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Key Regulatory Genes Controlling Photosynthesis in Soybean

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Abstract Soybeans are an important agricultural crop in China, and photosynthesis plays a crucial role in their growth and production. This study reviewed the research progress of expression regulation of soybean photosynthetic genes, studied the role of key regulatory genes such as *GmHY5*, *GmGLK1* and *GmPIF4* in promoting chlorophyll biosynthesis, regulating chloroplast development and regulating stress response, discussed the transcriptional, post transcriptional and post translational regulatory mechanisms regulating the photosynthetic process, emphasized the potential of gene transformation with soybean variety improvement as an example, explored the application of key regulatory genes in breeding plans, and emphasized the application of marker assisted selection and gene editing in breeding climate adaptive soybean varieties. This study aims to emphasize the importance of key regulatory genes in improving photosynthetic efficiency and provide strategies for future soybean breeding and agricultural practices.
Keywords Photosynthesis; Soybean; Regulatory genes; Gene expression; Transcription factors

1 Introduction

When it comes to plant growth, photosynthesis is actually a process of converting sunlight into energy (Wang et al., 2017). However, the matter of soybeans (*Glycine max*) is a bit complicated. Sometimes genes and the environment come together to affect this process (Chu et al., 2018; Tao and Han, 2024). Sunlight is not just about providing energy. It can also act as a signal, controlling genes related to photosynthesis (Halpape et al., 2023; Sun et al., 2023). When it comes to yield, photosynthetic efficiency is indeed quite crucial, but it depends on the situation - whether there is enough light and what the nutrients in the soil are all taken into account (Sun et al., 2017).

It's quite interesting about soybeans - photosynthesis is not determined by just a few genes. There are a bunch of genes and transcription factors competing behind it (Keller et al., 2023). Take *GmRPI2* for example. Experiments have found that it can increase the photosynthetic rate of leaves, and the chlorophyll content also rises accordingly. However, on the other hand, *GmFtsH25* is not bad either. After overexpression, not only did the photosynthetic efficiency increase, but even the starch content in the seeds increased (Wang et al., 2022b). Of course, the synthesis of chlorophyll still depends on *GmGATA58*. After all, the conversion of light energy is entirely handled by it (Zhang et al., 2020a). In fact, these findings are quite significant. After all, to increase soybean production, the ultimate goal is still to start with photosynthetic efficiency.

This study aims to clarify several things - how genes such as *GmRPI2*, *GmFtsH25*, and *GmGATA58* affect soybean photosynthesis. It's quite interesting to say that these genes behave differently in different environments, and they may even "fight" or "cooperate" with each other. Actually, it's quite important to understand the operation mechanism of these genes (although the process is indeed quite complex), after all, traditional breeding alone is not enough to increase soybean yield now. We focused on studying how these genes regulate photosynthetic efficiency, in other words, to enable soybeans to grow better in various fields. Of course, these findings may be helpful for cultivating new varieties in the future, but the specific application still depends on further research.

2 Regulation of Photosynthetic Gene Expression in Soybean

2.1 Role of transcription factors in photosynthetic regulation

When it comes to the photosynthesis of soybeans, in fact, there is a group of "conductors" manipulating behind it - those transcription factors (Kannan et al., 2019). For instance, this guy, GmGATA58, is specifically in charge of chlorophyll synthesis. Interestingly, when it was stuffed into *Arabidopsis thaliana*, the leaves became greener, but the plant did not grow large and the yield decreased instead (Zhang et al., 2020a). There is another rather amusing phenomenon. The gene called *GmRCAα* in soybeans is activated by two transcription factors, GmbZIP04g and GmbZIP0.07g. They are inserted into the activation region of the gene like keys, and thus the photosynthetic efficiency is affected (Zhang et al., 2016). Oh, by the way, it was recently discovered that G2-like transcription factors are also quite busy. They have to manage chlorophyll synthesis and also follow the biological clock. Photosynthesis is also involved a lot (Alam et al., 2022).

