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FOR EXCELLENCE

Photosynthesis

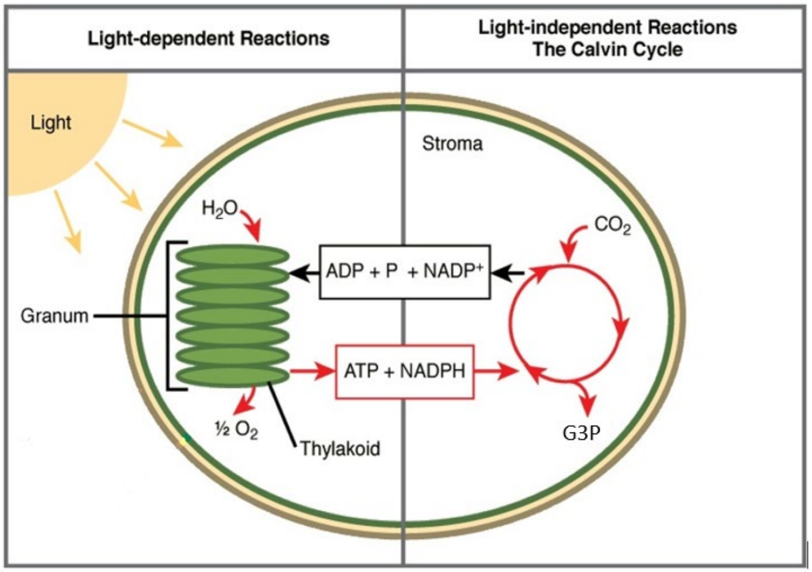
The vast majority of energy found within any ecosystem on Earth originates from the Sun itself and is transferred between organisms through complex food webs. Photosynthetic organisms such as plants and algae form the basis of these webs by converting sunlight, water, and carbon dioxide into usable energy. That energy can then be utilized by the photosynthetic organism, which itself may be consumed by other organisms for their own energy requirements. This handout will focus on explaining the steps involved in the most common version of photosynthesis, known as C_3 photosynthesis.

The purpose of the various anabolic redox reactions involved in photosynthesis is to generate a molecule of glyceraldehyde 3-phosphate (G3P), an important precursor to the carbohydrate glucose ($C_6H_{12}O_6$), a form of sugar, and other types of biomolecules. For every two G3P made, one molecule of glucose can be created.

The following equation and graphic provide a summary and general overview of the processes and reactants involved in photosynthesis:

Photosynthesis Equation			
Carbon dioxide +	Water —SUNLIGHT→	Sugar +	Oxygen
$6CO_2$	$6H_2O$	$C_6H_{12}O_6$	$6O_2$

Source: OpenStax Biology. Download for free at http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.56

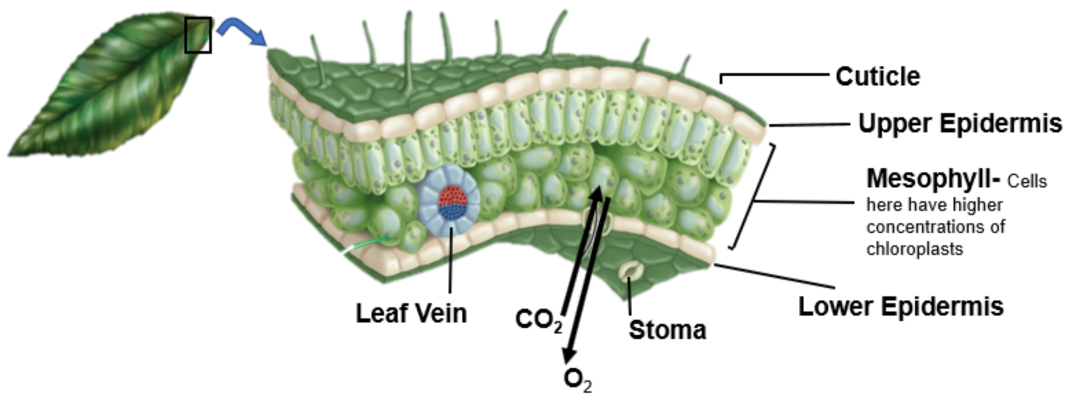


Source: OpenStax Biology. Download for free at http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.56

You can navigate to specific sections of this handout by clicking the links below.

