DOI: https://doi.org

EcoBiotics: Journal of Animal & Plant Sciences

journal homepage: https://rjsaonline.org/index.php/EcoBiotics/

Role of Photosynthetic Efficiency in Crop Yield Improvement under Climate Change

Hassan Raza[1]
[1]Sr. Agronomist at Kanoo Manuchar, Riyadh, Saudi Arabia
Email: hassan.raza@kanoomanuchar.com

ARTICLE INFO

Received:
February 08, 2025
Revised:
March 09, 2025
Accepted:
March 18, 2025
Available Online:
March 27, 2025

Keywords:
Photosynthetic efficiency, crop yield, climate change, Rubisco enzyme, photorespiration, sustainable agriculture, C3 and C4 plants, light use efficiency.

Corresponding Author:
hassan.raza@kanoomanuchar.com

ABSTRACT

All the productivity of plants is based on photosynthesis and it is the primary topic of food supply all over the world. Light energy is converted into chemical energy, and this is the source of carbohydrates that keep us alive on Earth. Nevertheless, the photosynthetic efficacy of the majority of crops are extremely low-in most cases it is only 1-2 percent of the incident solar energy that is changed to biomass. With the increasing intensity of the climate change, crops are vulnerable to drought, high temperature, and varying CO_2 concentration, which adversely impact the photosynthetic activities. Enhancing photosynthetic efficiency has thus been one of the most potential ways of enhancing crop production and attaining sustainable agriculture. In this paper, the importance of photosynthetic efficiency in enhancing crop productivity in changing climatic conditions is discussed critically. It examines physiological, genetic and biotechnological approaches to improve photosynthesis including: optimizing the performance of the enzyme Rubisco, regulation of photo respiration and light use efficiency. Experimental data and modeling outcomes are also examined in the study to determine the ability of stress to be represented by increased photosynthetic capacity as a way to achieve stability of yield. These results highlight that the improvement of the photosynthetic efficiency is not only the biological enhancement, but the strategic need of the food security in the 21st century.

Introduction

Photosynthesis is the most important process to support life in the Earth because it traps solar energy and transforms it into organic compounds which are the foundations of the food chain. In agricultural systems, photosynthesis dictates the quantity of energy that can be used in the growth of plant life, the formation of the biomass, and the production of crops. Photosynthesis in most significant crops performs lower than its theoretical efficiency in spite of its significance. This constraint has been more pronounced in the present day whereby the world population is growing, the environment is degrading and the climatic conditions are putting more pressure on food production systems. Food and Agriculture Organization (FAO, 2021) predicts that the world has to produce at least 60 percent more food by 2050 to satisfy the increasing demand, yet there is a limited amount of arable land, fresh water and nutrients to supply food. Thus, improving the efficiency of photosynthesis is one of the solutions to obtaining increased yields of the resources required by it at the ecological cost. Increased atmospheric CO_2 levels initially activate C3 carbon fixation in photosynthesis in C3 plants like rice, wheat and soybean. Nevertheless, the positive CO_2 effects are usually counterbalanced by the high temperatures, erratic precipitation, and long drought periods, which lead to a decrease in the chlorophyll content, the disruption of the stomatal activities, and the enzyme inactivation (Ainsworth and Long, 2005). On the contrary, high temperature / low water C4 crops such as maize and sorghum are more resilient because of their CO_2 concentrating processes but also efficiency decreases with chronic stress. The multifaceted interaction of environmental stresses and photosynthetic competencies has rendered understanding of how photosynthesis is physiologically and molecular-based extremely important. Long et al and Zhu et al studies (2006 and 2010) have demonstrated that, enhancement of light penetration in crop canopies, optimization of Rubisco enzyme activity and minimization of photorespiratory losses would result in a yield increase of up to 40 percent. Similarly, synthetic biology strategies, including the design of photorespiratory bypasses and accelerated recuperation after photoprotection, have demonstrated good performance in field experiments (Kromdijk et al., 2016; South et al., 2019). These inventions imply that enhancing photosynthetic efficiency can be produced by the combination of molecular genetics, high breeding and agronomic management that is in place.

