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Advances in the Application of Humic Acid in Agriculture: Impacts on Soil Fertility, Crop Growth, and Carbon Emissions

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ABSTRACT

This review explores the application of humic acid in agricultural systems, focusing on its impact on soil fertility, chemical properties, biological activity, crop growth, and carbon emissions. Humic acid enhances the stability and diversity of organic matter in the soil, improves soil structure, and increases nutrient availability. Research shows that humic acid significantly promotes crop growth, boosts yield and quality, and reduces CO_2 emissions in agricultural systems. Through various activation methods, the effectiveness of humic acid can be optimized, further advancing its role in soil improvement and sustainable agriculture.

KEYWORDS

Humic Acid; Soil Fertility Improvement; Carbon Emission

1. INTRODUCTION

Global warming has become a major environmental issue facing humanity today. Since the Industrial Revolution, the excessive reliance on fossil fuels such as oil and coal, along with large-scale deforestation, has significantly increased the concentration of carbon dioxide (CO_2) in the atmosphere, leading to a cumulative greenhouse effect that exacerbates global climate warming [1]. The greenhouse effect not only affects the balance of global ecosystems but also directly threatens human survival. According to research by Charkovska et al. [2], greenhouse gases in the atmosphere primarily consist of CO_2, methane (CH_4), and nitrous oxide (N_2O), with CO_2 contributing the most, accounting for over 80% of the greenhouse effect.

As an integral part of terrestrial ecosystems, farmland systems are not only significant participants in the global carbon cycle but also a major source of CO_2 emissions. CO_2 flux in agricultural soils mainly stems from root respiration, microbial activity, and the mineralization of soil organic matter. Additionally, agricultural practices, especially excessive fertilizer application and tillage, make farmland systems a significant source of atmospheric CO_2. Statistics indicate that carbon emissions from global farmland ecosystems account for approximately 25% of CO_2 emissions from human activities [2], with agricultural management practices such as fertilization and tillage having a notable impact on CO_2 emissions. In recent years, the overuse of fertilizers in agricultural production has degraded soil quality, leading to problems such as acidification, salinization, and compaction, which not only limit farmland productivity but also exacerbate greenhouse gas emissions, threatening the sustainability of agriculture.

In this context, reducing CO_2 emissions from agricultural soils and enhancing soil carbon sequestration capacity has become a critical goal in addressing climate change and achieving sustainable agriculture. Humic acid, as a core component of soil organic matter, can stimulate crop growth, enhance stress resistance, improve soil physical and chemical properties, enhance agricultural product quality, and increase fertilizer utilization. Studies have shown that raw humic acid applied directly to the soil has limited impact and slow efficacy compared to “activated” humic acid. Activated humic acid, transformed into a free or water-soluble state, demonstrates better performance [3]. Activation methods for humic acid primarily include physical, chemical, and biological techniques [4, 5], which break carbon chains, reassemble branch chains, and increase activity. Currently, industrially utilized mineral humic acid activation methods include mechanical activation, ultrasonic activation, and chemical activation. Research has shown that mechanical activation increases fulvic acid content in humic acid, ultrasonic activation enhances the total acidic functional groups, and chemical activation lowers molecular weight and modifies flocculation limits, altering the structure of humic acid. Chemical activation methods for humic acid include alkaline activation and oxidative activation, where the former enhances solubility by producing humate salts, and the latter uses strong oxidants such as nitric acid, hydrogen peroxide, and sulfuric acid to increase chemical and biological activity. Different activation methods influence the activation process and products of humic acid, thereby affecting crop growth differently. While research on humic acid’s effects on crop growth is abundant, the impact of various activated humic acids on plant growth characteristics is rarely reported. Building on previous studies, this paper uses two different chemically activated humic acids (alkaline and oxidative activation) and raw humic acid as test materials to compare their effects on plant growth, aiming to provide references for developing highly efficient activated humic acid fertilizers.

2. RESEARCH PROGRESS

As a new type of organic fertilizer, humic acid has been widely studied and applied globally in recent years. Research on its application effects has primarily focused on humic acid’s contribution to improving soil fertility, promoting crop growth, and supporting environmentally friendly agricultural production. The following highlights the main research progress areas regarding the application effects of humic acid fertilizers:

2.1. Improvement of Soil Fertility by Humic Acid

Humic acid, an essential organic substance in soil, contains various active groups such as carboxyl, phenolic hydroxyl, and quinone groups. These groups engage in complex adsorption and complexation reactions with minerals and metal ions in the soil, enhancing soil physical and chemical properties. Studies show that applying humic acid fertilizer can significantly improve soil structure, increase water-stable aggregate content, and enhance soil water and nutrient retention capacity. Furthermore, the colloidal structure of humic acid, with its amorphous form, stabilizes compounds with soil minerals, improving aeration, increasing porosity, and reducing bulk density, making soil more suitable for root growth.