Location of Photosynthesis

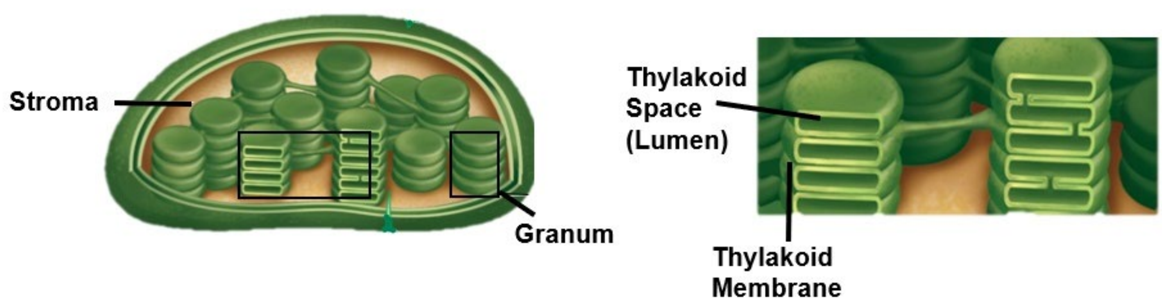
Photosynthesis occurs within specialized organelles called chloroplasts that are located in the cells of green plant tissues. As shown in the following graphic, chloroplasts are abundant within the mesophyll, a type of leaf tissue found in between layers of epidermis and a waxy cuticle that help to prevent the loss of water through evaporation. The stomata of each leaf allow for the diffusion of CO_2 and O_2 to and from chloroplasts through the protective epidermis and cuticle.



Source: Mader, S.S. & Windelspecht, M. (2016). Overview of photosynthesis. Biology (12th ed.). New York, NY: McGraw Hill Education.

Chloroplast Structure

Chloroplasts are membrane-bound organelles that are internally divided in a manner separating and facilitating the reactions required for photosynthesis. Inside each chloroplast, the light-dependent reactions take place in membrane-bound sacs called thylakoids. A stack of thylakoids may be referred to as a granum and multiple granum as grana. The internal space of each thylakoid is connected to adjacent thylakoids and may be referred to as either the thylakoid space or lumen. Surrounding the thylakoids is a fluid-filled space called the stroma, where light-independent reactions take place.

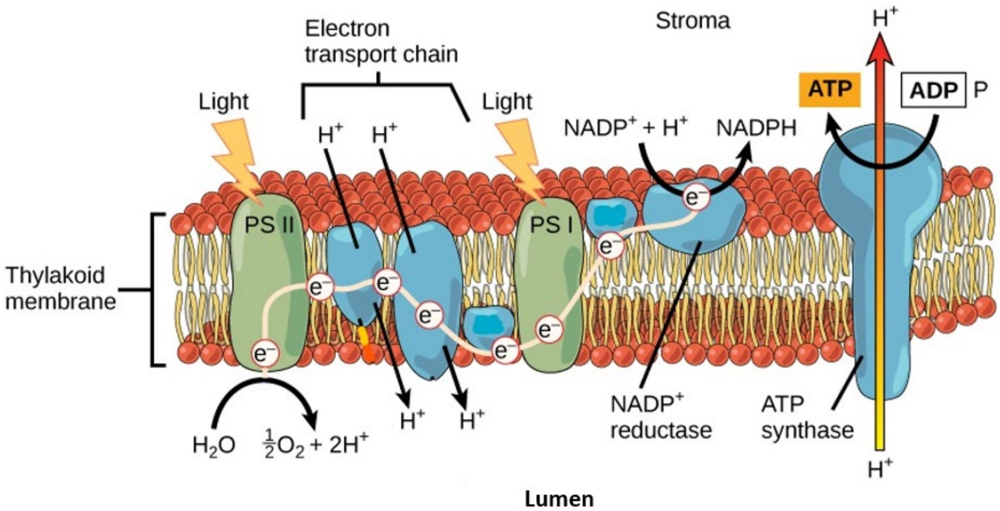


Source: Mader, S.S. & Windelspecht, M. (2016). Overview of photosynthesis. Biology (12th ed.). New York, NY: McGraw Hill Education.

Light-dependent Reactions

Reactions requiring the presence of light are known as photosystems and take place within the membrane of the thylakoids. This is where the various pigments that absorb energy from sunlight are located, usually some combination of chlorophylls and carotenoids. Photosystem II (PS II) is the initial phase of photosynthesis in which water molecules are broken down into hydrogen ions (H^+), electrons (e^-), and oxygen. The oxygen is released as a gas while the H^+ and e^- are retained. Then, e^- in Photosystem II enter a reaction center in the thylakoid membrane containing chlorophyll that captures energy from sunlight. The captured sunlight energy is absorbed by e^- in the reaction center, causing a jump to a high-energy state. This energy is then released in stages as the e^- travel through an ETC in the thylakoid membrane, causing H^+ from the stroma to be concentrated in the lumen as part of the process. As the e^- reaches the end of the ETC and moves on to be utilized in Photosystem I, the buildup of H^+ establishes a concentration gradient, thereby allowing chemiosmosis to take place through the enzyme ATP-synthase. As H^+ flow through the internal structure of the enzyme and back into the stroma, ADP is joined with phosphate, thus forming ATP. This ATP will be used later during the Calvin cycle.

