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Mechanistic Insights into Interfacial Interactions and Fertilizer Efficiency of Modified Biochar-Based Controlled Release Fertilizers

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Abstract: To address the prominent issues associated with conventional chemical fertilizers, including rapid nutrient release, low utilization efficiency, and environmental pollution, and to promote sustainable agricultural development, modified biochar-based controlled-release fertilizers have emerged as a research hotspot due to their multiple advantages, such as nutrient slow-release, soil improvement, and carbon sequestration. This paper systematically reviews the preparation methods of modified biochar and the effects of modification on its physicochemical properties. It focuses on analyzing the interfacial interaction mechanisms between modified biochar and fertilizer nutrients, and explores the long-term fertilization mechanisms of modified biochar-based controlled-release fertilizers in soil environments. Based on relevant experimental findings, the key factors affecting long-term fertilizer efficiency are discussed. Current limitations in existing studies are identified, and future research directions are proposed, providing theoretical references and practical guidance for the development, optimization, and industrial application of modified biochar-based controlled-release fertilizers.

Keywords: Modified biochar, controlled-release fertilizer, interfacial interaction, long-term mechanism, nutrient release, soil improvement.

1. Introduction

With the increasing contradiction between global population growth and limited arable land resources, the demand for higher crop yields continues to rise, making the extensive use of chemical fertilizers a key approach to improving agricultural productivity [1]. However, conventional fertilizers suffer from a fundamental mismatch between nutrient release rates and crop uptake patterns, resulting in low utilization efficiency. In China, nitrogen use efficiency is only 30%–35%, phosphorus efficiency is below 20%, and potassium efficiency is around 40%, all significantly lower than in developed countries. Unabsorbed nutrients are lost through runoff, leaching, and volatilization, leading not only to resource waste but also to soil compaction, water eutrophication, and atmospheric pollution, severely restricting sustainable agricultural development.

Biochar, a carbon-rich porous material produced from agricultural and forestry waste via high-temperature pyrolysis, features a large specific surface area, well-developed pore structure, abundant surface functional groups, and excellent adsorption capacity [2]. Due to its wide availability, low cost, and environmental friendliness, it has been widely applied in soil improvement, nutrient retention, and pollution remediation. However, pristine biochar has limited adsorption capacity and low surface activity, resulting in weak interactions with fertilizer nutrients and insufficient long-term release performance [3]. Through physical, chemical, or biological modification, its pore structure, functional groups, and surface charge properties can be regulated, enhancing nutrient adsorption, retention, and slow-release capacity, thereby enabling the development of high-performance modified biochar-based controlled-release fertilizers.

The core advantage of modified biochar-based controlled-release fertilizers lies in the interfacial interactions between biochar and nutrients, enabling slow nutrient release and sustained supply, while simultaneously improving soil properties. Current research mainly focuses on preparation optimization and release performance evaluation, whereas systematic studies on interfacial mechanisms and long-term efficiency remain limited. Clarifying the types and patterns of interfacial interactions and uncovering the intrinsic mechanisms governing long-term fertilizer performance are of great theoretical and practical significance.

2. Preparation and physicochemical regulation of modified biochar

2.1. Preparation Methods of Modified Biochar

The modification of biochar fundamentally aims to alter its surface structure and chemical properties through physical, chemical, or biological approaches, thereby enhancing its adsorption and binding capacity toward fertilizer nutrients. At present, commonly used modification strategies can be broadly categorized into three types: physical, chemical, and biological modification. These approaches differ significantly in their underlying mechanisms, process characteristics, and modification performance, and should be selected according to specific application requirements.

Physical modification involves the use of mechanical or thermal treatments to regulate the pore structure and specific surface area of biochar without the addition of chemical reagents, offering advantages in environmental compatibility and operational simplicity. Common methods include mechanical grinding, high-temperature activation, microwave treatment, and ultrasonic treatment [4]. Mechanical grinding reduces particle size and increases specific surface area, thereby enhancing surface activity. High temperature activation further develops pore structures and removes surface impurities, improving adsorption performance. Microwave and ultrasonic treatments disrupt inert surface structures, facilitating the exposure of functional groups and enhancing the adsorption capacity for nutrient ions.

