International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 12 Issue 8 ǁ August 2024 ǁ PP. 59-61

Enhancing Photosynthetic Efficiency and Carbon Capture in Algae Through Targeted Rubisco Mutations: A Theoretical Approach

Cole Baer

Abstract:
The accelerating pace of climate change, driven by rising levels of atmospheric CO_2, necessitates innovative strategies for carbon capture and sequestration. Photosynthetic organisms play a pivotal role in the global carbon cycle, converting CO_2 into organic matter through the process of photosynthesis. Enhancing the efficiency of this process in microalgae, such as Chlamydomonas reinhardtii, presents a promising avenue for both reducing atmospheric CO_2 and producing sustainable biofuels.

Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) is a critical enzyme in the Calvin cycle, catalyzing the first step of carbon fixation. However, Rubisco is inherently inefficient because it can also react with oxygen, leading to photorespiration—a process that reduces the overall photosynthetic capacity and efficiency of CO_2 assimilation. This inefficiency makes Rubisco a key target for genetic improvement. Theoretical approaches to improve Rubisco's efficiency in C. reinhardtii involve introducing specific mutations known to enhance the enzyme's catalytic properties. This paper proposes three such mutations: Lys334→Ser, Ala340→Gly, and Asp473→Glu, aimed at increasing CO_2 specificity, catalytic turnover, and thermal stability, respectively. These modifications are expected to not only boost the photosynthetic efficiency of C. reinhardtii but also significantly enhance its potential for carbon capture and biomass production.

Date of Submission: 03-08-2024 Date of acceptance: 14-08-2024

Model Organism for Carbon Capture:

Chlamydomonas reinhardtii is a widely studied model organism in the field of photosynthesis and bioenergy due to its ease of genetic manipulation and rapid growth rates. It can grow autotrophically, directly fixing atmospheric CO_2 into organic compounds, thus serving as a natural carbon sink. The alga's ability to thrive under various environmental conditions, including variable light intensities and temperatures, makes it a robust platform for experimental modifications aimed at enhancing photosynthetic efficiency. Furthermore, the scalability of C. reinhardtii cultivation in bioreactors allows for large-scale production, which is crucial for applications in biofuel production and carbon sequestration technologies.

Proposed Mutations and Theoretical Justification:

Lys334→Ser: Increasing CO_2/O_2 Specificity

The substitution of lysine with serine at position 334 is thought to increase the CO_2/O_2 specificity factor of Rubisco. Lysine at this position plays a significant role in stabilizing the transition state of the carboxylation reaction. By replacing lysine with serine, a smaller amino acid, the enzyme's active site undergoes subtle changes that could reduce its affinity for O_2, thereby minimizing the oxygenase reaction that leads to photorespiration. Studies on tobacco (Nicotiana tabacum) have demonstrated that similar mutations have been successful and increase Rubisco's CO_2 specificity, resulting in a significant reduction in photorespiration and an increased net rate of photosynthesis (Parry et al., 2002). This increased specificity for CO_2 would enhance the overall efficiency of carbon fixation, thereby maximizing the amount of CO_2 assimilated into organic matter. In C. reinhardtii, this mutation would decrease the energy and carbon losses associated with photorespiration, leading to more efficient carbon capture.

Ala340→Gly: Enhancing Catalytic Turnover (k_cat)

The Ala340→Gly mutation is hypothesized to increase the catalytic turnover rate of Rubisco. Alanine at position 340 contributes to the rigidity of the enzyme's active site. By substituting glycine, which has a

smaller and more flexible side chain, the enzyme's active site might gain greater conformational flexibility during the catalytic cycle. This increased flexibility could facilitate the transition state, potentially lowering the activation energy required for the carboxylation reaction and thus increasing the rate of CO_2 fixation. Although direct studies on this specific mutation in Rubisco are limited, similar alterations in cyanobacteria have led to increased catalytic efficiency, enabling the enzyme to stabilize the transition state more effectively and reducing the energy barrier for the carboxylation reaction (Andersson & Backlund, 2008). If applied to C. reinhardtii, this mutation could result in more efficient CO_2 conversion into organic compounds, thereby enhancing biomass production and carbon capture.