The image below shows, from left to right, the paths taken by e^- and H^+ through both photosystems after being split from water.



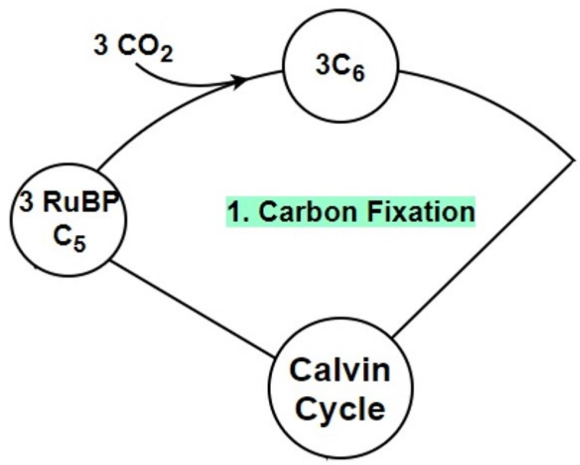
Source: OpenStax Biology. Download for free at http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.56

Photosystem I (PS I) is the second phase of photosynthesis and begins with the e^- from Photosystem II entering another chlorophyll reaction center. The e^- are again energized by sunlight before moving from the reaction center to the enzyme NADP-reductase. There, the enzyme attaches the e^- from Photosystem I and H^+ from the stroma to the coenzyme $NADP^+$. With the addition of e^- and H^+, the $NADP^+$ is thereby reduced and becomes NADPH. With both photosystems now complete, the ATP and NADPH that were produced and positioned in the stroma are now ready to be used in the Calvin cycle.

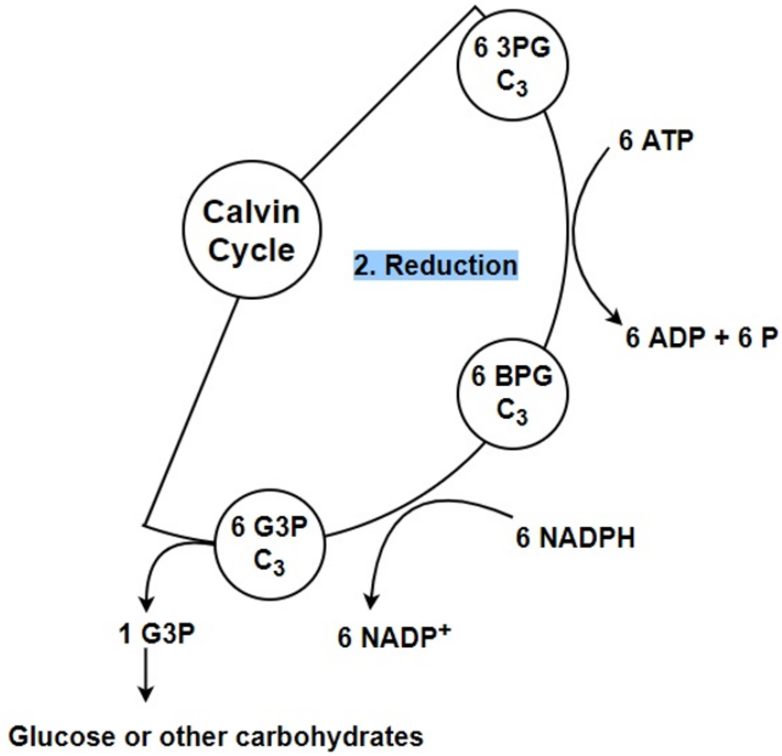
Light-independent Reactions (Calvin cycle)

The reactions of the Calvin cycle take place within the stroma and do not require sunlight. The Calvin cycle begins with the intake of atmospheric CO_2, to be combined with RuBP, forming the first in a series of metabolites that will eventually yield G3P. Each time the Calvin cycle is completed, one G3P molecule is retained for glucose production while the remaining five are converted into exactly enough RuBP to restart the cycle. The steps of the cycle may be broken down into the three phases listed below. Please note that C3, C5 and C6 refer to the number of carbon atoms present in each type of molecule during the Calvin cycle. For example, 3 RuBP C5 indicates that there are 3 RuBP molecules present, each containing 5 carbon atoms.

