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Biochar Coated Fertilizers in Sustainable Plant Nutrition Approaches

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HIGHLIGHTS

- Reviews advances (2015–2025) in biochar-coated controlled and slow-release fertilizers.
- Explains nutrient release mechanisms and kinetics governed by biochar properties.
- Highlights improvements in nutrient use efficiency, soil health, and yield.
- Evaluates environmental benefits, economic feasibility, and future research needs.

Abstract

The increasing need to ensure global food security and promote sustainable agricultural practices has necessitated the development of alternative approaches to the environmental problems caused by the use of traditional mineral fertilizers. This review article, prepared within this context, comprehensively examines the development of biochar-coated controlled-release fertilizers (BCSRFs) over the last decade (2015–2025). The study evaluates in detail the production techniques of BCSRFs, the properties of coating materials, nutrient release mechanisms, and the impacts of these systems on agricultural productivity and environmental sustainability. Furthermore, environmental gains such as increased nutrient use efficiency (NUE), reduced greenhouse gas emissions and nutrient leaching, as well as economic feasibility and scalability are discussed. With the potential to improve soil fertility and limit environmental losses, BCSRFs stand out as an innovative and promising solution for modern agricultural systems. This review aims to synthesize the existing literature and provide a scientific framework for future research and applications.

Keywords: Biochar; Controlled-release fertilizer; Slow-release fertilizer; Nutrient use efficiency

1. Introduction

The rapid growth of the global population is placing increasing pressure on agricultural production systems, making the provision of sufficient and safe food a strategic priority. Today, agricultural policies aim not only to increase crop yields but also to ensure that production processes are environmentally sustainable. Although conventional chemical fertilizers have long contributed significantly to yield enhancement in crop production, the inefficient uptake of nutrients by plants has led to serious productivity losses and environmental problems. In particular, low nutrient use efficiency results in a substantial proportion of applied fertilizers being lost before being absorbed by crops (Smith, 2020).

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Macronutrients, especially nitrogen (N) and phosphorus (P), are often inadequately retained in soil systems and are lost from agricultural fields through leaching, denitrification, ammonia volatilization, and surface runoff. These losses reduce economic efficiency for farmers while posing considerable environmental risks. The transport of nutrients into aquatic ecosystems accelerates eutrophication processes, adversely affecting the quality of lakes, rivers, and groundwater, while atmospheric emissions contribute to increased greenhouse gas concentrations and climate change (Johnson, 2018). These multidimensional challenges have intensified interest in next-generation fertilizer technologies that aim to synchronize nutrient supply more closely with the spatial and temporal requirements of plants.

In this context, biochar-based fertilizer systems have emerged in recent years as a promising alternative for sustainable agricultural practices. Biochar is a carbon-rich and chemically stable material produced through the pyrolysis of plant- or animal-derived biomass under oxygen-limited conditions. Owing to its high specific surface area, well-developed porous structure, and diverse surface functional groups, biochar enhances nutrient retention capacity in soils, improves cation exchange capacity, and positively influences water-holding properties (Lehmann and Joseph, 2015; Jeffery et al., 2011; Woolf et al., 2010). Moreover, its long-term carbon sequestration potential makes biochar an important tool in mitigating climate change.

These multifunctional properties make biochar a highly suitable component for the development of controlled- and slow-release fertilizers (Controlled Release Fertilizers, CRFs; Slow Release Fertilizers, SRFs). Fertilizer formulations coated with biochar or integrated within a biochar matrix regulate nutrient release kinetics, ensuring a more balanced nutrient supply within the plant root zone. This approach optimizes nutrient uptake by crops while substantially reducing nutrient losses to the environment (Luo et al., 2025). Consequently, agricultural productivity is enhanced, and the environmental footprint associated with fertilizer use is reduced.

This review comprehensively evaluates scientific studies published between 2015 and 2025 on biochar-coated controlled and slow-release fertilizers. The article examines production techniques, nutrient release mechanisms, performance across different agricultural systems, environmental impacts, and economic feasibility. In addition, current limitations, technical challenges, and future research trends are discussed to contribute to the development of sustainable nutrient management strategies. This study aims to provide an up-to-date and integrated reference for both the academic community and stakeholders in the agricultural sector.

