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Genetic Engineering for Increasing Crop Productivity by Manipulating Photosynthesis

*Aurobinda Behera, Akash Kumar Parida and Avinash Kumar
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha-751003, India
*Corresponding Author's email: aurobinda1999@gmail.com

Improving crop productivity is a critical requirement in the face of increasing global food demand, climate change and shrinking arable land. One of the most promising approaches is to genetically engineer plants to enhance photosynthetic efficiency — i.e., improve light capture, CO_2 assimilation, carbon fixation, and reduction of photorespiratory losses. By manipulating key genes in the calvin-benson cycle, electron transport, photorespiration bypasses, C_4/CAM pathways, and regulatory networks, genetic engineering offers a route to increase biomass and yield. This assignment reviews the molecular targets, engineering strategies, successes, limitations and ethical/regulatory considerations of photosynthesis manipulation in crops, and provides a future outlook.

Introduction

Photosynthesis is the fundamental process that sustains nearly all life on Earth by converting solar energy into chemical energy stored in carbohydrates. It is the primary determinant of plant growth and productivity, yet its natural efficiency in most crop plants remains remarkably low—typically between 1–3% of the incident solar radiation (Long *et al*., 2006). In the face of increasing global population, climate change, and shrinking arable land, enhancing photosynthetic efficiency has become a major scientific and agricultural goal. Genetic engineering offers a revolutionary approach to directly modify photosynthetic machinery to improve carbon fixation, light use efficiency, and biomass accumulation in crops. Through targeted gene transfer, synthetic biology, and regulation of key photosynthetic enzymes, researchers aim to redesign plant photosynthetic pathways for higher yield potential (Ort *et al*., 2015).

In recent decades, advances in molecular biology and biotechnology have enabled precise manipulation of chloroplast genes, introduction of more efficient carbon fixation pathways from cyanobacteria, and optimization of photorespiration processes. These genetic strategies are vital not only for increasing crop productivity but also for achieving sustainable agriculture under limited resource conditions (Zhu *et al*., 2020). Hence, exploring genetic engineering for photosynthesis improvement represents one of the most promising frontiers in plant science.

Molecular Targets for Genetic Manipulation

Calvin-Benson Cycle and Carbon Fixation

The Calvin-Benson cycle (CBC) involves enzymes that catalyse CO_2 fixation (via Rubisco), reduction and regeneration of ribulose-1,5-bisphosphate. Rubisco is notoriously slow and has a significant oxygenase activity that initiates photorespiration (Simkin, 2019). Genetic manipulation of key CBC enzymes such as sedoheptulose-1,7-bisphosphatase (SBPase), fructose-1,6-bisphosphate aldolase (FBPA) and phosphoribulokinase has demonstrated biomass increases in model plants (Simkin, 2019).

Photorespiration and Alternative Pathways

In C_3 plants, photorespiration reduces photosynthetic efficiency by releasing previously fixed CO_2 and consuming energy. Introducing synthetic alternative pathways or bypasses to reduce photorespiratory losses has been a key engineering strategy. For example, insertion of glycolate-metabolising enzymes in chloroplasts improved net photosynthesis and biomass in *Arabidopsis* and rice (Nazari *et al*., 2024).

C_4/CAM Pathway Components

Some engineering efforts aim to transfer or mimic traits of C_4 or CAM photosynthesis into C_3 crops (e.g., phosphoenolpyruvate carboxylase, NADP-malic enzyme) to concentrate CO_2 around Rubisco and reduce photorespiration (Nazari *et al*.,2024). These complex modifications may offer major gains under high temperature/high light conditions.

Light Harvesting, Electron Transport and Photoprotection

Apart from carbon fixation, enhancing the upstream light capture and conversion systems is important. For instance, accelerating the relaxation of photoprotection (NPQ) allows leaves entering shade to resume photosynthesis faster — engineering such regulatory networks led to ~20-30 % yield increases in soybean field trials (GenEngNews, 2019).

Regulation by miRNAs, Transcription Factors and Chloroplast Biogenesis

Recent research also highlights regulatory networks controlling photosynthetic development — small RNAs (miRNAs), transcription factors and chloroplast biogenesis genes are emerging as targets for boosting photosynthetic capacity (Nazari *et al*., 2024).

Engineering Strategies and Successes

Major engineering strategies include: (i) over-expression of target genes, (ii) knock-down or editing of negative regulators, (iii) multigene stacking to target multiple photosynthetic steps, and (iv) gene editing (e.g., CRISPR/Cas) to precisely adjust gene expression. Simkin *et al.* (2019) emphasise multi-target approaches as more likely to yield significant improvements in biomass. Field trials by the Realizing Increased Photosynthetic Efficiency (RIPE) project achieved up to ~40 % yield increases in crops engineered with photorespiratory bypasses (GenEngNews, 2019). Modeling studies in rice showed that a ~25 % increase in leaf photosynthetic rate could translate into ~22-29 % biomass gain (Cruz *et al*., 2013).