2.2 Epigenetic modifications influencing photosynthetic genes

When it comes to the photosynthesis of soybeans, there is actually an interesting perspective-epigenetic modification. Although there are not many studies specifically on soybeans, things like DNA methylation and histone modification can indeed affect gene expression. Take the *GmRPI2* gene for example. There are quite a few light-responsive elements hidden in its promoter region (Sun et al., 2023). Isn't this suggesting that epigenetics might be at play behind the scenes? There are even more mysterious ones, such as the PRR gene family, which governs circadian rhythms. Their expressions may also be led by epigenetic modifications (Wang et al., 2022c). To be honest, however, research in this area is still rather fragmented at present, and it's not clear exactly how it has an impact. But it is certain that these invisible chemical modifications are very likely quietly regulating the photosynthetic efficiency of soybeans.

2.3 Interaction of light and circadian rhythms with photosynthetic gene expression

It's quite interesting about soybeans - their photosynthetic gene expression completely follows the sun's rotation. When working in the fields during the day, you will find a bunch of photosynthesis related genes rushing to work, and at night they end up working (Locke et al., 2018). Especially the *GmPRR3b* gene, like an alarm clock, not only regulates the biological clock, but also worries about flowering time, forcibly aligning photosynthesis with external light (Li et al., 2020). When it comes to light intensity, oxidases such as PTOX and AOX can be activated, and they adjust their working state as soon as the light changes (Sun et al., 2017). What's even more amazing is the transcription factor GmCAMTA, which works day and night, but also needs to balance plant development and cope with environmental stress (Baek et al., 2023). To put it simply, the soybean photosynthesis system is a precision machine that automatically adjusts and follows the rhythm of the sun.

3 Key Regulatory Genes and Their Functions

3.1 GmHY5: enhancing chlorophyll biosynthesis and light response

Among soybeans, there is a "jack-of-all-rounder" called GmHY5, and this guy is quite capable. It is mainly in charge of chlorophyll synthesis. To put it simply, it makes the leaves greener (Zhang et al., 2020a). Interestingly, if GmHY5 does more work, the soybean leaves can indeed become greener and the photosynthetic efficiency will also increase - of course, this is only under the condition of just the right amount of light. However, it's not just about photosynthesis. This guy is very smart. It can sense changes in light and monitor whether there is enough nitrogen fertilizer in the soil. It's just like an environmental monitoring station. From this perspective, GmHY5 is truly a "jack-of-all-rounder" for soybeans to adapt to the environment. Whether it's sunny or cloudy, and whether the nutrition is sufficient or insufficient, it can help soybeans adjust their condition.

3.2 GmGLK1: regulation of chloroplast development and maintenance

There is a "housekeeper" called GmGLK1 in soybeans, which belongs to the GLK transcription factor family. This guy is mainly in charge of chloroplasts - from development to daily maintenance (Alam et al., 2022). It manages a large group of genes under its control, some responsible for chlorophyll synthesis, some for the biological clock, and some for regulating flowering time. Anyway, it has to deal with all the work related to chloroplasts. Interestingly, this housekeeper is quite sensitive. When encountering troubles such as heavy metal pollution, its working condition will change accordingly. This indicates that it is not only a butler, but also part-time as a security guard, helping soybeans cope with various environmental pressures. Simply put, GmGLK1 is an all-around player who not only ensures the normal functioning of chloroplasts, but also helps plants overcome difficulties.

3.3 GmPIF4: modulating photosynthetic adaptation to environmental stress

It's quite tricky for soybeans to encounter strong light, but there is a transcription factor called GmPIF4 that works quite well. This thing is quite interesting. It not only deals with photosynthesis, but also has to worry about not accumulating too much reactive oxygen species (ROS). Simply put, when the sunlight is too strong, GmPIF4 acts as a dispatcher, adjusting the expression of stress response genes (Zhang et al., 2023). Interestingly, it can also cooperate with proteins such as GmVTC2, one responsible for enhancing ROS scavenging ability and the other maintaining photosynthetic efficiency (Figure 1). However, speaking of which, this regulatory mechanism is not omnipotent, but it has indeed been of great help in dealing with fluctuating light environments, allowing plants to recover faster.

