Short Communication

Solar spectrum management and radiative cooling film for sustainable greenhouse production in hot climates

Hao Zou a,1, Chenxi Wang a,1, Jiaqi Yu a, Danfeng Huang b,*, Ronggui Yang c,*, Ruzhu Wang a,*

a Institute of Refrigeration and Cryogenics, Engineering Research Center of Solar Energy (Ministry of Education), Shanghai Jiao Tong University, Shanghai 200240, China
b School of Agriculture and Biology, Shanghai Jiao Tong University, Shanghai 200240, China
c State Key Laboratory of Coal Combustion, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Global food production needs to be increased by 50%–70% in the coming decades to feed the world [1]. However, more frequent weather extremes and global warming trends increase the risk of food crisis [2]. Greenhouse cultivation is regarded as one viable solution to this crisis, owing to its crop quality and quantity promotion ability with controlled microclimate. However, heat accumulation inside greenhouses is a serious obstacle for cultivation in the scenario of hot climates. Too heavy heat stress in greenhouse (even as high as 60 °C) can cause protein misfolding and harmful metabolites accumulation inside plant cells, shutting the basic physiology of crops [3]. Many areas thereby choose to stop planting during hot seasons, which cuts down the annual available time for planting in greenhouse.

Therefore, it is pivotal to cool the greenhouse in hot seasons. Among conventional greenhouse management, air temperature is often manipulated by growers. However, the effect of most of existing passive cooling methods, such as ventilation and external shading, is disappointing due to their limited cooling power. Alternative active cooling methods concerning fan-pad systems and heat pumps also show low feasibility due to their high costs and water consumption, daytime radiative cooling has attached much attention in recent years. The concept of radiative cooling is that terrestrial objects could spontaneously dump their heat to the colder outer space (~3 K) in the form of infrared thermal radiation through the atmospheric window (8–13 μm) [5]. Recent progress in nanophotonics provides spectrally selective surfaces that minimize absorption in the solar spectrum while maximizing thermal emission in the infrared region [5–9]. In the previous work, a glass-polymer hybrid metamaterial thin film which generates a noon-time radiative cooling power of 93 W/m² and forms a sub-ambient temperature about 10 °C [10] was reported. More significantly, the high-throughput and roll-to-roll manufacturing process of this metamaterial endow it with low cost and greater potential for large-scale applications such as agriculture. Herein, two specially designed radiative cooling films intended for eliminating air and soil heat stress inside greenhouse without sacrificing photosynthesis, respectively, are developed to achieve continuous agricultural production during hot seasons.

Excessive solar irradiation is the main reason for the over-temperature microclimate in greenhouse. The solar spectra entering the greenhouse consist of ultraviolet (UV), photosynthetically active radiation (PAR, 400–700 nm) that is truly needed for effective photosynthesis, and the near infrared radiation (NIR) (accounting for 50%) that undesirably heats up the greenhouse. The desirable cover material for summer cultivation is expected to block NIR to reduce temperature and heat stress while allowing PAR to pass through. This kind of NIR blocking films with selective transmission can reduce the cooling load without sacrificing photosynthesis. However, the existing visible-transparent NIR reflective materials always have high mid-infrared radiation (MIR)
Root zone temperature of plants is out of consideration in most cultivation practices, due to lack of efficient regulation strategies. However, many previous researches have clearly indicated that root zone temperature is more critical than air temperature in controlling crop growth. Partial root zone cooling can effectively help crops handle overtemperature stress, even though their aerial portions were exposed to the hot fluctuating temperatures. Root zone cooling management is reliable for mitigating heat stress in hot climates. One easy-to-think solution to this problem is mulching the soil surface to block away the solar irradiation, as excessive solar irradiation is the main source of overtemperature. Existing mulches used in agriculture are known as their warming effect during cold seasons, hiding their possible cooling effect as long as setting the right optical properties. Herein, a new soil cooling strategy with the new developed metamaterial film (RC) is proposed for agricultural cultivation in hot climates. The 90-μm-thick radiative cooling film (Fig. 1d) was made of an emission layer and a reflective layer, and then shielded with protecting layers. Distin-
guished from common plastic mulches, this mulch has an average emissivity of 0.94 within the atmospheric transmission window (8–13 μ m wavelength), and a solar reflectivity of 0.93 over the wavelength of 0.3–2.5 μ m. A sub-ambient effect of 3 °C was observed when the mulch was exposed to solar, while common mulches were heated up obviously. In an outdoor preliminary experiment, the soil temperature at 2 cm depth under the radiative cooling mulch can be reduced by 12.5 °C, compared to the case of bare soil.

