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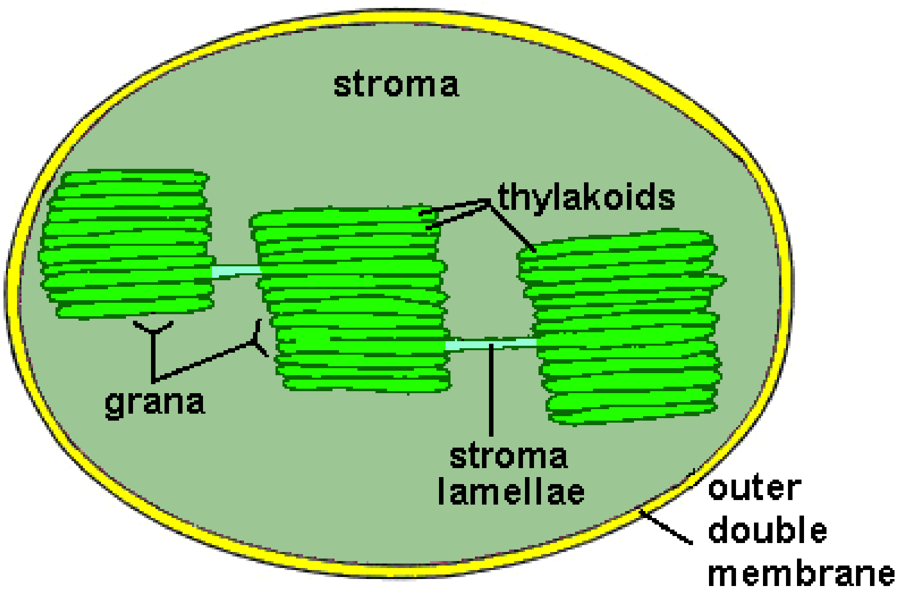
PHOTOSYNTHESIS

photosynthesis - the process in which carbon dioxide (CO_2) and water (H_2O) are used to produce carbohydrates and evolve oxygen (O_2) in the presence of light and chlorophyll; the net result is light energy (radiant energy) is converted into chemical energy in the form of fixed carbon compounds (carbohydrates).

chloroplast - the green plastid in which photosynthesis occurs.
chlorophyll - the green plant pigment in chloroplasts that absorbs the light needed for photosynthesis.
thylakoids - flattened, sack-like membranes inside a chloroplast; contain the chlorophyll.
granum (pl.**grana**) - stacks of thylakoids.
stroma lamellae (pl. **stroma lamella**) - tubular membranes that connect the grana in the chloroplast.
stroma - the fluid matrix of the chloroplast

Cross-section of a chloroplast



NET CHEMICAL EQUATION FOR PHOTOSYNTHESIS

$$6\,CO_2 + 6\,H_2O \xrightarrow[\text{chlorophyll}]{\text{light}} C_6H_{12}O_6 + 6\,O_2$$

carbon dioxide	water		carbohydrate	oxygen

This Net Equation is Made up of Two Separate Reactions

Light Reaction - the reaction that uses the water and light energy and evolves oxygen. It is also called the **Hill Reaction**.

Dark Reaction - the reaction that uses the carbon dioxide and produces the carbohydrate. It is also called the **Calvin-Benson Cycle** or **Photosynthetic Carbon Reduction (PCR) Cycle**.