4 Mechanisms of Gene Regulation in Photosynthesis

4.1 Transcriptional regulation by light-responsive genes

Soybeans are a very interesting crop, as their photosynthesis completely follows light. Speaking of this, we have to mention the *GmRPI2* gene - this guy encodes ribose-5-phosphate isomerase, which plays an important role in photosynthesis. In fact, its promoter region is particularly sensitive, and the photoresponsive elements inside are like switches (Sun et al., 2023). Experiments have shown that if this gene is overexpressed, the photosynthetic capacity of soybeans can indeed be improved. Not only do the leaves become greener, but the photosynthetic rate and sugar content also increase. But when it comes to photosynthesis, it also involves other genes, such as *GmRCAα*, which is responsible for Rubisco activating enzyme. Interestingly, it relies on transcription factors such as bZIP to initiate, and these proteins directly bind to its promoter region (Zhang et al., 2016). To put it simply, the soybean photosynthesis system is a precise sunlight sensor, with each link adjusting its working state according to changes in light.

4.2 Post-transcriptional regulation through RNA-binding proteins

In fact, there is another way to deal with soybean photosynthesis - post transcriptional regulation is also crucial. Those RNA binding proteins (RBPs) act as quality inspectors, specifically targeting the mRNAs involved in photosynthesis (Ku et al., 2022). Take GmZF392 protein as an example, it belongs to the CCCH zinc finger protein family and works in a unique way: it directly runs to the promoter region of the target gene and "codes" with specific cis elements (Lu et al., 2021). By doing this, mRNAs not only became more stable, but also improved translation efficiency, ultimately leading to an increase in oil content in soybean seeds. Simply put, this mechanism is to give the green light to photosynthesis related mRNAs, ensuring that they can smoothly transform into proteins and accurately find their job positions.

4.3 Post-translational modifications in photosynthetic enzymes

In the matter of photosynthesis in soybeans, protein modification (PTMs) actually secretly controls many key links. Just take GmDREB2A; For this protein, there is a region with a particularly high amount of serine/threonine on it, like an emergency braking device - as long as this region remains, the protein activity is suppressed (Mizoi et al., 2012). But in the event of drought or something like that, once this braking device is removed, the protein immediately becomes energetic. Not only does it become more stable itself, but it can also help enhance the stress resistance and photosynthetic efficiency of soybeans. Another interesting example is GmGATA58, a transcription factor specifically responsible for chlorophyll synthesis. However, it also has to act according to the PTMs. These modifications are like patching proteins, directly determining its activity and lifespan (Zhang et al., 2020a). To put it bluntly, the photosynthetic system of soybeans is like a precise mechanical watch, and these post-translation modifications are the masters who fine-tune the gears. A slight twist can change the accuracy of the entire watch's timekeeping.