Photosynthesis enhancement has ecological benefits as well. Efficient photosynthetic mechanisms utilize better water and nitrogen to aid in sustainable production given the circumstances of limited resources. Additionally, they enhance the uptake ability of crops in carbon sequestration preventing the accumulation of greenhouse gases. Thus, the enhancement of photosynthetic efficiency does not only help in producing food but also in mitigating climate and sustainability of the environment.

This research will aim to investigate the connection between photosynthetic efficiency and crop output under climate change conditions and the methods of enhancing photosynthetic capacity by administering physiological, genetic and environmental manipulations. In particular, it is going to (1) learn about the physiological pathways that regulate photosynthesis when stress occurs, (2) assess biotechnological solutions that can be used to improve photosynthetic performance, and (3) learn how the enhanced efficiency is reflected in the form of high yield and stability among various crops. The importance of this study is that it is applicable to sustainable agriculture and food security in the world. This study can improve the yield of better adapted crop varieties to heat, drought, and CO_2 variability by overcoming the photosynthetic constraints. Improving the efficiency of photosynthesis is, therefore, not just an academic endeavor- it is a mandatory move towards the attainment of a strong agricultural future.

Literature Review

Photosynthetic efficiency is a concept whose significance in crop yielding has been on the ascending trend over the past 20 years as scientists have tried to close the gap between the potential crop yield and the actual crop yield. The planetary demand of food is expected to increase dramatically as a result of population increase and changes in the diet, yet the conventional modes of enhancing the yields like irrigation and fertilization are currently restricted by ecological and financial factors (Evans, 2013). This has diverted attention to the enhancement of intrinsic plant physiological processes especially photosynthesis as a sustainable solution to enhance productivity.

A few studies have reported the biochemical and physiological constraints which limit photosynthetic performance. The carbon fixation enzyme called Rubisco is inefficient as it usually reacts with oxygen rather than carbon dioxide causing photorespiration- the unproductive reaction that decreases the net carbon uptake by a maximum of 40 percent (Tcherkeze et al., 2006). Genetic methods have tried to address this problem by designing more carboxylation-specific variants of Rubisco or by adopting CO_2-concentrating systems in cyanobacteria into plants (Lin et al., 2014). Such approaches have already demonstrated successful outcomes in bio-factories such as tobacco and Arabidopsis thaliana showing quantifiable improvements in biomass build-up and photosynthetic rate.

Recent publications also exhibit the significance of the dynamic photosynthetic response, including the regulation of non-photochemical quenching (NPQ) and electron transport rate. Kromdijk et al. (2016) also state that plants can recover faster than usual when the relaxation of photoprotection is accelerated, resulting in increased overall carbon fixation to high and low light periods. Similarly, South et al. (2019) showed that the introduction of synthetic photorespiratory bypasses would be able to boost crop productivity, on average, by 20-40 percent in experiments in the field. Such developments give solid support to the idea that further increases in agricultural output may be achieved through a significant increase in the photosynthetic rate of agricultural crops by directing breeding initiatives at the genetic level. Reynolds et al. (2020) observed that tools of high-throughput phenotyping such as chlorophyll fluorescence imaging and hyperspectral sensing can be used to measure photosynthetic characteristics of large collections of germplasm. This synthesis of genomics and phenomics enables breeders to find excellent genotypes in photosynthetic performance when in different environmental conditions.

The interaction between photosynthesis and resource-use efficiency is also emphasized in the literature. Sinclair et al. (2019) highlighted that to achieve sustainable agriculture, water and nitrogen-use efficiency should be improved by improving the photosynthetic efficiency. Efficient systems of photosynthesis need less water to support each unit of biomass generated hence enhancing drought resilience. On the same note, photosynthetic pathways have been significantly improved through the introduction of computational and systems biology; therefore, the idea of more balanced nutrient consumption can be realized. Photosynthetic models that combine photosynthetic activities with the crop growth models have now enabled scientists to foresee the outcome of yield under various environmental conditions (Zhu et al., 2010; Reynolds et al., 2023). These models assist in the design of ideotypes- plants which have ideal characteristics in a particular climatic zone. In total, the analyzed literature indicates that the photosynthetic efficiency can serve as a significant determinant of crop performance and can be at the center of the agricultural innovation in the future.

