PRESS RELEASE

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Successful Enhancement of the Thermotolerance of Photosynthesis in Microalgae

— Toward Heat-Resilient Production of Valuable Bioproducts and Food —

1 Key Points

■ **Direct involvement of reactive oxygen species in heat inactivation of photosynthesis**

We found that, at high temperatures, large amounts of reactive oxygen species (ROS)[(1)] are generated by the electron transport system of photosynthesis[(2)]. These ROS directly damage photosystem II (PSII)[(3)] and inhibit protein synthesis[(4)].

■ **Synergistic effects achieved by simultaneously enhancing the antioxidant defense and protein synthesis capacity**

By simultaneously overexpressing ROS-scavenging enzymes (superoxide dismutase [SOD] and catalase)[(5)] and a modified, oxidation-resistant translation elongation factor (EF-Tu)[(6)], we successfully mitigated structural damage to PSII at high temperatures while maintaining a high level of synthesis of the D1 protein[(7)], which plays a central role in PSII repair[(8)].

■ **A pathway toward biomanufacturing in harsh environments and increased crop production**

We demonstrated dramatic improvements in overall photosynthetic activity and survival at high temperatures. The findings are expected to help overcome the growth inhibition of microalgae caused by rising water temperatures in outdoor cultivation ponds during summer, enabling stable production of biofuels and valuable bioproducts, and potentially contribute to improved heat tolerance in crops.

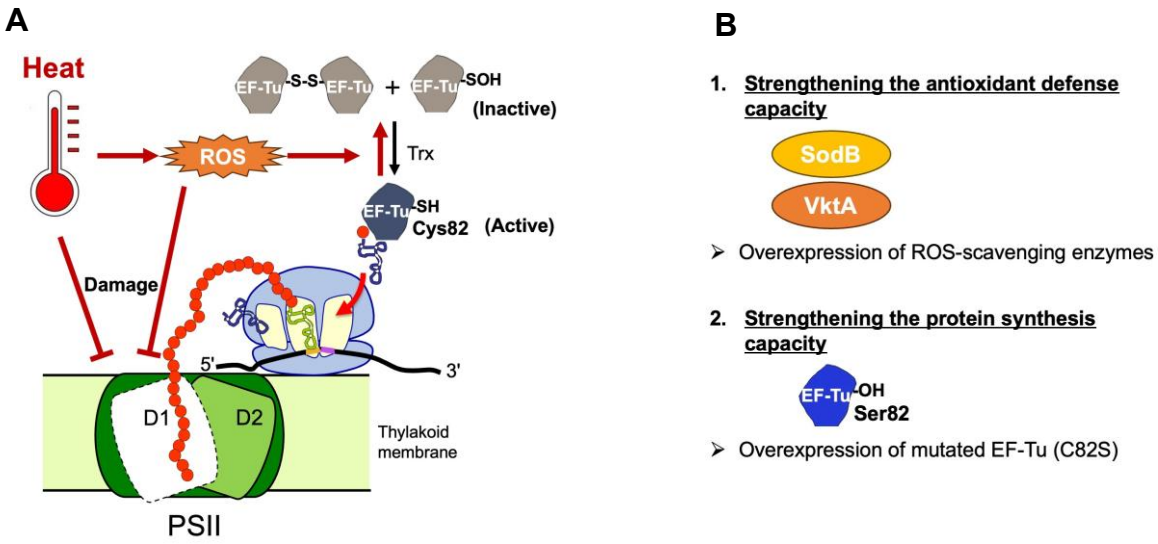


Figure 1. (A) Relationship between heat damage to photosystem II (PSII) and reactive

oxygen species (ROS). (B) Strategy for acquiring thermotolerance by simultaneously enhancing the antioxidant defense and protein synthesis capacity.

2 Overview

Professor Nishiyama and his colleagues, Graduate School of Science and Engineering, Saitama University, have developed a method to substantially improve the high-temperature tolerance of photosynthesis using cyanobacteria[9], a model microalgal organism.

Photosynthesis is extremely sensitive to heat, and photosystem II (PSII) is rapidly inactivated under heat stress. In this study, the researchers simultaneously strengthened an enzymatic system that eliminates intracellular reactive oxygen species (ROS) and the protein synthesis system (involving the translation factor EF-Tu) required to repair heat-damaged PSII. This provided "dual protection" by physically stabilizing PSII against heat-induced damage while maintaining a rapid repair cycle. As a result, they markedly suppressed the decline in photosynthetic activity at high temperatures and successfully improved the growth and survival of cells.

