Increasing the Efficiency of Photosynthesis in Photosynthetic Organism

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Abstract:

With global warming on the rise, a popular way to mitigate it is using the power of photosynthesis. In this reaction, carbon, a greenhouse gas, gets consumed to create carbohydrates. As useful as this reaction seems, it has its drawbacks. Sometimes oxygen gets consumed instead of carbon, forming a toxic compound called 3-phosphoglycolate. To fix this, the toxic compound has to get recycled through a side process of photosynthesis known as photorespiration. The energy sources required to fuel this reaction are carbon and ATP, which are used to convert the toxic compound to a usable substance. This energy reduces the efficiency of photosynthesis. However, with genetic engineering, scientists are discovering additional pathways to reducing photorespiration. A common and reliable way is to use agrobacterium as a method of gene insertion. The results from the experiments are promising, showing signs of increased growth and carbon consumption.

Introduction:

Scientists continue to diligently research this subject with the increased threat of global warming. The rise in global temperature is likely caused by the greenhouse effect [17]. In this effect, certain atmospheric gasses, such as carbon, capture infrared radiation (IR) or heat energy which warms the earth [17]. Due to this effect, the earth can maintain a warm and stable temperature suitable for sustaining life.

However, since the beginning of the industrial revolution, global temperatures have been steadily increasing [12]. This is caused by the burning of fossil fuels which releases carbon [12]. In turn, the environment has become unstable, causing raging fires and floods across the globe [12]. To mitigate climate change, scientists have been researching how one could take advantage of photosynthesis, which is arguably the most vital reaction on Earth. This simple reaction provides all life on earth with both food and oxygen. Additionally, photosynthesis consumes carbon dioxide, a greenhouse gas, to produce these necessities [5]. To summarize photosynthesis, this process takes place in the chloroplasts, capturing sunlight and carbon dioxide and releasing oxygen as a product [5]. The energy contained in adenosine triphosphate (ATP) and Nicotinamide adenine dinucleotide phosphate (NADPH) is then used in the Calvin-Benson cycle to convert CO2 into carbohydrates that feed the world [5].

As resourceful as photosynthesis is, there is a major drawback that largely contributes to its inefficiency, known as photorespiration. During the Calvin-Benson cycle, there is a 1:3 chance that the enzyme rubisco fixes oxygen instead of carbon [5]. This results in the creation of a toxic compound, 3-phosphoglycolate [5]. To recycle 3-phosphoglycolate, a number of resources including ATP and NADPH are required [5]. As a result, there are fewer resources to be used in the production of carbohydrates during photosynthesis.

Conversely, there are evolutionarily advanced plants that have completely removed the side process of photorespiration [11]. These plants are known as C4 because the first product of carbon fixation is the 4-carbon compound. Similarly, plants that use rubisco are known as C3 plants since they have a 3-carbon compound as their first product. One of the added benefits of C4 plants is the use of another enzyme known as phosphoenolpyruvate (PEP) to fix carbon [11]. An added benefit of PEP is that it has no oxygenase activity, thus entirely removing the chance for photorespiration [11]. As modern technology continues to evolve, scientists are exploring new ways to convert C3 plants to replicate C4 plants, such as genetic engineering using agrobacterium.

1. Global Warming

Global warming involves greenhouse gasses trapping sunlight in the Earth's atmosphere, causing the Earth's atmosphere to heat up. A natural method many organisms use to regulate greenhouse gases is photosynthesis. Though 32% of the earth's surface is covered in plants, greenhouse gases continue to thrive in the atmosphere [6]. Greenhouse gases are the reason why the Earth can sustain life by capturing infrared radiation (IR) within the Earth's atmosphere. Without these gasses, the Earth would be about 30 degrees Celsius cooler [7]. Other greenhouse gasses include water vapor, methane gas, and nitrous oxide [13]. These specific gasses are special because of their vibrations. For example, water vapor has its electrons located at one end, resulting in an irregular vibration pattern [13]. Similarly, with carbon, its electrons are symmetric, but due to bouncing with other carbon molecules, the vibrations of carbon bonds become irregular [13].

The culmination of the effect of these different gasses is called the greenhouse effect. In this process, strong, high-frequency visible light from the sun gets absorbed by the Earth's surface. About half of the energy from the sun is consumed by vegetation to maintain its photosynthetic cycle. With the remaining energy, the Earth releases a much weaker IR [17]. The released IR escapes to the Earth's atmosphere where it gets caught by various greenhouse gasses. Each molecule of gas contains the radiation for a duration of time and then releases it [17]. However, with several greenhouse gas molecules, the IR could bounce between multiple molecules before escaping the atmosphere [17]. When IR is trapped in the greenhouse gasses, the heat energy from IR warms the Earth, thus maintaining a stable temperature for life.