Chemical modification, which is currently the most widely applied and effective approach, involves oxidation, reduction, or loading reactions between chemical reagents and the biochar surface to regulate surface functional groups and charge properties. Common modifying agents include acids, bases, salts, and metal oxides. Acid modification removes surface impurities via oxidation and increases the abundance of oxygen-containing functional groups (e.g., carboxyl and hydroxyl groups), lowers the surface pH, and enhances the adsorption of cationic nutrients (e.g., NH_4^+, K^+, Ca^{2+}). Alkaline modification (e.g., NaOH, KOH) etches the biochar surface, enlarges pore structures, and increases basic functional groups, thereby improving the adsorption of anionic nutrients (e.g., PO_4^{3-}, NO_3^-). Metal oxide modification (e.g., Fe_3O_4, MgO, ZnO) introduces additional active sites via surface loading, enhancing the selective adsorption and fixation of nutrients, while also imparting functionalities such as magnetism that facilitate recovery and reuse [5].

Biological modification employs microorganisms or enzymes to functionalize the biochar surface. Interactions between microbial metabolites and the biochar surface improve surface properties and adsorption performance. This approach is environmentally friendly and sustainable; however, it is characterized by relatively long processing times and moderate modification effects, and thus remains at an exploratory stage. Common microorganisms include Bacillus and Pseudomonas, which can secrete organic acids and polysaccharides, thereby altering surface charge properties and functional group composition and enhancing nutrient adsorption and slow-release performance.

2.2. Effects of Modification on The Physicochemical Properties of Biochar

Modification primarily regulates the physicochemical properties of biochar by altering its specific surface area, pore structure, surface functional groups, and charge characteristics, thereby enhancing its interaction with fertilizer nutrients. Although pristine biochar possesses a certain pore structure and adsorption capacity, its limited functional groups and low surface activity restrict its performance. Modification significantly improves these properties, as reflected in the following aspects.

First, the optimization of specific surface area and pore structure. Both physical and chemical modifications effectively increase the specific surface area and pore volume of biochar. Mechanical grinding and high-temperature activation directly expand pore number and size distribution, while acid and alkaline etching in chemical modification disrupt dense surface structures, generating additional micropores and mesopores that provide sufficient space for nutrient adsorption and storage.

Second, the alteration of surface functional groups. Chemical modification is the primary approach for regulating functional group composition. Acid treatment significantly increases oxygen-containing functional groups, rendering the biochar surface more acidic and enhancing its adsorption capacity for cationic nutrients. Alkaline modification increases basic functional groups, improving adsorption of anionic nutrients. Metal oxide modification introduces new functional groups such as metal hydroxyls, further strengthening the specific adsorption capacity for nutrients.

Third, the regulation of surface charge properties. Surface charge directly determines the adsorption and binding behavior of nutrient ions. Modification can alter the isoelectric point and regulate surface charge density. Acid modification lowers the isoelectric point, resulting in negatively charged surfaces under neutral soil conditions and enhancing electrostatic adsorption of cationic nutrients (e.g., NH_4^+, K^+). In contrast, alkaline modification increases the isoelectric point, leading to positively charged surfaces and improved adsorption of anionic nutrients (e.g., PO_4^{3-}, NO_3^-). Additionally, metal oxide modification alters charge distribution through the introduction of metal ions, further enhancing selective adsorption of nutrient ions.

Finally, changes in elemental composition and chemical stability. Modification not only alters surface properties but may also affect elemental composition and chemical stability [6]. Metal oxide modification can introduce nutrient elements such as Fe, Mg, and Zn onto the biochar surface, enabling the simultaneous release of fertilizer nutrients and micronutrients for crops. High-temperature activation increases carbon content and enhances chemical stability, prolonging the residence time of biochar in soil and enabling long-term carbon sequestration and nutrient release.