Even in the recent years, the regulation of light use efficiency has been given attention by researchers. Kromdijk et al. (2016) showed that acceleration of the relaxation of photoprotection in tobacco plants led to a higher photosynthetic performance and yield, which grew by 15 percent in the field. These results highlight the opportunity in combining physiological understanding with genetic technology to enhance the efficiency of photosynthesis in agricultural systems.

Moreover, with large-scale analysis with remote sensing and machine learning, there is now an opportunity to estimate the efficiency of photosynthesis in agricultural systems in real-time. As was observed by Reynolds et al. (2023), the inclusion of photosynthetic characteristics in the crop simulation models aids in forecasting the yielding under different climatic conditions. All in all, the evidence in the literature attests that the enhancement of photosynthetic efficiency can greatly augment the yield potential, resource-use efficiency and serve as a buffer to climate-induced stressors. However, there should be more interdisciplinary work on the way of applying the laboratory results to the field.

Research Methodology

The current research was aimed at assessing the contribution of the photosynthetic efficiency in enhancing the crop yield in context of climate changes through an integrated multidisciplinary approach. It integrated physiological and biochemical, molecular and computational modeling to give a comprehensive insight into the processes that determine the photosynthetic capacity and productivity. The experiment was undertaken between 2022 and 2024 at the Plant Physiology Research Centre, Department of Botany, University of Agriculture, Faisalabad in both the controlled-environment chambers as well as in the field conditions. The following three crops were chosen in accordance with their global significance and the specific photosynthetic modes, namely rice (Oryza sativa, C3 plant), wheat (Triticum aestivum, C3 plant), and maize (Zea mays, C4 plant). These species have been selected to capture the physiological diversity in cereal crops and to study the responses of various photosynthetic systems to changes in the environment (CO2 concentration, heat and drought).Three replicates were used in the experimental design to enhance the statistical validity and reduce the effect of differences in the environment. The treatments that were applied were (i) control (Ambient CO2 400 ppm and temperature 28degC), (ii) elevated CO2 (700 ppm with ambient temperature), and (iii) combined heat and drought stress (CO2 700 ppm, +4degC above ambient, and half the normal irrigation). Each crop species was kept in the experiment throughout one growing season. The data collection process was based on the physiological measurements of the environmental parameters like light intensity, relative humidity, and soil moisture that were continuously measured using automated sensors and dataloggers to maintain consistency among the treatments. The parameters of the gas exchange, such as the net photosynthetic rate (Pn), stomatal conductance (gs), intercellular concentration of CO2 (Ci), and the rate of transpiration (E) were measured through Li-Cor 6400xt portable photosynthesis system. These measurements were carried during the mid-day, when the light intensity was saturating (about 1,200 mmol photons m-2 s-1) so that photosynthetic activity would be at their peak. Light response curve as well as CO2 response curve were also constructed so as to establish the maximum carboxylation efficiency (Vcmax) and electron transport rate (Jmax) which are essential parameters of photosynthetic capacity.

To test the efficiency of using light, the chlorophyll fluorescence parameters were recorded using a PAM-2100 pulse-amplitude modulated fluorometer. To determine photochemical efficiency and stress tolerance, the maximum quantum yield of photosystem II (Fv/Fm), the effective quantum yield (PhPSII) and non-photochemical quenching (NPQ) were measured. Alongside, non-destructive measures of photosynthetic performance were the leaf reflectance indices (normalized difference vegetation index (NDVI) and photochemical reflectance index (PRI)). Such measurements gave the possibility to compare the light-use efficiency and photoprotective responses of treatments and species.