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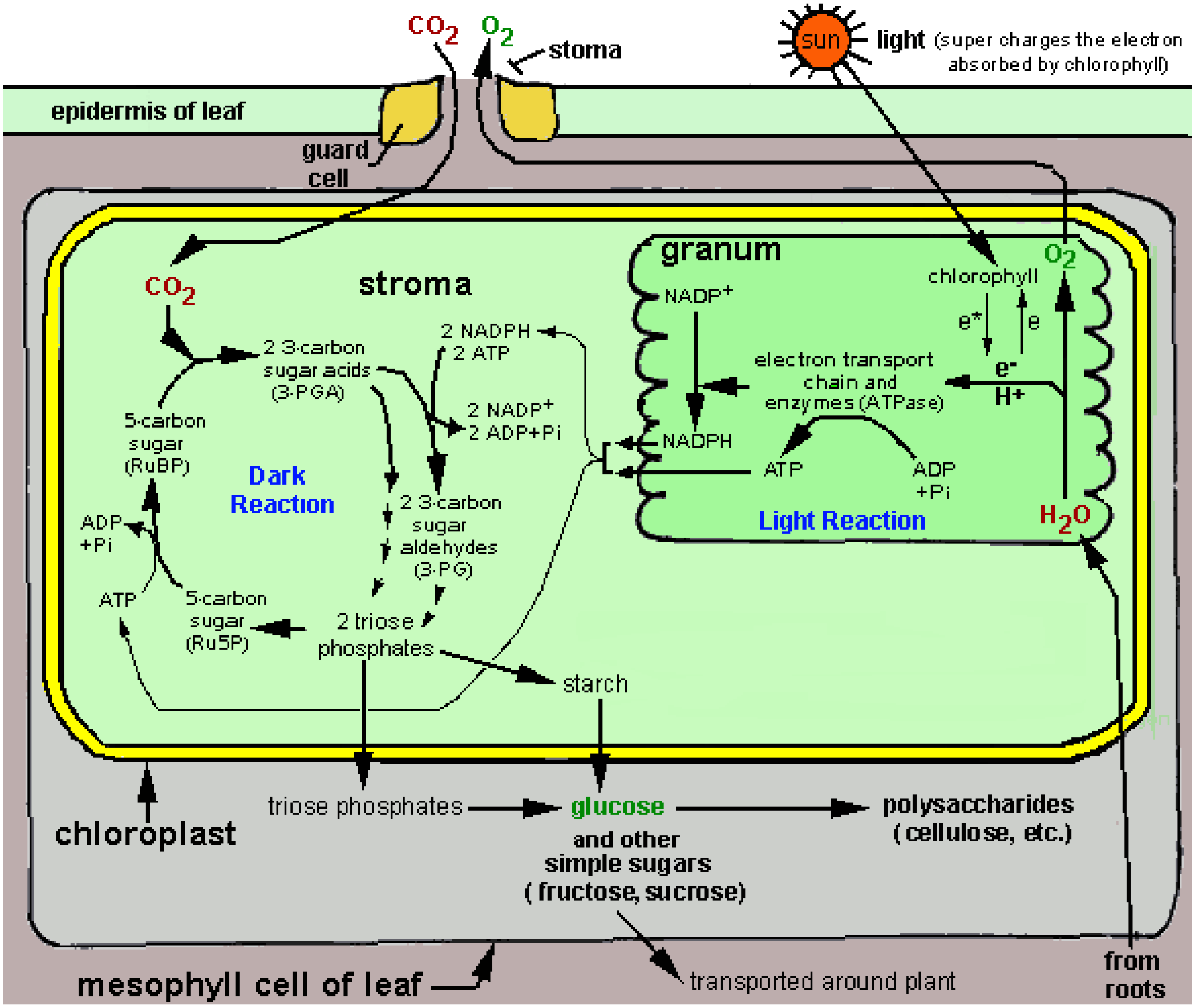
BIOCHEMICAL REACTIONS OF PHOTOSYNTHESIS - C-3 TYPE



Light Reaction

Inside the thylakoid membranes of the granum, water is split to produce oxygen (which is evolved as a by-product), electrons (e-) and hydrogen ions (H+). Each electron is then absorbed by chlorophyll, which also absorbs light (radiant energy) to bring the electron to a high energy state. The energized electron is passed from chlorophyll to the electron carriers of the electron transport chain. As the electron is transported, an energy gradient is generated (which actually uses the H+) which allows an enzyme (ATPase) to make ATP. When the electron gets to the end of the chain, it is pretty well drained of the added energy, and NADP+ acts as a terminal electron acceptor to utilize the last bit of energy in the electron to produce NADPH. Thus, radiant energy (e.g. light) is used to produce metabolic chemical energy (ATP and NADPH). **"Eureka"**, the plant has made chemical energy from light energy! But there is a problem. ATP and NADPH are short lived and cannot be stored or easily transported to where needed. The plant must figure out a way to save this precious chemical energy and that is where the Dark Reaction comes into the picture.

Dark Reaction

A very important enzyme (ribulose-bisphosphate carboxylase or rubisco) combines a 5-C sugar with a CO2 molecule to produce a 6-C compound that immediately breaks into 2 3-C sugar acids. This 3-C sugar acid is not very useable by the plant so through a series of reactions it is converted into sugars called triose phosphates. This requires metabolic energy, which is derived from the ATP and NADPH produced by the Light Reaction. The triose phosphate is used to produce glucose and other sugars or is stored as glucose in starch. Finally, **"Eureka" for real**, the plant has produced a stable, transportable, and storable form of chemical energy (e.g. sugars). For the cycle to continue, some of the triose phosphate must be used to replenish the original 5-C sugar, and this takes metabolic energy which is supplied by ATP from the Light Reaction. The Dark Reaction continues as long as the Light Reaction supplies it with energy in the form of ATP and NADPH, thus the Dark Reaction only occurs in the light!

