PHOTOSYNTHESIS

The process by which plants and certain bacteria use light energy to manufacture organic compounds is called photosynthesis. Green plants carry on this process by converting carbon dioxide and water into oxygen and organic compounds with the help of light. Carbohydrates and proteins comprise the bulk of the organic compounds produced. The magnitude of the process may be seen from the estimate that during a one-year period organisms on earth that are capable of photosynthesis transform about 150 billion tons of carbon (found mostly in the air as carbon dioxide) into organic matter. In the process, 400 billion tons of oxygen are released into the air. Since the products of photosynthesis are utilized by both plants and animals, all life on earth is ultimately dependent on this phenomenon for its existence. Figure 1 is a schematic representation of the energy cycle necessary for life on earth; the key position of photosynthesis in this scheme should be noted. *See* ENERGY; LIGHT; ORGANIC COMPOUNDS.

The portion of a green leaf which gives it its photosynthetic ability is a small, green particle called the chloroplast. It has been found by electron microscopy that the chloroplast is filled with platelike structures called lamellae. These lamellae are arranged in an orderly fashion, stacked one upon another; a single stack is a granum (plural, grana). It is believed that the structural matter of the grana consists of proteins and fats (lipid material). These provide the supporting structure for the photosynthetic pigments of which chlorophyll is the primary component. The remainder of the

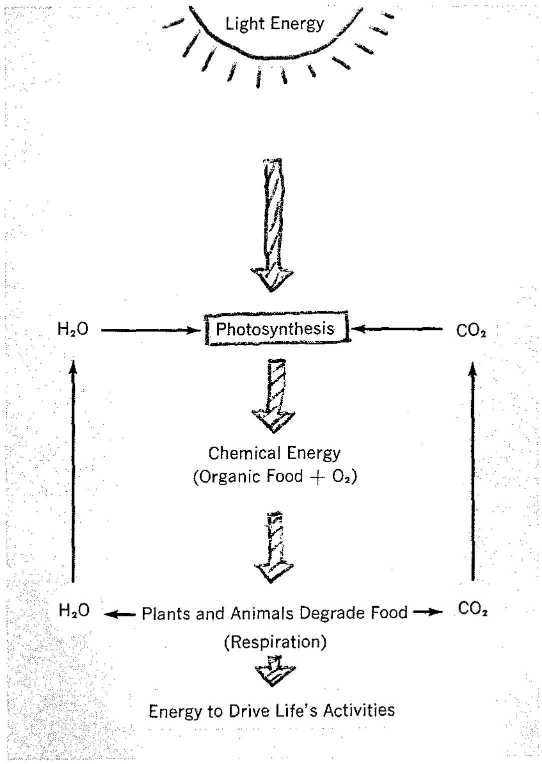


Fig. 1. Energy flow diagram. Photosynthetic organisms absorb solar light energy and by the process of photosynthesis convert it into chemical energy stored as food. Both plants and animals break these compounds down by respiration, releasing part of stored energy to carry on necessary life activities.

chloroplast is called stroma. Examples of the structural components are shown in Fig. 2.

Photosynthetic Process. The classical photosynthetic studies of Joseph Priestley (1733–1804), as well as the work of Jan Ingenhousz (1730–1799), Jean Senebier (1742–1809), and Nicolas de Saussure (1767–1845), established the overall process for converting carbon dioxide (CO_2) into carbohydrates. The reaction is stated as follows:

$$CO_2 + H_2O + \text{Light} \xrightarrow{\textit{Chlorophylls}} C(H_2O) + O_2$$

$$\text{Carbon Dioxide} + \text{Water} + \text{Light} \xrightarrow{\textit{Chlorophylls}} \text{Carbohydrate} + \text{Oxygen}$$

Chlorophylls are green pigments that capture the light energy for the reaction.

From the standpoint of raw materials, or substrates, and products, the above equation does not hold true for bacterial photosynthesis. Certain bacteria, for instance, produce sulfur instead of oxygen, with hydrogen sulfide being consumed instead of water. See BACTERIOLOGY.

When a mole of glucose (6×10^{23} molecules) has completely burned to carbon dioxide and water, about 672 kilocalories of heat energy are evolved. (One calorie is the amount of heat energy necessary to raise the temperature of one gram of water one degree centigrade. A kilocalorie is equal to 1,000 calories. A mole is the gram-molecular weight of a molecular substance.) Thus, when a mole of glucose is formed from carbon dioxide and water, at least 672 kilocalories of energy must be supplied. This is the minimum energy needed for driving photosynthesis.