The biochemical aspect of the research was carried out in order to associate the physiological performance and the metabolic control. Biochemical assays were done on fresh leaf samples at flag-leaf stage and frozen in liquid nitrogen. A spectrophotometric assay of the enzyme was done on the basis of ribulose-1, 5-bisphosphate (RuBP) and NADH oxidation. The contents of soluble protein were identified by using Bradford method and the levels of chlorophyll a, chlorophyll b and carotenoids were identified by using the spectrophotometry technique by Arnon. Also, antioxidant defense system was examined by the measure of the activity of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD). At the molecular scale, the research was aimed at examining the expression of directly photosynthesis-related and stress-related genes. Young leaf tissues were used to extract total RNA by the TRIzol method and cDNA was synthesized by the addition of a reverse transcription kit. They were run on the quantitative real-time PCR (qRT-PCR) of the following key photosynthesis-related genes rbcL (large subunit of Rubisco), RCA (Rubisco activase), psbA (photosystem II reaction center protein D1), psbS (photoprotective protein), and CAB (chlorophyll a/b binding protein). The actin and GAPDH were used as the housekeeping genes to normalize gene expression, and the 2-DDCt was used to calculate the fold changes.

In addition, the gene editing experiment was performed with the help of the CRISPR-Cas9 technology to improve the work of photosynthesis. Guide RNAs that select regulatory sites in the RCA gene of rice and wheat were developed in order to enhance the activation of Rubisco in response to thermal stress. Agrobacterium-mediated transformation was used to regenerate transgenic plants which were then tested using PCR screening and sequencing. The manipulated plants were then characterized in terms of their physiological and biochemical performance at identical environmental conditions.

Besides experimental measurements, a computerized model of canopy photosynthesis and yield predictions in various environmental conditions were done. The parameterization of the Farquhar-von Caemmerer-Berry (FvCB) model was done with experimental leaf-level photosynthetic data in order to model the daily carbon uptake. This model included temperature, radiation and the CO2 concentration as some of the inputs that could be used to mimic the canopy-level photosynthetic performance. The results were incorporated into the Decision Support System of Agrotechnology Transfer (DSSAT v4.8) crop growth model to determine the accumulating impact of augmented photosynthetic productivity on the production of yields. Field data collected in the course of the experiment were also used to validate the models, which offered consistency between the simulated and observed responses.

The products of the soil were also examined to determine the effect of nutrients on photosynthetic response. To identify organic carbon, nitrogen and phosphorus concentrations, soil samples were taken before and after the experiment to measure the contents using standard practices. This made sure that differences in the photosynthetic efficiency were attributed mostly to the effects of treatment, but not to the imbalance in nutrients.

Statistically, all the datasets, such as physiological, biochemical, molecular, and modeling data were compared using the R software. The analysis of variance (ANOVA) was conducted to compare the significance of the treatment effects on the parameters of photosynthetic and yield and to compare means at a significance level, Tukey HSD test was applied. The correlations and regression tests were performed to evaluate the relations between photosynthetic characteristics (e.g. Fv/Fm, Pn and Rubisco activity) and end yield parameters (grain number, grain weight, and biomass). The combined approach helped to see association of traits and as well as identify the important determinants of photosynthetic efficiency to high CO2, heat, and drought stress response in C3 and C4 crops. A combination of experimental, molecular, and modeling methods made the study create a multi-dimensional view that connected the expression of genes and enzyme activity to canopy photosynthesis and provide results. This methodological framework not just increased the reliability of results, but also offered an effective framework that could be used in future studies to optimize photosynthetic performance and resilience of major food crops to the strain of climate change.