The findings were published online in the international plant science journal *Plant and Cell Physiology* on November 11, 2026.

Title: Simultaneous reinforcement of the antioxidant defense and translational systems enhances the thermotolerance of photosystem II in *Synechocystis* sp. PCC 6803
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3 Research Background

Photosynthesis is a fundamental biological process in which light energy is used to synthesize organic compounds from CO_2, supporting the growth and biomass production of plants and microalgae. However, photosynthesis is highly vulnerable to environmental changes, and its function declines substantially during intense summer heat and abnormally high temperatures. In particular, the PSII complex, which is responsible for water splitting and oxygen evolution, is especially heat-sensitive and has been a major bottleneck limiting overall photosynthetic capacity.

Previous research has advanced the understanding of photoinhibition of PSII (inactivation caused by strong light stress), establishing that the "D1 protein synthesis and repair cycle," which rapidly repairs damage, is essential for protection. At high temperatures, however, it has been suggested that not only the PSII complex itself undergoes physical damage, but this repair cycle is also suppressed. The detailed mechanisms underlying this inhibition and specific ways to overcome it have remained unclear.

As global warming accelerates, crop yield losses caused by summer heat waves and declines in production efficiency due to rising water temperatures in outdoor microalgal cultivation ponds have become serious global challenges. It has therefore been necessary to identify, at the molecular level, the underlying mechanism of heat-induced photosynthetic inactivation and to develop heat-tolerant organisms capable of maintaining photosynthesis at high temperatures.

4 Research Findings

4-1. Discovery of the direct involvement of ROS in high-temperature damage to photosynthesis

When the cyanobacterium *Synechocystis* sp. PCC 6803 was exposed to a high temperature (46℃), rather than its normal growth temperature (32℃), the generation of ROS originating from the photosynthetic electron transport system increased approximately fourfold in the wild-type strain. Analysis using a protein synthesis inhibitor revealed that, under heat stress, ROS directly accelerate structural damage to the PSII complex itself while also inhibiting PSII repair.

4-2. Synergistic protection through simultaneous enhancement of antioxidant capacity and protein synthesis capacity

The research group generated the following genetically modified *Synechocystis* strains and performed comparative analyses:

- ROS-scavenging enzyme-enhanced strain (*sodB*+*vktA*): Overexpresses superoxide dismutase *SodB* and *VktA*, a highly active catalase derived from *Vibrio* bacteria.
- Modified translation factor strain (C82S): Expresses a modified translation elongation factor EF-Tu[6] in which a cysteine residue[10] has been mutated to prevent oxidation by ROS.
- Dual-enhancement strain (C82S+*sodB*+*vktA*): Combines both above modifications.

The dual-enhancement strain exhibited the greatest suppression of heat inactivation of PSII at 46℃. The ROS-scavenging enzymes markedly reduced ROS accumulation and prevented the structural disruption of PSII. In synergy with the modified EF-Tu, they also maintained the capacity for *de novo* synthesis of the D1 protein, which is essential for PSII repair, at approximately 1.6 times the level of the wild-type strain.

4-3. Marked improvements in photosynthetic activity and cell survival

Through this synergistic effect, the decline in total photosynthetic activity (oxygen-evolving capacity) at 46 ℃ was substantially mitigated. Furthermore, long-term cultivation experiments under sustained heat stress (40 ℃) confirmed that the dual-enhancement strain continued to survive and proliferate over extended periods while maintaining a high cell density, even under conditions in which wild-type cells became bleached and died.

5 Future Prospects

In large-scale outdoor cultivation of microalgae for biofuels and highly valuable substances, rising temperatures in cultivation ponds during summer have been a major obstacle to production. This technology is expected to enable stable, highly efficient bioproduction even under extreme heat, while keeping cooling costs low.

Furthermore, the photosynthetic PSII complex and the mechanisms involved in translation and repair (including EF-Tu and the D1 protein) are strongly conserved throughout evolution, from microalgae to higher plants (crops). Applying the fundamental principle demonstrated in this study—"coordinated enhancement of antioxidant defense and translational systems"—to major crops, such as rice, wheat, and soybean, could open the way to molecular breeding of heat-tolerant crops that maintain their yields even during heat waves associated with global warming.

