameters (N, P, K, pH, moisture, temperature, heavy metals) is critical.

e. AI-driven intelligent analysis and prediction: Deep integration of sensor data with AI (machine learning, deep learning) is essential for data denoising, fault diagnosis, and intelligent decision optimization.

f. Standardization and regulations: The absence of performance evaluation standards and environmental safety assessment frameworks for biochar-based sensors necessitates immediate attention.

2.5 Conclusion

The convergence of nanotechnology and sensor technology has transformed the role of biochar in smart agriculture. By precisely regulating nanostructure and surface chemistry, and incorporating sensing functionalities, biochar has transitioned from a passive amendment to an intelligent carrier equipped with environmental perception, information transmission, and responsive capabilities. Biochar-based sensors facilitate in-situ, real-time, and cost-effective monitoring of critical parameters within soil-water-crop systems, while the “Sense-Release” integration establishes closed-loop management paradigms. Despite existing challenges related to long-term stability and scalability, ongoing advancements in materials science, the Internet of Things (IoT), and artificial intelligence (AI) will enhance biochar's position as a fundamental intelligent carrier in smart agriculture, promoting its digital, intelligent, and ecological transformation.

3. Biochar-driven "carbon-water-nutrient" closed-loop management system: Establishing the resource circulation core of smart agriculture

The fundamental value of biochar in smart agriculture resides in its capacity to serve as a nexus for carbon, water, and nutrient cycles, facilitating the transition from traditional linear consumption models to efficient, collaborative closed-loop management systems. This section explores how biochar reconfigures resource circulation pathways and how advanced technologies enable precise sensing, informed decision-making, and dynamic regulation to achieve synergistic objectives of resource efficiency, emission reduction, and productivity enhancement.

3.1 Biochar: The multifunctional "engine" of closed-loop systems

Biochar significantly impacts the migration, transformation, and utilization efficiency of carbon, water, and nutrients within soil-plant systems, providing the material foundation for closed-loop management.

3.1.1 Carbon cycle reconstruction

See **Table 4**.

Regulatory methods	Mechanisms: enhancing solid retention from source to sink	
Long-term sequestration in inert carbon pools	Biochar's highly aromatic and biodegradation-resistant organic carbon (50–90%) remains stable in soils for centuries to millennia, thereby mitigating immediate CO_2 emissions from biomass decomposition. Global models indicate that sustainable biochar application could sequester up to 1 billion tons of CO_2 equivalent annually [29, 57].	
Bidirectional regulation of the priming effect	Initial biochar application may temporarily "prime" the decomposition of native soil organic matter (SOM), but high-quality biochar—particularly that produced at high temperatures—suppresses SOM mineralization through structural stability and adsorption protection, indirectly enhancing overall soil carbon storage [9, 58].	
Synergistic greenhouse gas emission reduction	N_2O emission reduction	Biochar can decrease N_2O emissions by 30–70% through substrate adsorption, enhanced aeration, and promotion of N_2O-reducing microbial genes [59, 60].
	CH_4 flux regulation	In paddy fields, biochar has been shown to reduce CH_4 emissions by fostering CH_4-oxidizing bacteria, while its impact in upland areas is negligible [61].

Table 4.
Mechanisms for carbon cycle reconstruction [9, 29, 57–61].

3.1.2 Water cycle optimization: From water retention to efficiency enhancement

See **Table 5**.

Regulatory methods	Mechanisms: From water retention to efficiency enhancement
Physical structure improvement and water retention enhancement	Biochar's porous structure lowers soil bulk density, increases total porosity, and enhances water retention (with field water capacity often rising by 15–50%), thereby reducing evaporation and surface runoff [62, 63]. In the semi-arid Loess Plateau of China, biochar application boosted soil water retention by 25%, alleviating water stress and achieving a 25% reduction in water usage [64].
Enhanced plant water use efficiency (WUE)	Improved soil moisture encourages root development and regulates stomatal conductance, resulting in increased dry matter production per unit of water used [65].

Table 5.
Mechanisms for water cycle optimization [62–65].

3.1.3 Nutrient cycle efficiency: From loss to recovery

See **Table 6**.

Regulatory methods	Mechanisms: From loss to recovery
Expanded nutrient storage and adsorptive slow release	Biochar's extensive surface area and functional groups effectively adsorb NH_4^+, NO_3^-, PO_4^{3-}, and K^+, reducing leaching (20–80% for nitrate) and facilitating slow nutrient release, thereby extending fertilizer efficiency [66, 67].
Regulation of nutrient	Transformation process nitrogen (N) transformation: The adsorption of NH_4^+ and the inhibition of nitrification decrease NO_3^- accumulation and N_2O emissions [68].
	Phosphorus (P) activation: Biochar raises pH in acidic soils, diminishing Fe/Al phosphate fixation, and releases fixed P by adsorbing Al^{3+}/Fe^{3+} [69, 70].
	The availability of potassium (K) and trace elements: Biochar is inherently rich in potassium, particularly when derived from straw-based raw materials. Its cation exchange capacity (CEC) enhances with aging, facilitating the retention and exchange of cations such as K^+, Ca^{2+}, and Mg^{2+}. Additionally, the surface functional groups of biochar have the capacity to complex trace metal elements, thereby influencing their availability and mobility.
Accelerated microbe-driven nutrient turnover	Biochar's porous structure fosters microbial biomass and activity, expediting the mineralization of organic matter and the release of nutrients [33].