Table 1 :(Data synthesized from Long *et al*., 2006; Kromdijk *et al*., 2016; South *et al*., 2019; Shen *et al*., 2019; Long *et al*., 2018.)

Genetic Modification Strategy	% Increase in Photosynthetic Efficiency	% Increase in Yield (approx.)
Rubisco optimization (rice, tobacco)	10	15
Photorespiration bypass (tobacco, rice)	20	40
NPQ acceleration (tobacco)	15	25
C_4 pathway gene transfer (rice)	18	30
Carboxysome introduction (synthetic CCMs)	25	35

Advantages and Promise

- Targeted manipulation of photosynthesis addresses a fundamental yield-limiting process rather than modifying downstream traits.
- Potential large gains in yield (20-40 %), which would make major impact given the slow improvements in many crops historically.
- Improvements may also enhance resource-use efficiency (e.g., water, nitrogen) when canopy assimilation is optimized (Nazari *et al*., 2024).
- Engineering photosynthesis may complement other yield-enhancing traits and help meet global food security targets.

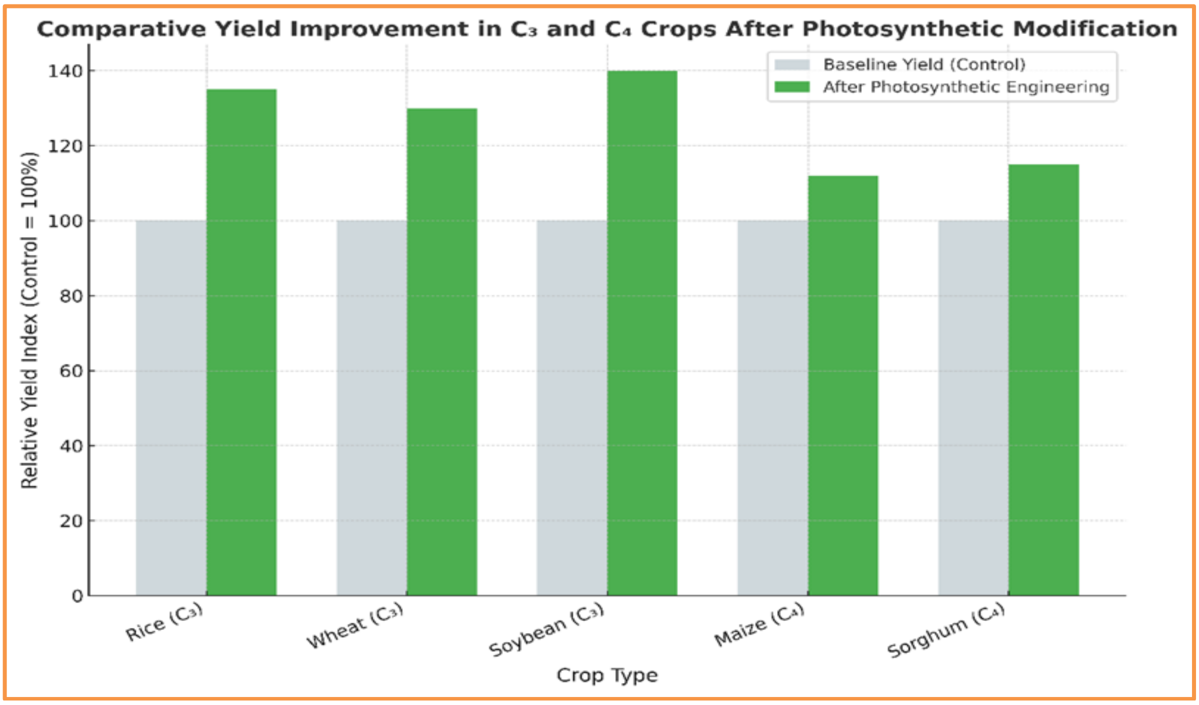

Figure 1. Comparative improvement in relative yield of major C_3 and C_4 crops after photosynthetic pathway engineering (Data compiled from Kromdijk *et al*., 2016; South *et al*., 2019; Zhu *et al*., 2020)

Limitations, Challenges and Disadvantages

- Leaf-level improvements may not scale to whole crop yield due to canopy, sink limitations, nutrient constraints, and feedback regulation (Cruz *et al*., 2013).
- Complexity: Photosynthesis is highly integrated with many physiological systems, and perturbing one enzyme may have unintended pleiotropic effects (Simkin, 2019).
- Field performance under variable environments may be lower than controlled conditions; for example, high CO_2 or optimal nutrient conditions may exaggerate gain.
- Regulatory, public acceptance and intellectual property issues associated with genetically engineered crops remain significant barriers.
- Risk of unintended consequences: e.g., altering carbon partitioning, source-sink balance or ecological interactions.