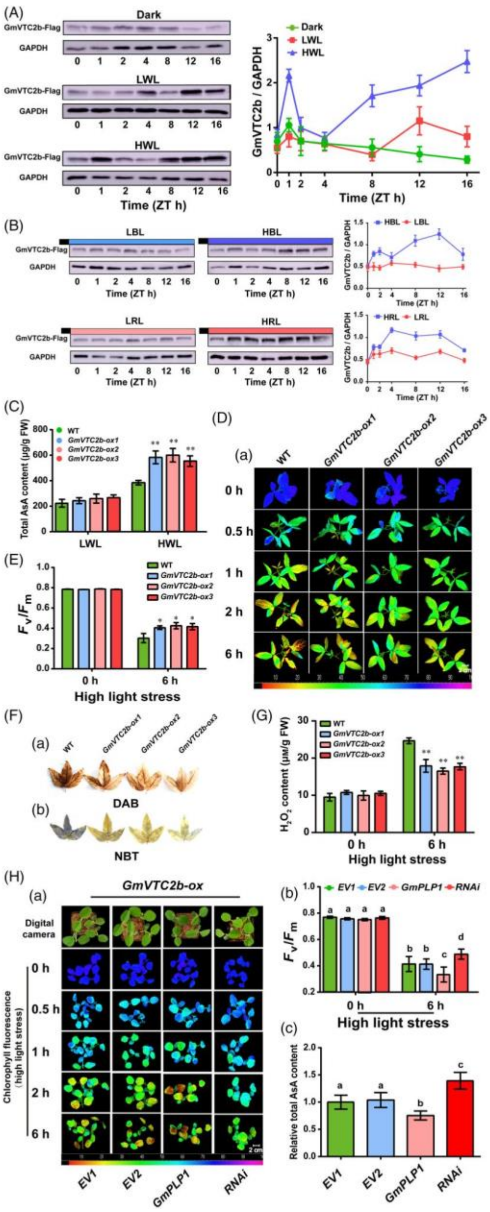

Figure 1 GmVTC2b improved soybean tolerance to high light stress. (A) Expression pattern analysis of the GmVTC2b protein under darkness, LWL (50 μmol/m^2/s) and HWL (1 800 μmol/m^2/s). Three-week-old *proGmVTC2b:GmVTC2b-Flag* transgenic soybean seedlings were placed under darkness to equilibrate for 2 days and then transferred to LWL (50 μmol/m^2/s), HWL (1 800 μmol/m^2/s) and constant darkness. (B) Expression analysis of the GmVTC2b protein in response to LBL (5 μmol/m^2/s), LRL (5 μmol/m^2/s), HBL (500 μmol/m^2/s) and HRL (600 μmol/m^2/s). (C) The total AsA content was measured in 3-week-old leaves of *GmVTC2b-ox* and WT soybean under LD (16 h light/8 h darkness) with LWL and HWL, respectively. (D, E) (C) Maximum efficiency of PSII photochemistry (*F*v/*F*m ratio) in *GmVTC2b-ox* and WT soybean under high light stress (1 800 μmol/m^2/s) for 0, 0.5, 1, 2 and 6 h *in vivo* imaging, and (D) the data were counted at 0 or 6 h. (F) (a) DAB and (b) NBT staining of the leaves in *GmVTC2b-ox* and WT soybean after 6 h of high light stress. (G) The H_2O_2 content was measured in the leaves of *GmVTC2b-ox* and WT soybean after 6 h of high light stress. (H) Phenotypic observations and the total AsA content showed that GmPLP1 inhibited the function of GmVTC2b under high light stress. Overexpression of *pCAMBIA3300* (*EV1*), *pFGC5941* (*EV2*), *pCAMBIA3300-GmPLP1-GFP* (*GmPLP1-ox*) and *pFGC5941-GmPLP1* (*RNAi*) in *proGmVTC2b:GmVTC2b-Flag* (*GmVTC2b-ox)* transgenic soybean leaves. (a) Maximum PSII photochemistry efficiency (F_v/F_m ratio) under high light stress (1 800 μmol/m^2/s) for 0, 0.5, 1, 2 and 6 h was captured using *in vivo* imaging, and (b) the data were obtained at 0 or 6 h. (c) The total AsA content was determined after 6 h. Values represent the means of three biological replicates. Asterisks indicate a significant difference from the corresponding controls (Student's *t*-test: 0.01 < **P* <0.05, ***P* < 0.01) (Adopted from Zhang et al., 2023)

5 Case Study: Enhancing Photosynthetic Efficiency in Soybean Cultivars

5.1 Overview of the selected soybean cultivar with improved photosynthetic traits

The soybean variety used in this research is quite unique - it has been specially modified to make the *GmFtsH25* gene work hard. This gene, belonging to the FtsH protease family, is involved in many things (Wang et al., 2022b). Interestingly, after allowing it to express more, the basal thylakoids in the chloroplasts piled up more, the photosynthetic efficiency rose sharply, and the starch also increased accordingly. However, the most tangible change is the yield variation. Compared with ordinary soybeans and varieties with gene knockout, the yield per plant is indeed significantly higher. Of course, the *GmFtsH25* gene is not omnipotent, but it does play a significant role in enhancing photosynthesis.

5.2 Genetic modifications and CRISPR-based targeting of key regulatory genes

Nowadays, when it comes to improving soybeans, scientists have tried many new methods. For instance, let the *GmFtsH25* gene work hard, and use gene scissors like CRISPR/Cas9 to fiddle with key regulatory genes. Take *GmRPI2* for example. When it was cloned and inserted into soybeans, the results were quite interesting - the photosynthetic rate increased, the leaves became greener, and even the sugar content increased. It was indeed different from the unmodified and gene-edited control groups (Sun et al., 2023). There's an even more amazing one. By using gene scissors to knock out the *GmGA3ox1* gene, it unexpectedly made the genes related to photosynthesis more active, especially the GmRCA family that controls the Rubisco activator. After such a disturbance, not only was photosynthesis enhanced, but the seed yield also increased accordingly. However, to be fair, although these methods are effective, the specific implementation still depends on the situation. After all, each gene has a different temperament.