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TYPES OF PLANTS BASED ON TYPES OF PHOTOSYNTHESIS
(all are based on modifications of the Dark Reaction)

C3 PLANTS

Examples - most plants, ex. bean, apple, tomato, tropical foliage plants

Day - stomata open, fix CO_2 by Dark Reaction into 3-carbon sugar acids

Night - stomata close

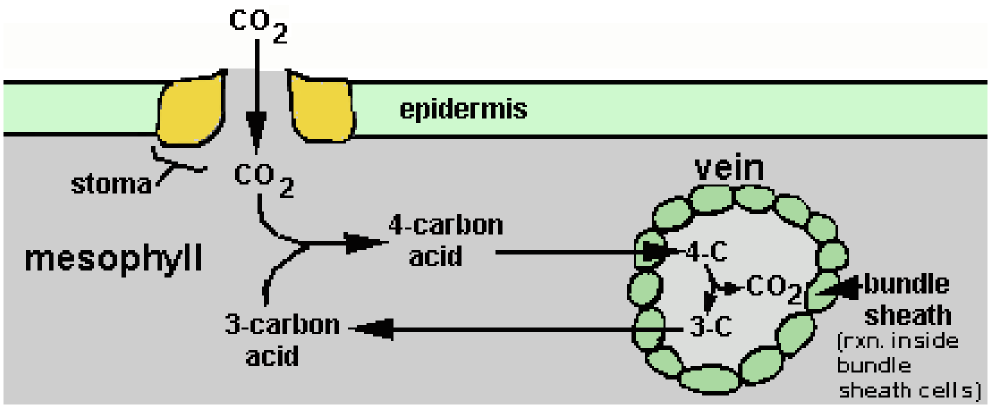
C4 PLANTS

Examples - some grasses, ex. corn, sorghum

Day - stomata open

- CO_2 fixed into 4-carbon acid in mesophyll cells
- 4-carbon acid travels to bundle sheath cells and releases $C0_2$ for the Dark Reaction

Night - stomata close



CAM PLANTS (Crassulacean Acid Metabolism Plants)

Examples - many desert plants, succulents, cacti

Night - stomata open

- $C0_2$ fixed into 4-carbon acids (malate) and stored in the vacuole of mesophyll cells until the next day

Day - stomata close (to conserve water during hot dry day)

- 4-carbon acid breaks down to release $C0_2$ inside the leaf for Dark Reaction.

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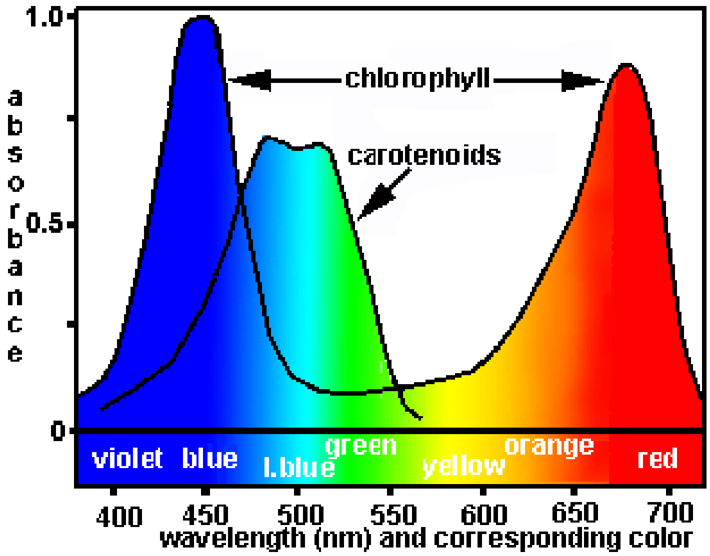
FACTORS AFFECTING PHOTOSYNTHESIS

1) Light (Radiant Energy)

a) Quality - the wavelength or color of light

Absorption Spectrum of Chlorophyll and Carotenoids



1) colored coverings - (see next page on plant canopy)
2) tungsten or incandescent lights - (see next page for spectrum)
3) fluorescent lights - (see next page for spectrum)
4) High Intensity Discharge (HID) lights

b) Quantity - the intensity or amount of light

1) Supplemental lighting - (see next pages for light saturation range)
2) Row orientation -
3) Orientation around buildings/structures

2) Carbon dioxide

a) Greenhouse depletion during day and ventilation
b) Carbon dioxide enrichment (see next pages for carbon dioxide saturation range)
c) CAM plants

3) Temperature
4) Leaf Age
5) Water Stress
6) Nutrition
7) Leaf damage and stomatal closing

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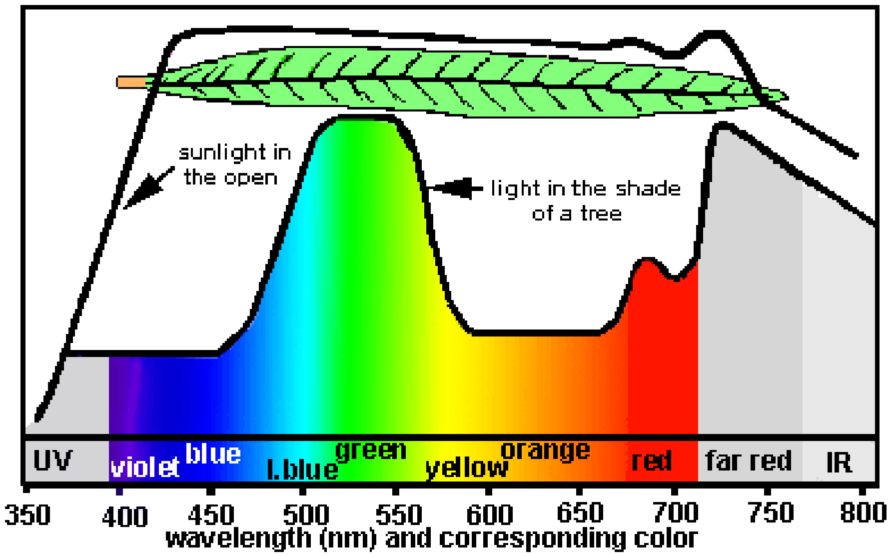
EFFECT OF LIGHT QUALITY ON PHOTOSYNTHESIS

