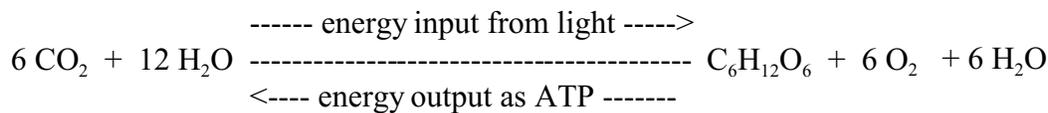


Photosynthesis and (Aerobic) Respiration

These two processes have many things in common.

1. occur in organelles that seem to be descended from bacteria (endosymbiont theory): chloroplasts and mitochondria
2. The organelles where these processes occur have complex internal membrane systems that are essential to the processes.
3. These processes rely on existing molecules in cells to carry out the energy conversion reactions: electron holders (NAD^+ , NADP^+), ADP and ATP, miscellaneous sugars, etc.
4. Photosynthesis and respiration are essentially the reverse of each other. Photosynthesis starts with CO_2 and reduces it to sugar; reduction requires energy, which is obtained from light. Respiration starts with sugar and oxidizes it to CO_2 ; oxidation releases energy which is collected as ATP.



Photosynthesis

Inside the chloroplasts are stacks of membrane sacks. Each sack is a thylakoid. The photosystems are located in the thylakoid membranes. The water compartment inside the thylakoid membrane is called the lumen. The water area outside of the thylakoid, but still within the chloroplast, is the stroma.

Photosynthesis occurs in two sets of reactions that are linked by electron carrier molecules ($\text{NADP}^+/\text{NADPH}$) and ADP/ATP . The two reactions go by several names. I'll be sticking to light reactions and Calvin cycle. (Alternate names you might have heard for the light reactions: photochemical reactions, light-dependent reactions. Alternate names you might have heard for the Calvin cycle: biochemical reactions, C3 cycle, carbon reduction cycle, and carbon fixation. There are two very misleading names floating around for the Calvin cycle that should be vaporized: light-independent reactions and dark reactions. At least five of the enzymes of the Calvin cycle, including the big deal one that starts the whole ride, are light activated.)

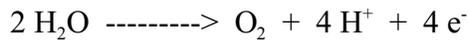
1. Light Reactions

Light is collected by the photosystems. There are two: PSII and PSI. Each consists of a reaction center containing 2 chl a and an antenna complex of accessory pigments and more chl a. (accessory pigments: chl b, carotenoids [carotenes and xanthophylls]) The photosystems are connected to each other via a chain of electron carrier molecules. The photosystems + electron carriers = Z-scheme. The Z-scheme is located in the thylakoid membrane.

Light energy is used to excite an electron in one of the reaction center chl a molecules in PSII. The excited electron leaves PSII and travels to PSI via the electron carriers. At PSI, the electron comes to rest at the PSI reaction center. The electron gets excited by more light energy, leaves

PSI, and travels to NADP^+ . Once two electrons reach NADP^+ , it is reduced to NADPH. $\text{NADP}^+/\text{NADPH}$ are located in the stroma.

How does PSII replace the electrons that keep leaving? By splitting water in a process called photolysis:



Photolysis occurs on the lumen side of the thylakoid membrane. The protons (H^+) that get released from water are trapped in the small lumen space by the thylakoid membrane. As the electrons move from PSII to PSI, more protons (H^+) are moved from the stroma to the lumen. Eventually, you get a pretty sizeable H^+ gradient between the lumen and the stroma. There is an enzyme that lets the chloroplasts harvest the energy of the gradient as ATP. The ATP is in the stroma.

2. The Calvin Cycle

see calvin.jpg

There are three phases to the Calvin cycle: carboxylation, reduction, and regeneration

A. Carboxylation

Carbon dioxide and RuBP (a C5 sugar) are combined to give two molecules of PGA (a C3 acid). The enzyme that catalyzes this reaction is abbreviated rubisco.

B. Reduction

This phase uses the 2/3 of the ATP and all of the NADPH produced during the light reactions. Each PGA molecule is reduced to PGald (a C3 sugar).

C. Regeneration

This phase uses the last of the ATP to turn a bunch of PGald molecules into a bunch of RuBP molecules so more carbon dioxide can be brought in.

D. For people dying to know what the abbreviations stand for:

rubisco = RuBP carboxylase and oxygenase

RuBP = ribulose-1,5-bisphosphate

PGA = 3-phosphoglyceric acid

PGald = 3-phosphoglyceraldehyde (also known as glyceraldehyde-3-phosphate)

ATP = adenosine triphosphate

ADP = adenosine diphosphate

$\text{NADP}^+/\text{NADPH}$ = nicotinamide adenine dinucleotide phosphate (oxidized/reduced)

Once you have lots of PGald, it can be used to make glucose, fructose, sucrose, and starch.

(The reactions of respiration, besides providing a means to change the stored calories of sugars into useable energy, let a cell start the process of converting carbons from carbohydrates into a variety of molecules: amino acids, nucleotides, pigments, hormones, etc.)

Besides looking at photosynthesis as a chloroplast event, you need to remember that it is also a leaf event.

Inside of a leaf are three tissues (functional collections of cells):

1. epidermis
 - holes for gas exchange called stomata (guard cells open and close the holes)
 - covered by a wax layer called cuticle)
2. vascular tissue
 - xylem + phloem together in a vascular bundle (vein)
3. mesophyll (ground tissue)
 - tightly packed layer of cells = palisade mesophyll
 - loose cell layer with lots of air spaces = spongy mesophyll

Most plants open their stomata during the day (light) so CO_2 enters the leaf for photosynthesis. Downside: water evaporates out of the stomata whenever they are open. Evaporation is fastest when the temperatures are highest, which would also be during the day. The stomata close at night when photosynthesis is not going on (no need to let in CO_2).