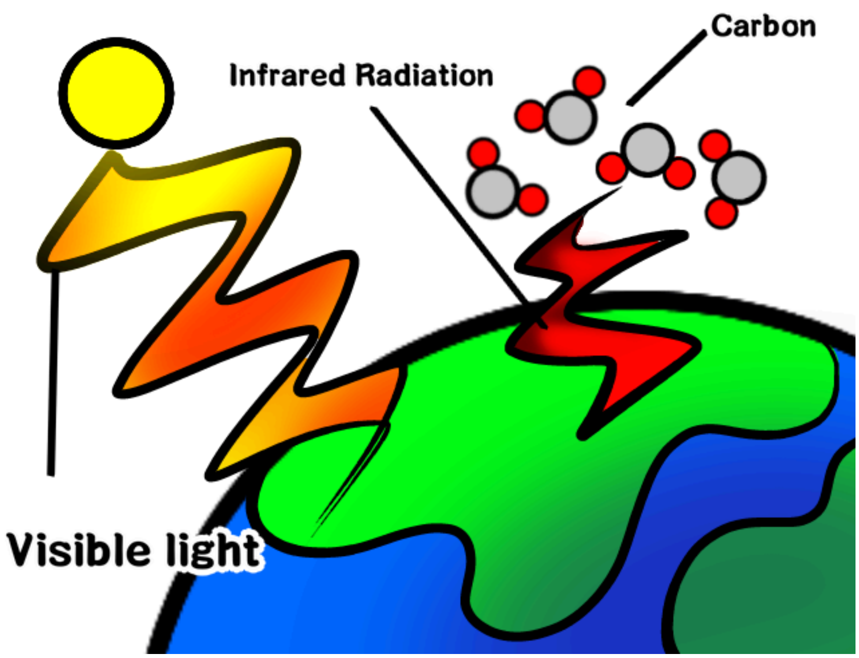

Figure 1 - The diagram shows the process of global warming. Light emitted from the sun in the form of visible light gets absorbed by the Earth's surface. The remaining light becomes weaker and turns in the IR. The IR bounces off the Earth's surface where it gets caught by greenhouse gasses like carbon dioxide. As a result, the trapped IR warms the Earth's surface.

Since the beginning of the Industrial Revolution, global temperatures have steadily risen [12]. The Industrial Revolution began over 250 years ago in the United Kingdom and spread its reach toward the Western world. To make room for agriculture, deforestation began to help feed the growing population [12]. Factories were created to automate the creation of products [12]. To fuel these factories, people burn fossil fuels, which in turn release carbon into the atmosphere [12]. Out of the many greenhouse gasses, carbon has been shown to have the strongest impact on global warming [7]. This is because carbon remains in the atmosphere for years. From analysis, it's generally believed that 15-30% of CO2 from today will remain in the atmosphere for thousands of years [7]. Furthermore, carbon is the most abundant greenhouse gas in the atmosphere [7]. After the start of the Industrial Revolution, the proportion of greenhouse gasses became unregulated, leading to further complications [7].

Some of the many effects of global warming can be seen in the Arctic. According to the National Oceanic and Atmospheric Administration, the thickness of glaciers has decreased by 60 feet since the 1980s [14]. Moreover, the ice in the Arctic during the summertime has shrunken by 40% since 1979 [14]. Beyond the Arctic, flooding has been more frequent along the US coastlines [3]. Additionally, evidence shows that there is a correlation between global warming and the dramatic increase in hurricane power [4]. This is all happening while atmospheric carbon dioxide has increased by 25% since 1958 and 40% since the Industrial Revolution [14]. Without a doubt, the significant increase in carbon dioxide plays a hand in the destruction of the environment.

