Inquire: Light-Dependent Reactions

Overview

How can light be used to make food? It is easy to think of light as something that exists and allows living organisms, such as humans, to see, but light is a form of energy. Like all energy, light can travel, change form, and be harnessed to do work. In the case of photosynthesis, light energy is transformed into chemical energy, which autotrophs use to build carbohydrate molecules. However, autotrophs only use a specific component of sunlight.

Big Question: What is the purpose of the light-dependent reactions of photosynthesis?

Watch: What is Light Energy?

The sun emits an enormous amount of solar energy in a spectrum from very short gamma rays to very long radio waves known as electromagnetic radiation. Humans can see only a tiny fraction of this energy, which we refer to as “visible light.” Visible light constitutes only one of many types of electromagnetic radiation emitted from the sun and other stars. Scientists differentiate the various types of radiant energy from the sun within the electromagnetic spectrum. The electromagnetic spectrum is the range of all possible frequencies of radiation. The difference between wavelengths relates to the amount of energy carried by them. Solar energy can be harnessed and used as energy for many different purposes. Humans use this energy in the form of solar panels that capture the energy and use it to power houses and other electrical dependent items. Plants use solar energy in much the same way. When a solar panel absorbs the energy from the sun, the energy can be stored in batteries for later use. Similarly, plants have two cycles — light-dependent reactions and the Calvin cycle — which allow them to capture, store, and use the energy to grow and produce. This process is known as photosynthesis.

Light energy initiates the process of photosynthesis when pigments absorb specific wavelengths of visible light. Organic pigments, whether in the human retina or the chloroplast thylakoid in a plant, have a narrow range of energy levels that they can absorb. Energy levels lower than those represented by red light are insufficient to raise an orbital electron to an excited (quantum) state. Energy levels higher than those in blue light will physically tear the molecules apart, in a process called bleaching. Our retinal pigments can only see (absorb) wavelengths between 700 nm and 400 nm of light: a spectrum that is therefore called visible light. For the same reasons, in plants, pigment molecules absorb light only in the wavelength range of 700 nm to 400 nm. Plant physiologists refer to this range for plants as photosynthetically active radiation.

Once a plant absorbs this light, the energy can then be transformed into chemical energy which can then be synthesized into sugar through the Calvin cycle.
Read: The Light-Dependent Reactions of Photosynthesis

Overview
In the first part of photosynthesis, the light-dependent reactions, pigment molecules (chlorophyll) absorb energy from sunlight. A photon (a packet of light energy) strikes photosystem II to start photosynthesis. Energy travels through the electron transport chain, picking up electrons and hydrogen molecules to transform ADP into ATP which is used for the formation of sugar molecules in the second stage of photosynthesis. Photosystem I absorbs a second photon in the form of a hydrogen molecule, which results in the formation of an NADPH molecule, another energy carrier for the Calvin cycle reactions.

What is Light Energy?
The sun emits an enormous amount of electromagnetic radiation (solar energy). Humans can see only a fraction of this energy, which is referred to as “visible light.” The manner in which solar energy travels can be described and measured as waves. Scientists can determine the amount of energy of a wave by measuring its wavelength, the distance between two consecutive, similar points in a series of waves, such as from crest to crest or trough to trough.

Visible light constitutes only one of many types of electromagnetic radiation emitted from the sun. The electromagnetic spectrum is the range of all possible wavelengths of radiation. Each wavelength corresponds to a different amount of energy carried.

Absorption of Light
Light energy enters the process of photosynthesis when pigments absorb the light. In plants, pigment molecules absorb only visible light for photosynthesis. The visible light seen by humans as white light actually exists in a rainbow of colors. Certain objects, such as a prism or a drop of water, disperse white light to reveal these colors to the human eye. The visible light portion of the electromagnetic spectrum is perceived by the human eye as a rainbow of colors.

How Light-Dependent Reactions Work
The overall purpose of the light-dependent reactions is to convert light energy into chemical energy. This chemical energy will be used by the Calvin cycle to fuel the assembly of sugar molecules.

