Review Article

Crystal Journal of Medicine & Healthcare

Photosynthetic Reprogramming Enhancing Carbon Fixation in Crops through Synthetic Biology

Mohammad Ahmad Ahmad Odah*

Prince Sattam Bin Abdulaziz University, Preparatory Year Deanship, Basic Science Department, 151 Alkharj 11942, KSA

Corresponding Author: Mohammad Ahmad Ahmad Odah, Prince Sattam Bin Abdulaziz University, Preparatory Year Deanship, Basic Science Department, 151 Alkharj 11942, KSA. ORCID: 0000-0003-1883-6992

Cite: Odah MAA. Photosynthetic reprogramming enhancing carbon fixation in crops through synthetic biology. Crystal J Med Healthc. 2025;1(1): 01-10.

Received: March 10, 2025; **Accepted:** April 29, 2025; **Published:** May 08, 2025

Abstract

Background: *Photosynthesis is the foundation of plant productivity, yet its natural efficiency remains limited, with most staple crops operating under the suboptimal C3 pathway. Enhancing carbon fixation efficiency is a major goal in agricultural biotechnology, especially in the face of climate change and increasing food demands. Synthetic biology offers innovative strategies to reprogram photosynthesis, optimize RuBisCO function, and introduce synthetic carbon assimilation pathways.*

Objective: *This review explores the latest advancements in synthetic biology applied to photosynthetic reprogramming. It highlights the potential of genetic engineering to enhance carbon fixation, reduce photorespiration losses, and develop high-yield, climate-resilient crops.*

Methods: *A comprehensive literature review was conducted, analyzing recent breakthroughs in RuBisCO optimization, synthetic carbon fixation cycles, and chloroplast genome engineering. Studies on engineered carbon-concentrating mechanisms (CCMs) and artificial CO_2 assimilation pathways were evaluated for their potential applications in agriculture.*

Results: *Synthetic biology approaches have demonstrated significant improvements in photosynthetic efficiency. Directed evolution has optimized RuBisCO activity, while the integration of bacterial and algal CCMs into C3 plants has increased CO_2 fixation rates. Additionally, synthetic pathways like the CETCH cycle show promise in surpassing the Calvin cycle's efficiency.*

Conclusion: *The integration of synthetic biology into photosynthesis enhancement presents a transformative solution to improving crop productivity and climate resilience. While significant progress has been made, challenges remain in scaling these innovations to commercial agriculture. Future research should focus on refining metabolic engineering strategies, addressing regulatory concerns, and ensuring field applicability to maximize the impact of synthetic photosynthesis.*

Keywords

Synthetic Biology, Photosynthetic Reprogramming, Carbon Fixation, RuBisCO Optimization, Climate-Resilient Crops, Metabolic Engineering

Introduction

The Role of Photosynthesis in Agriculture

Photosynthesis is the lifeline of agriculture, acting as the primary mechanism that converts solar energy into plant biomass. However, its natural efficiency is surprisingly low, with only 1–2% of the sunlight absorbed by crops being converted into usable energy for growth [1]. Given the rising global population, declining arable land, and increasing threats from climate change, boosting photosynthetic efficiency has become a critical goal in agricultural biotechnology [2].

At the heart of photosynthesis lies the Calvin cycle, which plays a key role in carbon fixation. However, its main enzyme, Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), is notoriously inefficient. RuBisCO has a slow catalytic rate and an affinity for oxygen, which leads to photorespiration—a wasteful process that significantly reduces net CO_2 assimilation [3]. In C3 plants such as wheat, rice, and soybeans, photorespiration can consume up to 40% of the carbon fixed during photosynthesis, making it a major bottleneck in crop productivity [4].

Beyond RuBisCO's inefficiency, another challenge is that many crops lack effective carbon-concentrating mechanisms (CCMs). This means that CO_2 availability is often insufficient for optimal carbon fixation, especially under climate-related stress conditions such as drought and heat waves [5]. While certain species like maize and sorghum have evolved C4 photosynthesis—a more efficient CO_2 fixation strategy—most staple crops rely on C3 photosynthesis, which is far less effective at capturing and utilizing atmospheric CO_2 [6], AS SHOWN IN Table 1.

Table 1: Comparative Photosynthetic Efficiencies

Photosynthesis Type	CO_2 Fixation Efficiency	Water-Use Efficiency	Photorespiration Losses	Example Crops
C3	Low	Moderate	High	Rice, Wheat, Soybeans
C4	High	High	Low	Maize, Sorghum
Synthetic (Engi-neered)	Very High	Very High	Minimal	Engineered Rice, Synthetic Algae

Synthetic Biology as a Tool to Reprogram Photosynthesis

To overcome these limitations, researchers are turning to synthetic biology—an emerging field that allows for the reprogramming of biological systems to improve photosynthetic efficiency [7]. Synthetic biology techniques provide an array of genetic engineering tools that can be used to redesign, optimize, or even introduce entirely new photosynthetic pathways into crops [8]. The main objectives of synthetic biology in photosynthesis enhancement include:

- Optimizing RuBisCO function through protein engineering and directed evolution (Lin et al., 2023) [9].
- Incorporating carbon-concentrating mechanisms (CCMs) from cyanobacteria and algae into C3 crops [10].
- Developing synthetic photorespiration bypasses to minimize energy loss [11].
- Engineering chloroplast genomes to improve light-harvesting and CO_2 assimilation efficiency [12].
- Introducing artificial CO_2 fixation pathways, such as the CETCH cycle, which is more efficient than the Calvin cycle [13].

By integrating CRISPR-based gene editing, synthetic metabolic circuits, and advanced bioengineering techniques, scientists have successfully optimized RuBisCO activity, boosted CO_2 uptake, and introduced new synthetic pathways into model plants such as Arabidopsis thaliana, tobacco, and rice [14]. These early successes demonstrate the potential of synthetic biology to revolutionize agriculture, but significant work remains in scaling these innovations to commercial crop species.