2. Properties Of Biochar And Its Role In Fertilizer Technology

Biochar is a carbon-rich and highly porous material produced through the pyrolysis of agricultural residues or various biomass sources at high temperatures under oxygen-free or oxygen-limited conditions (International Biochar Initiative, 2015). Owing to its unique structural and chemical characteristics, biochar has attracted increasing attention in the fields of agriculture, environmental engineering, and soil science. In the context of fertilizer technology, the importance of biochar primarily arises from its physicochemical properties and its strong potential to interact with nutrient elements. The physical and chemical characteristics of biochar vary significantly depending on the type of feedstock used and the parameters of the pyrolysis process, such as pyrolysis temperature, heating rate, and residence time (Weber and Quicker, 2018). Nevertheless, biochars generally exhibit high carbon contents (50–90%), large specific surface areas, and well-developed porous structures (Gaskin et al., 2010). The pore system of biochar consists of macro-, meso-, and micropores, which facilitate water retention, nutrient storage, and the formation of favorable microhabitats for soil microorganisms. The degree of porosity and surface area are among the most critical factors determining the capacity of biochar to adsorb nutrient elements (Kookana, 2010). From a chemical perspective, biochar surfaces contain various oxygen-containing functional groups, including carboxyl (–COOH), hydroxyl (–OH), carbonyl (C=O), and phenolic groups (Chen et al., 2011). These functional groups directly influence the surface charge, chemical reactivity, and ion exchange capacity of biochar. In particular, carboxyl and hydroxyl groups contribute to an increase in the cation exchange capacity (CEC) of biochar, thereby playing a crucial role in retaining positively charged nutrient ions such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) (Liang et al., 2006). The high cation exchange capacity of biochar represents a key mechanism for conserving nutrients in soil systems and enabling their more balanced release for plant uptake. Negatively charged sites on the biochar surface bind cationic nutrients through electrostatic interactions, effectively reducing losses via leaching and gaseous emissions (Glaser et al., 2002). This property is particularly advantageous in mitigating ammonium losses from nitrogen fertilizers and enhancing the retention of nutrients such as potassium and calcium within the soil profile (Taghizadeh-Toosi et al., 2011).

In the case of anionic nutrients such as phosphorus, biochar can promote nutrient retention through adsorption mediated by iron and aluminum oxides on its surface or through the formation of complexes with calcium, thereby contributing to the immobilization of phosphate ions (Chintala and Mohanty, 2016). All these interaction mechanisms clearly demonstrate that the integration of biochar into fertilizer formulations has significant potential to enhance nutrient use efficiency and reduce environmental nutrient losses. In addition to ion exchange and surface adsorption processes, biochar can also slow nutrient release by physically entrapping nutrient elements within its porous matrix. This characteristic enables biochar to function as an effective carrier and regulatory material in controlled- and slow-release fertilizer systems (Zhang et al., 2010). Overall, key findings from the literature on biochar-based controlled-release fertilizers are summarized in Table 1.