This energy requirement is the result of the role of water in the photosynthetic reaction. It is universally accepted that the source of oxygen is water and not carbon dioxide. This, of course, necessitates the breaking down of water into hydrogen and oxygen, a reaction which requires a large amount of energy. The major role of light is to supply the energy needed to break hydrogen away from its closely associated partner, oxygen—a rather difficult reaction—and ultimately to transfer the hydrogen to carbon dioxide to form a carbohydrate.

Phases in Photosynthesis. Photosynthesis consists of two phases: the light, or photochemical, phase during which light energy is trapped and stored, and the dark phase, also known as the energy utilization phase. The term "dark phase" does not mean that darkness is necessary for reactions to occur. The reactions proceed with the products of the light phase whether there is darkness or light. The rate of photosynthesis may be measured as a function of light intensity. It will then be seen that the rate of photosynthesis increases directly with the increase in light intensity up to a certain value, at which point it gradually attains a saturation level. Further increase in light intensity does not increase the overall rate of photosynthetic activity. This can only be explained if one assumes the existence of two phases, one of which is the light-independent dark phase.

Light Phase. The light, or photochemical, phase of photosynthesis begins with the absorption of light by chlorophyll and other accessory pigments such as carotenes and phycobilins. Some knowledge of the mechanics of color is necessary for an appreciation of the photochemical act. The visible region of the electromagnetic spectrum extends over a range of wavelengths. Light consisting of a

In many other chloroplasts lamellae are not differentiated into grana -- one sees only lamellae and matrix (stroma)