3. Interfacial Interaction Mechanisms of Modified Biochar Based Controlled Release Fertilizers

The slow-release performance of modified biochar-based controlled-release fertilizers fundamentally depends on the interfacial interactions between modified biochar and fertilizer nutrients [7]. These interactions involve complex physicochemical processes, primarily including physical adsorption, chemical bonding, and ion exchange, along with a certain contribution from physical encapsulation. These mechanisms act synergistically to achieve the slow release and sustained supply of nutrients.

3.1. Physical Adsorption

Physical adsorption represents the most fundamental and prevalent interfacial interaction between modified biochar and fertilizer nutrients. It is primarily governed by intermolecular forces such as van der Waals forces, hydrogen bonding, and hydrophobic interactions, through which nutrients are adsorbed onto the surface and within the pores of modified biochar. This process is reversible, and its effectiveness largely depends on the specific surface area, pore structure, and surface properties of the modified biochar.

Modified biochar possesses a well-developed pore structure and large specific surface area, providing abundant space for nutrient adsorption. Nutrient molecules can diffuse into micropores and mesopores of the biochar and become physically immobilized. For instance, microporous structures can adsorb urea molecules and nutrient ions, thereby reducing direct nutrient loss. In addition, surface functional groups such as hydroxyl and carboxyl groups can interact with nutrient molecules via hydrogen bonding, further enhancing adsorption capacity [8].

The strength of physical adsorption is influenced by factors such as temperature, pH, and nutrient concentration. Lower temperatures enhance intermolecular interactions and thus improve adsorption. Neutral or slightly acidic conditions favor the adsorption of cationic nutrients, whereas slightly alkaline conditions promote the adsorption of anionic nutrients. As nutrient concentration increases, adsorption capacity increases until saturation is reached. Furthermore, the matching between pore size and nutrient molecular size plays a critical role; when pore size is comparable to molecular size, a size-sieving effect may occur, enhancing adsorption stability.

It should be noted that physical adsorption is reversible. When nutrient concentrations in the soil decrease, adsorbed nutrients can be released via desorption into the soil solution for plant uptake, constituting an important mechanism for slow nutrient release. However, due to the relatively weak binding strength, excessive soil moisture or the presence of competing ions may lead to rapid desorption, thereby reducing long-term fertilizer efficiency. Therefore, physical adsorption typically operates in conjunction with chemical bonding and ion exchange to enhance nutrient retention.

3.2. Chemical Bonding

Chemical bonding refers to the irreversible interaction between modified biochar and fertilizer nutrients, in which stable chemical bonds are formed through chemical reactions, immobilizing nutrients on the biochar surface. This mechanism significantly enhances nutrient stability, reduces nutrient loss, and represents the core process underlying long-term fertilizer efficiency. Chemical bonding mainly includes coordination complexation, precipitation reactions, and covalent or ionic bonding, and its strength depends on the surface functional groups, charge properties of modified biochar, and the chemical characteristics of the nutrients.

Coordination complexation is the dominant form of chemical bonding. Oxygen-containing functional groups, nitrogen functional groups, and metal oxide-loaded sites on modified biochar can act as ligands, forming stable coordination complexes with nutrient ions. For example, carboxyl and hydroxyl groups can form coordination bonds with PO_4^{3-}, immobilizing phosphorus on the biochar surface and reducing its leaching loss. Metal ions such as Fe^{3+} and Mg^{2+} present on metal oxide-modified biochar can also form coordination complexes with PO_4^{3-}, further enhancing phosphorus fixation.

Precipitation reactions mainly occur between biochar and nutrients such as phosphorus, calcium, and magnesium. When metal ions are present on the biochar surface, they can react with PO_4^{3-} to form insoluble or sparingly soluble phosphate precipitates. These precipitates can gradually dissolve in soil, releasing phosphorus for plant uptake, thereby achieving long-term slow-release of phosphorus.