Table 6.
Mechanisms for nutrient cycle efficiency [33, 66–70].

3.2 Empowerment through intelligent technologies: Sensing, decision-making, and execution in closed-loop systems

While biochar provides the essential physical framework for closed-loop management, intelligent technologies—such as AI, IoT, and big data—equip the system with "nerves," "brain," and "limbs," enabling a transition from passive responses to proactive precision regulation.

3.2.1 Intelligent sensing layer

See **Table 7**.

Multi-dimension		**Real-time data collection**
In situ sensing networks	Dense deployment of low-cost, low-power smart sensor nodes	Soil sensors: Monitor volumetric water content (VWC), matrix potential, temperature, electrical conductivity (EC), pH, and ion-selective electrodes for nitrates (NO_3^-), ammonium (NH_4^+), and potassium (K^+) [47].
		Environmental sensors: Include weather stations and groundwater quality monitors.
		Crop physiological sensors: Utilize stem flow meters, leaf temperature sensors, and canopy hyperspectral imaging.
Biochar status monitoring		Embed fluorescent tracers or use wireless sensors (NFC/RFID) to track biochar distribution and aging [37].
Space-air-ground integrated monitoring		Combine UAV remote sensing with satellite data for macro-level insights.

Table 7.
Multidimensional, real-time data collection in the intelligent sensing layer [37, 47].

3.2.2 Intelligent decision-making layer

See **Table 8**.

Building of models	**AI-driven model prediction and optimization**
Multi-source data fusion and feature extraction	AI (deep learning) processes heterogeneous spatio-temporal data to extract key features such as water stress and nitrogen nutrition indices [71].
Mechanistic-AI hybrid model construction	Carbon cycle simulation: A modified RothC model, combined with real-time data, predicts soil organic carbon dynamics and greenhouse gas fluxes [71].
	Water-nutrient-crop coupling models: Integrate soil water dynamics (HYDRUS), nutrient transport (NLEAP), and crop growth models (WOFOST), utilizing AI for parameter calibration [72].
Closed-loop optimization decision engine	Employs reinforcement learning or multi-objective optimization to integrate real-time data, predictive outputs, and management goals, generating optimal regulatory instructions [72].

Table 8.
AI-driven model prediction and optimization in the intelligent decision-making layer [71, 72].

3.2.3 Intelligent execution layer

See **Table 9**.

3.3 Closed-loop efficiency: Typical cases and quantitative evidence

See **Table 10**.

Regulatory methods	Precision response and dynamic regulation
Water-char collaborative intelligent irrigation	AI-driven variable rate irrigation (VRI) adjusts water supply based on biochar-modified soil water retention maps and real-time demand predictions [73].
Fertilizer-char collaborative intelligent fertilization	Base fertilizer optimization: Adjusts dosage based on soil nutrient levels and biochar's adsorption potential.
	Topdressing precision: Controls the timing and type of topdressing based on real-time nutrient monitoring and biochar release dynamics [73].
Biochar "activity" regulation	Investigates external stimuli (electric/magnetic fields) or responsive materials to trigger biochar's nutrient release or pollutant adsorption on demand [74].

Table 9.
Precision response and dynamic regulation in the intelligent execution layer [73, 74].

Cases		**China's loess plateau: Water-char-nutrient synergy in dryland agriculture** [75–78].	**Netherlands greenhouse** Horticulture: AI-enabled Carbon-water-nutrient closed-loop Precision control [72, 79–81].
Challenges		Severe soil erosion, drought, soil infertility, and low fertilizer efficiency.	High resource consumption (water, fertilizer, energy), nutrient leaching, and greenhouse gas emissions in high-input systems.
Solutions		Large-scale application of straw biochar (20–40 t/ha) along with soil and water conservation measures; implementation of soil moisture sensor networks for supplementary irrigation; use of biochar-based slow-release fertilizers.	Mixing highly adsorptive biochar (5–15% v/v) into soilless culture substrates; establishing dense sensor networks; utilizing AI models to optimize nutrient solutions, irrigation, and CO_2 enrichment [72, 79, 81].。
Closed-loop efficiency	Water	Soil water retention increased by 18–35%, and water use efficiency improved by 20–30% [75]. Biochar enhanced substrate water retention, with AI control achieving 90% water-fertilizer use efficiency and 30–40% water savings [72, 79, 80].	
	Carbon	Soil organic carbon (SOC) increased, with carbon sequestration rates of 1.5–3.0 t C/ha/yr., and N_2O emissions reduced by 35–60% [75, 76].	Biochar sequestered organic carbon, and precise CO_2 control maximized photosynthetic efficiency, reducing fossil fuel-derived CO_2 emissions [72].
	Nutrients	Nitrogen use efficiency improved by 15–25%, phosphorus availability increased by 20–40%, and crop yields rose by 10–25% [75, 77].	Biochar reduced nutrient loss, with AI control achieving 25–35% fertilizer savings and a 70% reduction in nitrate leaching [71, 79, 80].
Intelligent upgrades/ outputs		UAV-based NDVI mapping for variable topdressing, optimizing resource precision [75, 78].	Achieved stable yields, improved quality (sugar content, vitamin C), and reduced environmental footprint [80].