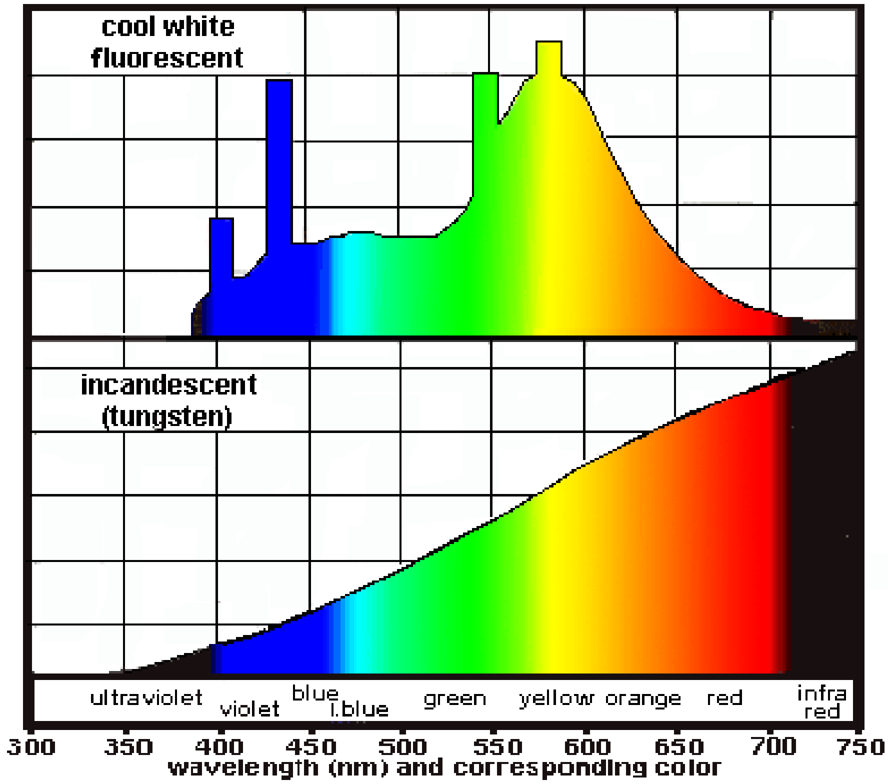
Light Quality Under a Plant Canopy in the Shade

Sunlight has all colors of visible light in similar proportions. When light passes through a leaf, more blue, orange and red wavelengths are removed by chlorophyll and carotenoids and more green-yellow and far red wavelengths are transmitted. Therefore, the shade of a tree is richer in green-yellow and far red wavelengths. Plants are partially "color blind" to the light in the shade.



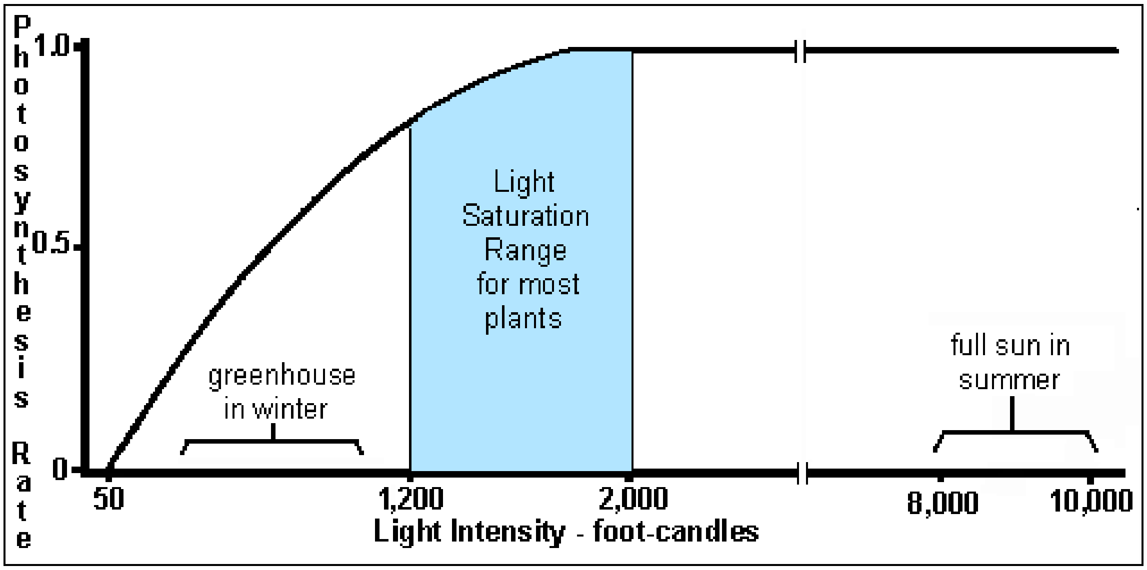
Light Quality from Artificial Light Sources