Moreover, long-term humic acid fertilizer application has shown notable effects on infertile soil. Studies indicate that continuous humic acid application on barren soils significantly increases organic matter content, enhances water retention, and improves nutrient supply. For example, long-term trials on poor soils in northeastern and southern China have demonstrated humic acid fertilizer’s effectiveness in enhancing soil properties, reducing bulk density, and increasing fertility, resulting in higher crop yields. These findings underscore humic acid fertilizer’s promising potential for soil improvement.

2.2. Regulation of Soil Chemical Properties by Humic Acid

Soil chemical properties, including organic matter content, nutrient availability, and pH, directly impact crop growth and soil fertility. Humic acid, rich in organic acids, enhances nutrient availability through complexation and chelation. For instance, humic acid can form complexes with phosphorus and potassium, increasing their availability, reducing phosphorus fixation, and improving phosphorus fertilizer utilization. Additionally, humic acid significantly raises exchangeable potassium content, boosting potassium fertilizer efficiency and promoting potassium absorption in crops .

Humic acid fertilizer also regulates soil pH, particularly effective in saline-alkaline and acidic soil improvement. By forming a buffering system through cation complexation, humic acid improves saline-alkali soil structure, promoting organic matter transformation and nutrient release. Furthermore, humic acid application reduces soil electrical conductivity, minimizes nutrient leaching, and enhances fertility. These studies provide robust evidence for humic acid fertilizer’s application in improving saline-alkali soils and enhancing soil chemical properties.

2.3. Enhancement of Soil Biological Activity by Humic Acid

Soil microorganisms and enzymes play essential roles in organic matter decomposition, nutrient cycling, and nutrient absorption in plants. Humic acid fertilizers significantly boost soil microbial activity, increasing diversity and abundance. Studies show humic acid fertilizers increase bacterial, fungal, and actinomycete populations, enhancing microbial activity. These microbes accelerate organic matter decomposition, release nutrients for plants, promote organic matter accumulation, and improve soil structure.

Humic acid fertilizers also elevate soil enzyme activity, particularly phosphatase, sucrase, and peroxidase. These enzymes are critical in organic matter decomposition and nutrient transformation, expediting the cycling of carbon, nitrogen, and phosphorus, thereby boosting soil fertility. Research demonstrates significant increases in soil enzyme and microbial activity following humic acid fertilizer application, enhancing nutrient cycling.

2.4. Promotion of Crop Growth and Yield by Humic Acid

Extensive research shows that humic acid fertilizer application significantly promotes crop growth, yield, and quality. Humic acid stimulates root development and enhances nutrient and water absorption, increasing biomass and yield. For instance, humic acid application increases chlorophyll content and strengthens cotton root development, improving fiber quality and yield. Humic acid also increases dry matter accumulation and grain yield in cereals like wheat and maize.

Humic acid fertilizer’s quality-enhancing effects on crops are widely recognized. Research indicates that humic acid fertilizer raises soluble sugar and protein content, improving the quality of vegetables and fruits. Moreover, humic acid enhances crop resistance to diseases and stresses, reducing pesticide use, lowering production costs, and increasing crop market value.

2.5. Impact of Humic Acid on Soil Carbon Emissions

With increasing concern over climate change, soil carbon emissions in farmland ecosystems have gained widespread attention. Humic acid application not only improves soil structure and organic carbon content but also inhibits organic matter mineralization, reducing CO_2 emissions. Studies show humic acid fertilizer effectively lowers soil organic carbon mineralization rates, reducing CO_2 emissions while increasing active organic carbon content [6]. Furthermore, humic acid promotes crop photosynthesis, increasing CO_2 absorption and enhancing farmland ecosystems’ carbon sequestration.

2.6. Limitations and Future Directions in Existing Research

While current research demonstrates humic acid fertilizer's significant role in improving soil structure, increasing crop yield, and reducing carbon emissions, several key issues remain unresolved. For instance, the effects of various application methods and dosages of humic acid fertilizer on soil carbon fluxes are unclear. Furthermore, humic acid fertilizer's effectiveness varies across climates and crop types. Future research should further investigate the mechanisms of humic acid in diverse farmland ecosystems, optimize fertilizer management to maximize its carbon reduction and sequestration effects.

3. CONCLUSION

As an effective soil conditioner, humic acid demonstrates substantial contributions to soil fertility and crop growth in agricultural production. While existing research confirms humic acid's benefits in enhancing crop yield and soil structure, its specific mechanisms and optimal application strategies require further investigation. Future research should focus on humic acid's impact in different farmland systems and explore the effects of various activated humic acids on plant growth to optimize its productivity under global climate change. Promoting humic acid application can not only support environmentally friendly agricultural development but also offer new solutions for global carbon cycle management, achieving both ecological and economic benefits.

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