Table 10.
Typical cases and quantitative evidence [71, 72, 75–81].

3.4 Challenges and advancing directions for closed-loop systems

a. Spatio-temporal heterogeneity and prediction challenges of biochar effects: Long-term field experiments and advanced data mining techniques are essential for developing precise predictive models.

b. Sensor cost, reliability, and deployment density: Innovations in high-precision, low-cost in-situ sensors and optimized deployment strategies are crucial.

c. Model complexity and edge intelligence: The development of lightweight AI models (TinyML) is necessary for facilitating real-time closed-loop responses.

d. System integration and standardization: Achieving interoperability among sensors and platforms requires the establishment of open standards for data interfaces and communication protocols.

e. Economic feasibility and scalable promotion: Policy support and cost reduction through economies of scale are vital for quantifying comprehensive benefits, including yield increases, cost savings, and emission reductions.

3.5 Conclusion

The biochar-driven “carbon-water-nutrient” closed-loop management system represents a significant innovation in smart agricultural resource management. Serving as the physical core, biochar enhances resource circulation through carbon sequestration, water conservation, and nutrient retention, while intelligent technologies function as the neural center, enabling precise collaborative regulation. Global case studies illustrate its potential to enhance resource efficiency (over 25% water savings and over 20% fertilizer savings), reduce environmental pollution (30–70% emissions reduction), and ensure food security (10–25% yield increase). Despite challenges related to prediction accuracy and system integration, the closed-loop system is poised to become a foundational element of smart agriculture, driving sustainable global agricultural transformation. Future research should prioritize the deep integration of biochar, intelligent technologies, and management practices to facilitate large-scale application.

4. Role of biochar in reconstructing climate-smart agriculture (CSA) systems

Climate-Smart Agriculture (CSA) seeks to achieve three interrelated objectives: sustainably increasing agricultural productivity, enhancing resilience to climate change, and minimizing greenhouse gas emissions or enhancing carbon sinks. Biochar, with its distinctive physico-chemical properties and multifaceted impacts on soil-plant-atmosphere systems, is transitioning from a passive soil amendment to a critical engineering tool for actively reconstructing and optimizing CSA systems, offering innovative and comprehensive solutions to meet these three objectives.

4.1 Core mechanisms of biochar in empowering CSA: A multilevel action framework

Biochar's contribution to CSA is multifaceted, forming a synergistic framework through its effects on soil physical, chemical, and biological processes, as well as interfacial reactions (**Figure 2**):

4.2 Cornerstone role: A significant carbon sink and emission reduction engine

4.2.1 Long-term carbon sequestration

The chemical stability of biochar is attributed to its highly aromatic carbon structure, which has a mean residence time (MRT) in soils ranging from centuries to millennia, significantly surpassing that of uncharred organic matter (which lasts only years to decades). Global assessments by Lehmann et al. [82] indicate that biochar's carbon fixation efficiency exceeds 50%, markedly higher than composting (<20%). Large-scale models [29] estimate that the global annual sequestration potential of biochar is approximately 1 billion tons of CO_2 equivalent, positioning it as one of the most promising negative emission technologies (NETs) in agriculture.

4.2.2 Greenhouse gas (GHG) emission reduction

a. N_2O emission reduction: Biochar significantly contributes to reducing soil N_2O emissions through mechanisms such as pH elevation, substrate adsorption, enhanced aeration, and the promotion of N_2O reduction. A meta-analysis encompassing 112 studies demonstrated that biochar reduces N_2O emissions by an average of 54% [83]. Field experiments in China's winter wheat-summer maize rotation system [84] confirmed a 38–45% reduction in annual N_2O emissions over a 3–4 year period with the application of 20–40 t/ha of biochar.