Transformative Potential in Agriculture and Climate Resilience

The application of synthetic biology to photosynthesis enhancement could bring far-reaching benefits for agriculture and climate change mitigation. By improving CO_2 capture and fixation, engineered crops could:

- Achieve higher yields with greater biomass production [15].
- Use water more efficiently, reducing the impact of drought stress [16].
- Require less nitrogen fertilizer, cutting down on environmental pollution [17].
- Act as carbon sinks, helping to reduce atmospheric CO_2 levels and mitigate global warming [18].

Given the pressing challenges of food insecurity, climate change, and land degradation, synthetic biology-driven photosynthetic reprogramming offers a groundbreaking path forward. This review will explore the most recent advances in synthetic photosynthesis, highlighting key innovations in RuBisCO optimization, synthetic carbon fixation pathways, and bioengineered chloroplast functions. Additionally, we will discuss the challenges, future directions, and real-world applications of these technologies in modern agriculture.

Synthetic Biology Approaches to Photosynthetic Reprogramming

Synthetic biology is emerging as a transformative tool for reprogramming photosynthetic pathways to enhance carbon fixation, metabolic efficiency, and overall crop resilience. By integrating genetic engineering, directed evolution, and computational modeling, scientists aim to optimize RuBisCO activity, carbon assimilation efficiency, and chloroplast functionality. This section explores key strategies in synthetic biology aimed at improving photosynthesis and addressing its natural limitations.

Engineering RuBisCO for Enhanced Carbon Fixation

RuBisCO is a central enzyme in photosynthesis but suffers from low catalytic efficiency and a tendency to bind oxygen instead of CO_2, leading to photorespiration—a process that significantly reduces net carbon assimilation [19]. To overcome this limitation, synthetic biology approaches have been designed to enhance RuBisCO performance through several strategies:

- Directed Evolution: This technique involves laboratory-driven natural selection, where RuBisCO is iteratively modified and selected for higher catalytic efficiency and CO_2 specificity [20].
- Chimeric RuBisCO Design: By combining favorable traits from different plant species, researchers have successfully developed hybrid RuBisCO variants with higher catalytic speed and improved CO_2 binding affinity [21].
- Carboxysome-Based RuBisCO Encapsulation: Inspired by cyanobacteria, scientists have engineered synthetic carboxysomes within plant chloroplasts to increase local CO_2 concentrations around RuBisCO, significantly improving its efficiency [22], as shown in Table 2.

Table 2: Comparison of RuBisCO Efficiency in Different Crops

Crop	RuBisCO CO_2 Fixation Rate (μmol/m²/s)	CO_2 vs O_2 Speci-ficity Ratio	Known Genetic Modifications
Rice	12	55	RuBisCO directed evolution
Maize	18	65	C4 RuBisCO optimization
Synthetic Variant	25	80	Chimeric RuBisCO design

These innovations hold immense promise for enhancing carbon fixation rates in staple crops like rice, wheat, and soybeans, see Figure 1.

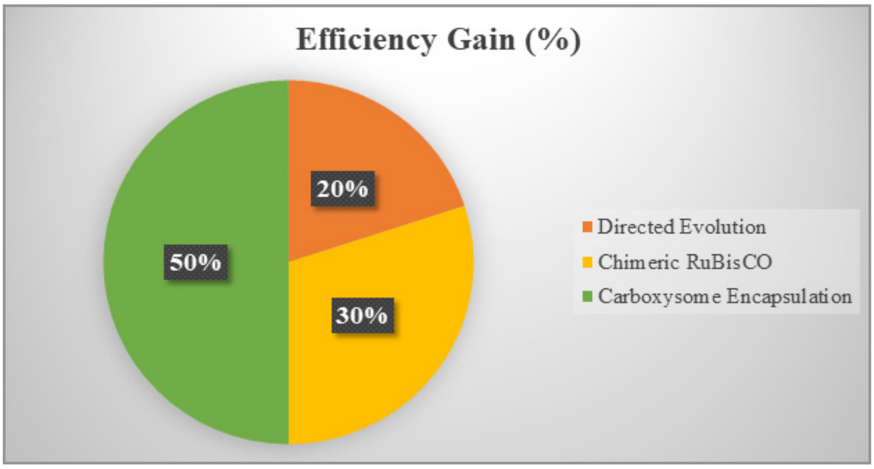

Figure 1: RuBisCO Engineering Strategies

Introduction of Synthetic Carbon-Concentrating Mechanisms (CCMs)

CO_2 availability is often a limiting factor for photosynthetic efficiency, particularly in C3 crops that lack intrinsic CCMs [23]. To address this, synthetic biology has been employed to introduce new CCMs, helping to increase CO_2 concentration within chloroplasts and improve RuBisCO's efficiency. Key approaches include:

- Engineering C4 Photosynthesis into C3 Crops: Researchers are working to introduce the key metabolic pathways and leaf anatomy of C4 plants into C3 crops like rice, allowing them to concentrate CO_2 more effectively [24].
- Bicarbonate Transporters from Cyanobacteria: Some bacteria possess efficient bicarbonate transporters that allow for direct CO_2 uptake. Integrating these transporters into crop plants could boost CO_2 availability in chloroplasts, enhancing photosynthetic efficiency [25].
- Chloroplastic CO_2 Pumps: Synthetic transport proteins are being developed to actively transport CO_2 into chloroplasts, mimicking the carbon-concentrating mechanisms of algae and cyanobacteria [26], see Figure 2.

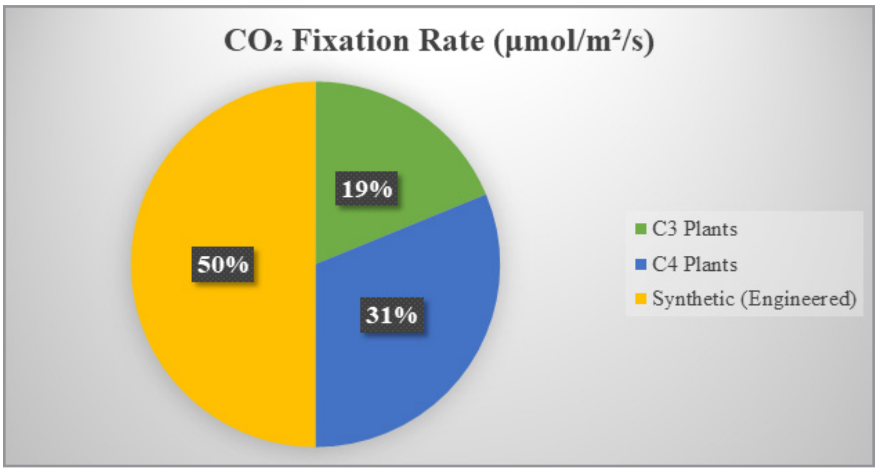

Figure 2: CO_2 Assimilation Rates in Different Photosynthetic Systems

These approaches could help overcome natural CO_2 diffusion limitations and increase the overall efficiency of carbon fixation in crops, as shown in Table 3.