Artificial lights emit different wavelengths (colors) of visible light. Fluorescent light are highest in the blue and yellow-orange region of the spectrum. Incandescent (tungsten) lights are poor in the blue region, moderate in the green region, high in the red and far red region of the spectrum, with up to 50% of their output in the infra red region (that's why they're hot).



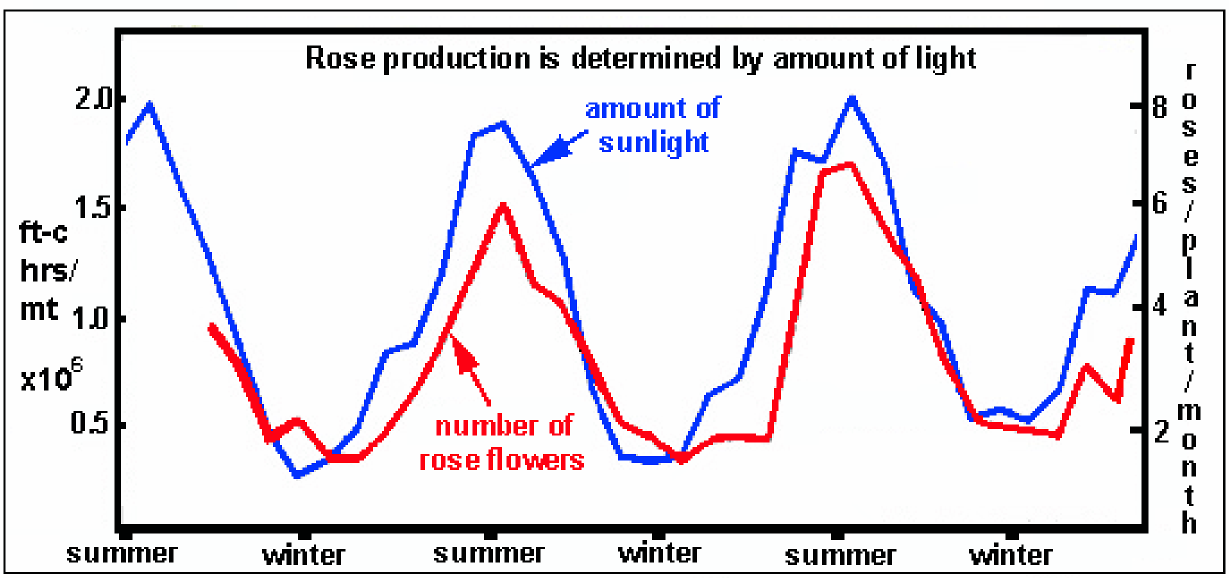
EFFECT OF LIGHT INTENSITY AND CO2 ON PHOTOSYNTHESIS

Effect of Light Intensity on Photosynthesis

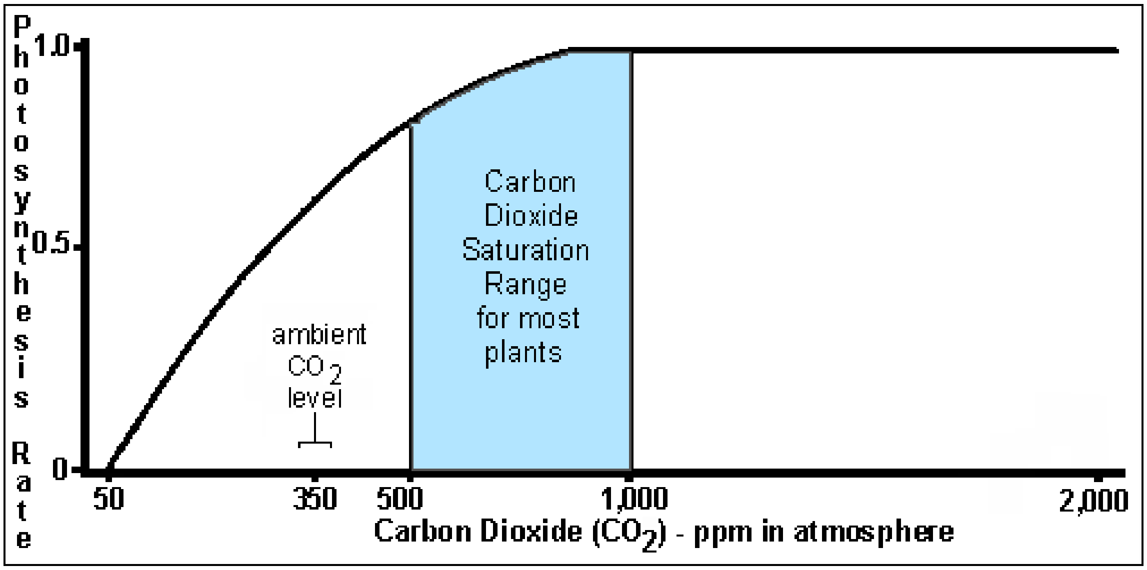


Relationship between Light Intensity and Rose Yield

(From: K. Post and J.E. Howland. *Proc. Amer. Soc. for Hort. Sci. 47:446-450, 1946)*