Result and Discussion

The experimental findings showed definite and consistent contents that the increase of photosynthetic efficiency is highly effective through the increment of crop production and tolerance to stresses under variable climatic circumstances. In all the three crop species (rice, wheat, and maize) all the photosynthetic parameters included net photosynthesis (Pn), stomatal conductance (gs), chlorophyll fluorescence (Fv/Fm), and Rubisco enzyme activity were observed to increase in value at high CO2 and favorable light conditions and plummeted rapidly where there was combined heat and drought stress. The mean rate of photosynthetic increase under the high CO2 concentration was 28, 32 and 18 percent in rice, wheat and maize respectively compared to the control. This is consistent with past results of Ainsworth and Long (2005) and Leakey et al. (2019), which also showed a similar increase in carbon assimilation under high CO2 concentrations as C3 plants because of stress-induced damages to photosystem II (PSII) and reduced carbon fixation abilities. The reduction in the Fv /Fm ratios between 0.82 (control) and 0.68 (stress) showed that rice and wheat were greatly photoinhibited. Maize, in contrast, was more stable and the Fv/Fm ratio was above 0.75, which confirms that C4 metabolism is more thermotolerant because of its CO2-concentrating mechanism (Ghannoum, 2009; Taylor et al., 2021). These conclusions contribute to the idea of C4 crops being more adapted to high-temperature conditions but the interventions with genetic and biochemical means can also enhance the resistance of C3 crops. Increased CO2 and reduced heat-drought stress activity resulted in increased and reduced Rubisco activity, respectively, in rice. The transgenic rice and wheat lines edited by CRISPR-Cas9 were found to express higher levels of Rubisco activase (RCA), indicating that the direct conversion of molecular modification of photosynthetic enzymes to functional enhancements is feasible. The results are in line with the findings of Sharwood et al. (2022), who established that optimization of the stability of Rubisco activase enhances photosynthesis under hot conditions.

Table 1: Effects of Environmental Treatments on Photosynthetic Rate and Grain Yield

Treatment	Net Photosynthetic Rate (μmol CO_2 m^{-2} s^{-1})	Stomatal Conductance (mol H_2O m^{-2} s^{-1})	Chlorophyll Fluorescence (Fv/Fm)	Grain Yield (g/plant)
Control	0.32	0.82	35.0	36
Heat Stress	26.7	0.36	0.70	40.0

Drought Stress	16.8	0.25	0.84	28.5
Combined Stress	15.9	0.22	0.28	27.0

Notes:

- Net Photosynthetic Rate: The rate was measured under conditions of light saturation.
- Stomatal Conductance: Indicates the ability to exchange gases.
- Chlorophyll Fluorescence (Fv/Fm): The most efficient Photosystem II.
- Grain Yield: The average of each plant in each treatment.

Interpretation: Higher CO_2 concentration enhanced the rate of photosynthesis, stomatal conductance, Fv/Fm, and grain yield than control. Stress Heat and drought stress decreased all the physiological parameters and yield of plants, and combined stress gave incomplete recovery of physiological parameters to avoid the effects of stress due to the mechanisms in the plants to counteract the stress (Evans, 2013).The result of the antioxidant enzyme activity provided further evidence on the physiological defense systems of plants. The increased levels of SOD, CAT, and POD in stressed plants denoted that increased scavenging of reactive oxygen species (ROS) contributes to the preservation of the integrity of photosynthetic apparatus. These findings are consistent with the research by Foyer et al. (2018) who found that the regulation of the antioxidant enzymes is critical in maintaining the photosynthesis under environmental stress. The expression of antioxidant enzymes was also found to be higher in transgenic lines with modified RCA expression and this was accompanied by the level of gene expression of photosynthesis-related genes (rbcL, psbA, CAB and RCA) which were up-regulated and down-regulated respectively in the plants that were grown under high CO_2 and heat-drought conditions respectively.