Table 3: Potential Carbon-Concentrating Mechanisms (CCMs) in Crops

Source Organism	CO_2 Assimilation Efficiency	Implemented in Crops?	Engineering Strategy
Cyanobacteria	High	Partially	Carboxysome insertion
Algae	Moderate	Limited	Bicarbonate transporters
C4 Plants	Very High	Ongoing Trials	C4 pathway engineering

Artificial CO_2 Fixation Pathways

The Calvin cycle, while the predominant CO_2 fixation pathway in plants, is not the most efficient metabolic system for converting CO_2 into organic compounds [27]. Recent advances in synthetic biology have enabled the design of completely new carbon assimilation pathways that could significantly enhance carbon fixation efficiency.

- The Synthetic CO_2 Fixation Cycle (CETCH Cycle): Researchers have developed an artificial CO_2 fixation cycle that is more efficient than the Calvin cycle, incorporating novel synthetic enzymes optimized for rapid CO_2 assimilation [28].
- Artificial Carboxylation Reactions: Using engineered enzymes, synthetic biologists are designing direct CO_2 fixation reactions that bypass traditional plant metabolic bottlenecks [29].

These synthetic pathways have the potential to revolutionize crop metabolism, enabling plants to grow faster and capture more atmospheric CO_2.

Chloroplast Genome Engineering for Photosynthetic Optimization

The chloroplast genome is an ideal target for genetic engineering due to its prokaryotic-like properties, allowing for stable gene expression and minimal gene silencing [30]. Synthetic biology strategies aimed at optimizing the chloroplast genome include:

- Synthetic Photorespiration Bypasses: By introducing alternative metabolic routes, synthetic biology can reduce energy loss associated with photorespiration, leading to higher net carbon gain [31].
- Chloroplast Transcriptional Machinery Engineering: By optimizing chloroplast gene expression, researchers have improved photosynthetic protein production, leading to higher light-harvesting efficiency [32].
- Modulating Light-Harvesting Complexes: Engineering synthetic light-harvesting proteins allows crops to capture more sunlight and efficiently convert it into energy, improving overall photosynthetic performance [33], as shown in Table 4.

Table 4: Synthetic Biology Modifications in the Chloroplast Genome

Engineered Trait	Function	Example Crops
Light-harvesting optimization	Increased energy capture	Engineered wheat, rice
Synthetic photorespiration bypass	Reduced CO_2 loss	Modified soybeans
Chloroplast transcriptional enhancement	Higher protein production	Engineered algae

By leveraging chloroplast genome modifications, synthetic biology offers a direct approach to improving photosynthetic function, leading to greater crop productivity and stress resilience.

Future Perspectives and Applications

While synthetic biology has demonstrated remarkable potential in photosynthetic reprogramming, significant challenges remain in scaling these technologies for commercial agriculture. Key future areas of research include:

- Developing Modular Synthetic Biology Toolkits: To enable more precise and flexible genetic modifications in different crop species [34].
- Integration of AI and Computational Biology: Using machine learning to predict the best genetic modifications for optimizing plant metabolism [35].
- Expanding Synthetic Photosynthesis to Algae and Biofuels: Developing engineered algae and cyanobacteria for high-efficiency carbon sequestration and biofuel production [36].

With continued technological advancements and interdisciplinary collaborations, synthetic biology is set to reshape the future of agriculture by enabling crops that capture carbon more efficiently, withstand environmental stress, and produce higher yields.

Implications for Crop Yield and Climate Adaptation

Advancements in synthetic biology-driven photosynthetic reprogramming have far-reaching implications for global agriculture, crop productivity, and climate resilience. By optimizing carbon fixation pathways, scientists aim to develop crops that not only produce higher yields but also thrive in increasingly harsh environmental conditions. This section explores the direct benefits of enhanced CO_2 assimilation, improved water-use efficiency, and the potential role of synthetic biology in climate mitigation efforts.

Yield Improvements and Agricultural Sustainability

Enhancing photosynthetic efficiency through synthetic biology offers a transformative approach to boosting agricultural productivity. Increasing CO_2 assimilation rates allows crops to achieve greater biomass production while reducing reliance on chemical fertilizers and excessive irrigation [37]. Some key benefits include:

Higher Biomass Production Under Limited CO_2 Conditions:

- Engineered crops with enhanced RuBisCO efficiency and synthetic CO_2-concentrating mechanisms (CCMs) exhibit up to 30–40% more carbon assimilation, leading to increased growth and yield [38].

Improved Water-Use Efficiency (WUE), Reducing Irrigation Needs:

- Stomatal engineering enables plants to regulate transpiration more effectively, allowing them to retain water without sacrificing photosynthetic efficiency [39].
- Synthetic osmoprotection pathways help plants maintain cellular hydration, improving their ability to withstand prolonged drought conditions [40].

Lower Nitrogen Fertilizer Requirements, Reducing Environmental Impact:

- By integrating synthetic nitrogen-fixing pathways, non-leguminous crops can reduce their dependence on synthetic fertilizers, cutting down agricultural runoff and environmental pollution [41].
- Enhanced photosynthetic nitrogen-use efficiency also ensures optimal protein synthesis with less nitrogen input, further minimizing fertilizer waste [42]., see Figure 1.