After a complete planting period, the harvestable production of Chinese cabbage was increased by 127.35% in comparison to the bare soil cultivation (Fig. 1e). We believe this soil cooling strategy can improve crop growth and increase yield during hot summers, with no need for complex devices and additional energy consumption. Based on its wide applicability in different climate conditions, this radiative cooling mulch promises a new opportunity for tackling the global food crisis in face of global warming, especially for those under-developed countries whose agriculture suffers from arid hot climates. The very hot summer all around the world currently may stimulate the requirement of this new radiative cooling mulch for sustainable agriculture.

In the past few years, radiative cooling technology has emerged as a new development direction with great potential for various applications to solve the environmental problems of sustainable agriculture.
application fields. In this communication, we laid out our vision for this technology in agriculture. The considerable overall market size of the agricultural application is a valuable opportunity for daytime cooling materials and technology. While this technology could be a game changer, however, many challenges still exist before its penetration into real markets. The main roadblock to widespread acceptance of radiative cooling materials is the cost considering agriculture is a cost-sensitive sector. Many efforts have been devoted to designing cost-effective materials through large-scale fabrication technologies, such as high-throughput roll-to-roll processing [10]. Obtaining competitive prices still represents a significant challenge for radiative cooling materials in the near future. In agricultural scenario, although extended lifetimes and yield promotion release the using pressure of radiative cooling films, excessive one-time investment still hides its widely spread potential. Another concern is the unwanted surface contamination in real-world environments. Especially for field usage, solid contaminants such as dust or soil will easily accumulate on the surfaces of radiative cooling materials, leading to an obvious degradation of cooling performance. Self-cleaning materials which can potentially suppress dust and soil accumulation provide a viable solution [13]. Moreover, the performance of radiative cooling materials largely depends on the local meteorological parameters including total water vapor column, cloud coverage, and wind velocities [14]. Evaluation of the practical performance of all daytime radiative cooling methods should be location-specific and rely on massive trial testing across various sites.

For now, most radiative cooling materials are designed with static optical properties. This potentially leads to undesired cooling effects during cold winters, especially for high-latitude regions. From a photonic design point of view, switchable materials based on thermochromic or electrochromic additives represent a promising direction to dynamically regulate spectral properties in both solar and long-wavelength bands [15]. Another alternative is introducing mechanical structures which can roll up or peel off the surface radiative cooling materials according to varying external conditions. Despite needing additional components, the mechanical switching method still holds great potentials due to its high reliability and low cost. In conclusion, the radiative cooling technology is promising to shape the energy consumption of the agricultural sector in the background of global warming. Addressing the issues mentioned above will be the future research direction in this field.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Hao Zou, Chenxi Wang, Ruzhu Wang, and Danfeng Huang conceived and designed the experiment. Ronggui Yang designed, synthesized, and characterized the materials. Hao Zou, Chenxi Wang, and Jiaqi Yu processed the experimental data. Hao Zou, Ruzhu Wang, and Jiaqi Yu wrote and revised the manuscript. Ruzhu Wang conceived the research idea and led this research project. Ruzhu Wang, Ronggui Yang, and Danfeng Huang revised the manuscript and guided the overall research. All the authors discussed the results and revised the paper.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2023.06.015.

References


Hao Zou is a Ph.D. candidate at the Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University. He received his Bachelor’s degree of Agriculture from China Agricultural University in 2020. His research focuses on the food-water-energy nexus in greenhouse.

Chenxi Wang received his Ph.D. degree at Shanghai Jiao Tong University. He is now a postdoctoral research fellow at the University of Hong Kong. His research interest includes radiative cooling, water harvesting, and responsive materials.
Danfeng Huang is a professor at School of Agriculture and Biology, Shanghai Jiao Tong University. Her research interest includes the precision production technology of facility agriculture, nutritional physiology of horticultural plants and vegetable quality and safety management.

Ronggui Yang is a professor of Energy and Power Engineering, Huazhong University of Science and Technology. He was a professor of Mechanical Engineering at the University of Colorado Boulder (2006–2019) after receiving his Ph.D. degree from Massachusetts Institute of Technology in 2006. His research interest focuses on the fundamentals of transport phenomena (thermal conduction, thermal radiation, liquid–vapor phase-change heat transfer) and the applications of micro/nanotechnologies for thermal and energy systems.

Ruzhu Wang is a chair professor at Shanghai Jiao Tong University and the director of the Institute of Refrigeration and Cryogenics. He graduated from Shanghai Jiao Tong University in 1984, 1987, and 1990 with his Bachelor’s, Master’s and Ph.D. degrees, respectively. His research interest includes solar energy, heat pumps, thermal driven sorption cycles, and green building energy systems.