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Research Progress on Activation and Modification Techniques of Humic Acid

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ABSTRACT

Humic acid is a naturally occurring organic substance found extensively in soils, coal, and peat, characterized by a complex molecular structure with abundant functional groups. Recent advancements in activation and modification techniques, such as oxidation, alkalization, and biological modification, have significantly enhanced the solubility, stability, and bioactivity of humic acid. These techniques have broadened its applications in agricultural productivity, soil improvement, and environmental protection. This review summarizes the principles and effects of various activation and modification techniques and discusses their roles in agriculture and environmental management. It also highlights the current achievements and limitations in the field, as well as potential directions for future research on humic acid activation and modification.

KEYWORDS

Humic acid; Activation techniques; Modification techniques; Soil improvement

1. INTRODUCTION

Humic acid (HA) is a complex natural organic macromolecule widely present in soils, coal, peat, and other natural environments. As a resource rich in multiple functional groups—such as hydroxyl, carboxyl, and ketone groups—it plays a significant role in improving soil structure, promoting plant growth, enhancing fertilizer efficacy, and in the fields of water purification and heavy metal remediation. With the advancement of modern agriculture and environmental science, conventional forms of humic acid products reveal limitations, such as poor solubility and low bioactivity, which restrict their effectiveness in addressing contemporary agricultural and environmental needs. Consequently, research on the activation and modification of humic acid has garnered significant interest to enhance its applicability across different fields.

The purpose of this review is to provide a comprehensive overview of the latest research on humic acid activation and modification technologies, including various methods, mechanisms, and practical applications in agriculture and environmental management. This review also aims to offer theoretical and technical support for future development in humic acid-based applications.

2. MAIN BODY

2.1. Structure and Functional Characteristics of Humic Acid

Humic acid molecules have a complex structure rich in aromatic rings and various functional groups, such as hydroxyl, carboxyl, and ketone groups. These groups impart HA with high reactivity, enabling it to bind with soil cations or pollutants through chelation, adsorption, and ion exchange mechanisms. These structural characteristics contribute to HA’s unique ability to improve soil structure, increase nutrient availability, promote plant growth, and boost stress resistance. Activation and modification of humic acid primarily aim to enhance these properties, making HA more suitable for agricultural yield enhancement and environmental restoration.

2.2. Activation Techniques for Humic Acid

Activation techniques for HA include oxidation, alkalization, and oxidation-alkalization combinations, each altering HA’s molecular structure and functional groups to improve solubility, stability, and bioactivity.

2.2.1. Oxidation Activation

Oxidation activation utilizes oxidants, such as hydrogen peroxide or potassium permanganate, to induce oxidative reactions in HA molecules, improving solubility and reactivity. Research has shown that oxidation leads to molecular fragmentation in HA, creating more active sites and increasing its capacity to bind with heavy metals or pollutants. For instance, oxidation treatment significantly enhances HA's water solubility and metal adsorption properties, making it highly effective in heavy metal pollution remediation. Oxidized HA not only improves soil structure and nutrient absorption but also aids in adsorbing and immobilizing pollutants in soil and water.

2.2.2. Alkaline Activation

Alkaline activation typically involves the use of basic substances, such as sodium hydroxide, to ionize carboxyl and phenolic hydroxyl groups within HA, forming water-soluble HA salts. Studies show that alkalized HA has significantly increased solubility, making it suitable for use in liquid fertilizers, irrigation, and soil amendments. The alkalization process enhances HA’s chelating properties, improving the bioavailability of trace elements in soils. Alkalized HA performs well in promoting crop growth and stress resistance, particularly in enhancing drought resistance and modifying saline soils.

2.2.3. Oxidation-Alkalization Combined Activation

The oxidation-alkalization combined activation method integrates the advantages of both oxidation and alkalization techniques, significantly improving HA’s solubility and bioactivity. Studies have shown that this combined treatment can increase HA solubility by over tenfold, significantly enhancing its agricultural and environmental applications. For example, when applied to soil, HA produced through oxidation-alkalization can increase nitrogen utilization rates by over 20%, mitigating nitrogen leaching losses. This method is widely used to produce slow-release fertilizers, extending the duration of fertilizer effects, reducing application frequency, and improving nitrogen efficiency.

2.3. Modification Techniques for Humic Acid

Modification techniques for HA focus on enhancing its stability, efficacy, and suitability for specific environments through physical, chemical, and biological methods.

2.3.1. Chemical Modification

Chemical modification introduces new functional groups into the HA molecular structure to enhance stability and adsorption properties under specific conditions. Common chemical modification methods include nitration, metal chelation, and graft copolymerization. Nitrated HA improves nitrogen retention and slow-release properties, making it more effective in fertilizers; metal-chelated HA increases the bioavailability of trace elements in soil, making it ideal for nutrient-poor soils.

2.3.2. Physical Modification

Physical modification includes microwave, ultrasonic, and nanocomposite techniques, which alter the molecular weight, microstructure, and particle size of HA to enhance its adsorption and chelating capacity. Microwave and ultrasonic treatments alter HA's molecular structure and weight distribution, improving its soil mobility and adsorption. Nanocomposite modification, in which HA is combined with nanoparticles, significantly enhances its effectiveness in water and soil pollution remediation.

2.3.3. Biological Modification

Biological modification uses microbial fermentation and other biological methods to activate HA, releasing and enhancing active components within the HA molecular structure. Studies indicate that biologically modified HA performs well in plant growth regulation and soil microbial community optimization. In the remediation of saline soils and heavy metal-contaminated soils, biologically modified HA significantly promotes root growth and stress resistance, contributing to crop yield and quality improvement.

2.4. Applications of Activated and Modified Humic Acid

2.4.1. Agricultural Applications

In agriculture, HA is primarily used to improve soil properties and boost crop yields. Activated HA can improve soil structure, regulate nutrient availability, and enhance plant resistance to stress, significantly increasing crop growth rates. For example, in saline-alkali soil remediation, activated HA can lower soil pH, increase organic matter content, and improve soil fertility, resulting in increased crop yields. In heavy metal-polluted soils, HA effectively adsorbs heavy metals, reducing their bioavailability and mitigating toxicity to crops.

2.4.2. Environmental Protection Applications

HA-modified products exhibit superior adsorption and chelation abilities, making them highly effective for water pollution control and heavy metal wastewater treatment. Activated HA has a significantly higher adsorption capacity than untreated HA and demonstrates excellent removal of heavy metals, such as lead and copper, from water. Furthermore, HA can be used as an ecological restoration material for abandoned mining areas and contaminated soils, aiding in ecological restoration and promoting the reestablishment of balanced ecosystems in degraded environments.

3. CONCLUSION

The activation and modification of humic acid play a vital role in enhancing its functional properties and expanding its application scope. Techniques such as oxidation, alkalization, and biological modification significantly increase HA's solubility, stability, and bioactivity, enabling it to be effectively applied in agriculture, soil improvement, and environmental remediation. However, challenges remain, such as the high costs and complexities of certain modification processes, limiting large-scale application. Future research should focus on developing more environmentally friendly and cost-effective activation methods, as well as investigating the molecular structure-activity relationship of HA to further enhance its application potential and provide more effective solutions for modern agriculture and environmental protection

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