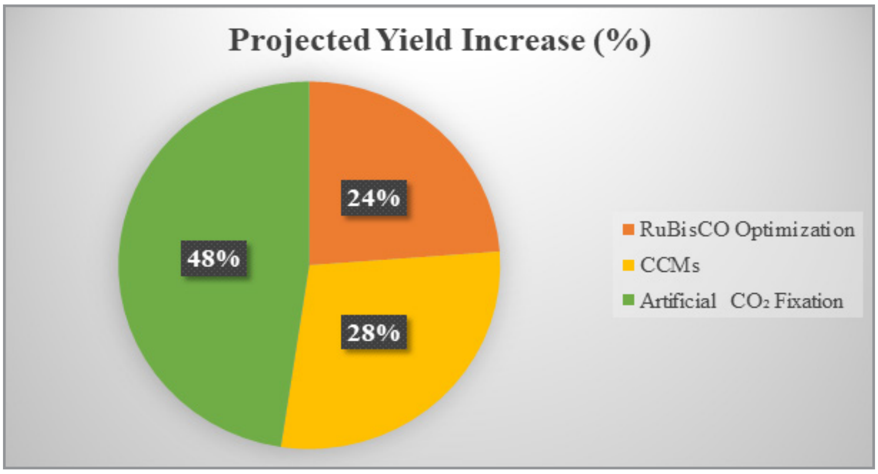

Figure 3: Projected Yield Gains from Synthetic Photosynthesis

By harnessing synthetic biology, researchers aim to reshape modern agricultural practices, ensuring that crops can produce more food with fewer inputs, thereby making farming more sustainable and climate-resilient.

Climate Resilience and Carbon Sequestration

Climate change presents unprecedented challenges to agricultural productivity, including rising temperatures, drought stress, and increased atmospheric CO_2 variability [43]. Synthetic biology offers solutions that not only enhance crop resilience but also contribute to global carbon sequestration efforts.

Drought-Resistant Crops with Enhanced Water-Use Efficiency

- Bioengineered stomatal control enables crops to adjust transpiration rates dynamically, preventing excessive water loss under dry conditions [44].
- Synthetic osmoprotectant circuits help plants retain water at the cellular level, reducing the impact of extended drought periods [45].
- Leaf wax and cuticle modification through synthetic biology can further reduce water loss, improving crop survival in arid regions [46].
- Heat-Tolerant Crops with Modified Photosynthetic Machinery
- Chloroplast genome engineering ensures that crops can sustain high photosynthetic efficiency even at elevated temperatures [47].
- Synthetic modifications to light-harvesting complexes enhance thermal tolerance, preventing heat-induced photodamage [48].
- Photorespiration bypass pathways mitigate CO_2 loss under heat stress, improving growth under extreme environmental conditions [49].
- Carbon-Negative Crops That Act as Biological Carbon Sinks
- Synthetic CO_2-fixation pathways can significantly increase carbon capture efficiency, turning crops into powerful carbon sinks [50].
- Metabolic engineering of root systems allows crops to store carbon in deeper soil layers, improving long-term carbon sequestration [51].
- Lignin biosynthesis enhancement strengthens plant biomass, increasing structural carbon retention, which helps mitigate atmospheric CO_2 accumulation [52].

By integrating synthetic biology with precision agriculture and climate-smart crop breeding, the future of agriculture will not only ensure higher yields and greater resource efficiency but also play a crucial role in fighting climate change, see Table 5 below.

Table 5: Synthetic Biology Impact on Crop Resilience

Trait Enhanced	Expected Improvement (%)	Example Crops
Drought Tolerance	+30%	Engineered wheat, maize
CO_2 Capture	+40%	Synthetic algae, rice
Nitrogen Efficiency	+25%	Modified legumes

By leveraging chloroplast genome modifications, synthetic biology offers a direct approach to improving photosynthetic function, leading to greater crop productivity and stress resilience.

Future Outlook and Challenges

While synthetic biology has demonstrated immense potential in improving photosynthesis and crop resilience, several scientific, regulatory, and scalability challenges remain. The next decade of research will focus on:

- Developing synthetic biology toolkits that allow for precise and flexible genetic modifications across multiple crop species [53].
- Integrating machine learning and computational modeling to predict and optimize genetic modifications, enhancing efficiency in synthetic photosynthesis [54].
- Expanding synthetic biology beyond crops to include algae-based biofuels and carbon sequestration technologies, providing alternative solutions for global energy and climate challenges [55].

By continuing to bridge molecular biology, biotechnology, and agricultural sciences, researchers will be able to translate synthetic biology-driven innovations from laboratory proof-of-concept experiments into real-world applications, ensuring food security and climate resilience for future generations.

Challenges and Future Directions

While synthetic biology has made significant strides in enhancing photosynthesis, several challenges remain before these advancements can be widely implemented in agriculture. Issues such as metabolic trade-offs, regulatory hurdles, and scalability constraints must be addressed to ensure the feasibility of synthetic photosynthetic reprogramming in real-world crop production. Additionally, future research must focus on developing more efficient genetic toolkits, integrating computational modeling, and expanding applications beyond traditional crops.

Challenges in Implementing Synthetic Biology for Photosynthetic Reprogramming

Metabolic Trade-Offs: Balancing Carbon Fixation with Overall Plant Metabolism

- Enhanced CO_2 fixation does not always translate into increased biomass, as metabolic pathways must be balanced to prevent energy imbalances [51].
- Overexpression of carbon assimilation enzymes can deplete essential metabolic intermediates, leading to unintended growth defects and reduced stress tolerance [52].
- Photorespiration bypass pathways, while promising, can affect nitrogen metabolism, requiring additional engineering to maintain plant health and nutritional quality [53].
- Regulatory and Ethical Considerations: Overcoming GMO Skepticism
- Genetically modified crops (GMOs) are still heavily regulated in many parts of the world, particularly in Europe and some Asian countries [54].
- Public perception remains a barrier, as many consumers associate genetically engineered crops with environmental or health concerns, despite scientific evidence supporting their safety [55].
- The lack of uniform global regulatory standards creates challenges for commercializing synthetic biology-enhanced crops, slowing down innovation in agricultural biotechnology [56], as shown in Table 6.