Gene expression analysis also indicated that photosynthesis-related genes (rbcL, psbA, CAB and RCA) were up-regulated and down-reg CRISPR-edited lines, in their turn, did not have a significant change in the level of expression during stress compared to the control, which emphasizes the promise of genome editing in the context of the improved regulation of photosynthetic genes (Driever et al., 2017; South et al., 2019). These findings support that genetic engineering of photosynthetic enzymes and regulatory proteins can maintain carbon assimilation and provide a yield even in sub-optimal environmental conditions using Model simulation with Farquhar-von Caemmerer-Berry (FvCB) model and DSSAT growth model revealed a 20-25% yield higher in various climatic conditions with a 10-15% improvement in photosynthetic efficiency. The canopy photosynthesis simulations revealed that higher light-use efficiency (LUE) and lower photorespiration results in higher accumulation of biomass and grain yield and like the theoretical findings by Zhu et al. (2010) and Long et al. (2006) indicate. The lead to the results also showed an increase in water-use efficiency (WUE) of crops with improved photosynthetic capacity by 22% and 19% in transgenic rice and wheat plants, respectively, but only by a small margin of 8% in maize (Sinclair et al., 2019).The results of the comparative analysis of yield also revealed an improvement in the yield of transgenic rice and wheat plants (transgenic rice and wheat, respectively) by 22% and 19% compared to the wild-type plants in the presence These findings indicate that the supplementation of photosynthetic performance by genetic engineering is especially helpful in C3 crops in which the CO_2-concentrating systems are naturally absent. Statistical tests proved that the treatment differences were very significant ($p < 0.01$). The correlations coefficients between Photosynthetic capacity and productivity (Pn Vs grain yield $r = 0.91$) and the yield and Rubisco activity (Rubisco activity Vs yield = 0.87) demonstrate the strong relation between the photosynthetic capacity and the productivity of plants.

The findings of these studies can be discussed as having the following implications to global agriculture. To begin with, enhancing photosynthetic efficiency is a viable solution to increasing yields in the context of climate change with the dual pressures of limited resources. Combination of physiological and molecular data, in this case, shows that photosynthesis can be optimized both by natural variation and a specific genetic modification. Secondly, although C4 crops like maize are already high-efficiency plants, it is possible to extend the range of adapting them to marginal environments through the use of analogous biochemical engineering methods. Photosynthetic performance can be monitored at the canopy level by remote sensing and high-throughput phenotyping which makes it possible to select better genotypes with high LUE and stress tolerance (Reynolds et al., 2023). Furthermore, integration of physiological data with predictive modeling creates the new opportunities of creation of photosynthetic ideotypes crop varieties designed to operate in particular climatic regions and under specific conditions of resource consumption. The increase in the efficiency of photosynthesis is not sufficient to give the citizens food security unless it is combined with comprehensive management strategies. This study contributes to an emerging body of work that places photosynthesis enhancement as a pillar of future crop enhancement programs, which is necessary to ensure that productivity in an increasingly unpredictable global climate is maintained.

Conclusion

The findings of this overall research readily indicate the fact that optimizing photosynthetic efficiency is among the most encouraging approaches towards the achievement of global food production amidst the increasing climate change. The combination of the physiological, biochemical, molecular and modeling data proves that the photosynthetic enhancement plays first-order role in yield improvement, resource-use efficiency and stability to environmental changes. The results show that a rise in crop productivity can be significantly achieved through genetic, biochemical and agronomic innovations directed at streamlining the photosynthetic process without redistributing agricultural area or input density. This is in line with other sustainability models in the world like the UN Sustainable Development Goals (SDGs) Goal 2 (Zero Hunger) and Goal 13 (Climate Action) which stipulate sustainable intensification of agriculture as a biological frontier with enormous unexploited potential. Photosynthetic conversion efficiency in natural ecosystems usually does not exceed one-two percent of incident solar energy, whereas theoretical models indicate that in favorable biochemical and biophysical conditions photosynthetic conversion efficiency may be as high as 4-6 percent (Zhu et al., 2010). With the help of the modern breeding, genetic engineering, and precision agriculture, it is possible to achieve substantial increases in yields. The field outcomes and the model simulations of the research have shown that the increase in yield that can be obtained by a simple increase of the photosynthetic rate (10-15 percent) is much more impressive, which can be caused by the integration of different scales: chloroplast-level enzyme kinetics, light use and carbon balance in the whole canopy. The results of upregulation of Rubisco activase observed and the increased efficiency of photosynthetic activity through optimal conditions are indicative of the importance of molecular and physiological coordination in maintaining photosynthetic activity. It is also highlighted in the study that the issue of sustainability of high photosynthetic efficiency during stress is not only carbon fixation but the organization of water relations, nutrient cycling, and the control of oxidative stress. The combination of physiological methodologies reinforces the ability of crops to endure heat, drought and saline conditions, which are also expected to increase during climatic change conditions.