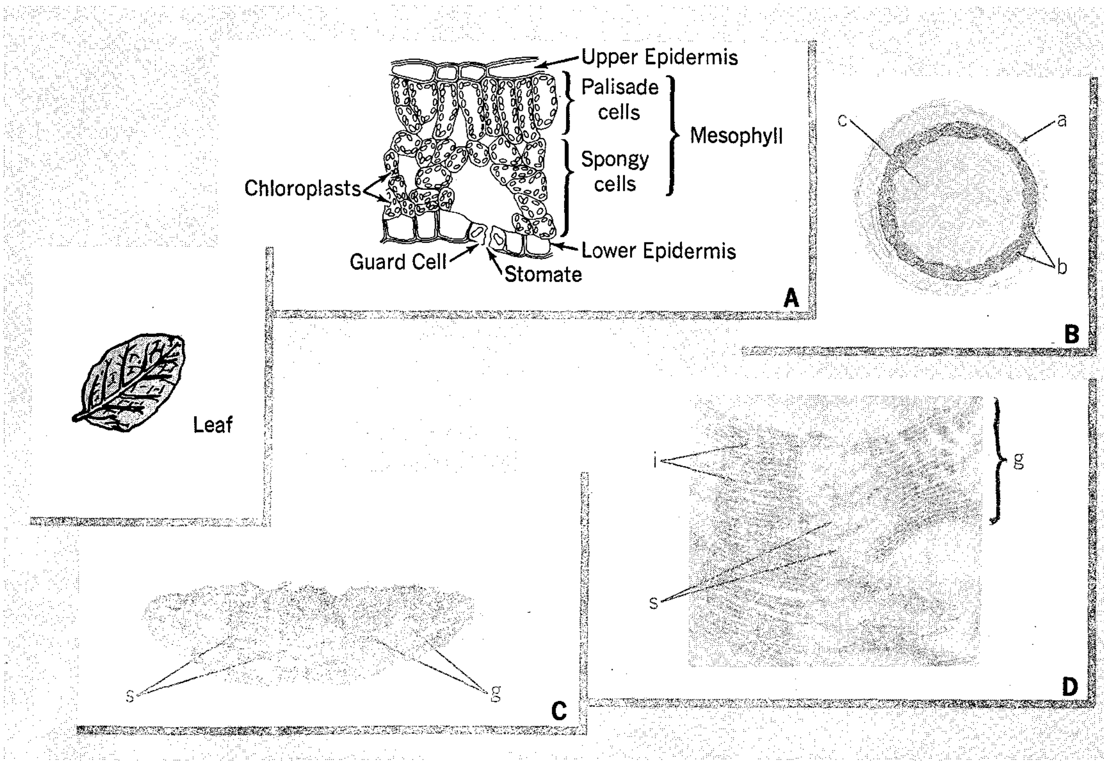


Fig. 2. Site of photosynthesis in higher plants. (A) Diagrammatic sketch of a portion of the cross section of a leaf seen under light microscope; note chloroplasts in both palisade and spongy cells. (B) Single spongy cell from mature spinach leaf, enlarged 1,000 times. (C) Single chloroplast from spinach leaf, enlarged 12,000 times; note stacks of lamellae (darker area), called grana; rest of chloroplast is called stroma. (D) Portion of chloroplast enlarged 30,000 times; note stacks of lamellae, each of which is a granum. [After Mr. George Schidlovsky]

mixture of wavelengths in the visible spectrum and having the same relative intensities as in sun light is called white light.

The sensation of color results when one or more of the wavelengths is lacking, or if the relative intensities change. One of the ways in which this may occur is through absorption of one or more wavelengths by certain chemical compounds. The appearance of color when this happens shows that the light has lost energy. The energy that was lost is used to raise an electron in the absorbing molecule from its ground state (the state of its lowest possible energy) to a higher energy state.

For any given atom, there is a specific amount of energy necessary for the elevation of its electron to a higher energy state. Light is absorbed only as energy packets called quanta. The amount of energy in a quantum depends on its wavelength. Thus, there will be a definite wavelength at which a quantum will have energy exactly equivalent to that needed to raise an electron to a higher state.

The electron, on achieving this higher-energy state, may either dissipate this energy as heat by returning to its original ground level or transfer this new energy to another chemical species.

It is the latter reaction which occurs in photosynthesis. The mechanism by which this energy transfer occurs, however, is not yet clearly understood. It is believed that the transfer is due to the unique nature of photosynthetic pigments. These pigments seem to have the ability to exist in an energized state long enough to contact energy receptors and transfer energy to them.

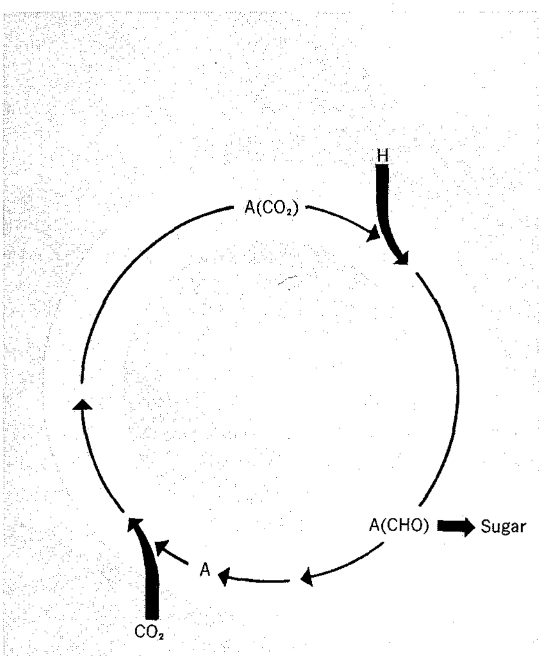
The pigments involved in the photochemistry of photosynthesis are the green chlorophylls (cyclic tetrapyrroles with magnesium in the center of the ring), the yellow to orange carotenoids (long-chain polyenes), and blue to red phycobilins (straight-chain tetrapyrroles in complex with protein). The chlorophylls, comprising the bulk of the photosynthetic pigments, exist in several forms. Chlorophyll *a* and chlorophyll *b* predominate.

(or light -- this light emission is called fluorescence)

All photosynthetic organisms contain chlorophyll *a*, but vary widely in respect to other pigments. While chlorophyll and carotenoids are found in both higher plants and algae, the phycobilins are found only in red and blue-green algae. It has been demonstrated that the carotenoids (such as carotene and xanthophyll), which absorb light in the blue region of the spectrum, and the phycobilins, which absorb light in the green to red region, are capable of transferring the energy of their activated states to chlorophyll. The chlorophyll absorbs light in both the blue and the red. It is possible by the use of monochromatic (of a single color) light to measure the rate of photosynthesis as a function of the light's wavelength.