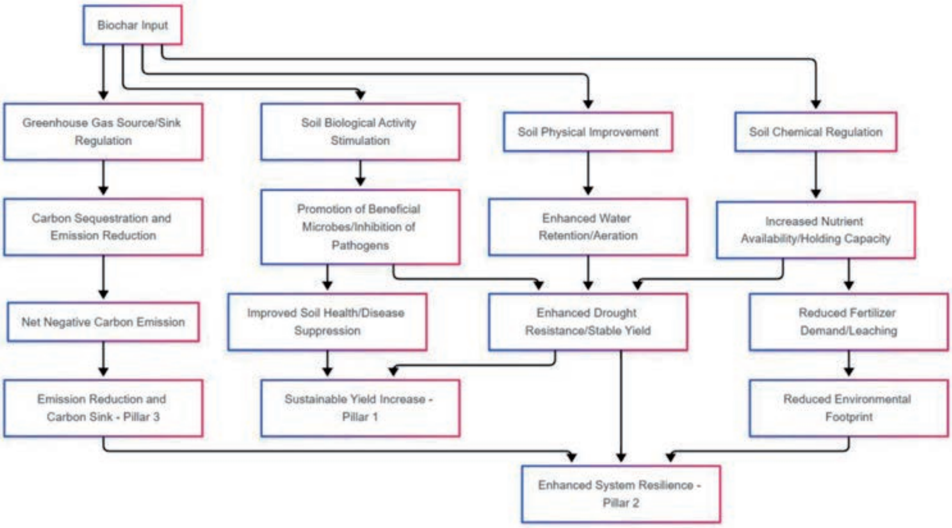

Figure 2.
Multilevel action framework of biochar in empowering climate-smart agriculture (CSA) three pillars.

b. CH_4 flux regulation: The impact of biochar on CH_4 emissions is complex and depends on soil moisture and properties. In paddy fields, low doses of biochar can reduce CH_4 emissions by promoting oxidizing bacteria, while high doses or pore-blocking effects may lead to increased emissions. Meta-analysis [85] indicated an insignificant impact on upland CH_4, with variable effects in paddy fields (ranging from −37% to +66%), but overall, there was a significant reduction in the net greenhouse effect (GWP).

c. Indirect emission reduction: Biochar enhances nutrient use efficiency (NUE), which decreases the demand for chemical nitrogen and the associated production and transport emissions [86, 87]. Improved root growth and photosynthetic efficiency further enhance crop carbon assimilation.

4.3 Enhanced resilience: Fundamental support for drought resistance, yield protection, and nutrient efficiency

4.3.1 Water use efficiency (WUE)

The porous structure of biochar (characterized by high surface area and porosity) improves soil water-holding capacity (WHC), thereby increasing the available water content (AWC), particularly in sandy soils.

a. Improved water retention: Biochar can enhance soil AWC by 10–50%, with high-temperature biochar typically yielding better performance [87].

b. Reduced evapotranspiration and optimized transpiration: Biochar diminishes direct soil evaporation and fosters deep root growth, optimizing transpiration (T/ET ratio) and WUE. In arid and semi-arid regions, the application of biochar (20 t/ha) resulted in a 25% increase in maize WUE and an 18–30% increase in wheat WUE [88].

c. Long-term trials in Colombia [89] demonstrated that biochar improved maize survival and yield stability during the dry season.

4.3.2 Nutrient cycle efficiency and pollution control

a. Enhanced nutrient retention: Biochar's surface functional groups and cation exchange capacity (CEC) effectively adsorb NH_4^+, K^+, Ca^{2+}, and $NH_2{}^+$, thereby reducing leaching. Its pores also capture dissolved organic carbon (DOC) and anions (PO_4^{3-}), ensuring nutrient availability in highly leached tropical soils [66].

b. Improved nutrient use efficiency (NUE): By minimizing losses and enhancing the rhizosphere microenvironment, biochar boosts nutrient absorption, leading to higher yields with equal or reduced fertilizer inputs. Meta-analysis indicates a 15–20% increase in NUE and a 10–25% increase in phosphorus use efficiency (PUE) [87, 90].

c. Non-point source pollution control: The adsorption of nutrients and organic pollutants (such as pesticides and antibiotics) mitigates the risk of migration to water bodies [91].

4.3.3 Enhanced soil health and biological activity

Biochar offers physical protection and carbon sources for soil microorganisms, leading to increased microbial biomass, diversity, and activity, including enzyme activity. Robust microbial communities are essential for nutrient cycling, soil structure stability, and disease suppression. Certain biochars can directly inhibit soil-borne pathogens (e.g., Fusarium, Rhizoctonia) and induce plant systemic resistance (ISR), thereby reducing dependence on pesticides [92].