5.3 Evaluation of enhanced photosynthetic efficiency and yield improvement

To determine whether these genetically modified soybeans are reliable or not, several hard indicators mainly need to be considered. Let's start with the GmFtsH25. After getting it to work more, the most obvious change is that there is more starch and the output also goes up. Interestingly, the performance of GmRPI2 is not bad either - the photosynthetic rate has increased, the leaves are greener, and the sugar content has also risen, all of which are helpful for increasing production. The most surprising thing was the *GmGA3ox1* gene. After knocking it out with CRISPR technology, a bunch of photosynthetically related genes were activated instead, and the yield actually increased in the end (Figure 2) (Hu et al., 2022). From this perspective, making some adjustments to key genes does work, but the specific approach to achieve the best results may still require further exploration. After all, the mechanism of action of each gene is not exactly the same. Some are suitable for overexpression, while others have better knockout effects.

6 Applications of Key Regulatory Genes in Soybean Breeding

6.1 Marker-assisted selection for photosynthetic efficiency

There is now a clever method for soybean breeding - marker assisted selection (MAS), which relies on genetic markers to select good seedlings. Research has discovered some particularly interesting QTL loci, such as 172 that are associated with phosphorus efficiency and photosynthetic traits, of which 12 regions actually affect both traits simultaneously (Li et al., 2016). Isn't this equivalent to finding a "double champion"? Planting such soybeans in phosphorus deficient fields should result in high photosynthetic efficiency. There is a more detailed study that identified 30 key SNP loci through GWAS method, which are associated with photosynthetic performance at different phosphorus levels (Yang et al., 2020). However, speaking of which, although these markers are quite effective, the actual operation still depends on the specific situation. After all, breeding new varieties is like playing a puzzle, you have to combine all these marker advantages together. If all these markers can really be used, perhaps a new variety that is both high-yielding and stress resistant can be cultivated, but this matter cannot be rushed, it needs to be done step by step.

6.2 Integration of gene editing techniques in soybean breeding programs

Gene editing technology is becoming increasingly precise nowadays. The CRISPR-Cas9 tool can precisely refine the key genes of photosynthesis (Wan et al., 2022). For instance, when the *GmRPI2* gene was edited using

Agrobacterium, the results were quite interesting - not only did the photosynthetic capacity of soybeans increase, but their leaves also became greener (Sun et al., 2023). There is a more practical example. By tamping the E2 gene that controls the flowering time and its homologues, single mutations and double mutations were created. Unexpectedly, it had a particularly significant impact on the flowering and harvest of soybeans in high-latitude regions (Wang et al., 2022a). However, to be fair, although gene editing is quite effective, the specific operation still depends on the target trait. After all, the function of each gene is not exactly the same. These cases at least demonstrate that using gene editing to improve the photosynthetic efficiency and other agronomic traits of soybeans is a feasible approach.