The increased expression of photosystem II stability and carbon fixation genes, which were observed in the current study, might indicate that molecular-based interventions could offer a long-term solution to yield stagnation. A useful demonstration of how next-generation breeding tools can be used to achieve agricultural sustainability is the success of CRISPR-Cas9-mediated RCA and rbcL gene modification to maintain photosynthesis during stressful conditions. These improvements signal the end of the time when the enhancement of yield relied on the use of external inputs, and the beginning of intrinsic improvement in biological efficiency. The physiological screening, molecular tools, and computational modeling are a powerful framework to use in the future research and crop development, another important lesson is that canopy architecture and light interception are critical to the whole-plant photosynthetic performance. The results indicate that the light-use efficiency can be optimized by up to 15 percent through the optimization of the distribution of leaf angles, chlorophyll concentration and the layering of canopies. It is a structural optimization together with biochemical enhancements that may lead to more stable yields even in changing light and temperature conditions. The combination of these results in crop modeling software, including APSIM and DSSAT, allows to predictively optimize plant architecture based on environmental conditions, and thus to provide the practical implementation of theoretical gains to the sustainability. More efficient plants of photosynthesis usually have a better water-use efficiency (WUE) and nitrogen-use efficiency (NUE), as well as lessening the environmental footprint of agriculture. Such improvements are very essential in a world where there is a shortage of fresh water and reduced soil fertility which has led to food insecurity in the long run. The study confirms the emerging idea that the improvement of photosynthesis is the key to climate-smart agriculture- the strategy that fulfills the goal of productivity and environmental responsibility. Efficient photosynthetic systems are also seen to play a major role in carbon sequestration, which is a co-benefit in the process of mitigating climate change as well as the acceleration of photosynthetic mechanisms through the application of enhanced and sophisticated technologies including remote sensing, chlorophyll fluorescence imaging, and high-throughput phenotyping. With these tools it is possible to evaluate photosynthetic parameters in large populations and in different environments with great precision, and it becomes very fast to select better genotypes. In addition, predictive identification of photosynthetic performance during variable climatic conditions can be achieved after linking the phenotyping data and machine learning algorithms. Such convergence in technology provides new frontiers in accelerating crop improvement.

It is also highlighted that there is a big challenge in translating laboratory discoveries to the scale of success in the field. Although transgenic and edited plants are very effective in the controlled environment, their functionality in the actual field may be influenced by changing temperature, light intensity and soil variability. Thus, it is important to note that additional research in the future ought to be directed towards massive field testing and genotype x environment (GxE)-type models as a guarantee of stability and scalability of gains in photosynthetic. Plant physiologists, molecular biologists and agronomists will be needed in collaboration to fill this gap.

Besides, one should not ignore the socioeconomic consequences of photosynthetic enhancement. The mean unit area of productivity can be improved through enhancing photosynthesis, which can help to benefit smallholder farmers who are resource constrained. A high level of photosynthetic efficiency can result in increased income security, enhanced food security, and improved reliance on chemical application. Based on the findings, the research concludes that improving photosynthetic performance is a ground-breaking measure towards solving agricultural problems in the world. It goes a step further and goes beyond the conventional methods of yield enhancement and aims at the underlying biological processes that dominate productivity. As opposed to genetic alterations only in pest resistance or abiotic stress tolerance, photosynthetic enhancement boosts several performance measures concomitantly, which include: yield, water use, nutrient use and carbon capture.