Table 1. Summary of Studies on Biochar-Based Controlled-Release Fertilizers

Material / Modification	Type of Modification	Research Findings	Release Duration	References
Biochar + Bentonite / Sepiolite	Mineral binder and structural modification	The convoluted pore structure enhances urea adsorption capacity, while mineral binders effectively slow nutrient release.	30 days	(Shi et al., 2020); (Wen et al., 2017)
Biochar + Maleic Anhydride Resin Modification	Polymer / chemical modification	Covalent bonding between maleic anhydride and urea significantly delays nutrient release; effective across different soil textures.	4 days	(Mumtaz et al., 2019)
Biochar + Alginate Coating	Biopolymer modification	Incorporation of biochar particles within an alginate matrix enables nutrient entrapment and delayed release; improves water retention capacity.	25–40 days	(Liu et al., 2021)
Biochar + Chitosan Coating	Natural polymer modification	Chitosan–biochar composites provide controlled release of urea and NPK, enhance microbial activity, and contribute to soil pH buffering.	20–35 days	(Zhang et al., 2020)
Biochar + Zeolite	Mineral additive	The high cation exchange capacity of zeolite combined with the porous structure of biochar increases ammonium retention and promotes slow nutrient release.	18–28 days	(Huang et al., 2019)
Biochar + Lignin Coating	Biopolymer coating	Lignin-coated biochar reduces nitrogen losses and ensures stable nutrient release under temperature fluctuations.	15–25 days	(Kalpage et al., 2022)
Biochar + Nanosilica	Nano-mineral modification	Nanosilica-coated biochar restricts urea diffusion and enhances particle integrity.	22–30 days	(Li et al., 2021)
Biochar + Chitosan–PVA Hydrogel	Hydrogel modification	The hydrogel structure retains nutrients within the gel matrix and enables gradual release in response to irrigation.	40–60 days	(Kumar et al., 2023)
Biochar + Polylactic Acid (PLA)	Biodegradable polymer	PLA coating combined with biochar forms a stable and environmentally friendly controlled-release system.	20–45 days	(Ahmed et al., 2020)
Biochar + Mg/Fe Oxide Coating	Functional metal oxide modification	Metal oxide surfaces adsorb phosphate, enabling slow and controlled phosphorus release.	30–50 days	(Wang et al., 2023)

Compiled from the literature based on recent studies on biochar-based controlled-release fertilizers.

As summarized in Table 1, the nutrient release behavior of biochar-based controlled- and slow-release fertilizers is strongly influenced by the type of modification applied. Distinct differences are observed among mineral-based, polymer-based, hydrogel-based, and functional material modifications in terms of both release duration and underlying mechanisms. Mineral-based systems, such as biochar combined with bentonite, sepiolite, and zeolite, generally exhibit moderate release durations (18–30 days) (Shi et al., 2020; Wen et al., 2017; Huang et al., 2019). Their performance is primarily governed by adsorption and cation exchange processes, which enhance nutrient retention but provide limited control over diffusion-driven release.

Therefore, these systems are more suitable for improving nutrient holding capacity rather than achieving long-term controlled release. In contrast, polymer- and biopolymer-based modifications, including maleic anhydride resin, alginate, chitosan, lignin, and PLA, provide improved control over nutrient release (typically 15–45 days) (Mumtaz et al., 2019; Liu et al., 2021; Zhang et al., 2020; Kalpage et al., 2022; Ahmed et al., 2020). These materials form semi-permeable barriers around fertilizer particles, thereby regulating water penetration and nutrient diffusion. Among these, alginate- and chitosan-based systems also enhance soil biological activity and water retention, highlighting their multifunctional role.

Hydrogel-based modifications, particularly chitosan–PVA systems, demonstrate the longest release durations (up to 60 days) (Kumar et al., 2023). This is attributed to their swelling–deswelling mechanisms, which enable more effective regulation of nutrient release. Such systems are especially promising in water-limited environments where synchronized nutrient and water availability is critical. Additionally, nano- and metal oxide-based modifications, such as nanosilica and Mg/Fe oxides, introduce targeted functionalities, including improved structural stability and selective nutrient adsorption, particularly for phosphorus (Li et al., 2021; Wang et al., 2023). While these systems enable more precise nutrient management, they may involve higher production complexity and cost. Overall, this comparison indicates that no single modification strategy is universally optimal; rather, each system offers specific advantages depending on agronomic objectives. While mineral-based systems provide cost-effective solutions, polymer and hydrogel-based systems offer enhanced control over nutrient release. Therefore, future fertilizer design should focus on hybrid systems that combine these complementary properties.