3.3. Ion Exchange

Ion exchange is a reversible chemical process involving the exchange between exchangeable ions on the surface of modified biochar and nutrient ions in fertilizers. Through this process, nutrient ions are adsorbed onto the biochar surface while exchangeable ions are released, enabling both nutrient fixation and controlled release. The strength of ion exchange depends on the cation exchange capacity (CEC), surface charge density of biochar, and the charge and ionic radius of nutrient ions.

The ion exchange capacity of modified biochar is strongly influenced by its surface functional group composition. Acid modification increases the abundance of oxygen-containing functional groups, thereby enhancing CEC and improving the exchange capacity for cationic nutrients. In contrast, alkaline modification increases basic functional groups, enhancing the exchange capacity for anionic nutrients.

Due to its reversible nature, when nutrient ion concentrations in soil decrease, adsorbed nutrients on the biochar surface can be exchanged with other ions in the soil solution and released for plant uptake. This reversibility enables modified biochar-based controlled-release fertilizers to dynamically regulate nutrient release rates according to crop demand, allowing for more precise nutrient supply.

3.4. Physical Encapsulation

Physical encapsulation refers to the process of enclosing fertilizer nutrients within the pores or on the surface of modified biochar through specific preparation techniques, forming a protective layer that prevents direct contact between nutrients and soil solution, thereby slowing nutrient release. This mechanism relies on the well-developed pore structure and favorable shaping properties of modified biochar and is commonly observed in coated modified biochar-based controlled-release fertilizers.

During preparation, fertilizer nutrients can be uniformly mixed with modified biochar and subjected to processes such as compression molding and coating treatment, resulting in a dense encapsulation layer on the surface of fertilizer granules [9]. This layer inhibits rapid water infiltration into the granules, thereby reducing nutrient dissolution and release rates. Meanwhile, the modified biochar within the encapsulation layer can further adsorb and immobilize nutrients released from the fertilizer, achieving a dual slow-release effect through encapsulation and adsorption.

The effectiveness of physical encapsulation depends on the thickness, compactness of the encapsulation layer, and the pore structure of modified biochar. Thicker and denser layers slow water penetration and nutrient release rates. A more developed pore structure enhances nutrient adsorption and retention, further extending the release period. In addition, the degradation rate of the encapsulation layer also affects long-term fertilizer efficiency. By selecting appropriate coating materials and optimizing the ratio of modified biochar, the degradation rate can be regulated to match nutrient release with crop uptake dynamics.

4. Long Term Fertilizer Efficiency Mechanisms of Modified Biochar Based Controlled Release Fertilizers

The long-term fertilizer efficiency of modified biochar-based controlled-release fertilizers arises from a complex, multi-process synergistic system. The core lies in regulating the interfacial interactions between modified biochar and fertilizer nutrients to achieve slow nutrient release and sustained supply, while simultaneously improving soil conditions through the soil amendment functions of modified biochar, thereby optimizing crop growth and enhancing nutrient use efficiency. Ultimately, this leads to prolonged fertilizer effectiveness.

This long-term efficiency is mainly governed by three interrelated mechanisms: nutrient slow-release, soil environment regulation, and crop uptake promotion. These mechanisms interact synergistically to ensure the persistence and stability of fertilizer performance.

4.1. Nutrient Slow-Release Mechanism

The nutrient slow-release mechanism represents the core of long-term fertilizer efficiency. It is primarily achieved through interfacial interactions: physical adsorption, chemical bonding, ion exchange, and physical encapsulation between modified biochar and fertilizer nutrients. These processes regulate nutrient release rates, aligning nutrient availability with crop growth cycles, reducing nutrient loss, and improving nutrient use efficiency.

The nutrient release process can generally be divided into three stages: rapid release, slow release, and stable release. The rapid release stage occurs during the initial application period, when soil moisture is sufficient and a portion of free nutrients not adsorbed or immobilized by modified biochar rapidly dissolves into the soil solution. These nutrients are readily available for seedling uptake, meeting the early-stage nutrient demand of crops [10]. Although the release rate is relatively high, the total amount released is limited, mainly serving to alleviate nutrient deficiency during the seedling stage. Kinetic analyses indicate that the rapid dissolution of surface crystalline nutrients is the primary characteristic of this stage.