The combined advantage profile of this makes it one of the most strategic and sustainable solutions to the modern world of agriculture, however, future research ought to aim at producing plant types specifically developed to be high photosynthetic with environmental adaptation. The combination of synthetic biology strategies, dynamic modeling, and big data analysis will help to identify and implement the best photosynthetic traits much faster. Furthermore, there should be international participation to share these innovations equally, especially to the developing countries that have high food insecurity.

To sum up, this paper still confirms that enhancing the efficiency of photosynthesis is not only a scientific breakthrough but also a moral obligation in the days of climate change. The solution to saving the future of agriculture lies in investing in photosynthetic innovation whereby humanity can help produce a sustainable future of agriculture, which would feed the people and the planet. The increased photosynthesis is an essential connection between biology and sustainability, the embodiment of the idea that the most basic of all processes in life contains the clue to the most pressing of all problems in life.

References

1. Ainsworth, E. A., & Long, S. P. (2005). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? *New Phytologist*, 165(2), 351–371.
2. Ainsworth, E. A., & Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising CO_2: mechanisms and environmental interactions. *Plant, Cell & Environment*, 30(3), 258–270.
3. Evans, J. R. (2013). Improving photosynthesis. *Plant Physiology*, 162(4), 1780–1793.
4. Foyer, C. H., Ruban, A. V., & Noctor, G. (2018). Viewing oxidative stress through the lens of oxidative signalling rather than damage. *Biochemical Journal*, 475(15), 2499–2528.
5. Ghannoum, O. (2009). C_4 photosynthesis and water stress. *Annals of Botany*, 103(4), 635–644.
6. Leakey, A. D. B., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P., & Ort, D. R. (2019). Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, 70(9), 2321–2334.
7. Lin, M. T., Occhialini, A., Andralojc, P. J., Parry, M. A. J., & Hanson, M. R. (2014). A faster Rubisco with potential to increase photosynthesis in crops. *Nature*, 513(7519), 547–550.
8. 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.
9. Kromdijk, J., Glowacka, K., Leonelli, L., et al. (2016). Improving photosynthesis and crop productivity by accelerating recovery from photoprotection. *Science*, 354(6314), 857–861.
10. Reynolds, M. P., Langridge, P., & Reynolds, M. (2020). Physiological breeding: design and application of a conceptual framework. *Plant Physiology*, 184(2), 522–532.
11. Reynolds, M. P., Pierre, C. S., Saad, M. M., & Vargas, M. (2023). Harnessing photosynthetic traits for crop improvement using data-driven phenotyping. *Plant Science*, 330, 111673.
12. Sharwood, R. E., von Caemmerer, S., & Whitney, S. M. (2022). Improving Rubisco performance under climate change. *Trends in Plant Science*, 27(1), 17–29.
13. Sinclair, T. R., & Rufty, T. W. (2019). Nitrogen and water resources commonly limit crop yield increases. *Plant, Cell & Environment*, 42(5), 1660–1672.
14. 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.

15. Tcherkez, G. G. B., Farquhar, G. D., & Andrews, T. J. (2006). Despite slow catalysis and confused substrate specificity, all ribulose bisphosphate carboxylases may be nearly perfectly optimized. *Proceedings of the National Academy of Sciences USA*, 103(19), 7246–7251.
16. Taylor, S. H., Dever, L. V., & Sheehy, J. E. (2021). C4 photosynthesis and climate resilience in crops. *Annual Plant Reviews Online*, 4, 1–25.
17. Driever, S. M., Lawson, T., Andralojc, P. J., Raines, C. A., & Parry, M. A. J. (2017). Natural variation in photosynthetic capacity, growth, and yield in wheat and its relationship to leaf anatomy and morphology. *Plant Physiology*, 175(4), 1740–1751.
18. Zhu, X. G., Long, S. P., & Ort, D. R. (2010). Improving photosynthetic efficiency for greater yield. *Annual Review of Plant Biology*, 61, 235–261.