3. Production And Coating Technologies

The performance of biochar-coated controlled- and slow-release fertilizers (BCSRFs) in agricultural systems largely depends on the production processes employed and the characteristics of the coating techniques used. Over the past decade, numerous innovative synthesis and modification methods have been reported in the literature for the development of these fertilizers. These approaches aim to regulate nutrient release kinetics and limit environmental losses within the soil–plant system by integrating the advantageous properties of biochar—such as high surface area, porosity, and chemical reactivity—with fertilizer nutrients (Rubel and Wei, 2025). The main production and coating strategies highlighted in recent studies are summarized below. Physical coating techniques are based on forming a protective coating layer around the fertilizer core or a biochar–fertilizer composite. This coating layer restricts direct contact between nutrients and water, thereby enabling a diffusion-controlled release mechanism and regulating the rate at which nutrients are transferred into the soil. Among physical methods, spray coating is one of the most widely applied techniques. In this approach, fertilizer granules or biochar particles are coated by spraying biochar suspensions containing binding agents, such as polymer solutions. Spray coating allows precise control over coating thickness and the formation of relatively homogeneous surface layers, enabling fine-tuning of nutrient release rates (Lawrencia et al., 2021). In addition, the suitability of this process for automation makes it particularly attractive for industrial-scale production. Another physical coating approach is the dipping method, which involves immersing the fertilizer or biochar–fertilizer mixture into a solution containing the coating material, followed by drying. Coating thickness can be gradually increased by repeating the dipping and drying steps. Although this method is relatively simple to implement, the homogeneity and reproducibility of the coating layer are generally more limited compared with spray coating techniques (Chen et al., 2018).

In addition to physical methods, modification techniques based on altering the chemical properties of biochar and polymer-based composite approaches have been extensively investigated to improve controlled-release performance. Chemical surface activation is typically achieved by treating biochar with acidic or alkaline solutions, which can increase the abundance and reactivity of functional groups on the biochar surface. Acid treatments, in particular, promote the formation of carboxyl groups, thereby enhancing cation exchange capacity and increasing the adsorption potential for nutrient elements (Wang et al., 2015). Composite fertilizers produced by combining biochar with biodegradable polymers have gained significant attention in recent years within controlled- and slow-release fertilizer technologies. Polymers such as starch, chitosan, polylactic acid (PLA), and polyvinyl alcohol (PVA) are used in conjunction with biochar to form a matrix structure that encapsulates nutrient elements. This polymer matrix not only supports the nutrient retention capacity of biochar but also regulates nutrient release rates by linking them to polymer degradation behavior and water permeability (Cen et al., 2021). Such composite systems are considered particularly effective strategies for reducing leaching and gaseous losses associated with nitrogen fertilizers (Rubel, 2021).

4. Innovative Approaches

In recent years, approaches based on nanotechnology and advanced materials science have gained increasing importance in the development of biochar-coated controlled- and slow-release fertilizers (BCSRFs). These innovative strategies aim to enhance the structural and chemical properties of biochar, thereby improving nutrient retention and enabling more effective controlled nutrient release. In nanotechnology-based applications, the incorporation of nanoscale materials into the biochar matrix or their inclusion within fertilizer coating layers has been widely investigated. Nanoparticles such as nanozeolites and nano-hydroxyapatite, owing to their high specific surface areas and reactive surface properties, can form stronger interactions with nutrient ions, thereby increasing nutrient retention capacity and allowing more precise control over nutrient release rates (Dong et al., 2025). Such nano-additives offer particular advantages in limiting soil losses of highly mobile nutrients, especially nitrogen and phosphorus.

At the same time, growing awareness of the environmental impacts associated with synthetic polymers has shifted attention toward the use of biodegradable and environmentally compatible biopolymers in BCSRF production. Polymers based on chitosan, alginate, and starch, when combined with biochar, are considered sustainable coating materials that regulate nutrient release while decomposing in soil without leaving harmful residues (Rafique et al., 2025). Beyond their role in controlled-release mechanisms, these biopolymers also contribute positively to soil health by improving water-holding capacity and stimulating microbial activity.Overall, nanotechnology- and biopolymer-based production and coating approaches provide a strong foundation for the development of next-generation fertilizer systems that maximize the functionality of biochar in agricultural applications, enhance nutrient use efficiency, reduce environmental losses, and align with the objectives of sustainable agriculture (Rafique et al., 2025).

5. Nutrient Release Mechanisms, Kinetics, And The Influence Of Environmental Factors

The primary function of biochar-coated controlled- and slow-release fertilizers (BCSRFs) is to deliver plant nutrients into the soil at a rate and continuity that are synchronized with the temporal nutrient demands of crops. This function does not rely on a single release pathway; rather, it operates through a multicomponent system in which physical barrier effects, biochar–nutrient interactions, and environmental conditions act simultaneously. Nutrient release behavior can vary substantially depending on the structural characteristics of the fertilizer formulation, the chemical and surface properties of biochar, the nature of the coating material, and the physical and chemical properties of the receiving soil (Shaviv, 2000).

