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Research Progress on the Impact of Soil Temperature Control Systems on Soil Physicochemical Properties and Crop Growth

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Abstract

Soil temperature is one of the key factors affecting soil ecosystems and crop growth. In recent years, the application of Soil Temperature Control Systems (STCS) has gradually increased in agriculture and protected cultivation, improving soil environments and optimizing crop growth conditions through active regulation of soil temperature. This paper reviews the technical types of STCS, their regulatory effects on soil physicochemical indicators (temperature, humidity, nutrients, microorganisms, etc.), and their mechanisms of influence on crop physiological metabolism, yield, and stress resistance. It summarizes the current research deficiencies and outlines future development directions.

Keywords

Soil Temperature Control System, soil physicochemical properties, crop growth, research progress.

1. Introduction

Soil temperature is a crucial parameter in the Soil-Plant-Atmosphere Continuum (SPAC), directly affecting soil biochemical reaction rates, microbial activity, root development, and crop growth cycles. Under natural conditions, soil temperature is constrained by factors such as climate, vegetation cover, and soil texture, making it difficult to meet the demands of high-value crops or off-season cultivation. Soil Temperature Control Systems (STCS) actively regulate the soil thermal environment through artificial heating, cooling, or insulation technologies and have been widely applied in greenhouse agriculture, cultivation in alpine regions, and precision agriculture. This paper systematically analyzes the impact of STCS on soil physicochemical properties and crop growth, providing a theoretical basis for optimizing agricultural temperature control technologies.

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2. Organization of the Text

2.1. Technical Principles and Classification of Soil Temperature Control Systems

2.1.1. Main Working Principles and Technical Types Soil Temperature Control Systems

primarily consist of three components: temperature sensors, controllers, and actuators. Temperature sensors monitor soil temperature in real-time and transmit data to the controller; the controller issues commands to the actuator based on preset temperature ranges; and the actuator adjusts soil temperature through heating or cooling devices. Based on different working principles, STCS can be classified into heating systems, cooling systems, and heating-cooling hybrid systems. Heating systems are mainly used in cold seasons or regions to increase soil temperature through heating devices; cooling systems are suitable for hot seasons or regions to reduce soil temperature through cooling devices; and heating-cooling hybrid systems have both heating and cooling functions, allowing flexible adjustment of soil temperature according to actual needs. (1) Geothermal utilization systems: regulate soil temperature by circulating geothermal water or refrigerant through underground pipes (e.g., geothermal heating systems in Dutch greenhouses). (2) Electric heating systems: embed heating cables made of resistance wires or carbon fibers, suitable for localized precise temperature control (e.g., electric heated beds for seedling nurseries). (3) Phase Change Material (PCM) temperature control: utilize the latent heat properties of materials like paraffin wax and fatty acids to buffer diurnal temperature fluctuations (e.g., PCM mulching technology in arid regions of northwest China). (4) Solar-driven systems: combine solar collectors with heat storage devices to achieve low-carbon temperature control (e.g., solar soil heating systems in Israel).

2.1.2. Technical Characteristics and Application Scenarios

Table 1. Technical Characteristics and Application Scenarios Technical Type

Type of technology	Temperature Control Range (°C)		
Geothermal Utilization	15~40	Medium	Large greenhouses, facility agriculture
Electric Heating	5~50	High	Seedling cultivation, experimental research
phase-change material	-10~35	Low	Open-field cultivation, water-saving agriculture
Solar-Driven	10~45	Low	Regions with abundant sunlight

2.2. Impact of Soil Temperature Control Systems on Soil Physicochemical Indicators

2.2.1. Dynamic Regulation of Soil Temperature

The core function of Soil Temperature Control Systems is precise regulation of soil temperature. Through real-time monitoring and adjustment, STCS can maintain soil temperature within the optimal range for crop growth, thereby enhancing crop growth rate and physiological activity. Studies have shown that suitable soil temperature significantly promotes the growth and development of crop roots, increasing their ability to absorb water and nutrients, and

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subsequently improving overall crop growth performance. Electric heating systems can increase surface soil temperature by 5~15℃, significantly shortening seed germination time, such as advancing the potato planting period by 7~10 days. PCM materials can reduce root zone temperature by 3~8℃ in summer, alleviating high-temperature stress, such as increasing strawberry root activity by 20%~30% [1-2].

2.2.2. Soil Microorganisms and Nutrient Cycling Soil Temperature Control

Systems have a significant impact on soil organic matter content and nutrient availability. Suitable soil temperature can stimulate soil microbial activity, accelerating the decomposition and mineralization of organic matter, thereby increasing the content of available nutrients in the soil. At the same time, STCS can also affect nutrient dissolution, diffusion, and adsorption processes by regulating soil temperature and moisture conditions, thus altering nutrient availability. Studies have shown that under suitable soil temperatures, crop absorption and utilization efficiency of nutrients significantly improve, benefiting crop growth, development, and yield enhancement. (1) Water evaporation suppression: Constant temperature control reduces soil moisture fluctuations, achieving water-saving efficiencies of 15%~25%, such as in tomato drip irrigation combined with temperature control systems. (2) Nitrogen mineralization rate: For every 1℃ increase in soil temperature, the nitrogen mineralization rate increases by about 10%, but high temperatures (>35℃) may accelerate nitrogen volatilization losses. (3) Microbial community structure: Under optimal temperature conditions (20~30℃), bacterial abundance increases, and the proportion of fungi decreases, promoting organic matter decomposition (e.g., bacterial diversity in the maize rhizosphere increases by 15%). (4) Enzyme activity response: Urease and phosphatase activities initially increase and then decrease with rising temperature, with peak activity occurring in the 25~30℃ range.