2. Photorespiration

The process of photosynthesis supplies about 87% of the world's energy through photosynthetic fuels [5]. There are two different sections of photosynthesis: light-dependent and light-independent. Light-dependent reactions occur in the thylakoid membrane and involve extracting electrons from water [5]. Alternatively, llight-independent reactions occur in the stroma, and carbon is converted into carbohydrates [5]. To involve carbon in the light-independent reaction, the enzyme rubisco is used for carboxylation [5]. Carbon combines with multiple elements and results in carbohydrates. However, 30% of the time, rubisco confuses carbon with oxygen and catalyzes oxygenation [5]. This reaction creates two molecules of 3-phosphoglycerate and a 2C sugar otherwise known as 3-phosphoglycolate [5]. 3-phosphoglycolate is a toxic compound to the chloroplast. To fix their mistake, 3-phosphoglycolate goes through a series of reactions to convert 3-phosphoglycolate into one molecule of both CO2 and 3-phosphoglycerate [5]. This process is known as photorespiration, and it is always occurring [18]. The price of photorespiration is NADPH, ATP, and carbon. This takes up 25% of photosynthetic ability and significantly reduces photosynthesis [9].

Plants that go through photorespiration are known as C3 plants because they create a 3-carbon sugar. However, a small percentage of plants use an enzyme called PEP instead of Rubisco to catalyze carboxygenation in the first step of carbon fixation [11]. Unlike rubisco, PEP has no oxygenation activity and cannot initiate photorespiration [11]. This allows all of their resources to be directed toward photosynthesis. As a result, a 4-carbon compound is created, which is why plants that use PEP are called C4 plants. Generally, C4 plants tend to be more productive and stronger than their C3 peers [11]. Examples of C4 plants include sugarcane, sorghum, and maize [11].

However, the use of PEP is not the only reason C4 plants tend to outperform C3 plants. A large portion of their effectiveness comes from the Kranz anatomy, which is the unique anatomy of the leaf [11]. Within the Kranz anatomy is a bundle sheath concentrated with the majority of the chloroplasts that confines rubisco in a set place as seen in Figure 2 [10]. Surrounded by the bundle sheath is a thin layer of mesophyll cells otherwise known as the internal leaf tissue [10]. While rubisco is not used for the first step of carbon fixation, it is used for the next. Since rubisco is confined to the bundle sheaths, carbon can be directly pumped to rubisco from the surrounding mesophyll cells [10]. As a result, all oxygenation activity from rubisco is eliminated [11]. This also eliminates the side process of photorespiration.

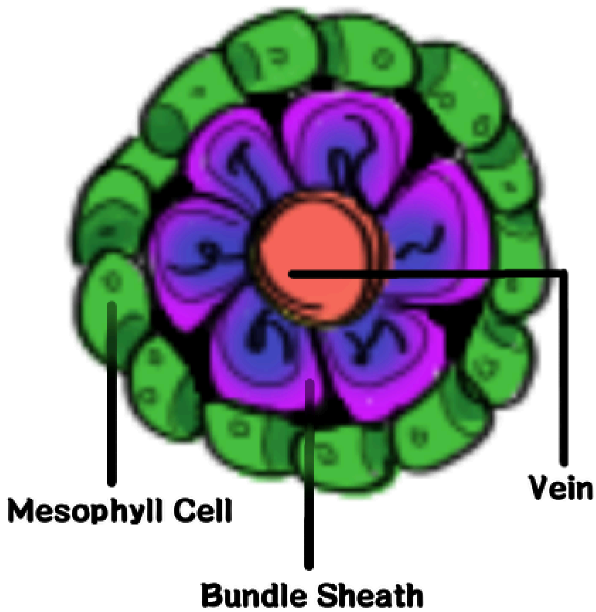

Figure 2 - The image showcases and labels the structure of the Kranz anatomy. Rubisco is located within the bundle sheath cells, which are surrounded by mesophyll cells. With the rubisco bound to the bundle sheaths, carbon dioxide can be directly transported from the mesophyll cells to the bundle sheaths. As a result, rubisco cannot interact with oxygen and catalyze oxygenation.

3. C3-C4 Engineering

Much effort has been placed into genetically modifying C3 plants successfully to C4 plants. A more basic method is cross-breeding two different plants, but this causes multiple complications [2]. This method only works for C3 plants that share similar structures and genes to the relative C4 plants. As a result, there are a limited number of plant species that can be possibly used for cross-breeding [2]. Another complication would be the complex nature of traits. To define a single trait, an extensive amount of specific genes are needed. Furthermore, it can be challenging to predict the outcome of which genes will be passed to the next generation.

Knowing this, a multitude of different companies have developed other methods to solve this problem. One company, named Living Carbon, is researching possibilities to increase the photosynthetic ability of trees through genetic engineering [8]. The company mainly performs tests on poplar trees because they cannot reproduce on their own. They use gene technology to insert the desired genes into the poplar tree. Specifically, Living Carbon uses agrobacterium, a bacterium that causes tumors in plants by inserting its own gene. First, the company switches the tumor-causing genes in the +bacterium with pLC0102, a plasmid containing genes from pumpkin and algae [8]. Then the agrobacterium is used to insert the desired genes into poplar trees.