One of the dominant mechanisms governing nutrient transfer from BCSRF systems into the soil solution is diffusion-controlled release. The biochar matrix or coating layer surrounding the fertilizer core functions as a physical barrier that restricts the rapid and uncontrolled transport of nutrient ions into the external environment. As water penetrates this layer under soil moisture conditions, nutrients within the fertilizer dissolve and migrate outward along a concentration gradient in a gradual manner (Fan and Li, 2017). In this process, the release rate is determined by coating thickness, pore structure, permeability, and the aqueous solubility of the nutrient elements. The Higuchi model, which is frequently applied to describe diffusion-controlled release behavior, proposes that the cumulative amount of nutrient released is proportional to the square root of time, thereby providing a kinetic basis for this mechanism (Higuchi, 1961). In addition to diffusion, the high specific surface area of biochar and the functional groups present on its surface enable nutrient regulation through adsorption–desorption equilibria. Both cationic and anionic nutrient species can be temporarily retained on charged sites of the biochar surface via electrostatic attraction or chemical bonding (Sposito, 2008). When nutrient concentrations in the soil solution decline or plant root uptake intensifies, surface-bound nutrients can desorb back into the solution phase, becoming available for plant absorption. This dynamic equilibrium promotes the prolonged and controlled presence of nutrients in the rhizosphere, thereby contributing to sustained plant nutrition (Jindo et al., 2014).

Nutrient release kinetics are not governed solely by fertilizer and biochar properties but are also strongly influenced by environmental conditions. Soil pH affects the ionization state of functional groups on the biochar surface and alters surface charge distribution, thereby shaping adsorption and desorption processes. Under acidic conditions, the solubility of certain nutrients may increase, while the cation exchange capacity of biochar can decline (Novak et al., 2009). Increases in temperature can accelerate nutrient dissolution and diffusion processes, leading to higher release rates, while also influencing the degradation rate of biopolymer-based coating materials (Du et al., 2019). Soil moisture content is critical for nutrient dissolution and transport across coating layers; under insufficient moisture conditions, release is markedly slowed, whereas excessive moisture may enhance leaching losses (Trenkel, 2010). Moreover, soil microorganisms can directly affect nutrient release dynamics by accelerating the degradation of biodegradable coatings, with the biochar-induced stimulation of microbial activity further contributing indirectly to these processes (Gul et al., 2015).

6. Agricultural And Environmental Performance

The primary objective in developing biochar-coated controlled- and slow-release fertilizers (BCSRFs) is to enhance agricultural productivity while mitigating the environmental problems associated with conventional fertilizer use. In recent years, scientific studies have demonstrated that these fertilizer systems offer substantial advantages in terms of both crop production and environmental sustainability. By releasing nutrients at a balanced rate aligned with plant growth stages, BCSRFs improve nutrient uptake efficiency and support crop development. In contrast, the rapid nutrient release commonly observed with conventional fertilizers may exceed plant uptake capacity, leading to nutrient imbalances or phytotoxic effects, whereas controlled-release mechanisms largely alleviate these limitations. Evidence reported in the literature indicates that BCSRF applications in crops such as maize, wheat, rice, and various vegetable species result in higher biomass production, grain yield, and nutrient content compared with conventional fertilizers. In addition, biochar improves soil structure by enhancing water-holding capacity and creating favorable habitats for beneficial microorganisms, thereby indirectly promoting plant growth. The positive effects of BCSRFs on soil health extend beyond nutrient supply alone. Biochar incorporation contributes to increased soil organic matter content, improved aggregate stability, and reduced erosion risk. These structural improvements stimulate root development and promote a more balanced movement of water and nutrients within the soil profile. Furthermore, the porous structure of biochar provides suitable microhabitats for soil microbial communities, increasing microbial diversity and biological activity. Supporting beneficial microorganisms that play key roles in nutrient cycling enhances overall soil ecosystem functionality and resilience (Jeffery et al., 2011; Liu et al., 2021; Lehmann et al., 2011)