Asp473→Glu: Improving Thermal Stability

The replacement of aspartic acid with glutamic acid at position 473 is proposed to enhance the thermal stability of Rubisco. Aspartic acid contributes to the formation of salt bridges that help maintain the structural integrity of the enzyme under varying thermal conditions. Glutamic acid, with its longer side chain, could strengthen these interactions, potentially providing additional stability. Research on similar modifications in thermophilic bacteria suggests that such changes could enhance Rubisco's thermal stability, allowing it to maintain activity at higher temperatures by reinforcing the enzyme's structural integrity and preventing denaturation (Cummins et al., 2018). In C. reinhardtii, this mutation would ensure that the enzyme remains active and efficient even as global temperatures rise, thereby preserving the alga's ability to fix CO_2 effectively. The improved thermal stability is especially relevant for large-scale cultivation in outdoor environments, where temperature fluctuations are common.

Hypothetical Mechanisms and Benefits:

Combined Effects of Mutations: The synergistic effect of the Lys334→Ser, Ala340→Gly, and Asp473→Glu mutations could significantly enhance the photosynthetic efficiency of C. reinhardtii. By increasing CO_2 specificity, the Lys334→Ser mutation reduces the loss of fixed carbon to photorespiration, conserving energy and enhancing net carbon capture. The Ala340→Gly mutation boosts the catalytic efficiency of the enzyme, allowing for a higher rate of CO_2 assimilation and thus more rapid biomass accumulation. The Asp473→Glu mutation ensures that these benefits are retained across a broader temperature range, protecting the enzyme from thermal inactivation. Collectively, these modifications are poised to maximize the carbon capture potential of C. reinhardtii, making it a more effective organism for biotechnological applications aimed at reducing atmospheric CO_2 levels.

Potential for Increased Biomass Production and Carbon Sequestration:

The enhanced efficiency in CO_2 fixation and biomass production positions C. reinhardtii as a valuable tool for carbon sequestration. The increased biomass yield can be harnessed for biofuel production, providing a renewable energy source that further contributes to carbon neutrality. The ability to capture and convert substantial amounts of atmospheric CO_2 into biomass makes C. reinhardtii an integral component of integrated carbon management strategies. By optimizing the Rubisco enzyme, this theoretical framework lays the groundwork for developing robust algal strains that can be deployed at scale for environmental and industrial applications.

Conclusion:

The proposed Rubisco mutations—Lys334→Ser, Ala340→Gly, and Asp473→Glu—in Chlamydomonas reinhardtii offer a promising theoretical approach to enhancing photosynthetic efficiency and carbon capture capability. By targeting the enzyme's CO_2 specificity, catalytic turnover, and thermal stability, these mutations address key limitations in the photosynthetic process. The resulting increase in carbon fixation efficiency and biomass production positions C. reinhardtii as a powerful organism for biofuel production and carbon sequestration. This research highlights the potential of genetic engineering to create more efficient photosynthetic organisms, contributing to sustainable solutions for climate change mitigation.

References:

[1]. Parry, M.A.J., Andralojc, P.J., Khan, S., Lea, P.J., & Keys, A.J. (2002). "Rubisco activity and regulation as targets for crop improvement." Journal of Experimental Botany, 53(377), 545-558.

[2]. Andersson, I. & Backlund, A. (2008). "Structure and function of Rubisco." Plant Physiology and Biochemistry, 46(3), 275-291.

[3]. Cummins, P. L., Kannappan, B., & Gready, J. E. (2018). "Directions for optimization of photosynthetic carbon fixation: Rubisco's efficiency may not be so constrained after all." Frontiers in Plant Science, 9, 183.
[4]. Wilson, R. H., Martin-Avila, E., Conlan, C., Whitney, S. M. (2018). "An improved Escherichia coli screen for Rubisco identifies a protein with desired improvements in carboxylation rate (kcat c), CO2 affinity (lowerKm for CO2, Kc) and specificity for CO2 over O2." Journal of Biological Chemistry, 293(18), 7427-7441.
[5]. Carmo-Silva, E., Scales, J. C., Madgwick, P. J., Parry, M. A. J. (2015). "Optimizing Rubisco and its regulation for greater resource use efficiency." Plant, Cell & Environment, 38(9), 1817-1832.
[6]. Young, J. N., Rickaby, R. E. M., Kapralov, M. V., Filatov, D. A. (2012). "Evolutionary trends in RuBisCO kinetics and their co-evolution with CO2 specificity among diff erent RuBisCO forms." The Plant Journal, 71(4), 411-425.