The slow-release stage occurs during the mid-term period after application. At this stage, free nutrients have largely been depleted, and nutrients retained by modified biochar through physical adsorption, chemical bonding, and ion exchange begin to be gradually desorbed and released. The release rate during this stage is relatively stable, providing a sustained nutrient supply to support crop growth during critical stages such as tillering, stem elongation, and flowering.

The stable release stage occurs in the later period. At this stage, the remaining nutrient content in modified biochar decreases, and the release rate gradually slows down, yet still maintains a certain level to meet nutrient demands during grain filling and maturation, preventing late-stage nutrient deficiency. Nutrient release in this stage primarily depends on the gradual decomposition of chemically bound nutrients and ion exchange processes, exhibiting relatively stable release kinetics and effectively extending the fertilizer lifespan [11].

In addition, the pore structure and surface properties of modified biochar significantly influence the slow-release mechanism. A well-developed pore structure allows for greater nutrient storage and prolongs release duration, while abundant surface functional groups enhance nutrient binding and regulate release rates. Different modification methods lead to variations in release mechanisms; for example, acid-modified biochar primarily relies on physical adsorption and ion exchange, whereas metal oxide-modified biochar mainly depends on chemical bonding and coordination complexation.

4.2. Soil Environment Regulation Mechanism

In addition to enabling long-term nutrient release, modified biochar-based controlled-release fertilizers improve soil physicochemical properties and regulate soil microbial communities, thereby optimizing the soil environment for crop growth and indirectly enhancing long-term fertilizer efficiency. This mechanism mainly involves soil physicochemical improvement and microbial regulation.

Improvement of soil physicochemical properties is one of the core functions of modified biochar. With its developed pore structure, large specific surface area, and abundant functional groups, modified biochar can effectively enhance soil aeration, water retention, and nutrient retention, regulate soil pH, and remediate heavy metal contamination, thereby providing a favorable environment for crop growth [12]. Specifically, the pore structure increases soil porosity and improves aeration, facilitating root respiration and growth; the large surface area enhances water retention, reduces evaporation losses, and increases soil moisture content, which is particularly beneficial in arid and semi-arid regions; surface functional groups adsorb and retain nutrient ions, reducing leaching losses and improving soil fertility retention; additionally, modified biochar can regulate soil pH, with acid-modified biochar lowering pH in alkaline soils and alkaline-modified biochar increasing pH in acidic soils, thereby promoting neutral conditions and improving nutrient availability.

Soil microbial regulation serves as an important auxiliary mechanism for enhancing long-term fertilizer efficiency. Modified biochar provides carbon sources and habitats for soil microorganisms, promoting the growth of beneficial microbes while inhibiting harmful ones, thereby optimizing microbial community structure and enhancing microbial activity. This, in turn, facilitates nutrient transformation and cycling in soil and improves nutrient utilization efficiency. For example, carbon sources in modified biochar can stimulate the growth of beneficial microorganisms such as nitrogen-fixing, phosphate-solubilizing, and potassium-solubilizing bacteria. Nitrogen-fixing bacteria convert atmospheric nitrogen into ammonium, phosphate-solubilizing bacteria convert insoluble phosphorus into soluble forms, and potassium-solubilizing bacteria convert insoluble potassium into available forms, thereby increasing the availability of soil nutrients and providing a sustained nutrient supply for crop growth.

4.3. Crop Uptake Promotion Mechanism

The long-term effectiveness of modified biochar-based controlled-release fertilizers is ultimately reflected in the ability of crops to absorb and utilize nutrients. In addition to regulating nutrient release and improving soil conditions, modified biochar can directly promote root development and enhance nutrient uptake capacity, thereby strengthening long-term fertilizer efficiency [13]. This mechanism mainly includes root growth promotion and enhancement of nutrient uptake capacity.

