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Land Desertification Management from a Cross-Disciplinary Perspective: Enhancing Sustainable Land Development through Integrated Biological Management Techniques

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Abstract: Land desertification is a significant ecological degradation phenomenon that threatens human survival and health worldwide. The primary factors contributing to land desertification include vegetation loss, soil nutrient depletion, bare soil surfaces, wind and water erosion, and the consequent decline in land productivity. Controlling and reversing land desertification is a critical ecological challenge faced by countries globally. Among various strategies, biological interventions that curb the desertification process and enhance the self-regulation capacity of land ecosystems are considered essential tools for global desertification control and research. This review focuses on the mainstream technologies currently employed in the biological control of desertification, including soil microbial technologies, genetic engineering for plant improvement, and intelligent irrigation systems. Furthermore, it proposes a comprehensive application framework for integrating these technologies to effectively combat desertification.

Keywords: Land desertification; biological management; soil microorganisms; genetically engineered plants; intelligent irrigation systems.

1. Introduction

Land desertification is a widespread ecological disaster occurring at a global scale. It is driven by both natural factors and human activities that accelerate land degradation and ultimately convert productive land into desert[1]. Desertification threatens global biodiversity, reduces vegetation cover, degrades soil structure[2], intensifies water scarcity, and negatively affects human health. The main manifestations of desertification include reduced vegetation, loss of soil nutrients, exposure of bare soil surfaces, intensified wind and water erosion, and the decline of land productivity[3]. The process is influenced by both natural and anthropogenic drivers. Climatic factors such as rising temperatures and increasing drought frequency accelerate degradation, while human pressures—including overgrazing, deforestation[4], and soil salinization from poor irrigation practices[5]—further exacerbate it.

This article focuses on three major areas of biotechnological advancement for desertification control: soil microbial technologies, genetic engineering for plant improvement, and intelligent irrigation systems. Soil microorganisms promote plant growth and ecosystem stability through

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symbiotic interactions with roots[6]. Genetic engineering enhances plant physiological traits, improving drought and saline-alkali tolerance for survival in stressed environments. Intelligent irrigation systems optimize water delivery by monitoring soil moisture and plant demand, enabling the efficient use of limited water resources. This review analyzes recent progress in these technologies, discusses current challenges, and offers perspectives for advancing desertification control. The integrated application of microbial, genetic, and irrigation innovations is likely to provide a more comprehensive and sustainable solution to land desertification.

2. Discussion and Perspectives for Enhancing Sustainable Land Development through Integrated Biological Management Techniques

This article discussed three key technologies for controlling land desertification: soil microbial applications, genetic engineering of plants, and intelligent irrigation systems.

Soil microorganisms are central to maintaining soil stability and integrity. They serve as critical connectors between aboveground vegetation and belowground processes in terrestrial ecosystems. With advancements in molecular biology, particularly the widespread application of high-throughput sequencing technologies, our understanding of soil microbial communities has become significantly more comprehensive. Soil microflora can exert both positive and negative effects on plant growth. Positive effects occur when beneficial microbes suppress pathogens and support plant health, whereas dominance of pathogenic microorganisms leads to growth inhibition.

In recent years, scientific research has increasingly focused on the effects of tebuconazole application on soil bacterial diversity and soil enzyme activity[7], as well as on the impacts of salt-tolerant bacteria on soil fertility[8]. Findings indicate that neutral or positive soil microbial effects tend to dominate under conditions of low soil fertility, whereas negative impacts on soil microorganisms become more prominent as soil fertility increases. Additionally, recent studies have shown that in communities with lower plant diversity, plants are more susceptible to the influence of specific pathogens, while pathogen impacts tend to diminish as plant richness increases[9].

Researchers have also explored the effects of various factors, such as thinning[10] and edge effects[11], on soil microbial communities. Compared with natural forests, plantation forests are more prone to fires and other natural disturbances due to over-cultivation. Furthermore, nutrient cycling and material flow within plantations often enter a negative feedback loop; as forest stands age, nutrients from the litter layer are not effectively transferred back to the soil surface. Therefore, improving plantation quality and stand structure through thinning is critical for sustainable forestry management. Thinning increases essential soil nutrients (N, P, K), reduces competition for resources, and enhances forest growth. Agricultural intensification may amplify edge effects, but their extent and impacts on belowground agricultural ecosystems remain poorly understood and require further study.

Various types of microplastics, including low-density polyethylene, polyamide, polystyrene, polyhydroxyalkanoate, polybutadiene styrene, and polylactide, have been studied for their impacts on soil ecosystems. Soil microorganisms play critical roles in the carbon and nitrogen cycles through processes such as immobilization, degradation, ammonification, nitrogen fixation, nitrification, and denitrification. Microplastics may affect greenhouse gas emissions by altering carbon and nitrogen cycling. They can change microbial gene abundance, community structure, and soil respiration, with potential implications for climate change.