6 Publication Information

Journal	*Plant and Cell Physiology*
Title	Simultaneous reinforcement of the antioxidant defense and translational systems enhances the thermotolerance of photosystem II in *Synechocystis* sp. PCC 6803
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8 Glossary

(1) Reactive oxygen species (ROS)

Highly reactive forms of oxygen, commonly abbreviated as ROS (reactive oxygen species). When chemically stable oxygen molecules receive electrons or excitation energy, they may be converted into unstable species containing unpaired electrons. These are known as reactive oxygen species, and they cause oxidative damage to a variety of biological substances, including proteins, nucleic acids, and lipids. Representative ROS include superoxide ($O_2^{\bullet -}$), hydrogen peroxide (H_2O_2), hydroxyl radicals (•OH), and singlet oxygen ($^1O_2$). ROS are inevitably generated during photosynthesis, including when captured light energy is transferred to reaction centers and during electron transport reactions.

(2) Photosynthesis

A series of reactions in which light energy is used to produce sugars from carbon dioxide and water. Photosynthesis is an essential biological activity for the survival of photosynthetic organisms, including plants, algae, and cyanobacteria. The sugars produced by photosynthesis also serve as a source of carbon for all life on Earth. Oxygen produced by photosynthesis has formed the oxygen component of the atmosphere, accounting for approximately 21% of its composition, and supports the respiration of aerobic organisms on Earth, including humans.

(3) Photosystem II (PSII)

A key molecular apparatus that converts light energy into chemical energy during photosynthesis. Located in thylakoid membranes, PSII is a large molecular complex containing more than 20 types of proteins, approximately 40 chlorophyll molecules, as well as carotenoids and lipids. Within this complex, solar light energy is converted into chemical energy through charge separation, and oxygen is evolved during the energy conversion process.

(4) Protein synthesis

Also known as translation. Protein synthesis takes place in large molecular machinery. The protein synthesis (translation) system consists of ribosomes and RNA molecules and synthesizes proteins according to the sequence information encoded in messenger RNA (mRNA).

(5) ROS-scavenging enzymes

Enzymes that eliminate and detoxify reactive oxygen species. Representative examples include superoxide dismutase (SOD), which converts superoxide into hydrogen peroxide, as well as catalases and peroxidases, which convert hydrogen peroxide into water.

(6) EF-Tu

One of the peptide elongation factors involved in the protein synthesis (translation) system. EF-Tu transports aminoacyl-tRNA to the A site of the ribosome. Together with EF-G, it supports peptide elongation, the process in which amino acids are joined one by one to form a peptide. Research by Prof. Nishiyama and colleagues has shown that EF-

Tu, like EF-G, is a target of ROS and is inactivated by oxidative damage.

(7) D1 protein

A major protein constituting the reaction center of PSII. Photochemical energy conversion (charge separation) in PSII occurs at chlorophyll molecules associated with the D1 protein. When PSII is damaged by light, D1 is among the first proteins to be damaged and degraded. The repair cycle then operates, and newly synthesized D1 protein, produced through transcription and translation, is rapidly inserted into the PSII complex.

(8) PSII repair

PSII is susceptible to photoinhibition and is readily inactivated under strong light. This phenomenon is called photoinhibition. In living organisms, however, inactivated PSII is rapidly repaired. The damaged D1 protein in the reaction center is degraded, and newly synthesized D1 protein, produced through transcription and translation, is inserted into PSII, reactivating the complex. When the rates of damage and repair are balanced, photoinhibition is not pronounced; when the rate of damage exceeds the rate of repair, photoinhibition occurs. Degradation and synthesis take place continuously in living organisms.

(9) Cyanobacteria

Prokaryotic photosynthetic microorganisms considered to be the ancestors of plant chloroplasts. They are thought to have appeared on Earth approximately 3.2 billion years ago and to have been the first organisms to perform oxygen-evolving photosynthesis. They still retain much of their ancient form and inhabit lakes, ponds, and oceans. The genome of one cyanobacterial species, *Synechocystis* sp. PCC 6803, was sequenced in 1996 by a Japanese research group (Kazusa DNA Research Institute). Because it is also readily transformed (genetically manipulated), this species is widely used throughout the world as a model organism for photosynthesis research and other studies.

(10) Cysteine residue

A residue of cysteine, one of the amino acids that constitute proteins. Oxidation of cysteine residues can result in the formation of a disulfide bond between two cysteine residues or the formation of sulfenic acid at a single cysteine residue. Many proteins and enzymes have activities that are regulated by oxidation–reduction reactions involving cysteine residues.

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