Modified biochar promotes root growth by improving soil conditions and providing growth-stimulating substances, increasing root length, root-to-shoot ratio, and root surface area, thereby enhancing the spatial extent and efficiency of nutrient uptake. For instance, humic substances and amino acids present in modified biochar can act as growth stimulants, promoting root cell division and development. Improvements in soil aeration and water retention further create favorable conditions for root growth, reducing stress caused by hypoxia or drought.

At the same time, modified biochar enhances nutrient availability by regulating nutrient forms in soil, thereby facilitating plant uptake. For example, it can convert insoluble phosphorus and potassium into more available forms and immobilize ammonium nitrogen, reducing nitrogen volatilization and making nutrients more accessible to plant roots. In addition, surface functional groups of modified biochar can interact with organic acids secreted by plant roots, promoting nutrient absorption and transport.

5. Key Factors Influencing the Fertilizer Efficiency of Modified Biochar Based Controlled Release Fertilizers

The long-term fertilizer efficiency of modified biochar-based controlled-release fertilizers is influenced by multiple factors, primarily including the properties of modified biochar, fertilizer formulation and preparation processes, soil environmental conditions, and crop types. These factors interact with each other and collectively determine the duration and effectiveness of fertilizer performance. Identifying these key factors provides a basis for the optimization and rational application of modified biochar-based controlled-release fertilizers.

5.1. Properties of Modified Biochar

The properties of modified biochar are the core factors affecting long-term fertilizer efficiency, including specific surface area, pore structure, surface functional group composition, ion exchange capacity, and modification method. A larger specific surface area and more developed pore structure result in greater nutrient adsorption capacity and a longer nutrient release period. A higher abundance and activity of surface functional groups enhance chemical bonding and ion exchange interactions with nutrients, leading to more effective nutrient fixation and improved long-term performance. Higher ion exchange capacity further strengthens the dynamic adsorption and release of nutrient ions, enabling sustained nutrient supply.

Biochar prepared using different modification methods exhibits significant variations in properties and, consequently, in long-term fertilizer performance. Chemically modified biochar generally has higher functional group density and ion exchange capacity than physically or biologically modified biochar, resulting in stronger nutrient fixation and slower release, and thus a longer fertilizer lifespan. Physically modified biochar primarily relies on pore structure optimization for nutrient release and typically exhibits a shorter effectiveness period [14]. Biologically modified biochar shows intermediate performance between physical and chemical modification but offers better environmental compatibility.

In addition, the particle size of modified biochar also affects long-term efficiency. Smaller particle sizes provide larger specific surface areas and greater contact with nutrients, improving adsorption and fixation. However, excessively small particle sizes may lead to aggregation, which reduces the effectiveness of pore structures.

5.2. Fertilizer Formulation and Preparation Processes

Fertilizer formulation and preparation processes directly affect nutrient content, release rates, and long-term performance. In formulation design, the ratio of modified biochar to fertilizer nutrients is critical. Excessively high biochar content may result in insufficient nutrient supply to meet crop demands, whereas excessively low biochar content limits nutrient adsorption and retention, hindering effective slow-release performance.

Preparation processes mainly influence the interaction between modified biochar and nutrients, the encapsulation effect, and particle morphology. Common preparation methods include blending and granulation, coating, and impregnation [15]. These methods differ significantly in their slow-release performance. Coating methods form a protective layer that effectively slows nutrient release and extends fertilizer duration, although they are relatively complex and costly. Blending and granulation methods are simple and cost-effective but often result in weaker interactions between biochar and nutrients, leading to relatively poorer slow-release performance. Impregnation methods allow nutrients to penetrate into the pore structure of biochar, enhancing adsorption and retention, with performance generally between coating and blending methods. In addition, preparation parameters such as temperature, pressure, and reaction time can influence the interfacial interactions between modified biochar and nutrients, thereby affecting long-term fertilizer efficiency.