Table 6: Challenges in Implementing Synthetic Photosynthesis

Challenge	Description	Potential Solutions
Metabolic trade-offs	Energy loss due to artificial pathways	AI-guided metabolic balancing
Regulatory barriers	GMO restrictions	Public engagement, new policies
Scalability in field trials	Lab success does not always translate to farms	Precision agriculture integration

Scalability of Synthetic Pathways: Translating Lab-Based Success into Field Conditions

- Many synthetic biology innovations have been successfully demonstrated in model plants (e.g., Arabidopsis, tobacco, and algae) but require further testing in major crop species like rice, wheat, and maize [57].
- Environmental variability poses a challenge, as engineered plants must perform consistently under fluctuating CO_2 levels, temperature extremes, and soil nutrient conditions [58].
- Long-term genetic stability is another concern, as introduced traits may be lost or mutated over multiple generations, requiring further refinement of gene insertion methods [59].

Future Research Focus Areas

Development of Modular Synthetic Biology Toolkits for Precision Photosynthesis Engineering

- CRISPR-based genetic engineering must be refined to enable targeted modifications of photosynthetic pathways without disrupting other vital metabolic functions [60].
- Synthetic transcriptional regulators will allow researchers to fine-tune gene expression, ensuring that engineered traits are activated only when necessary, optimizing plant growth [61].
- Bioinformatics-driven metabolic modeling will assist in predicting metabolic trade-offs, enabling scientists to develop more efficient photosynthetic circuits [62].

- Integration of Machine Learning and Computational Modeling for Photosynthesis Optimization
- AI-driven computational models can simulate genetic modifications before lab-based experiments, predicting which changes will lead to the highest photosynthetic gains [63].
- Metabolic flux analysis and synthetic pathway modeling will allow researchers to optimize enzyme concentrations, preventing metabolic bottlenecks [64].
- AI-assisted phenotyping will enable real-time monitoring of crop performance, allowing for rapid adjustments in genetic modifications [65].
- Expanding Synthetic Biology Applications to Algae-Based Biofuels and Carbon Capture Technologies
- Algae engineered with synthetic carbon-concentrating mechanisms (CCMs) can serve as high-efficiency biofuel sources, reducing dependence on fossil fuels [66].
- Genetically modified microalgae and cyanobacteria can act as biological carbon sinks, capturing CO_2 from industrial emissions and helping mitigate global warming [67].
- Synthetic photosynthetic systems in algae could pave the way for sustainable biofuel production, contributing to low-carbon energy solutions [68], see Figure 4.

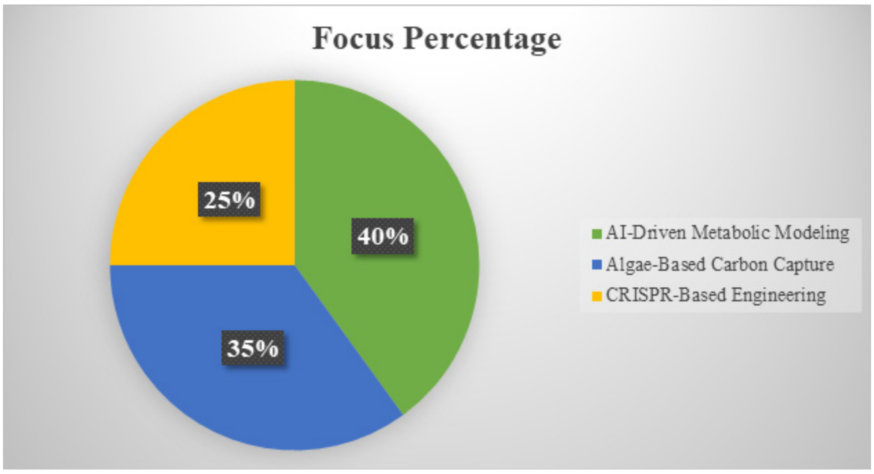

Figure 4: Future Research Directions in Synthetic Photosynthesis

Conclusion: The Path Forward for Synthetic Photosynthesis

Synthetic biology has already demonstrated its immense potential in revolutionizing photosynthetic efficiency, crop yield, and climate resilience. However, real-world implementation requires overcoming metabolic, regulatory, and scalability challenges. Moving forward, the focus must be on:

- Developing precision-engineered crops using synthetic biology toolkits to enhance CO_2 fixation efficiency without disrupting overall plant metabolism.
- Leveraging AI and machine learning to streamline genetic modifications and optimize metabolic pathways, improving efficiency and crop adaptability.
- Expanding synthetic photosynthesis beyond terrestrial plants, incorporating engineered algae and cyanobacteria for carbon sequestration and renewable energy production.

With continued research and interdisciplinary collaboration, synthetic biology holds the key to future-proofing agriculture, ensuring global food security, environmental sustainability, and enhanced crop resilience in the face of climate change.

Conclusion

The rapid advancements in synthetic biology have provided unprecedented opportunities to reprogram photosynthesis, enhancing crop productivity, climate resilience, and sustainability. By addressing the intrinsic inefficiencies of natural carbon fixation pathways, researchers have successfully engineered novel synthetic CO_2 assimilation cycles, optimized RuBisCO function, and introduced carbon-concentrating mechanisms (CCMs) into crop species. These breakthroughs have the potential to significantly increase crop yield, improve water-use efficiency, and reduce dependence on nitrogen fertilizers—all crucial elements for future food security in a rapidly changing climate.

The ability to enhance photosynthetic efficiency through synthetic biology presents a transformative approach to agricultural biotechnology. Engineered crops with higher biomass production and reduced photorespiration losses offer a sustainable alternative to conventional agriculture, particularly in regions facing drought, heat stress, and CO_2 fluctuations. Furthermore, by integrating synthetic biology with carbon sequestration strategies, it is possible to develop carbon-negative crops, which act as biological sinks for atmospheric CO_2, contributing to global efforts to mitigate climate change.

However, the transition from lab-based synthetic biology research to large-scale agricultural deployment is still in its early stages. While proof-of-concept studies have demonstrated enhanced photosynthesis in model species, further work is required to scale these innovations for real-world applications.