2.2.3. Soil pH and Salt Migration The impact of Soil Temperature Control

Systems on soil pH is mainly reflected in two aspects. On the one hand, by regulating soil temperature, the activity and metabolic processes of soil microorganisms can be altered, thereby affecting the decomposition of soil organic matter and the release of nutrients. The acidic or alkaline substances produced by these processes can impact soil pH. On the other hand, STCS may also affect the acid-base balance of soil solutions by altering soil moisture evaporation and infiltration processes. However, current research on the specific impact of STCS on soil pH is insufficient and requires further in-depth exploration. Long-term heating may lead to salt accumulation on the surface (e.g., soil EC values increase by 0.2~0.5 dS/m under electric heating systems), necessitating leaching measures[3-4].

2.3. Impact of Soil Temperature Control Systems on Crop Growth

2.3.1. Regulation of Crop Physiological Metabolism

Soil Temperature Control Systems have a significant impact on crop yield and quality. By optimizing the soil temperature environment, STCS can promote crop photosynthesis and material accumulation processes, increasing crop yield and quality. Studies have shown that under suitable soil temperatures, crop photosynthesis efficiency significantly improves, and dry matter accumulation increases, benefiting crop yield enhancement. At the same time, STCS can also affect crop quality indicators such as protein content, sugar content, and vitamin content by regulating soil nutrient supply and water use processes. These changes are important for improving crop nutritional value and market competitiveness. Appropriate warming (20~25℃) promotes root branching and absorption area, such as increasing cucumber root length by 30%~50%. Warming during low-temperature periods can enhance leaf RuBisCO enzyme activity, improving light energy utilization efficiency (e.g., increasing the

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photosynthetic rate of winter wheat by 15%~20%). In vineyards, controlling nighttime soil temperature (18-20℃) increases fruit soluble solids content by 2-3 Brix and anthocyanin synthesis by 15%. Lettuce grown at 20℃ soil temperature has 30% higher vitamin C content and 50% lower nitrate content compared to the control group[5-6].

2.3.2. Yield and Quality Improvement Soil Temperature Control

Systems can also regulate the crop growth period. By adjusting soil temperature, the growth rate and developmental process of crops can be altered, affecting the length of the crop growth period and the timing of various developmental stages. This is significant for meeting market demand, adjusting crop planting structures, and improving agricultural production efficiency. For example, in protected cultivation, STCS can advance or delay the time of crop market entry, satisfying consumer demand for fresh fruits and vegetables; in dryland farming, STCS can extend the crop growth period, improving crop yield and quality. STCS increases the yield of facility crops such as tomatoes and peppers by 10%~30% and enhances fruit sugar content by 1~2 Brix. Precise temperature control enables off-season market entry (e.g., strawberry prices in winter increase by 2~3 times). Geothermal systems improve the overwintering survival rate of highland barley in alpine regions from 40% to 75%. Pest and disease suppression: A constant temperature environment reduces the incidence of soil-borne diseases (e.g., the incidence of tomato wilt disease decreases by 50%)[7-8].

3. Use Cases and Challenges

3.1. Typical application cases

(1) Venlo greenhouse geothermal system in the Netherlands: the temperature of the root zone is maintained at 18~22°C throughout the year, and the annual yield of tomato reaches 70 kg/m^2.
(2) Solar temperature-controlled greenhouses in Northwest China: the minimum temperature at night in winter rises from -5°C to 8°C, and the northern boundary of wolfberry cultivation is moved northward by 200 km.

3.2. Existing problems and optimisation direction

(1) Energy consumption and economy: electric heating system has high operating costs, and low energy consumption technologies (e.g. biomass coupling system) need to be developed.
(2) Long-term ecological effect: continuous heating may destroy the balance of soil microorganisms, need to study the sustainable temperature control threshold.
(3) Intelligent upgrading: combining IoT and AI algorithms to achieve dynamic temperature control (e.g. feedback adjustment based on crop physiological signals).

4. Conclusion

Soil temperature control systems can significantly improve soil physicochemical properties and crop productivity by regulating the soil thermal environment, but their application needs to balance ecological safety and economic benefits. Future research should focus on:(1) Developing low-carbon and low-cost composite temperature control technologies; (2) Quantifying the long-term effects of STCS on soil microbial networks;(3) Constructing intelligent temperature control models based on crop needs.

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