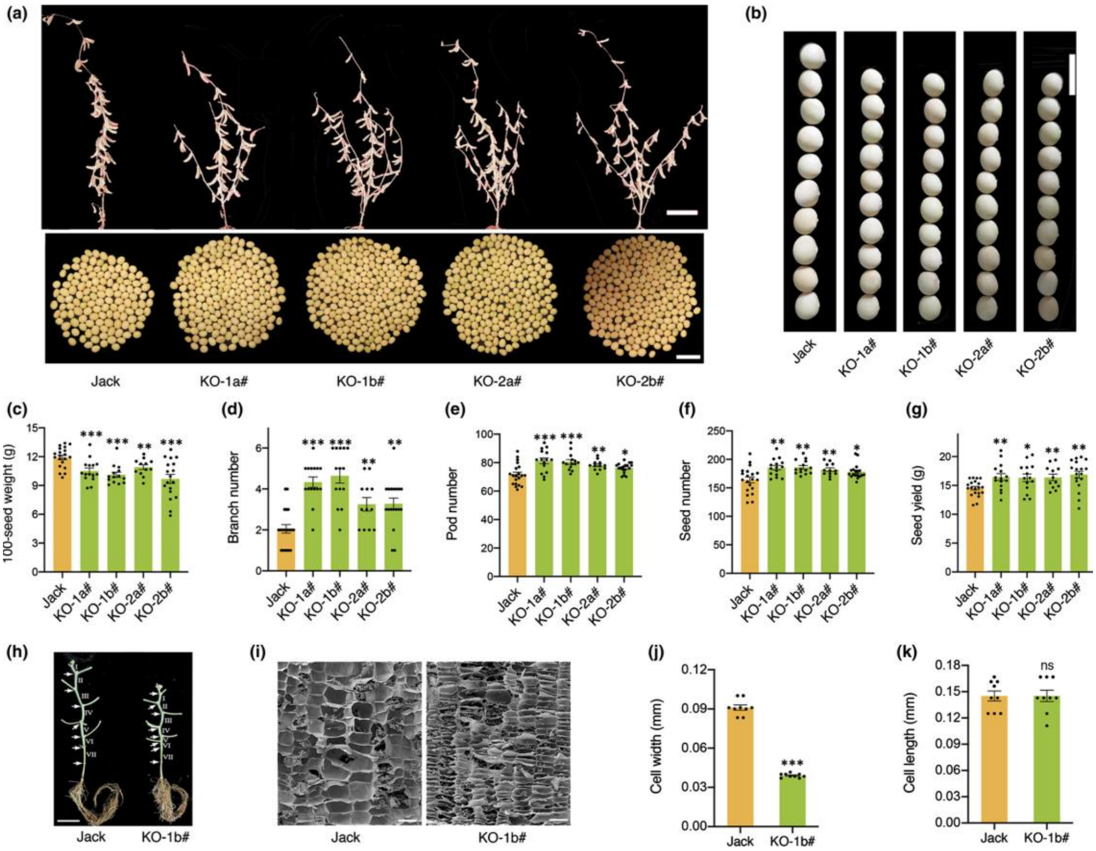

Figure 2 Knockout of *GmGA3ox1* increased seed yield in soybean. Morphology of Jack and *gmga3ox1* mutants at harvest. Bar, 10 cm. The parts below this image are the phenotypes of the seed yield per plant of Jack and *gmga3ox1* mutants. Bar, 2 cm. Seed phenotypes of Jack and *gmga3ox1* mutants after harvest. Bar, 1 cm. (c–g) Comparison of 100-seed weight (c), branch number (d), pod number (e), seed number (f) and seed yield per plant (g) for Jack and *gmga3ox1* mutants from 2019-Nanjing. There were 20, 15, 14, 12 and 18 Jack, KO-1a#, KO-1b#, KO-2a# and KO-2b# plants, respectively. (h) Differences in internodes between Jack and KO-1b#. The arrows indicate the node positions. Bar, 5 cm. (i) Scanning electron micrograph of longitudinal sections within the middle part of internode V between Jack and KO-1b#. Bar, 200 μm. (j, k) Cell width (j) and cell length (k) of internode V from both Jack and KO-1b# (n = 9). The error bars denote ± SEM. For (c-g), the value of each plant is represented by a dot. For (j, k), the value of each replication is represented by a dot. Two-tailed t-tests were used for statistical analysis. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; ns, not significant (Adopted from Hu et al., 2022)

6.3 Potential of key regulatory genes in developing climate-resilient soybean varieties

When it comes to cultivating soybean varieties that can adapt to climate change, the key lies in the genes that govern both photosynthesis and stress resistance. For example, the GmSGF14 gene family is quite important, not only controlling flowering time, but also related to stress resistance - studies have found that certain haplotypes are particularly adapted to local environments (Jiang et al., 2023). The *GmPRR3b* gene is also very interesting. Through GWAS analysis, it was found that it can regulate the biological clock, allowing soybeans to bloom normally at different latitudes (Li et al., 2020). However, in actual breeding, it has been found that the effects of these genes are often closely related to local climate conditions. If these key genes can be utilized, it is indeed possible to cultivate more robust soybean varieties that can ensure yield no matter how the weather changes. Of course, this requires long-term observation, as climate adaptation cannot be rushed.