From an environmental perspective, one of the most notable advantages of BCSRFs is their potential to reduce greenhouse gas emissions and minimize nutrient losses through leaching. In particular, emissions of potent greenhouse gases such as nitrous oxide, which are commonly associated with nitrogen fertilizer applications, can be mitigated through the regulatory effects of biochar on nitrification and denitrification processes. Moreover, the high adsorption capacity and cation exchange capacity of biochar limit the downward transport of nitrate and phosphate ions within the soil profile, thereby reducing the risks of groundwater contamination and eutrophication. These attributes are critically important for the protection of water resources and the maintenance of ecosystem balance. Overall, biochar-coated controlled- and slow-release fertilizers play a significant role in the development of sustainable agricultural systems by enhancing nutrient use efficiency and reducing environmental losses.

7. Economic Analysis And Commercial Viability

Although the advantages of biochar-coated controlled- and slow-release fertilizers (BCSRFs) in terms of agricultural productivity and environmental sustainability have been clearly demonstrated in the literature, their large-scale adoption largely depends on the establishment of economic feasibility. Over the past decade, research has increasingly focused on evaluating the commercial potential of BCSRFs by examining their production processes from a cost–benefit perspective (Rubel and Wei, 2025). These studies provide holistic assessments that consider not only production costs but also long-term economic gains and indirect benefits. Current evidence indicates that the initial production costs of BCSRFs are generally higher than those of conventional mineral fertilizers. This is primarily attributable to factors such as the establishment of pyrolysis infrastructure for biochar production, processing and modification of biochar, procurement of coating materials, and the technical complexity of manufacturing processes (Campion and Field, 2023). In small- and medium-scale facilities, the proportion of fixed costs per unit of product is relatively high, further increasing overall production costs. However, with ongoing technological advancements, more efficient utilization of agricultural residues as biochar feedstocks, and expansion of production scale, unit production costs are expected to decline over time (Rubel and Wei, 2025). Large-scale manufacturing facilities, benefiting from economies of scale, may enable BCSRFs to become cost-competitive with conventional fertilizers.

Life Cycle Analysis (LCA), which is increasingly employed in economic evaluations, allows the environmental performance of BCSRFs to be assessed alongside economic considerations. LCA-based studies suggest that, across stages ranging from raw material acquisition to production, application, and end-of-life phases, BCSRFs may exhibit a lower environmental footprint than conventional fertilizer systems (Osman et al., 2024). Key advantages include enhanced carbon sequestration potential, reduced greenhouse gas emissions particularly nitrous oxide (N_2O) mitigation of water pollution, and optimization of energy use. Although certain environmental burdens arise during the production phase, long term benefits such as improved soil health, reduced nutrient losses, and increased crop yields are reported to outweigh these impacts, resulting in a net environmental gain (Sparrevik et al., 2013).

From an economic perspective, the cost of biochar production remains one of the key factors limiting its large-scale application in agriculture. The production cost of biochar varies widely depending on feedstock type, pyrolysis technology, and production scale, typically ranging between 300 and 1,200 USD per ton (Roberts et al., 2010; Shackley et al., 2011). In comparison, conventional mineral fertilizers such as nitrogen and phosphorus fertilizers are generally less expensive on a per-unit basis, which provides a short-term economic advantage for farmers (Liu et al., 2021). The economic contributions of BCSRFs should not be evaluated solely in terms of production costs. Their application in agricultural systems also offers long-term and indirect economic benefits for farmers. Improved nutrient management leads to higher yields and enhanced crop quality, thereby increasing farm income (Santos and Soares, 2025). Greater nutrient use efficiency enables reduced fertilizer input per unit area, while the controlled-release characteristic lowers application frequency and associated labor costs (Bhatt and Sharma, 2023). Additionally, environmental benefits such as reduced water and air pollution contribute to the preservation of ecosystem services, helping to lower societal costs over the long term. In some regions, carbon credit schemes, environmental incentives, and support mechanisms further enhance the economic attractiveness of BCSRF adoption (Rubel and Wei, 2025). Overall, the widespread commercial adoption of biochar-coated controlled- and slow-release fertilizers is closely linked to reductions in production costs, increased farmer awareness of both short and long-term benefits, and the implementation of appropriate policy and incentive frameworks. Market analyses indicate that, in response to the growing demand for sustainable agricultural practices, BCSRFs possess significant commercial potential in the future (Cheng et al., 2024).