4.4 Intelligent regulation: Biochar as a "sensing-response" carrier in CSA

The value of biochar extends beyond its inherent improvement properties; it also encompasses its integration with modern information technologies (sensors, IoT, AI) as an "intelligent carrier," facilitating dynamic sensing and precision regulation of CSA systems:

a. Integration of biochar-based sensors: Miniature environmental sensors (such as temperature/humidity, pH, and ion-selective electrodes) embedded in biochar particles monitor soil moisture, salinity, nutrients (NO_3^-, K^+), and pollutants in real time [93].

b. IoT and data-driven decision-making: Data collected from biochar-based sensors is aggregated on cloud platforms, where AI models (including machine learning and deep learning) generate variable irrigation and fertilization prescriptions, predict crop stress, and optimize management strategies [17].

c. Closed-loop feedback regulation: AI-driven automatic control systems implement precise water and fertilizer supply, with biochar enhancing soil buffering capacity for stable and effective regulation [17].

4.5 Typical cases: Validation from theory to practice

Dryland Agriculture in China's Loess Plateau: Large-scale field trials [94] demonstrated that straw biochar (15–30 t/ha) combined with film mulching:

a. Increased soil organic carbon by 20–50% and water retention by 15–30%.

b. Reduced spring maize irrigation needs by 1–2 times during critical growth stages, resulting in improved WUE by 20–35%.

c. Maintained relatively high yields during extreme drought years, significantly enhancing system resilience.

Australia's "Soil Carbon Initiative" and Carbon Agriculture Projects: Established agricultural carbon credit (ACCU) market mechanisms enable farmers to engage in biochar projects, verifying carbon sequestration and emission reduction benefits through scientific monitoring, and trading carbon credits for profit [95, 96]. Blockchain technology tracks biochar origin and carbon credit generation, ensuring transparency.

4.6 Challenges and optimization pathways

Cost-effectiveness: The costs associated with raw material collection, pyrolysis, transportation, and field application remain significant barriers to scaling. There is a need to optimize pyrolysis technology (mobile, small-scale, combined heat and power), develop high-value applications, and leverage revenues from carbon markets.

Effect variability: The effects of biochar are influenced by feedstock, pyrolysis conditions, soil type, climate, and crop management. The development of big data and AI-based predictive models is essential for "site-specific" and "material-specific" precision solutions [97].

Long-term effect monitoring: There is a need for more long-term (>10 years) agronomic and environmental effect data under various management practices.

Standardization and Policy Integration: The lack of unified biochar product quality standards, carbon accounting methods, and certification systems poses challenges. Urgent integration of biochar into national and regional CSA strategies and agricultural subsidy systems is necessary.

4.7 Conclusion: Toward the core of smart agricultural systems

Biochar has evolved from a mere soil amendment to a fundamental component of Climate-Smart Agriculture (CSA) systems. By facilitating irreversible carbon sequestration, significantly reducing greenhouse gas (GHG) emissions (particularly N_2O), revolutionizing water and nutrient efficiency management, and comprehensively improving soil health and biological activity, it provides robust scientific and technological support for the three pillars of CSA. Notably, biochar's integration with modern information technologies (IoT, sensor networks, AI) as a functional intelligent carrier ushers in a new paradigm of precision sensing, data-driven decision-making, and dynamic feedback regulation in smart agriculture. Global cases, such as efficient dryland practices in China's Loess Plateau and innovations in Australia's carbon agriculture market, underscore its technical feasibility and numerous benefits. Despite challenges related to cost optimization, effect prediction, long-term monitoring, and policy standard integration, biochar—with its unique cross-scale functions and strong system integration potential—has become an indispensable engineering tool for advancing agriculture toward a future characterized by high yields, efficiency, resource conservation, environmental sustainability, and resilience. Its comprehensive integrated application signifies a paradigm shift from passive response to active design and regulation of sustainable eco-production systems in agriculture.

5. Future outlook: Artificial intelligence and policy innovation—Toward an intelligent, fair, and resilient biochar system

Biochar's role in smart agriculture and environmental regulation is evolving, presenting a new phase filled with opportunities and challenges. Its transition from "passive amendment" to "active intelligent regulatory core" relies heavily on the profound integration of artificial intelligence (AI) and the collaborative innovation of policy systems. This section delineates key future pathways, concentrating on AI-driven technological advancements and the collaborative design of policy, ethics, and market frameworks to maximize biochar's potential in tackling global environmental challenges and supporting sustainable agriculture.

5.1 AI-driven biochar systems: From precision to prediction, from response to adaptation

Future applications of biochar will be intricately woven into the "nervous system" of the "Smart Earth," with AI functioning as its "brain" to achieve unprecedented levels of precision, predictability, and adaptability.

5.1.1 AI-optimized biochar "customized" design and production

Multi-Objective Joint Optimization Model: Moving beyond single-performance optimization (e.g., carbon sequestration, adsorption capacity), we will develop AI models leveraging reinforcement learning and multi-objective evolutionary algorithms. These models will consider target application scenarios (e.g., enhancing water retention in sandy soils, reducing cadmium in acidic soils, and enriching greenhouse CO_2), available raw material properties, cost constraints, and environmental regulatory requirements. The model will automatically identify optimal pyrolysis process parameters (temperature curve, heating rate, residence time, catalyst utilization) and potential modification strategies (e.g., nano-iron loading, microbial inoculation), generating biochar design schemes that meet specific "performance envelopes" (e.g., high stability, high phosphorus adsorption, low PAHs generation) [98].