On the basis of the above experiments, the relative efficiency of the photosynthetic pigments may be ascertained. By means of this action spectrum (relative activity as a function of the wavelength of light), it has been conclusively established that chlorophyll is the primary pigment in photosynthesis, for it both absorbs light energy and accepts the energy of the activated accessory pigments. The ultimate act of the light reaction is the breaking down of water to give oxygen and [H]. This [H] has the ability to reduce carbon dioxide. The process of adding a hydrogen atom (or an electron) is called reduction.

Fig. 3. Path of carbon in photosynthesis. CO_2 = carbon dioxide; A = CO_2 acceptor; $A(CO_2)$ = an acid (phosphoglyceric acid); A(CHO) = an aldehyde (phosphoglyceraldehyde); [H] = reducing entity.



During this final light reaction, another compound of vital importance to the photosynthetic organism is formed. This is adenosine triphosphate, or ATP, a compound containing "high-energy" phosphate bonds.[3] Compounds with high-energy bonds facilitate the synthesis of many other compounds. (The bulk of ATP needed for synthetic reactions is generated during respiration, however.)

Dark Phase. We may consider that the dark phase consists of a series of cyclic chemical reactions taking place with the help of the products produced in the light phase. The first step is the fixation of carbon dioxide. This involves an initial condensation with a five-carbon sugar (called ribulose diphosphate), represented by the symbol A (see Fig. 3). This reaction and all subsequent ones are helped along by the catalyzing effects of enzymes. The condensation product of the above reaction is eventually split into two molecules of a three-carbon compound (called phosphoglyceric acid), represented by $A(CO_2)$. Each is then converted into an aldehyde (called phosphoglyceraldehyde), A(CHO). It should be noted that this is a reductive reaction, that is, hydrogen has been added. It is at this point that the reducing entity [H], provided by the light phase, is utilized. Further reactions ultimately lead to glucose and it is then that (A), the acceptor of CO_2, is regenerated.

Figure 4 is a schematic summary of our understanding of photosynthesis. The light and dark phases are represented by the two rectangular blocks. The upper block represents the light phase. Light and water come from the outside. The end products are oxygen and the reducing entity [H], whose nature is not definitely known. The mechanism of oxygen's evolution is not clearly settled either. It is known that light is absorbed by pigments (chlorophylls, for example) and that the "excited" pigment molecules are able to start photochemical reactions leading to the products of the light phase.

The bottom rectangular block is shaded to show that it is the dark phase. Carbon dioxide combines

[3] The formation of ATP by photosynthetic reactions is called photophosphorylation.

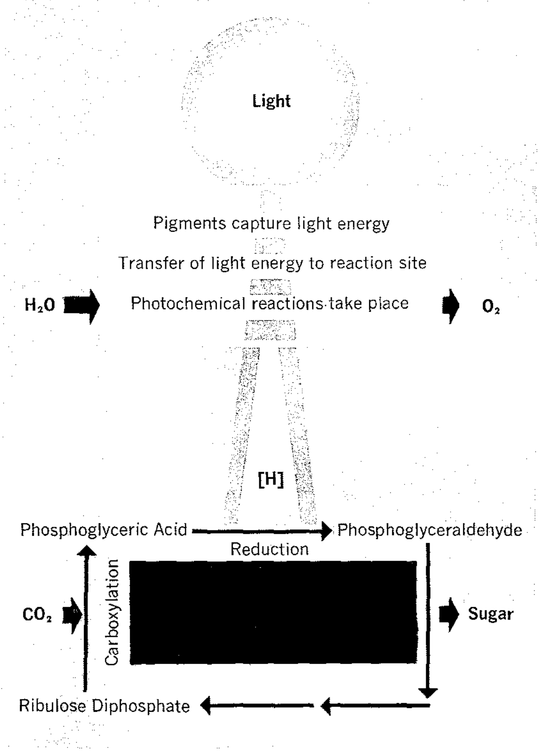


Fig. 4. Schematic summary of photosynthesis.

with a five-carbon compound called ribulose diphosphate. This reaction is the carboxylation step and leads to the formation of phosphoglyceric acid. The reducing agent [H] reduces the phosphoglyceric acid to an aldehyde called phosphoglyceraldehyde. This is the reducing step. Two molecules of phosphoglyceraldehyde can combine to form a molecule of sugar. The cycle continues by the regeneration of ribulose diphosphate. Thus the plant has succeeded in synthesizing its own food from the very simple compounds CO_2 and H_2O.

For further information *read* ECOLOGY; PLANT KINGDOM.

[GOVINDJEE]