Some plants have a system that lets them open their stomata at night to collect and store CO_2 . During the day, they can close their stomata to conserve water, but still do photosynthesis. These plants are known as CAM plants. CAM == Crassulacean acid metabolism. CAM was first discovered in members of the Crassulaceae family. CAM has since been found in many angiosperm families (both monocots and dicots), a seedless vascular plant, and a gymnosperm.

CAM plants grow in arid habitats: deserts, alpine regions, as epiphytes.

All CAM plants have at least some succulence (water storing).

Two CAM plants are important from the money end of things: pineapple and orchids.

PEP = phosphoenolpyruvate, a C_3 acid.

CO_2 can be attached to PEP by the enzyme PEP carboxylase.

At night, the stomata are open. Starch is broken down to produce PEP. PEP combines with CO_2 to form a C_4 acid. This C_4 acid is stored in the vacuole. During the day, the stomata close. The C_4 acid is broken down to release CO_2 and a C_3 acid. The C_3 acid is converted back to starch. The CO_2 enters the Calvin cycle.

CAM is estimated to occur in ~ 10% of plant species. C_3 photosynthesis (where the only carbon reactions are the Calvin cycle ones) occurs in ~ 89% of species. The remaining ~1% do C_4 photosynthesis. Although C_4 accounts for only a fraction of the photosynthesis it attracts a lot of study because (1) it is a highly efficient form of photosynthesis and (2) it accounts for the high productivity of such major crops as corn, sugar cane, sorghum, and millet.

rubisco = RuBP carboxylase and oxygenase

$O_2 + RuBP \rightarrow PGA + C2 \text{ acid}$

$2 C2 \text{ acid} \rightarrow PGA + CO_2$

The CO_2 lost because of the oxygenase reaction is called photorespiration. It is a problem under conditions of high temperatures, high light intensities, and low water. Under these conditions, a C3 plant might lose 50% of its carbon via photorespiration.

How can you decrease photorespiration? Keep rubisco away from O_2 . Some plants do these by engaging in C4 photosynthesis.

C4 plants have a distinctive leaf anatomy. There is a prominent ring of cells around the vascular bundles = the bundle sheath. The mesophyll cells form a ring that is tightly appressed to the bundle sheath cells. Kranz anatomy.

In a mesophyll cell, CO_2 and PEP combine to form a C4 acid. The C4 acid is sent to a bundle sheath cell. In the bundle sheath cell, the CO_2 is released from the C4 acid and enters the Calvin cycle. The C3 acid that remains goes back to the mesophyll cell, is made back into PEP, and is ready to carry more CO_2 . (Rubisco is located only in the bundle sheath cells.) So, a CO_2 shuttle system delivers CO_2 to rubisco; the leaf anatomy keeps O_2 away from the bundle sheaths. Result \Rightarrow no photorespiration.

Downside to C4: the CO_2 shuttle is not a free ride. It adds 2 ATP to the standard 3 ATP (for the Calvin cycle) needed per CO_2 . So C4 is only cost effective for plants in an environment where photorespiration is a common problem.

By the way, C3 plants include wheat, rice, daisies, petunias, roses, fruit trees, and conifers.

One final thing to remember about photosynthesis is that it is a whole plant event. The roots need to take in essential elements from the soil. Many of the elements that plants require have some role in photosynthesis: sulfur, magnesium, iron, manganese, chlorine, nitrogen, copper, phosphorus. Potassium is needed to open the stomata to let in CO_2 . There needs to be an adequate water supply coming in from the roots to keep the stomata open. Under conditions of water stress, like can occur on a July afternoon, the stomata will close (at least partly if not completely).

Review

Photosynthesis and Respiration

What do photosynthesis and respiration have in common? In what way are they essentially the reverse of each other?

Photosynthesis

Be able to describe the structure of a chloroplast: thylakoid (thylakoid membrane + lumen), stroma. Which set of photosynthetic reactions occurs in the thylakoid? Which in the stroma?

How are the light reactions and the Calvin cycle reactions linked? ==> NADP⁺/NADPH, ATP/ADP

light reactions:

photosystems, Z-scheme, electron carrier molecules, photolysis, H⁺ gradient, ATP synthesis

Calvin Cycle

three phases of the Calvin cycle: carboxylation, reduction, and regeneration

rubisco

What is the sugar that is produced as a result of the carbon reduction process? What are the possible fates of the sugar once a plant has accumulated a lot of it?

Besides looking at photosynthesis as a chloroplast event, you need to remember that it is also a leaf event.

Inside of a leaf are three tissues (functional collections of cells): epidermis, vascular tissue, mesophyll (ground tissue)

What are CAM plants? How do they manage to do photosynthesis if their stomata are closed during the day for water conservation? In what habitats do you find CAM plants?

CAM is estimated to occur in ~ 10% of plant species. C3 photosynthesis (where the only carbon reactions are the Calvin cycle ones) occurs in ~ 89% of species. The remaining ~1% do C4 photosynthesis. Why do C4 plants attract so much attention? What is photorespiration? What is rubisco? How is it involved in photosynthesis? How is it involved in photorespiration?

C4 plants have Kranz anatomy. How does Kranz anatomy relate to C4 photosynthesis?

Be able to give at least two examples each of C3 plants, C4 plants, and CAM plants.

Why is the root system important to photosynthesis?