Real-Time Process Control and Quality Prediction: The deployment of multimodal sensors (infrared thermal imaging, gas composition mass spectrometry, pressure vibration sensing) in pyrolysis reactors will facilitate the use of deep learning (CNN, LSTM) to analyze real-time data streams. This approach will accurately predict reaction progress, key product characteristics (specific surface area, functional group distribution), and dynamics of potential pollutant (PAHs) generation, providing real-time feedback to regulate heating power, feed rate, and carrier gas flow, thereby achieving "self-perception-self-decision-self-optimization" in intelligent production [99].

5.1.2 Constructing biochar-environment-crop "digital twins"

Multi-scale, multi-physics coupled simulation models will be developed, encompassing microscale (reactions within biochar pores, interactions between microorganisms and char surfaces), mesoscale (carbon-water-nutrient flow in rhizosphere microdomains), and macroscale (water-carbon fluxes at field and regional scales). These models will integrate physical (water flow, heat conduction), chemical (adsorption-desorption, redox), and biological (microbial community dynamics, crop physiology) processes. High-performance computing and artificial intelligence (e.g., physics-informed neural networks, PINNs) will be utilized to tackle complex coupling challenges, facilitating ultra-high-precision simulations of system behaviors following biochar application [100].

Farmers or managers will be able to input localized data related to soil, climate, crops, management practices, and proposed biochar parameters into the digital twin platform. Utilizing twin simulations, the platform will forecast the long-term impacts (5–10-year scale) of biochar application on crop yield, WUE, nitrogen and phosphorus loss risk, net greenhouse gas balance, and soil health indicators across various scenarios (e.g., normal years, droughts, heavy rainfall), providing visual comparisons and optimal decision-making recommendations.

5.1.3 AI-enabled real-time closed-loop control systems

A dense sensing network will be established across agricultural fields through the deployment of high-density, low-cost, low-power multi-parameter soil sensors (measuring moisture, temperature, pH, electrical conductivity, and specific ions such as NO_3- and NH_4^+), crop physiological sensors (monitoring stem flow, leaf temperature, and canopy spectroscopy), and environmental sensors (including weather stations and groundwater monitoring). Lightweight AI models (e.g., TinyML) will be implemented at field gateways or edge computing nodes to process sensor data streams in real time. Based on predefined optimization goals (e.g., maximizing water use efficiency, minimizing nitrogen leaching), along with predictions from digital twins, the models will dynamically generate control instructions: automatically adjusting the switch and flow rate of drip irrigation valves (facilitating biochar-water synergistic regulation), controlling intelligent fertilizer dispensers to deliver liquid fertilizers on demand (enabling biochar-nutrient synergistic regulation), and regulating ventilation in greenhouses to optimize CO_2 concentration (supporting biochar mineralization for CO_2 supply). This establishes a second/minute-level closed-loop system of “perception-analysis-decision-execution,” maximizing the spatial and temporal efficiency of biochar regulation [101].

5.2 Policy innovation: Developing an incentive-compatible, equitable, and risk-controlled governance ecosystem

The realization of technological potential is intrinsically linked to proactive and systematic policy design and institutional safeguards. Future policies must achieve groundbreaking innovations across four dimensions: incentives, equity, risk, and collaboration.

5.2.1 Smart policy toolkit

A high-credibility monitoring, reporting, and verification (MRV) platform for biochar carbon sequestration and emission reduction will be established using remote sensing (satellite/UAV monitoring of crop growth and vegetation coverage changes), Internet of Things (IoT) technologies (real-time monitoring of soil carbon pools and N_2O emissions), and blockchain (providing tamper-proof records of biochar production, transportation, and application data). AI models will integrate multi-source data to automatically and accurately account for the actual carbon sequestration and emission reduction benefits at the plot scale, enabling a shift from “input-based” to “result-based” subsidy distribution and carbon credit issuance, thereby significantly enhancing policy efficiency and fairness (**Figure 3**) [102].

A “policy simulator” based on Agent-Based Modeling (ABM) and system dynamics will be developed to simulate the behavioral responses of stakeholders (e.g., farmers, enterprises, consumers) under various policy combinations (e.g., carbon tax rates, subsidy intensities, biochar standard requirements). This simulator will predict the short-term and long-term impacts of policies on biochar market penetration, environmental benefits (such as carbon sequestration and water quality), social equity (including smallholder participation), and industrial development, providing a “sandbox simulation” for policy formulation and reducing trial-and-error costs [103].