Ethical, Biosafety and Regulatory Considerations

Genetically engineering photosynthesis raises issues of biosafety (e.g., altered interactions with environment), equity (access for smallholder farmers) and regulation (GMO acceptance). Transparent field trials, environmental risk assessment and inclusive deployment strategies are essential. Research must be designed to ensure benefit sharing and avoid exacerbating inequities.

Future Directions

- Expanding multigene, tissue-specific and developmentally regulated interventions to optimise photosynthesis in non-leaf tissues (e.g., ears in cereals) (Simkin, 2019).
- Integrating engineering of photosynthesis with other improvements (nutrient use efficiency, stress tolerance) to yield stable gains under field conditions.
- Advancing gene-editing tools and synthetic biology to precisely redesign photosynthetic machinery.
- Ensuring translational research in major crops and in diverse agro-ecologies (including India and other developing countries) to maximise global impact.

Conclusion

The manipulation of photosynthesis through genetic engineering represents a transformative avenue for boosting global food security. By fine-tuning the molecular machinery responsible for light capture, carbon fixation, and energy conversion, scientists are moving closer to creating next-generation "super crops" with enhanced productivity and resilience. Integrating Rubisco optimization, photorespiration bypasses, and carbon-concentrating mechanisms can substantially improve yields, especially under climate stress (Ort *et al.*, 2015; Long *et al.*, 2018). Nonetheless, such interventions must proceed within ethical and ecological boundaries to ensure environmental safety and societal acceptance.

In conclusion, genetic engineering of photosynthesis stands as a sustainable innovation for the 21st century, combining plant physiology, molecular genetics, and biotechnology to meet the dual challenges of rising food demand and climate change. The coming decade is likely to witness the translation of these experimental successes into major food crops, revolutionizing global agriculture and ensuring food security for generations to come.

References

1. "Bioengineering Better Photosynthesis Increases Yields in Important Food Crop." 2019. *Genetic Engineering & Biotechnology News* (online article).
2. Cruz MD, Purcell LC, Ainsworth EA. 2013. Can exploiting natural genetic variation in leaf photosynthesis contribute to increasing rice productivity? A simulation analysis. *Journal of Experimental Botany* 64(7):1893-1902.
3. Kromdijk, J., Glowacka, K., Leonelli, L., Gabilly, S. T., Iwai, M., Niyogi, K. K., & Long, S. P. (2016). Improving photosynthesis and crop productivity by accelerating recovery from photoprotection. *Science*, 354(6314): 857–861.
4. Long, S. P., Marshall-Colon, A., & Zhu, X. G. (2018). Meeting the global food demand of the future by engineering crop photosynthesis and yield potential. *Cell*, 161(1): 56–66.
5. Long, S. P., Zhu, X. G., Naidu, S. L., & Ort, D. R. (2006). Can improvement in photosynthesis increase crop yields? *Plant*, *Cell & Environment*, 29(3): 315–330.
6. Nazari M, Kordrostami M, Ghasemi-Soloklui A, Eaton-Rye JJ, Pashkovskiy P, Kuznetsov V, Allakhverdiev SI. 2024. Enhancing photosynthesis and plant productivity through genetic modification. *Cells* 13(16):1319.
7. Ort, D. R., Merchant, S. S., Alric, J., Barkan, A., Blankenship, R. E., Bock, R., Long, S. P., & Zhu, X. G. (2015). Redesigning photosynthesis to sustainably meet global food and bioenergy demand. *Proceedings of the National Academy of Sciences USA*, 112(28): 8529–8536.
8. Shen, B. R., Wang, L. M., Lin, X. L., Yao, Z., Xu, H. W., Zhu, C. H., Teng, H. Y., Cui, L. L., Liu, E. E., & Zhang, J. J. (2019). Engineering a new photorespiratory bypass to increase photosynthetic efficiency and crop yield in rice. *Molecular Plant*, 12(2): 199–214.
9. Simkin AJ. 2019. Genetic Engineering for Global Food Security: Photosynthesis and Biofortification. *Plants* 8(12):586.
10. South, P. F., Cavanagh, A. P., Liu, H. W., & Ort, D. R. (2019). Synthetic glycolate metabolism pathways stimulate crop growth and productivity in the field. *Science*, 363(6422): eaat9077.
11. Zhu, X. G., Long, S. P., & Ort, D. R. (2020). Improving photosynthetic efficiency for greater yield. *Annual Review of Plant Biology*, 71: 669–697.