8. Future Perspectives

Biochar-coated controlled- and slow-release fertilizers (BCSRFs) have demonstrated significant progress over the past decade as an innovative technology within sustainable agriculture frameworks. The existing literature indicates that these fertilizer systems have been extensively investigated across a broad spectrum, including production techniques, nutrient release dynamics, impacts on agricultural productivity, environmental benefits, and economic feasibility. The findings presented in this review highlight the considerable potential of BCSRFs to enhance nutrient use efficiency, thereby increasing agricultural productivity while simultaneously reducing environmental nutrient losses. Nevertheless, important knowledge gaps remain, particularly regarding their performance under diverse soil–climate conditions, long-term impacts, and adaptability to large-scale agricultural applications.

Future research trends suggest that the integration of biochar-based controlled-release fertilizers with advanced technologies represents a promising direction. In particular, the development of smart fertilizer systems integrated with sensor technologies and artificial intelligence–based decision-support tools may enable real-time monitoring of soil and plant nutrient status and allow dynamic adjustment of nutrient release rates accordingly (Ma and Li, 2020). Such systems have the potential to respond effectively to rapid environmental changes and crop growth stages, thereby maximizing nutrient use efficiency. Another emerging research area involves the synthesis of nano-scale biochar particles and their incorporation into fertilizer formulations. Nano-biochar applications, owing to their high specific surface area and enhanced surface reactivity, may improve nutrient retention and enable more precise control over nutrient release (El-Naggar et al., 2019). However, the long-term environmental impacts and potential toxicological risks of nano-sized materials in soil ecosystems have not yet been fully elucidated. Consequently, comprehensive environmental impact assessments and safety evaluations are required before the widespread adoption of nano-biochar–based fertilizers.

An additional critical dimension in the advancement of BCSRF technologies is waste management within the framework of the circular economy. The valorization of agricultural and industrial waste streams for biochar production and the subsequent incorporation of biochar into fertilizer formulations can reduce waste volumes while generating high value-added products (Jindo et al., 2014). This approach promotes more efficient use of natural resources and contributes to the development of sustainable production systems. Finally, the widespread adoption of biochar-coated controlled- and slow-release fertilizers in agricultural practices requires the establishment of appropriate policy frameworks and the development of standardization processes. Incentive mechanisms, quality standards, and regulatory policies at national and international levels can facilitate the adoption of these innovative fertilizer technologies by both producers and farmers (Trenkel, 2010). In this context, policy and regulatory measures supported by robust scientific evidence represent key drivers for accelerating the integration of BCSRFs into sustainable agricultural systems.

9. Conclusion

This study provides a comprehensive evaluation of biochar-coated controlled- and slow-release fertilizers (BCSRFs) by integrating their agronomic performance, environmental impacts, and economic feasibility within the framework of sustainable plant nutrition. Unlike previous studies that have predominantly focused on either agronomic or environmental aspects, this work offers a holistic assessment that links nutrient release behavior, soil improvement mechanisms, and economic considerations. The findings clearly demonstrate that BCSRFs have significant potential to reduce nutrient losses through leaching, volatilization, and runoff, while simultaneously enhancing nutrient use efficiency and crop productivity. In addition, the role of biochar as a multifunctional component—improving soil physical properties, supporting microbial activity, and contributing to long-term carbon sequestration—has been critically evaluated in the context of fertilizer systems.A key contribution of this study lies in highlighting the economic dimension of BCSRFs, emphasizing that although initial production costs remain relatively high compared to conventional fertilizers, long-term agronomic benefits and environmental gains may offset these costs under appropriate management and scaling conditions. This integrated perspective contributes to bridging the gap between laboratory-scale research and field-level applicability.

Overall, this study positions BCSRFs as a viable and forward-looking strategy for sustainable agriculture, while also underlining the need for interdisciplinary approaches combining soil science, material engineering, and economic analysis to support their wider adoption.

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