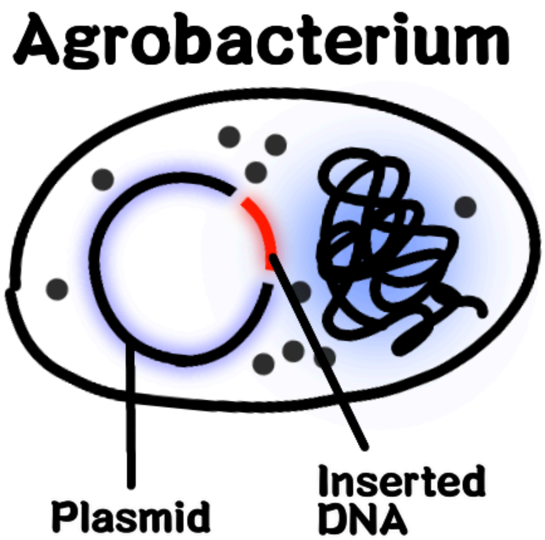

Figure 3 - The image showcases the inner structure of an agrobacterium, a bacterium that causes tumors in plants by inserting its DNA. Scientists have genetically engineered plants by removing the tumor-causing DNA in the plasmid and inserting the desired genes. As a result, agrobacterium inserts the desired DNA instead of the tumor-causing DNA into the plant.

Using real-time polymerase chain reaction (qRT-PCR) analyses, inserting the pLC0102 plasmid into poplar trees led to a significant reduction in the production of 3-phosphoglycolate [8]. This means plants conducted photorespiration significantly less than the control group. Following 17 weeks after the gene was inserted, Living Carbon noticed that the gene-edited poplar trees were growing faster compared to the control group. After 21 weeks, the gene-edited poplar trees had a 53% increase in biomass [8]. This is a strong indicator of an efficient carbon assimilation rate because trees are mostly made from carbon. The company plans to fill a 3,200-acre plot of land provided by its carbon partners with their genetically enhanced poplar trees in the near future [8].

Living Carbon isn't unique in its approach. Another company known as Realizing Increased Photosynthetic Efficiency (RIPE) plans to engineer C3 to C4 crops to fulfill global food needs. They plan to equip farmers with higher-yielding crops so that the increasing population can have enough food to lead a productive life [15]. To reach this goal, they have researched various ways to insert the desired genes into crops. One of the researched methods is through agrobacterium, a method similar to Living Carbon, to insert a gene. Furthermore, they have been partnering up with farmers to plant their crops [15].

Furthermore, other companies including RIPE are using new C3 to C4 advances to implement photosynthetic enhancing genes on food crops used by farmers. RIPE wishes to harness the power of science to help feed the world. Carbon-consuming enhanced crops are much faster than unedited crops growing. As a result, there is an increase in food production which can help fill the global food supply needs.

With new research being conducted, scientists have learned more about unknown components in C4 plants. Using gene sequencing technology on crops such as maize, scientists have gained key findings about the genes used in the development of the Kranz Anatomy [16]. For example, scientists have approximated that more than 2000 genes are expressed differently between C3 and C4 plants [16]. As new insights are learned, the effectiveness of C3-C4 engineering continues to improve.

Discussion:

With all the novel and developing methods of gene editing, the future seems promising with new advances in gene editing technology each day. Many of the hopes in advancing this technology are to reduce greenhouse gasses in the atmosphere. Photosynthesis is a powerful reaction essential to life. The consumption of carbon proves vital to the fight against climate change. Therefore, C3 to C4 engineering has endless impactful possibilities on the environment besides simply slowing the rate of global warming.

In many reforestation efforts, the slow growth of trees requires a lengthy amount of time before beneficial environmental changes can be seen. However, with the elimination of photorespiration, trees can grow larger and stronger in a relatively short amount of time. This allows trees to have an immediate effect on the environment. This allows destroyed habitats to be cultivated quickly and restored. Additionally, with the infertility of poplar trees, these gene-edited trees cannot pose a large threat to outcompeting local wildlife. Therefore, gene-edited trees will not decrease biodiversity but rather increase it.

The utility of C3-C4 engineering is endless, and each new scientific advance opens more and more realms of possible benefits. As the climate crisis draws nearer, the increase in urgency has driven many to action. Genetic engineering is a realistic form of action to combat climate change.

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