This review also discussed the effects of different pest control methods[12], composting methods[13], irrigation methods[14], herbicides[15], and environmental stresses[16] on soil microorganisms. Among current research findings, reductive soil pest control has been shown to be an effective agricultural strategy for improving soil quality, restructuring microbial communities, and promoting plant growth in degraded soils. This approach stimulates the proliferation of beneficial microbial communities, thereby enhancing soil health and increasing plant disease resistance. Additionally, the large-scale application of earthworm compost and mushroom residue

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has been found to increase the availability of soil nutrients and enhance the diversity of soil bacterial communities in grassland ecosystems, contributing to the sustainable development of agricultural systems. Winter irrigation quotas have also demonstrated multiple positive effects on the soil microenvironment, effectively promoting plant growth while improving soil health.

The application of genome editing tools in crop improvement to increase yield, enhance nutritional value, improve quality, and confer resistance to biotic and abiotic stresses represents a critical area of GeEd technology for enhancing plant resilience[17]. Among these tools, CRISPR/Cas9 has been extensively studied for plant GeEd and stress resistance improvement. Current research primarily focuses on drought resistance, salt and alkali resistance, disease resistance, and the coordinated enhancement of multiple stress tolerances[18]. However, several challenges remain. Delivering genome-editing reagents is limited by the rigidity of plant cell walls and genomic complexity[47]. Regenerating edited protoplasts remains difficult, and effective regeneration protocols exist for only a few forest tree species[48]. Additionally, many existing methods still rely on tissue culture to regenerate plants from edited cells, a process that can be time-consuming for many plant species[19].

At present, there are limited reports on the integration of biotechnology with intelligent irrigation systems. However, the use of computing power derived from large-scale datasets for computer vision and artificial intelligence is expected to become increasingly common in future agricultural production and management[20]. Artificial intelligence and computational tools can improve the efficiency, scalability, and robustness of agricultural automation systems. The integration of advanced technologies such as deep learning and spectral analysis will further enhance the intelligence of agricultural automation equipment and systems, thereby improving land productivity and quality[21]. A major challenge is the need for continuous and stable internet connectivity, which is often lacking in rural areas of developing countries where crop production demand is high. Overcoming this barrier will be essential for the widespread adoption of intelligent systems in agricultural management[22]. Future agricultural and land management will require the integrated application of soil microbial technologies, plant genetic engineering, and intelligent irrigation systems (Figure 1).

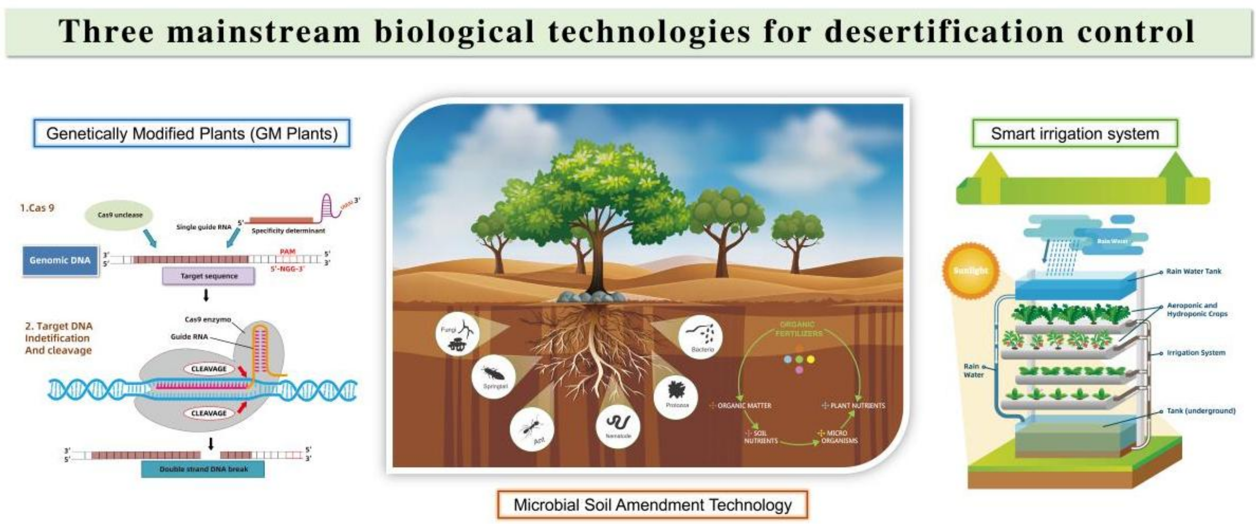

Figure 1.Three mainstream biological technologies for desertification control in the future research

Declaration of Competing Interest

There exist no competing interests.

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