Effect of Carbon Dioxide Enrichment on Photosynthesis



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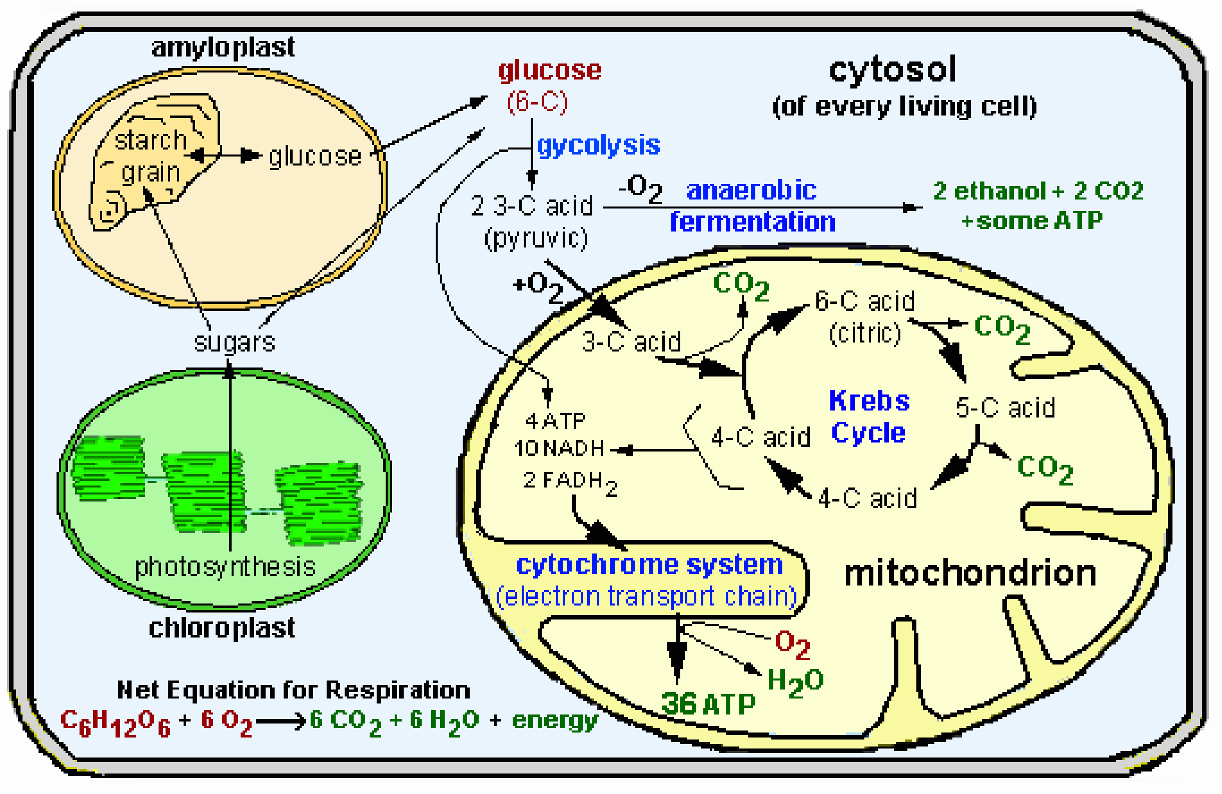
BIOCHEMICAL REACTIONS OF RESPIRATION



Glycolysis

Glycolysis is the first series of reactions of respiration. It occurs in the cytosol of the cytoplasm of the cell. The 6-carbon glucose molecule is broken into 2 3-carbon acids (called pyruvic acid). Metabolic energy is produced from breaking one carbon-carbon bond. If no oxygen is present, the 3-carbon acid goes to Anaerobic Fermentation. If oxygen is present (which is most of the time), the 3-carbon acid moves into the matrix of the mitochondrion and enters the Krebs Cycle.