The light-dependent reactions begin in a grouping of pigment molecules and proteins called a photosystem. Photosystems exist in the membranes of thylakoids, flattened sacs inside a chloroplast. A pigment molecule in the photosystem absorbs one photon, a quantity or “packet” of light energy, at a time. A photosystem is made up of the antenna molecule, the reaction center, and the primary electron acceptor.

A photon of light energy travels until it reaches a molecule of chlorophyll. The photon causes an electron in the chlorophyll to become "excited." The energy given to the electron allows it to break free from an atom of the chlorophyll molecule. Chlorophyll is therefore said to “donate” an electron.

To replace the electron in the chlorophyll, a molecule of water is split. This splitting releases an electron and results in the formation of oxygen (O₂) and hydrogen ions (H⁺) in the thylakoid space. Technically, each breaking of a water molecule releases a pair of electrons, and therefore can replace two donated electrons.
The replacing of the electron enables chlorophyll to respond to another photon. The oxygen molecules produced as byproducts find their way to the surrounding environment. The hydrogen ions play critical roles in the remainder of the light-dependent reactions.

Keep in mind that the purpose of the light-dependent reactions is to convert solar energy into chemical carriers that will be used in the Calvin cycle. In eukaryotes and some prokaryotes, two photosystems exist. The first is called photosystem II, which was named for the order of its discovery rather than for the order of the function.

After the photon hits, photosystem II transfers the free electron to the first in a series of proteins inside the thylakoid membrane called the electron transport chain. As the electron passes along these proteins, energy from the electron fuels membrane pumps that actively move hydrogen ions against their concentration gradient from the stroma into the thylakoid space.

Generating an Energy Carrier: ATP

In the light-dependent reactions, energy absorbed by sunlight is stored by two types of energy-carrier molecules: ATP and NADPH. The energy that these molecules carry is stored in a bond that holds a single atom to the molecule. For ATP, it is a phosphate atom, and for NADPH, it is a hydrogen atom. A small amount of energy is used to allow ADP to pick up a third phosphate which forms a molecule of ATP in a process called photophosphorylation (adding a phosphate).

Generating Another Energy Carrier: NADPH

The remaining function of the light-dependent reaction is to generate the other energy-carrier molecule, NADPH. As the electron from the electron transport chain arrives at photosystem I, it is re-energized with another photon captured by chlorophyll. The energy from this electron drives the formation of NADPH from NADP+ and a hydrogen ion (H+). Now that the solar energy is stored in energy carriers, it can be used to make a sugar molecule. It takes a total of two photons to fully reduce one molecule of NADP+ to NADPH.

Reflect: Adjusting to Life With Less Light

Poll: Not all photosynthetic organisms have full access to sunlight. Why do you think some organisms receive less light?

- Organisms grow underwater where light intensity and quality decrease
- Organisms grow in competition for light
- Plants on the rainforest floor must be able to absorb any bit of light that comes through

Expand: Understanding Pigments

Discover

Different kinds of pigments exist, and each absorbs only specific wavelengths (colors) of visible light. Pigments reflect or transmit the wavelengths they cannot absorb, making them appear a mixture of the reflected or transmitted light colors.
Chlorophylls

Chlorophylls and carotenoids are the two major classes of photosynthetic pigments found in plants and algae; each class has multiple types of pigment molecules. There are five major chlorophylls: \( \text{a, b, c, and d} \), and a related molecule found in prokaryotes called \( \text{bacteriochlorophyll} \). **Chlorophyll a** and **chlorophyll b** are found in higher plant chloroplasts and will be the focus of the following discussion.

Carotenoids

With dozens of different forms, carotenoids are a much larger group of pigments. The carotenoids found in fruit — such as the red of tomato (lycopene), the yellow of corn seeds (zeaxanthin), or the orange of an orange peel (\( \beta \)-carotene) — are used as advertisements to attract seed dispersers. In photosynthesis, **carotenoids** function as photosynthetic pigments that are very efficient molecules for the disposal of excess energy. When a leaf is exposed to full sun, the light-dependent reactions are required to process an enormous amount of energy. If that energy is not handled properly, it can do significant damage. Therefore, many carotenoids reside in the thylakoid membrane, absorb excess energy, and safely dissipate that energy as heat.