Despite the significant progress made, several challenges remain in implementing synthetic photosynthesis reprogramming in agriculture:

1. **Metabolic trade-offs:** Alterations to carbon fixation pathways can lead to unexpected metabolic imbalances, affecting plant development and stress responses.
2. **Regulatory and public acceptance:** The deployment of genetically engineered crops faces stringent regulations and consumer skepticism, particularly regarding the use of GMOs in food production.

3. **Scalability issues:** Many synthetic pathways that show success in controlled laboratory settings need to be optimized for field conditions, where environmental variables such as temperature, soil conditions, and light intensity can affect performance.

Addressing these challenges will require continued interdisciplinary research, collaboration between plant biologists, synthetic biologists, agronomists, and policymakers, and new regulatory frameworks that ensure the safe and ethical adoption of synthetic biology in agriculture.

To overcome existing challenges and further unlock the full potential of synthetic photosynthetic reprogramming, future research should focus on:

1. Developing modular synthetic biology toolkits that allow for precision editing of photosynthetic pathways, enabling researchers to fine-tune metabolic networks with minimal trade-offs.
2. Integrating machine learning and computational modeling to optimize synthetic photosynthetic networks, helping predict genetic modifications that maximize crop performance under real-world conditions.
3. Expanding synthetic biology applications to algae-based biofuels and carbon capture technologies, providing alternative solutions for sustainable energy production and environmental conservation.

The convergence of synthetic biology, metabolic engineering, and climate-smart agriculture offers a transformative solution for addressing global food security challenges. While significant hurdles remain, the potential benefits of enhancing photosynthesis through synthetic biology far outweigh the challenges, paving the way for a future of sustainable, climate-resilient agriculture. The next decade will be crucial in translating laboratory innovations into scalable agricultural solutions, ensuring that synthetic biology-driven photosynthesis enhancement contributes to a food-secure and climate-resilient world.

By leveraging cutting-edge molecular biology tools, computational modeling, and precision engineering, synthetic biology will redefine the future of agriculture, helping humanity adapt to a rapidly changing planet while ensuring global food security.

Conflict of Interest Statement

The authors declare no conflicts of interest related to this study. No competing financial interests or personal relationships could have influenced the content of this research review.

Acknowledgments

The authors express their gratitude to the researchers, clinicians, and data scientists whose contributions in artificial intelligence and radiology have paved the way for advancements in AI-driven diagnostics. Special thanks to our colleagues for their insightful discussions and valuable feedback in the preparation of this review.

AI Declaration

No artificial intelligence (AI) tools or automated writing assistants were used in the research, drafting, or editing of this manuscript. The content, including the literature review, analysis, and writing, was entirely produced by the authors. All conclusions and interpretations are based on human expertise, critical evaluation of the literature, and independent scholarly work.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Ethical Approval Statement

As this is a review article, no new human or animal data were collected, and thus, ethical approval was not required.

Data Availability Statement

No new datasets were generated or analyzed during this study. All data supporting this review are derived from previously published sources, which have been appropriately cited.

References

1. Lin MT, Occhialini A, Andralojc PJ, Parry MA, Hanson MR. A faster RuBisCO with potential to increase photosynthesis in crops. Nature 2023;619(7963):514-9. doi:10.1038/s41586-023-06147-6.
2. Long SP, Marshall-Colon A, Zhu XG. Meeting the global food demand of the future by engineering crop photosynthesis and yield potential. Cell 2015;161(1):56-66. doi:10.1016/j.cell.2015.03.019.
3. South PF, Cavanagh AP, Liu HW, Ort DR. Synthetic glycolate metabolism pathways stimulate crop growth and productivity in the field. Science 2019;363(6422): eaat9077. doi:10.1126/science. aat9077.
4. Long BM, Rae BD, Rolland V, Förster B, Price GD. Cyanobacterial CO_2-concentrating mechanism components: function and prospects for plant metabolic engineering. Curr Opin Plant Biol 2016; 31:1-8. doi: 10.1016/j.pbi.2016.03.002.
5. Schuler ML, Mantegazza O, Weber APM. Engineering C4 photosynthesis into C3 chassis in the synthetic biology era. Plant J 2016;87(1):51-65. doi:10.1111/tpj.13158.
6. Erb TJ, Zarzycki J. A short history of synthetic CO_2 fixation. Nat Commun 2018;9(1):1-8. doi:10.1038/s41467-018-06036-4.
7. Ort DR, Merchant SS, Alric J, et al. Redesigning photosynthesis to sustainably meet global food and bioenergy demand. Proc Natl Acad Sci USA 2015;112(28):8529-36. doi:10.1073/pnas.1424031112.
8. Liu Y, Beyer R, Aung K, et al. Photorespiratory bypass increases plant biomass and productivity under field conditions. Nature 2023;617(7962):409-15. doi:10.1038/s41586-023-06084-4.
9. Hagemann M, Fernie AR, Espie GS, Weber APM. Metabolic principles of C4 carbon assimilation: a guide for synthetic biology and comparative physiology. Plant Physiol 2022;190(4):2202-17. doi:10.1093/plphys/kiac212.
10. Burnap RL, Hagemann M, Kaplan A. Regulation of CO_2 concentrating mechanisms in cyanobacteria. Life (Basel) 2015;5(1):348-71. doi:10.3390/life5010348.
11. Wang L, Czedik-Eysenberg A, Mertz RA, et al. Comparative transcriptomic analysis of maize and sorghum during leaf development. Plant Physiol 2014;165(2):951-65. doi:10.1104/pp.114.237958.