Anaerobic Fermentation

Anaerobic fermentation occurs in the cytosol of the cytoplasm, and only occurs when there is no oxygen present. The 3-carbon acid from glycolysis is broken down into ethanol (a 2-C compound) and CO_2; this happens for each of the 2 3-C acids from glycolysis. Some metabolic energy (ATP) is produced from breaking one more carbon-carbon bond. But, there is a carbon-carbon bond left in ethanol that is never broken, thus anaerobic fermentation results in incomplete respiration of the original glucose. This produces enough energy to keep only small organisms (e.g. microorganisms) alive; higher plants/animals die if they only have anaerobic fermentation for extended periods of time.

Krebs Cycle

The Krebs Cycle occurs when oxygen is present and occurs in the matrix of the mitochondrion. The 3-carbon acid from glycolysis (pyruvic acid) loses a CO_2, then combines with a 4-carbon acid to produce a 6-carbon acid (citric acid). The 6-carbon acid is broken down into a 5-carbon acid, then a 4-carbon acid, breaking a carbon-carbon bond, releasing CO_2 and producing metabolic energy (ATP, NADH and $FADH_2$) with each degradation. The original 4-carbon acid is replenished, and the cycle goes again. The cycle turns 2 times for each glucose (e.g. once for each 3-C acid produced by glycolysis).

Cytochrome System

The most useful form of metabolic energy is ATP. So the various metabolic energy compounds produced by glycolysis and the Krebs Cycle move to the inner membranes of the mitochondrion. In the inner membrane is an electron transport chain called the cytochrome system, which is very similar to what we saw in Photosynthesis. The metabolic energy compounds (NADH and $FADH_2$) donate their electrons to the electron transport carriers of the electron transport chain, an energy gradient is produced, and an enzyme (ATPase) produces ATP. Oxygen acts as a terminal electron acceptor to keep the chain flowing, and combines with H^+ to produce water.

Overall

Now the plant has converted all the original energy that was stored in the carbon-carbon bonds of glucose back into the various metabolic energy compounds it needs to power its metabolism. The plant can use the NADH or $FADH_2$ directly, or convert it to ATP for metabolism. Remember, these forms of metabolic energy cannot be stored or transported very easily, so respiration must occur in every cell and it must occur at the exact time the metabolic energy is needed.

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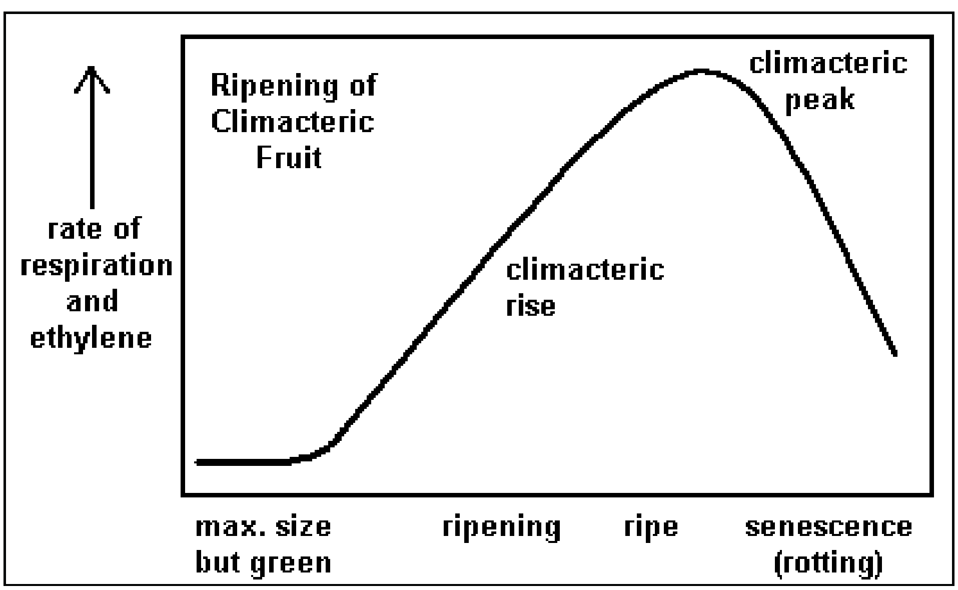
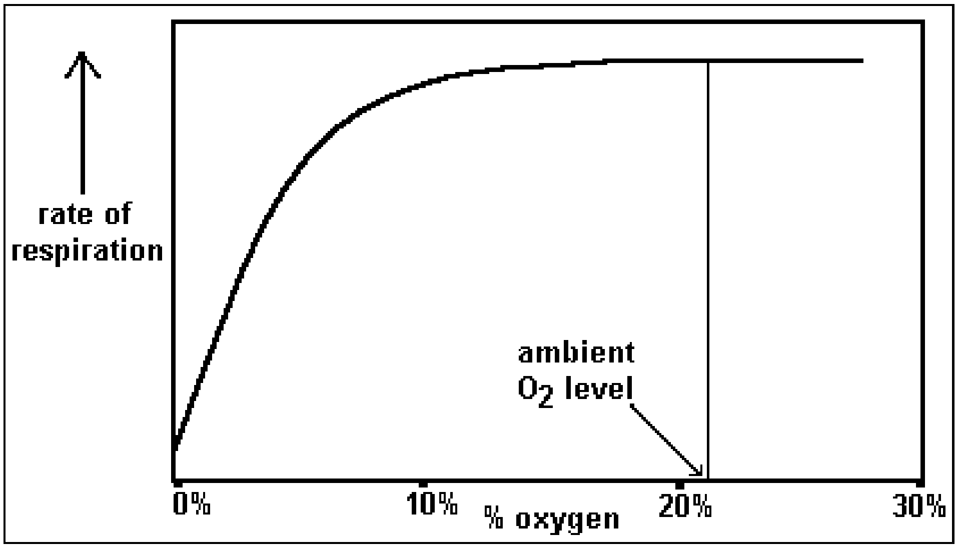
<table>
<tr><th colspan="2">FACTORS AFFECTING RESPIRATION</th></tr>
<tr><td>Tissue Activity</td><td>young tissue has higher respiration than older tissue</td></tr>
<tr><td>Ripening Fruit and Climacteric Rise</td><td>respiration increases when a fruit