7 Challenges in Manipulating Regulatory Genes for Photosynthesis

7.1 Complexity of gene networks and redundancy issues

The gene regulation of soybean photosynthesis is actually much more complicated than imagined. The main reason is that these genes do not work alone, but form a complex "social network" (Almeida Silva et al., 2020). In this network, various genes are interconnected, some responsible for photosynthesis, some for sugar metabolism, and some for disease resistance, with overlapping functions. Just like the *GmFtsH25* gene, although it can indeed improve photosynthetic efficiency and yield, it has connections with multiple components of the photosynthetic system, and a single pull can activate the entire body. What's even more troublesome is the issue of gene redundancy - many copies of genes with similar functions come together, appearing to be carved from the same mold, but in reality, the division of labor may be completely different. These homologous genes are often grouped in the same functional module, but the specific functions of each gene still need to be verified one by one. So, it is indeed quite difficult to precisely regulate a specific gene without affecting other functions.

7.2 Trade-offs between photosynthetic efficiency and growth

When it comes to reforming homosexuals, one often has to face the awkward situation of "pressing down one thing and seeing another pop up". Take the transcription factor GmGATA58 for example. After overexpressing it in *Arabidopsis thaliana*, the leaves became greener and the photosynthetic rate increased, but the plants grew poorly and the yield decreased instead (Zhang et al., 2020a). This is like modifying the engine of a car. The horsepower increases, but the fuel consumption also soars sharply. Similar examples include GmETO1, a gene responsible for phosphorus absorption. Although it can make the root system more developed, it may affect other physiological functions (Zhang et al., 2020b). Therefore, improving photosynthesis cannot merely focus on a single indicator; a comprehensive consideration is necessary - just as in traditional Chinese medicine, the principle of "sovereign, minister, assistant, and messenger" is emphasized, which involves enhancing the main functions while also taking into account the overall balance. After all, plants are an organic whole. If any link is changed too much, it may actually be counterproductive.

7.3 Regulatory and safety concerns in genetic modification

The matter of developing genetically modified soybeans actually faces many restrictions (Lopez et al., 2019). For example, the *GmFtsH25* gene that can improve photosynthetic efficiency, although the laboratory data is good, if it is really to be promoted and applied, a large number of safety tests have to be passed (Wang et al., 2022b). There are mainly three things to worry about: Will it damage the ecology? Is it safe to eat? Will the common people accept it? Regulatory authorities are keeping a close watch, demanding that all potential risks be ruled out - for instance, what if other genes are accidentally altered? Will new allergens be produced? All these unexpected situations need to be verified repeatedly. So nowadays, it often takes over a decade for genetically modified crops to move from the laboratory to the field. Ultimately, having technology alone is not enough. It is also necessary to do a good job in popular science, lay out and explain the safety data clearly, and gradually win the public's trust. After all, when it comes to food safety, one can never be too cautious.

8 Future Directions

8.1 Prospects of advanced genomic techniques in understanding photosynthetic regulation

There are now many new weapons in the study of soybean photosynthesis. CRISPR-Cas9 is indeed a useful "gene scissor", like the *GmRPI2* gene. After being edited by it, soybeans not only have stronger photosynthetic capacity, but also their yield has increased (Sun et al., 2023). However, gene editing alone is not enough, it also needs to be combined with other technologies. For example, by analyzing high-density genetic maps, it was discovered that there are many associations between phosphorus efficiency and photosynthetic characteristics, especially in those key genomic regions, which are truly treasure loci for breeding (Li et al., 2016). RNA Seq technology is also very awesome. Through the gene co expression network constructed by massive data, we have dug out the regulation modules behind photosynthesis (Almeida Silva et al., 2020). These technologies each have their own strengths, and when combined, they are like equipping researchers with a "super toolbox" that can both see the big picture and accurately locate it. Although the regulatory network of photosynthesis is indeed complex, with the help of these advanced technologies, the path to improving soybean varieties has become increasingly broad.

8.2 Exploring synergistic effects of key regulatory genes

The key to photosynthesis in soybeans lies in the "teamwork" among genes. Take the bZIP transcription factor for example. It forms a "secret connector" with the promoter of the Rubisco activator gene (*GmRCAα*), and this combination directly affects photosynthetic efficiency (Zhang et al., 2016). Interestingly, biological clock genes also join in the fun - those gene nodes that are sensitive to day-night changes, if their expression times are accurately adjusted, photosynthetic performance can be further enhanced (Locke et al., 2018). When it comes to dealing with different lighting conditions, the two oxidases, PTOX and AOX, work in perfect harmony. Studies have found that they are like the "regulators" of the photosynthetic system and can automatically adjust according to the intensity of light (Sun et al., 2017). So, rather than working alone to modify a certain gene, it is better to study clearly how these genes "cooperate". Once these collaborative mechanisms are understood, perhaps smarter ways can be found to increase production. After all, photosynthesis is a systematic project that emphasizes "teamwork".