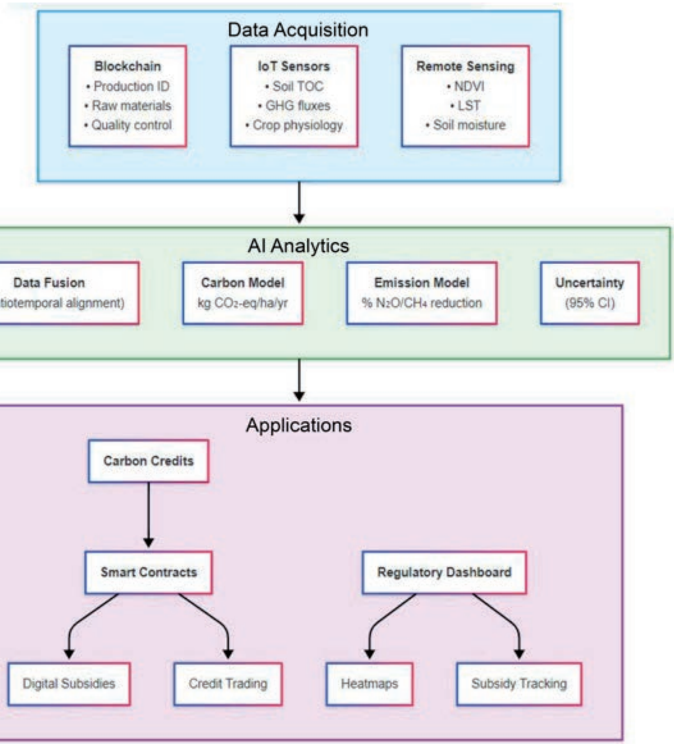

Figure 3.
Precision carbon sequestration MRV system for biochar based on AI and blockchain.

5.2.2 Embedding equity and inclusive mechanisms

A "Universal Biochar" initiative will be launched, establishing dedicated funds to support the research, development, and promotion of modular, low-cost, low-emission small/mini pyrolysis equipment designed for smallholders (e.g., solar-assisted heating). Community sharing models, such as biochar production cooperatives, will be developed to minimize investment costs for individual farmers. Policies will be implemented to provide smallholders with technical training, initial equipment subsidies, or microcredit guarantees, ensuring they can easily access carbon benefits through the intelligent monitoring, reporting, and verification (MRV) system outlined above [104].

In international carbon credit transactions and large-scale biochar investment projects, mandatory fair trade certification or community benefit-sharing funds will be required. The rights and interests of local communities, particularly indigenous peoples and smallholders, regarding land rights, resource rights, free, prior, and informed consent (FPIC), and carbon income sharing (e.g., a minimum of 20%) will be clearly stipulated, with independent third-party supervision mechanisms established [105].

Governments and non-governmental organizations will collaborate to provide digital skills and biochar knowledge training for farmers, especially in resource-constrained areas. Multilingual, user-friendly AI-assisted decision-making mobile applications will be developed to offer farmers free, locally optimized biochar application advice and risk alerts.

5.2.3 Dynamic risk governance and adaptive regulation

For the application of biochar in conjunction with new technologies (e.g., nano-modification, genetic engineering bacteria coupling), an "adaptive regulatory sandbox" facilitated by AI will be established. Innovative trials will be permitted within a controlled scope and timeframe. AI-driven real-time monitoring networks (see Section 6) will comprehensively collect environmental, health, and social impact data. Regulatory agencies will dynamically adjust regulatory requirements—such as modifying application limits and adding monitoring indicators—based on real-time data and AI risk prediction models, achieving a "regulate while developing, learn while regulating" approach [106].

The insurance industry will be encouraged to develop AI-based risk assessment models for long-term (e.g., 30-year) environmental liability insurance products for biochar. Premiums may fluctuate dynamically according to plot risk levels (soil properties, groundwater vulnerability, biochar pollutant levels) and enterprise risk management levels (e.g., the adoption of intelligent monitoring). Blockchain technology will ensure the traceability of historical data and liability determination.

An international organization, such as the FAO or UNEP, will lead the establishment of an open global biochar application case database, with a particular emphasis on long-term monitoring data (over 10 years) and unforeseen negative events. AI will be employed for big data mining to identify potential emerging risk signals, thereby establishing cross-border risk information sharing and early warning mechanisms.

5.2.4 Promoting cross-sectoral collaboration and global governance

A domestic "Biochar-Climate-Agriculture-Environment" policy coordination office will be established to dismantle departmental silos across agriculture, environmental protection, climate, science and technology, and industry. This office will also create a high-level coordination agency. Its primary objective will be to comprehensively formulate national biochar strategies, ensuring that agricultural subsidy policies, climate change commitments (NDCs), soil protection regulations, circular economy goals, and biochar industry development policies are seamlessly integrated and aligned with mutual incentives.