5.3. Soil Environmental Conditions

Soil environmental conditions are important external factors affecting nutrient release and long-term fertilizer performance, including soil temperature, moisture, pH, and texture. Increased soil temperature accelerates nutrient dissolution and desorption, as well as interfacial reactions between biochar and nutrients, thereby increasing release rates and shortening the fertilizer duration. Appropriate soil moisture levels facilitate nutrient dissolution and diffusion, improving plant uptake while enhancing nutrient adsorption and retention by modified biochar, thus promoting long-term efficiency. Excessive moisture leads to rapid nutrient leaching and reduced effectiveness, whereas insufficient moisture slows nutrient dissolution and limits crop uptake.

Soil pH influences the surface charge properties of modified biochar and the chemical forms of nutrients, thereby affecting release behavior. Neutral soil conditions favor stable interfacial interactions and optimal long-term performance. In acidic soils, negatively charged biochar surfaces enhance adsorption of cationic nutrients, slowing release but potentially causing precipitation of nutrients such as phosphorus and calcium, reducing their availability. In alkaline soils, positively charged surfaces enhance adsorption of anionic nutrients but may increase nitrogen volatilization, negatively affecting fertilizer performance.

Soil texture also plays a significant role. Clay soils, with low aeration and high water retention, tend to exhibit slower nutrient release and longer fertilizer duration but may lead to nutrient accumulation. Sandy soils, with high aeration and low water retention, are prone to nutrient leaching and shorter fertilizer duration; the application of modified biochar-based fertilizers can significantly improve nutrient retention and extend effectiveness. Loamy soils, with balanced aeration, water retention, and fertility, provide the most favorable conditions for nutrient release and crop uptake, resulting in optimal long-term performance.

5.4. Crop Types

Crop types differ significantly in growth cycles, nutrient demand patterns, and root uptake capacity, thereby influencing the long-term performance of modified biochar-based controlled-release fertilizers [16]. Crops with longer growth periods require sustained nutrient supply and are better suited to fertilizers with extended release durations, ensuring nutrient availability throughout the entire growth cycle. In contrast, crops with shorter growth periods have more concentrated nutrient demands during early and mid-growth stages and are better matched with fertilizers of moderate release duration to avoid nutrient waste.

Root system characteristics also play a critical role. Crops with well-developed root systems and higher root-to-shoot ratios have greater nutrient uptake capacity and can more effectively utilize nutrients released from modified biochar-based fertilizers. Conversely, crops with shallow or less developed root systems have limited nutrient uptake capacity and require fertilizers with relatively faster release rates to ensure sufficient nutrient availability during early growth stages.

6. Conclusions

Modified biochar-based controlled-release fertilizers, as a new class of green fertilizers, offer a promising solution to overcome the limitations of conventional chemical fertilizers. Owing to their multiple advantages, including controlled nutrient release, soil improvement, and carbon sequestration with emission reduction, they provide an effective pathway toward sustainable agricultural development.

The interfacial interaction mechanisms primarily involve physical adsorption, chemical bonding, ion exchange, and physical encapsulation. These processes act synergistically to achieve nutrient fixation and gradual release. The long-term fertilizer efficiency is governed by the coordinated effects of nutrient slow-release, soil environment regulation, and crop uptake promotion, enabling sustained nutrient supply, improved soil conditions, and enhanced nutrient uptake capacity, thereby prolonging fertilizer effectiveness and improving nutrient use efficiency.

The long-term performance of modified biochar-based controlled-release fertilizers is influenced by multiple factors, including the properties of modified biochar, fertilizer formulation and preparation processes, soil environmental conditions, and crop types. Understanding the roles and interactions of these factors provides a scientific basis for the optimization and rational application of such fertilizers.

With continued advances in research and technological development, modified biochar-based controlled-release fertilizers are expected to achieve large-scale and industrialized application. They hold significant potential for increasing crop yields, improving soil quality, reducing environmental pollution, and promoting sustainable agricultural development, thereby providing strong support for high-quality agricultural development.

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