ripens.</td></tr>
</table>

Temperature	• respiration decreases when temperature decreases. • respiration ceases at about freezing temperatures (32 ºF) • increasing temperature increases respiration, until temperature gets too high, then respiration decreases when tissue deteriorates.
Oxygen	• respiration decreases when oxygen decreases. • under no oxygen, anaerobic respiration occurs. 
Carbon dioxide	• respiration decreases when carbon dioxide increases
Controlled Atmosphere Storage	• high CO_2 (approx. 2-5%) • low 0_2 (approx. 3%) • low temperature (approx. 32 ºF) • high humidity (approx. 90%) • ethylene removed (scrubbed)
Hypobaric Storage	• similar to controlled atmosphere storage, but in addition it has low pressure (light vacuum) to reduce 0_2 and remove ethylene from the storage container and from inside the plant tissue.
Wounding & Physical Damage	• wounded, damaged or infected tissue has higher respiration than healthy tissue
Water content	• dry tissue has decreased respiration; for example, dry seeds

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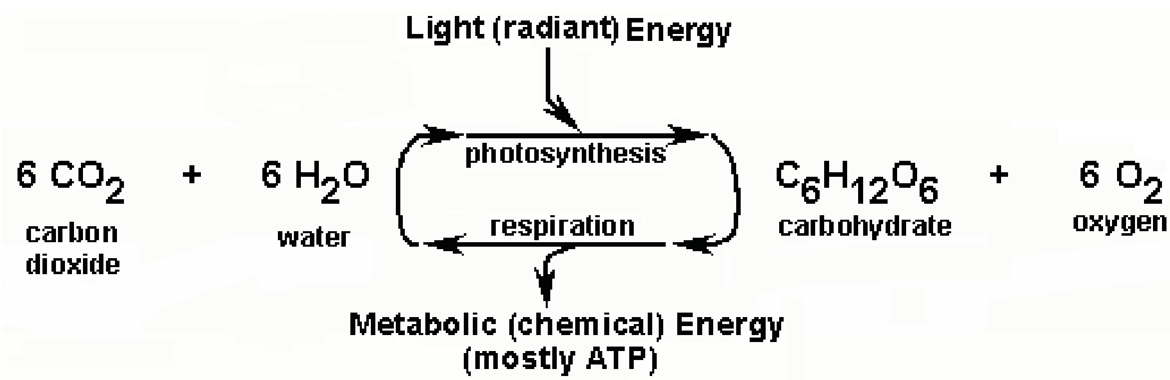
SUMMARY OF REACTIONS OF PHOTOSYNTHESIS AND RESPIRATION

			From Net Equation	
Reactions	**When Occurs**	**Where Occurs**	**Inputs**	**Outputs**
		PHOTOSYNTHESIS		
Light Reaction (Hill Reaction)	only in light	grana of chloroplast	H_20, light energy	O_2
Dark Reaction (Calvin-Benson Cycle, PCR)	only when Light Reaction occurs	stroma of chloroplast	CO_2	carbohydrate
		RESPIRATION		
Glycolysis	all the time (if O_2 present)	cytosol of cytoplasm	carbohydrate (glucose)	metabolic energy
Anaerobic Fermentation	only when no O2 present	cytosol of cytoplasm	-	CO_2, ethanol, some metabolic energy
Krebs Cycle (TCA Cycle)	all the time (if O_2 present)	matrix of mitochondria	-	CO_2, metabolic energy
Cytochrome System	all the time (if O_2 present)	inner membranes of mitochondria	O2	H_2O, metabolic energy (ATP)

NET EQUATION
OVERALL CHEMICAL REACTIONS OF PHOTOSYNTHESIS AND RESPIRATION



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