A Global Biochar Innovation and Governance Alliance (GBIGA) will be initiated, establishing a global coalition of diverse stakeholders, including governments, research institutions, enterprises, NGOs, and farmer organizations. Its core responsibilities will encompass: (1) promoting open science and sharing research data and models; (2) coordinating international standard mutual recognition (e.g., EBC, IBI); (3) establishing fair and transparent global carbon accounting methodologies; (4) facilitating technology transfer to developing countries and capacity building; (5) collaboratively addressing cross-border environmental risks (such as biochar particle migration); and (6) negotiating governance rules to prevent carbon leakage and carbon colonialism [107].

Biochar applications that adhere to high standards—such as sustainable feedstocks, low-carbon processes, strict pollution control, and equity—will be actively promoted for formal inclusion in the Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC), the Carbon Offsetting and Reduction Scheme for International

Aviation (CORSIA), the EU Carbon Border Adjustment Mechanism (CBAM), and other global climate policy tools as qualified methods for emission reduction and removal. This will create a stable and expansive international demand market for biochar [108].

6. Conclusions: Co-shaping a smart and sustainable future from soil to system

Biochar, a material rooted in ancient charcoal-burning practices, is experiencing a significant transformation driven by disruptive technologies such as artificial intelligence, as well as innovative policies. It is evolving from a simple soil amendment to a central component of smart agriculture and environmental sustainability regulation systems. This chapter systematically outlines the pathway, mechanisms, and extensive prospects of this transformation while thoroughly analyzing the associated challenges.

a. Core essence of the paradigm shift: The value of biochar transcends its inherent physical and chemical properties (such as porosity, alkalinity, and adsorption) and now encompasses its new roles as an intelligent carrier (integrating sensors and nanomaterials), a system connector (linking carbon, water, and nutrient cycles), and an information node (blockchain recording lifecycle data). Biochar serves as a crucial bridge between the physical world (soil, crops, environment) and the digital landscape (AI models, IoT, blockchain).

b. Transformative power of triple synergy:

1. Technological synergy (AI + Biochar): AI is deeply integrated throughout the biochar value chain, including design, production, monitoring, simulation, decision-making, and closed-loop control. This integration represents a shift from “experience-driven” to “data and model-driven” processes, unlocking unprecedented levels of precision, predictability, and adaptability.

2. System synergy (carbon-water-nutrient closed loop): As a central medium, biochar reconstructs the “carbon-water-nutrient” cycle within the smart agriculture framework, enabling multi-objective collaborative optimization of resource efficiency (water and fertilizer conservation), environmental emission reduction (carbon sequestration, N_2O reduction, pollution control), and productivity enhancement. This robustly supports the implementation of Climate-Smart Agriculture (CSA).

3. Governance synergy (policy-market-ethics): Blockchain technology ensures transparent traceability and trust, while innovative policy tools (intelligent subsidies, carbon MRV, adaptive regulation) create effective incentives and risk prevention measures. Integrating fairness, ethics, and social participation into standards and governance frameworks is essential for ensuring the equitable distribution of technological benefits and preventing new forms of inequality. The convergence of the “circular economy and blockchain” fosters the resource utilization of biomass waste and the green transformation of industries.

d. Call to action for the future: To effectively transform biochar from potential into reality, it is imperative to:

   1. Continuously enhance fundamental research and technological innovation, focusing on long-term behaviors under complex environmental interactions, assessing environmental health risks associated with new biochars (e.g., nano-biochars), and developing more efficient and inclusive AI models and hardware.

   2. Accelerate the iterative cycle of policy, market, and technology by rapidly refining incentive-compatible, equitable, effective, and risk-controllable policy frameworks and market mechanisms through "policy laboratories" and regulatory sandbox pilots, thereby facilitating large-scale applications.

   3. Commit to responsible innovation by prioritizing ethical reviews, social impact assessments (SIA), fair benefit sharing (FPIC), smallholder empowerment, and global justice in technology development and project implementation, fostering broad public trust.

   4. Strengthen global collaboration and knowledge sharing by establishing a robust global alliance (such as GBIGA), collaboratively formulating regulations, sharing knowledge, coordinating actions, and bridging gaps to ensure biochar technology serves as a global public good that benefits all nations, particularly the most vulnerable regions and communities.

The synergy of biochar with smart agriculture and environmental practices presents a pathway toward a more resilient, efficient, and equitable agricultural and ecological system. This journey is fraught with scientific uncertainties, technical complexities, competing interests, and ethical considerations. Nevertheless, by deeply integrating advanced intelligent technologies, innovative policy frameworks, and a steadfast commitment to sustainable development and equity, humanity can transform biochar—an ancient material—into a pivotal tool for cultivating a smart, green, and inclusive future. From the microcosm of soil to the global ecosystem, a profound, sustainable revolution driven by biochar is unfolding, illuminated by the light of wisdom.

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Conflict of interest

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