8.3 Potential for cross-species application of photosynthetic genes

The matter of "borrowing genes" among different crops has indeed opened up new ideas. For example, when the GmGATA58 transcription factor of soybeans was stuffed into *Arabidopsis thaliana*, the chlorophyll increased and the photosynthetic rate accelerated, but the plants did not grow large and the yield shrank instead (Zhang et al., 2020a). This indicates that although the photosynthesis mechanism is largely similar among different plants, the specific effect still depends on whether they adapt to the local environment or not. Another interesting example is the *GmPRR3b* gene, which governs both the biological clock and the flowering time in soybeans (Li et al., 2020). If this multifunctional gene can be successfully transplanted into other crops, it might help them adapt to a wider range of climates. However, to be honest, cross-species applications cannot be blindly copied. After all, each crop has its own "temperament". The genetic cues obtained from soybean research do indeed offer new directions for improving other cash crops, but how and how much to use them still require repeated trials and adjustments.

9 Conclusion

When studying the photosynthesis of soybeans, several genes were found to be particularly interesting. GmRPI2 can be regarded as a "jackpot" - if it does more work, the photosynthetic rate, chlorophyll and sugar content of soybeans will increase accordingly. However, what is even more surprising is the "ambiguous relationship" between phosphorus efficiency and photosynthetic traits. Those discovered QTL loci are simply like the code hidden in the genes, specifically managing the photosynthetic performance of soybeans in a phosphorus-deficient environment. The transcription factor GmGATA58 is a bit "capricious". Although it can make the leaves greener in *Arabidopsis thaliana*, the plants do not grow well instead. Another interesting thing is that the expression of photosynthetic genes in soybeans planted in the ground follows the sun, completely in accordance with the circadian rhythm. By constructing the global gene co-expression network, researchers have figured out the "command system" of photosynthesis - which genes are the "chief commanders" and which are the "department heads", and now they have a clear idea. These findings not only explain the operational mechanism of photosynthesis in soybeans but also provide precise targets for variety improvement.

Soybean breeding now has a new direction - the discovery of the *GmRPI2* gene is particularly exciting. As long as its expression level is appropriately increased, the photosynthetic efficiency of soybeans can be elevated to a new level. Interestingly, however, those QTL loci linked to phosphorus efficiency have been of great help when growing soybeans in phosphorus-deficient soil, enabling us to select varieties that remain resilient under harsh conditions. The *GmGATA58* gene is a bit "demanding". Although it can regulate chlorophyll synthesis, it needs to be operated with extreme caution, otherwise it is easy to affect the growth of the plant. There is another practical finding - the photosynthetic gene activity of soybeans is locked to the circadian rhythm, which suggests that we should "act according to the weather" in field management and take corresponding measures when photosynthetic activity is the strongest. The most remarkable one is the Global Gene co-expression network, which is like obtaining the "circuit diagram" of soybean photosynthesis and can precisely locate the most critical control nodes. These discoveries not only make the breeding goals clearer, but may also give rise to a brand-new set of high-yield cultivation techniques.

The key to soybean photosynthesis still depends on the expression of regulatory genes. These genes are like conductors of a band, regulating various processes such as chlorophyll synthesis and circadian rhythm regulation. Now, by integrating genetic, molecular biology, and physiological data, we have finally figured out how these genes form cliques and cooperate with each other. However, to truly apply the discoveries in the laboratory to the fields, there are still several hurdles to overcome. The next focus should be on finding ways to transform these achievements into tangible varieties, such as cultivating genetically modified soybeans that are both high-yielding and drought resistant. The star genes *GmRPI2* and *GmGATA58* do provide direction for breeding, but the specific operation to maximize strengths and avoid weaknesses still requires repeated experimentation. If these regulatory genes can be used properly, it will not only increase soybean production, but also greatly benefit food security and promote green agriculture. Of course, this requires close collaboration between researchers and breeding experts to gradually turn laboratory results into crops in farmers' fields.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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