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Cool Photonics for Sustainable Agriculture

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Abstract

High temperatures cause thermal stress, impair plant physiology, and reduce crop yield. In a recent publication in Nexus, Wang *et al*. describe a radiative cooling mulch for soil cooling. This technique increases crop yield in hot climates by alleviating thermal stress on plant roots and reducing soil evaporation, facilitating sustainable agriculture in regions prone to thermal stress.

Agriculture has played a vital role in shaping human society throughout history. However, the task of feeding a growing global population amidst the challenges of climate change is formidable. Crops, being living organisms, exhibit high sensitivity to temperature fluctuations. Exceeding the physiologically preferred temperature range leads to enzymatic inactivation, chlorophyll impairment, protein misfolding, and crop mortality[1]. Even a slight increase of 2°C in local temperature can cause significant reductions in wheat, rice, and maize yield, impacting both temperate and tropical regions[2]. The limited availability of agricultural water resources further complicates the implementation of irrigation-based adaptation strategies[1]. Therefore, optimizing temperature conditions presents a fundamental opportunity for improving crop yield during summer. However, traditional cooling methods such as air conditioning or evaporative cooling require costly infrastructure and result in significant resource consumption, whether it is energy or water. Therefore, a sustainable solution alleviating thermal stress is crucial for improving crop yield. In the recent issue of Nexus, Wang *et. al*.[3] introduced an effective approach to passively regulate soil thermal dynamics using photonic mulch films that control radiation energy and cool crop roots. The cooling mulch demonstrates the potential to promote crop growth and increase harvestable yields in hot summers by alleviating thermal stress on crop roots and reducing soil evaporation.

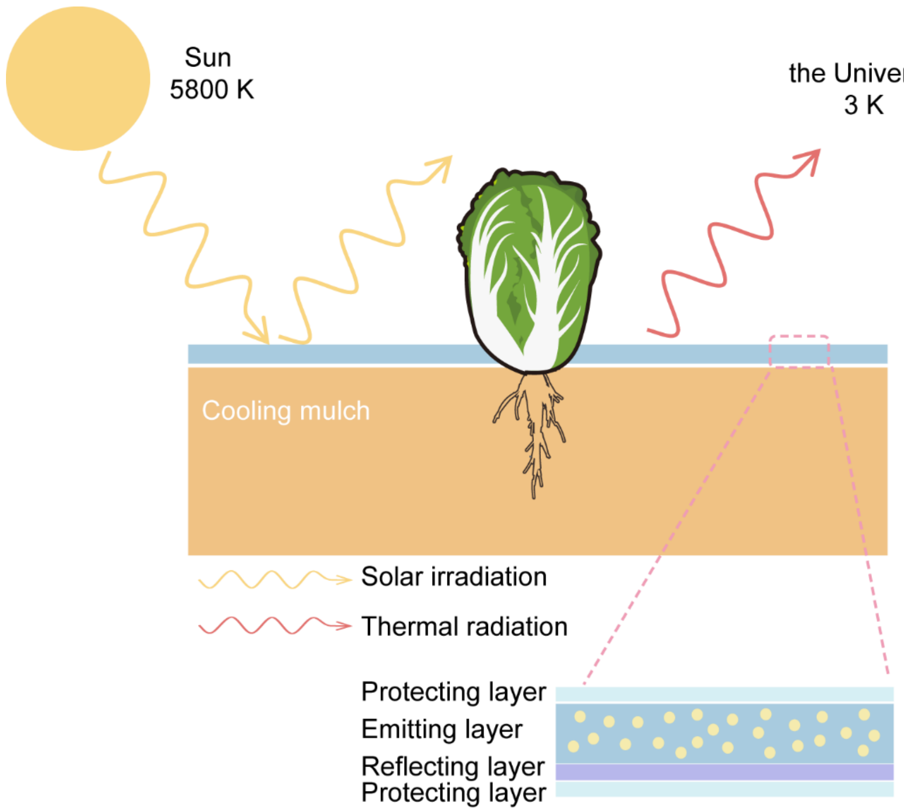

Figure 1 Schematic diagram illustrating the use of cooling mulch in agriculture.

Thermal radiation is one of the primary means of thermal energy transfer. The terrestrial radiative cooling process spontaneously dissipates heat to outer space (~3K) through infrared radiation without any additional energy input[4,5]. Previously, realizing efficient radiative cooling during daytime was challenging because common objects like soil intensively gain heat from sunlight. Recent advancements in terrestrial radiative cooling materials, particularly those scalable manufactured ones[5], have made their deployments in large-scale applications possible.