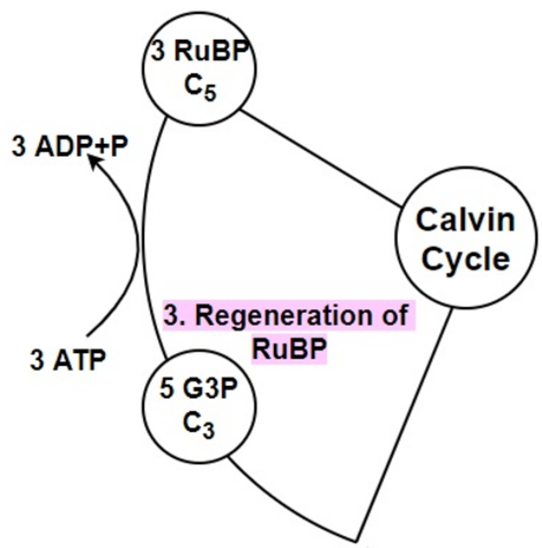
1. Carbon Fixation: As three molecules of CO_2 are brought into the stroma, three molecules of five-carbon RuBP are present. These will each be combined by the enzyme RubisCO. This results in three molecules of an unstable six-carbon intermediate metabolite that immediately break down into six three-carbon molecules of 3PG (3-PGA in some sources).

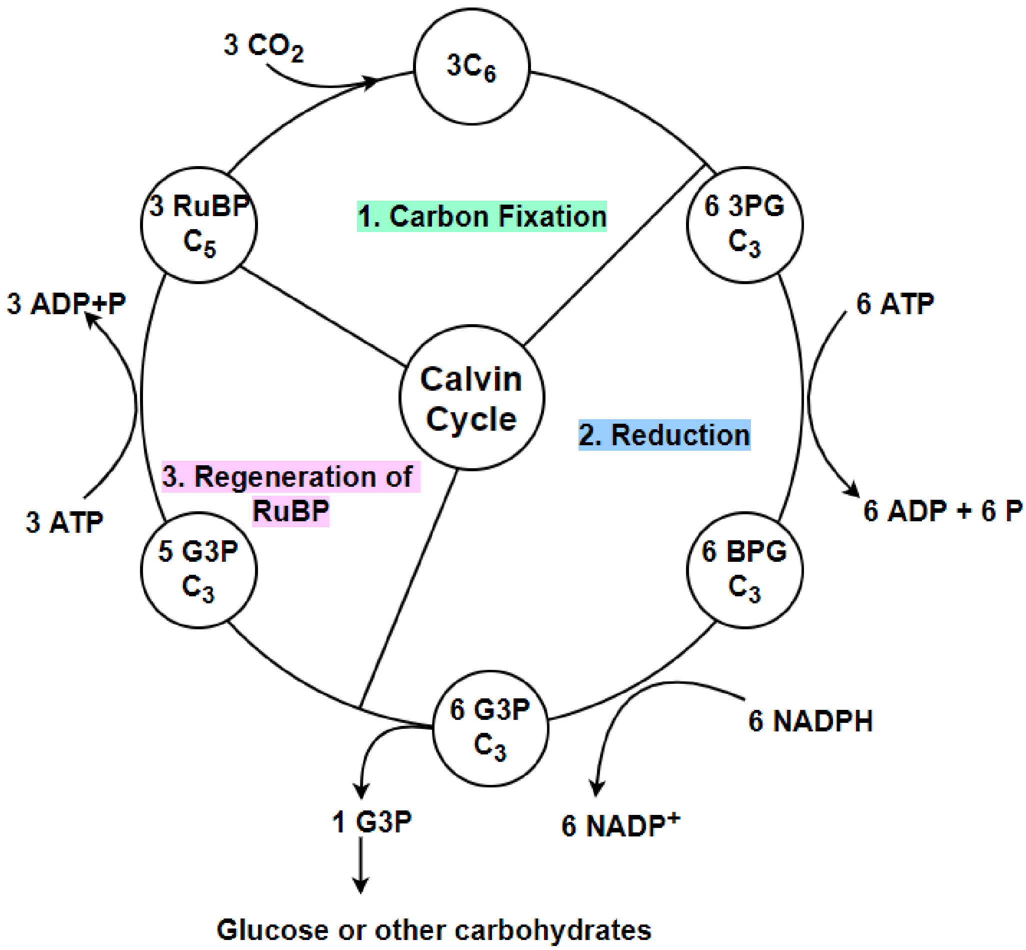


2. Reduction: Six molecules of ATP and NADPH, created earlier by the photosystems, are used to reduce the 3PG into six molecules of BPG, then into G3P. One molecule of G3P exits the cycle to be used in the production of glucose at the end of the reduction phase. The exit of this three-carbon molecule of G3P corresponds to the initial intake of the three carbon atoms contained within the three molecules of CO_2.



3. Regeneration: The remaining five molecules of G3P are converted back into RuBP by the application of three molecules of ATP. This results in exactly enough RuBP to restart the cycle.





The Calvin cycle must be completed twice in order for enough G3P to be available to produce one molecule of the sugar glucose. Thus, this process satisfies the equation for photosynthesis stated at the beginning of this handout: $6CO_2 + 6H_2O$ + Sunlight = $C_6H_{12}O_6 + 6O_2$.