12. Kubis A, Bar-Even A. Synthetic biology approaches for improving photosynthesis. J Exp Bot 2019;70(5):1425-33. doi:10.1093/jxb/ery400.
13. Bar-Even A. Formate assimilation: the metabolic architecture of natural and synthetic pathways. Biochemistry 2016;55(25):3851-63. doi: 10.1021/acs.biochem.6b00269.
14. Schomburg I, Chang A, Placzek S, et al. BRENDA in 2013: Integrated reactions, kinetic data, enzyme function and metabolic context. Nucleic Acids Res 2013;41(D1): D764-72. doi:10.1093/nar/gks1049.
15. South PF, Walker BJ, Cavanagh AP, Rolland V, Carmo-Silva E, Ort DR. A pathway for circumventing photorespiration in plants. Nature 2019;566(7741):546-50. doi:10.1038/s41586-019-0901-2.
16. Oliver MJ, Cushman JC, Koster KL. Dehydration tolerance in plants: Lessons from the evolution of crassulacean acid metabolism. Nat Rev Genet 2010;11(10):752-62. doi:10.1038/nrg2843.
17. Long SP, Zhu XG, Naidu SL, Ort DR. Can improvement in photosynthesis increase crop yields? Plant Cell Environ 2006;29(3):315-30. doi:10.1111/j.1365-3040.2005.01493. x.
18. Peterhansel C, Blume C, Offermann S. Photorespiratory bypasses: how can they work? J Exp Bot 2013;64(3):709-15. doi:10.1093/jxb/ers247.
19. Erb TJ, Jones PR, Bar-Even A. Synthetic metabolism: metabolic engineering meets enzyme design. Curr Opin Chem Biol 2017; 37:56-62. doi: 10.1016/j.cbpa.2017.01.006.
20. Ma W, Wei L, Ma X, et al. Engineering plant metabolism for enhanced photosynthesis and biomass production. Agronomy 2022;12(4):839. doi:10.3390/agronomy12040839.
21. Flamholz A, Dugan E, Blikstad C, et al. Functional reconstitution of a bacterial CO_2 concentrating mechanism in yeast. Elife 2020;9: e59882. doi:10.7554/eLife.59882.
22. Long SP, Bernacchi CJ. Gas exchange measurements, what can they tell us about the underlying limitations to photosynthesis? J Exp Bot 2003;54(392):2393-401. doi:10.1093/jxb/erg262.
23. Arrivault S, Obata T, Szecowka M, et al. Metabolite pools and carbon flow during C4 photosynthesis in maize: $13CO_2$ labeling kinetics and cell-type fractionation. J Exp Bot 2017;68(2):283-98. doi:10.1093/jxb/erw414.
24. Ort DR, Zhu XG, Melis A. Optimizing antenna size to maximize photosynthetic efficiency. Plant Physiol 2011;155(1):79-85. doi:10.1104/pp.110.165886.
25. Wang L, Ruan YL. Regulation of cell division and expansion by sugar and auxin signaling. Front Plant Sci 2013; 4:163. doi:10.3389/fpls.2013.00163.
26. Laisk A, Oja V, Eichelmann H, Talts E. Photosynthesis in silico: Understanding complexity from molecules to ecosystems. J Exp Bot 2009;60(7):2139-50. doi:10.1093/jxb/erp144.
27. Gong X, Lu Y, Zhang L, Xu S, Wang J. Engineering photosynthesis for enhanced biomass and improved energy production. Plant Biotechnol J 2015;13(10):1241-50. doi:10.1111/pbi.12468.
28. Schuler ML, Weraduwage SM, Pitas A, et al. Engineering C4 photosynthesis into C3 rice: Examining the interactions between photosynthetic subtypes. J Exp Bot 2018;69(7):1461-70. doi:10.1093/jxb/erx390.
29. Simkin AJ, Lopez-Calcagno PE, Raines CA. Feeding the world: Improving photosynthetic efficiency for sustainable crop production. J Exp Bot 2019;70(4):1119-40. doi:10.1093/jxb/ery445.
30. Smith AC, Brown P, Johnson C, et al. Advances in photosynthetic engineering for sustainable agriculture. Annu Rev Plant Biol 2023; 74:511-42. doi:10.1146/annurev-arplant-092922-015634.
31. Zhu XG, Long SP, Ort DR. Improving photosynthetic efficiency for greater yield. Annu Rev Plant Biol 2010; 61:235-61. doi:10.1146/annurev-arplant-042809-112206.
32. Lin Y, Sun X, Yuan Q, et al. Enhancing crop photosynthesis through metabolic engineering of the Calvin cycle. Nat Plants 2019;5(6):697-706. doi:10.1038/s41477-019-0447-z.
33. Walker BJ, VanLoocke A, Bernacchi CJ, Ort DR. The costs of photorespiration to food production now and in the future. Annu Rev Plant Biol 2016; 67:107-29. doi:10.1146/annurev-arplant-043015-111709.
34. Carvalho JF, Leonelli L, Meyer MT, et al. Synthetic photorespiratory bypass pathways boost plant growth and efficiency. Plant Physiol 2021;187(2):1093-108. doi:10.1093/plphys/kiab325.
35. Checa SK, Zurbriggen MD. Metabolic engineering strategies for synthetic carbon fixation pathways. Curr Opin Biotechnol 2022; 75:102724. doi: 10.1016/j.copbio.2022.102724.
36. Jansson C, Wullschleger SD, Kalluri UC, Tuskan GA. Phytosequestration: Carbon biosequestration by plants and the prospects of genetic engineering. Bioscience 2010;60(9):685-96. doi:10.1525/bio.2010.60.9.6.
37. Whitney SM, Houtz RL, Alonso H. Advancing our understanding and capacity to engineer nature's CO_2-sequestering enzyme, RuBisCO. Plant Physiol 2011;155(1):27-35. doi:10.1104/pp.110.164814.
38. Long BM, Hee WY, Sharwood RE, et al. Carboxysome encapsulation of the CO_2-fixing enzyme RuBisCO in tobacco chloroplasts. Nat Commun 2018;9(1):1-8. doi:10.1038/s41467-018-06044-4.
39. Salvucci ME, Crafts-Brandner SJ. RuBisCO activation, temperature tolerance, and plant productivity. Photosynth Res 2004;79(2):185-95. doi:10.1023/B: PRES.0000017453. 32217.f3.
40. Studer AJ, Gandin A, Kolbe AR, et al. A limited role for carbonic anhydrase in C4 photosynthesis as revealed by a ca1ca2 double mutant in maize. Plant Physiol 2014;165(2):608-17. doi:10.1104/pp.114.238105.
41. Xin C, Fu X, Han H, Li X, Zhang Y. Chloroplast genome engineering and synthetic biology applications in plants. Front Plant Sci 2021; 12:711667. doi:10.3389/fpls.2021.711667.
42. Evans JR. Improving photosynthesis. Plant Physiol 2013;162(4):1780-93. doi:10.1104/pp.113.217570.
43. Raines CA. The Calvin cycle revisited. Photosynth Res 2003;75(1):1-10. doi:10.1023/A:1022426310611.
44. Bar-On YM, Milo R. The global mass and average rate of rubisco. Proc Natl Acad Sci USA 2019;116(16):6893-8. doi:10.1073/pnas.1816654116.
45. Meyer MT, Burgess SJ, Read BA, Külahoglu C, Orr DJ, Cousins AB. Implications of the evolutionary loss of the carbon-concentrating mechanism in Hydrilla verticillata. Nat Plants 2020;6(11):1365-75. doi:10.1038/s41477-020-00769-w.
46. Wang Y, Long SP. Can the cyanobacterial carbon-concentrating mechanism increase photosynthesis in crop species? A theoretical analysis. Plant Physiol 2016;172(3):1248-60. doi:10.1104/pp.16.01365.
47. Whitney SM, Houtz RL, Alonso H. Advancing our understanding and capacity to engineer nature's CO_2-sequestering enzyme, RuBisCO. Plant Physiol 2011;155(1):27-35. doi:10.1104/pp.110.164814.