The cooling mulch used in Wang *et al.*'s study is a glass-polymer composite with glass microspheres randomly and uniformly dispersed in a polymer matrix. Due to phonon-enhanced Fröhlich resonances, the composite has high infrared emissivity in the atmospheric window (8-13 μm) while being transparent in the solar spectrum. When a back reflector is applied, it reflects most of the solar light, achieving 93% total solar reflectance and 94% emissivity in the atmospheric window (Fig. 1). This enables the mulch to maintain a relatively low temperature even in direct sunlight. The cooling mulch results in a remarkable 12.5°C decrease in soil temperatures than that under bare soil conditions, alleviating thermal stress on crop roots without requiring additional energy input. As a result of optimized surface energy flow, the soil beneath the cooling mulch maintained favourable temperature conditions for crop growth compared to bare soil and regular mulch treatments. Moreover, the application of cooling mulch resulted in a significant increase in the germination rate of cherry radish, rising from 39.6% under bare soil conditions to 81.3% following the application of cooling mulch. Field test results indicated that the cooling mulch led to an impressive 127.4% increase in the fresh weight of Chinese cabbage compared to conventional bare soil cultivation[3]. These improvements can be attributed to a reduction in root thermal stress, highlighting the potential of cooling mulch to improve agricultural productivity in hot climates. Furthermore, the study extended a global analysis to assess the suitability of cooling mulch across diverse geographical and climatic conditions. These findings revealed that cooling mulch effectively reduces soil temperatures and mitigates stress on crops in various regions, demonstrating its versatility and potential for widespread adoption. The discussion further explores the implications of this technology for sustainable agriculture, emphasizing its role in addressing the intertwined challenges of food security and water scarcity. The cooling mulch offers a cost-effective and energy-efficient method to enhance crop yield, aligning with the objectives of sustainable development.

The application of photonic cooling materials in agriculture encompasses a range of challenges and opportunities, with particular emphasis on the sector's sensitivity to cost, especially for underprivileged populations in developing regions. Innovations such as polymer-based technologies and advanced roll-to-roll manufacturing processes[6] have shown promise in reducing costs, meeting the high-volume requirements of the agriculture industry and mirroring the cost-reduction successes seen in the photovoltaics industry over the past two decades. Concurrently, environmental considerations, particularly in relation to waste management and pollution from material decomposition[7], necessitate the adoption of degradable alternatives to mitigate adverse impacts on soil health and the broader ecosystem.

Looking ahead to a sustainable agriculture system, photonic materials have the potential to make significant contributions in this field. Greenhouse facilities are a crucial element of the future agricultural system as they provide a stable environment for plant growth, allowing for year-round food production. However, the suboptimal optical properties of traditional greenhouse envelopes and lighting infrastructures result in substantial energy consumption to regulate the internal environment. By incorporating existing greenhouses with advanced photonic materials, we can reduce the excessive reliance on energy consumption. Fundamentally, photosynthesis is an optical process in which chloroplasts convert photon energy into chemical energy. Through the utilization of photonic design to optimize sunlight quantity, quality, and distribution within greenhouses, we can enhance the efficiency of photosynthesis, ultimately leading to increased agricultural output. For example, the recent work demonstrated that the incorporation of a spectral-shifting microphotonic film with specific fluorescent dyes can enhance crop yield. The film optimizes the light spectrum for photosynthesis by converting less efficient green light into more effective red light, resulting in increased crop production[8]. Another compelling example involves the implementation of luminescent solar concentrators in greenhouses. These advanced photonic materials and systems not only generate off-grid and rooftop power but also ensure the availability of abundant sunlight for optimal crop growth[9]. Moreover, our understanding of the interaction between light and crops opens up avenues for further investigations and innovations in agricultural photonics. For example, research indicates that wheat requires approximately 15 minutes to regain maximum photosynthetic efficiency after transitioning from shade to sunlight. To avert this effect, incorporating delayed persistent luminescence in the greenhouse envelope or mulch can help offset the photosynthesis lost due to cloud shading[10].

The work by Wang *et al.* serves as a catalyst to stimulate interest and intention within the scientific community to further promote advanced photonics in agriculture. The implementation of cooling mulch offers a feasible solution to the global food-water crisis and significantly contributes to the pursuit of sustainable development in agriculture. It is essential to foster interdisciplinary research teams comprising material scientists, engineers, and biologists to propel this field forward. Additionally, collaborations with policy makers, industrial producers, and farmers are necessary for successful adoption. A significant focus of future research in this field will involve investigating scalable and cost-effective methods for producing these photonic materials. In conclusion, applying photonic materials in sustainable agriculture heralds a new era of efficiency and environmental responsibility. By addressing the energy-intensive limitations of traditional greenhouse systems and enhancing the natural process of photosynthesis, photonic technologies offer a viable path toward realizing a more sustainable and productive agricultural future. This paradigm shift aligns with the global imperative of food security and embodies the principles of sustainable development, holding the promise of a harmonious coexistence between human agricultural practices and the natural environment. It is time for the global community to unite in exploring and amplifying the role of photonics and other engineering systems within agriculture, recognizing its potential to catalyse a shift towards more sustainable and productive farming methodologies.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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