Absorption of Pigments

Each type of pigment can be identified by the specific pattern of wavelengths it absorbs from visible light: This is termed the **absorption spectrum**. The graph below shows the absorption spectra for chlorophyll \( a \), chlorophyll \( b \), and a type of carotenoid pigment called \( \beta \)-carotene (which absorbs blue and green light). Notice how each pigment has a distinct set of peaks and troughs, revealing a highly specific pattern of absorption. Chlorophyll \( a \) absorbs wavelengths from either end of the visible spectrum (blue and red), but not green. Because green is reflected or transmitted, chlorophyll appears green. Carotenoids absorb in the short-wavelength blue region, and reflect the longer yellow, red, and orange wavelengths.
Photosynthetic Organisms

Many photosynthetic organisms have a mixture of pigments, and by using these pigments, the organism can absorb energy from a wider range of wavelengths. Not all photosynthetic organisms have full access to sunlight. Some organisms grow underwater where light intensity and quality decrease and change with depth. Other organisms grow in competition for light. Plants on the rainforest floor must be able to absorb any bit of light that comes through because the taller trees absorb most of the sunlight and scatter the remaining solar radiation.

When studying a photosynthetic organism, scientists can determine the types of pigments present by generating absorption spectra. An instrument called a spectrophotometer can differentiate which wavelengths of light a substance can absorb. Spectrophotometers measure transmitted light and compute from it the absorption. By extracting pigments from leaves and placing these samples into a spectrophotometer, scientists can identify which wavelengths of light an organism can absorb. Additional methods for the identification of plant pigments include various types of chromatography that separate the pigments by their relative affinities to solid and mobile phases.

Lesson Toolbox

Additional Resources and Readings

Photosynthesis: Crash Course Biology #8
- A Crash Course video covering light-dependent reactions
  - https://www.youtube.com/watch?v=sQK3Yr4Sc_k&t=10s

Clark Science Center
- An interactive animation of the light reactions of photosynthesis

Making Sense of Biology
- A video explaining the light-dependent reactions of photosynthesis
  - https://www.youtube.com/watch?v=PFbYpsUV-4c

Lesson Glossary

- **absorption spectrum**: range of wavelengths of electromagnetic radiation absorbed by a given substance
- **carotenoids**: photosynthetic pigment (yellow-orange-red) that functions to dispose of excess energy
- **chlorophyll a**: form of chlorophyll that absorbs violet-blue and red light and consequently has a bluish-green color; the only pigment molecule that performs the photochemistry by getting excited and losing an electron to the electron transport chain
- **chlorophyll b**: accessory pigment that absorbs blue and red-orange light and consequently has a yellowish-green tint
- **electron transport chain**: group of proteins between PSII and PSI that pass energized electrons and use the energy released by the electrons to move hydrogen ions against their concentration gradient into the thylakoid lumen
- **photon**: distinct quantity or "packet" of light energy
**photosystem**: group of proteins, chlorophyll, and other pigments that are used in the light-dependent reactions of photosynthesis to absorb light energy and convert it into chemical energy

**photosystem I**: integral pigment and protein complex in thylakoid membranes that uses light energy to transport electrons from plastocyanin to NADP+ (which becomes reduced to NADPH in the process)

**photosystem II**: integral protein and pigment complex in thylakoid membranes that transports electrons from water to the electron transport chain; oxygen is a product of PSII

**primary electron acceptor**: pigment or other organic molecule in the reaction center that accepts an energized electron from the reaction center

**reaction center**: complex of chlorophyll molecules and other organic molecules that is assembled around a special pair of chlorophyll molecules and a primary electron acceptor; capable of undergoing oxidation and reduction

**spectrophotometer**: instrument that can measure transmitted light and compute the absorption

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**Check Your Knowledge**

1. Which of the following structures is not a component of a photosystem?
   - A. ATP synthase
   - B. antenna molecule
   - C. reaction center
   - D. primary electron acceptor

2. The overall function of light-dependent reactions is to convert solar energy into chemical energy in the form of NADPH and ATP.
   - A. True
   - B. False

3. Chlorophylls and carotenoids are the two major classes of photosynthetic pigments found in plants and algae.
   - A. True
   - B. False

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**Answer Key**:
1. A  2. A  3. A

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