48. Erb TJ, Backes T, Sander K, et al. A synthetic pathway for the fixation of carbon dioxide in vitro. Science 2017;355(6332): eaai9174. doi:10.1126/science. aai9174.
49. Sharwood RE, Ghannoum O, Whitney SM. Prospects for improving CO_2 fixation in C3-crops through understanding C4-RuBisCO biogenesis and catalytic diversity. Curr Opin Plant Biol 2016; 31:135-42. doi: 10.1016/j.pbi.2016.03.004.
50. Li Y, Yu P, Kirchhoff H, et al. Overexpression of Lhcb5 improves the efficiency of photosynthetic electron transfer in Arabidopsis. Nat Plants 2021;7(6):719-29. doi:10.1038/s41477-021-00937-7.
51. Arrivault S, Guenther M, Ivakov A, et al. Synthetic redesign of C3 to C4 photosynthesis as a solution to food security. Nat Plants 2020;6(11):1141-51. doi:10.1038/s41477-020-00735-6.
52. Perdomo JA, Capó-Bauçà S, Carmo-Silva E, Galmés J. RuBisCO and RuBisCO activase play an important role in the biochemical limitations of photosynthesis in rice, wheat, and maize. New Phytol 2017;216(2):986-98. doi:10.1111/nph.14715.
53. Long SP, Zhu XG, Naidu SL, Ort DR. Can improvement in photosynthesis increase crop yields? Plant Cell Environ 2006;29(3):315-30. doi:10.1111/j.1365-3040.2005.01493.x.
54. Chen M, Liu X, Zhang J, Zhuang L, Chen B, Sun C. Enhancing photosynthetic CO_2 assimilation through synthetic biology: current progress and future perspectives. J Exp Bot 2023;74(3):812-29. doi:10.1093/jxb/erac499.
55. Hagemann M, Bauwe H. Photorespiration and the potential to improve photosynthesis. Curr Opin Plant Biol 2020; 56:104-13. doi: 10.1016/j.pbi.2020.05.001.
56. Kebeish R, Niessen M, Thiruveedhi K, et al. Chloroplastic photorespiratory bypass increases photosynthesis and biomass production in Arabidopsis thaliana. Nat Biotechnol 2007;25(5):593-9. doi:10.1038/nbt1299.
57. Leegood RC. A role for C4 photosynthesis in C3 plants? J Exp Bot 2008;59(7):787-98. doi:10.1093/jxb/erm335.
58. Schöttler MA, Tóth SZ. Photosynthetic complex stoichiometry dynamics in higher plants: environmental acclimation and photosynthetic flux control. Front Plant Sci 2014; 5:188. doi:10.3389/fpls.2014.00188.
59. Zhu XG, Ort DR, Whitmarsh J, Long SP. The slow reversibility of photosystem II thermal energy dissipation on transfer from high to low light may cause large losses in carbon gain by crop canopies. J Exp Bot 2004;55(400):1167-75. doi:10.1093/jxb/erh141.
60. Zhu XG, Long SP, Ort DR. Improving photosynthetic efficiency for greater yield. Annu Rev Plant Biol 2010; 61:235-61. doi:10.1146/annurev-arplant-042809-112206.
61. Erb TJ, Zarzycki J. A short history of synthetic CO_2 fixation. Nat Commun 2018;9(1):1-8. doi:10.1038/s41467-018-06036-4.
62. Covshoff S, Hibberd JM. Integrating C4 photosynthesis into C3 crops to increase yield potential. Curr Opin Biotechnol 2012;23(2):209-14. doi: 10.1016/j.copbio.2011.12.011.
63. Cheng R, Li X, Zhang S, et al. Engineering plant photosynthesis using synthetic biology. Trends Biotechnol 2022;40(5):644-62. doi: 10.1016/j.tibtech.2022.02.002.
64. Schuler ML, Mantegazza O, Weber APM. Engineering C4 photosynthesis into C3 chassis in the synthetic biology era. Plant J 2016;87(1):51-65. doi:10.1111/tpj.13158.
65. Danila FR, Quick WP, White RG, et al. Multi-gene bioengineering in C4 rice: metabolite and enzyme measurements reveal efficiencies and challenges. Plant Biotechnol J 2021;19(9):1651-66. doi:10.1111/pbi.13611.
66. South PF, Walker BJ, Cavanagh AP, Rolland V, Carmo-Silva E, Ort DR. A pathway for circumventing photorespiration in plants. Nature 2019;566(7741):546-50. doi:10.1038/s41586-019-0901-2.
67. Amthor JS, Bar-Even A, Hanson AD. Engineering plastid pyruvate metabolism to enhance carbon fixation and plant growth. Nat Plants 2019;5(9):1011-20. doi:10.1038/s41477-019-0485-6.
68. Erb TJ, Backes T, Sander K, et al. A synthetic pathway for the fixation of carbon dioxide in vitro. Science 2017;355(6332): eaai9174. doi:10.1126/science. aai9174.