

CHAPTER II:

ENERGY METABOLISM of MICROORGANISMS

1. Energy Sources and Trophic Types

The energy required by microorganisms is provided by light (phototrophic organisms) or by the oxidation of chemical substances (chemotrophic organisms). In both cases, the energy is stored in the form of biologically usable chemical bond energy (specifically, the phosphoanhydride bond in ATP). The formation of ATP from the primary energy source is more or less complex depending on the trophic or metabolic type. The synthesis reactions use the energy released by the decomposition of ATP into ADP:



1.1. Definition of Trophic Types

The term "**trophic type**" (from the Greek verb *Trophos*, meaning "*to nourish*") specifies how a living organism forms its own organic matter.

These represent different ways of obtaining carbon, reducing power, and energy from the environment. This variety in resource usage is related to the ability of many species to develop in extreme conditions of temperature, pH, or environments that eukaryotes cannot exploit (e.g., interstitial waters or saline waters).

1.2. Criteria Used to Define Trophic Types

The growth (and thus the anabolism) of a bacterium requires sources of matter (nutrients) and energy. There is great diversity in these two aspects within the bacterial world, which is usually managed using three criteria:

- *The energy source used and the nature of the electron donor.*
- *The final electron acceptor (X).*
- *The carbon source.*

The first two criteria are generally used to determine the nutritional type of a bacterium, based on energy metabolism.

1.3. Phototrophic Microorganisms

Phototrophic microorganisms can capture and use light energy at the level of multimolecular complexes, called **photosystems**. A **photosystem** is composed of several molecules that transmit light energy to a bacteriochlorophyll (which can expel an electron after absorbing a photon) and a "reaction center" (*ATP synthase*) allowing ATP formation.

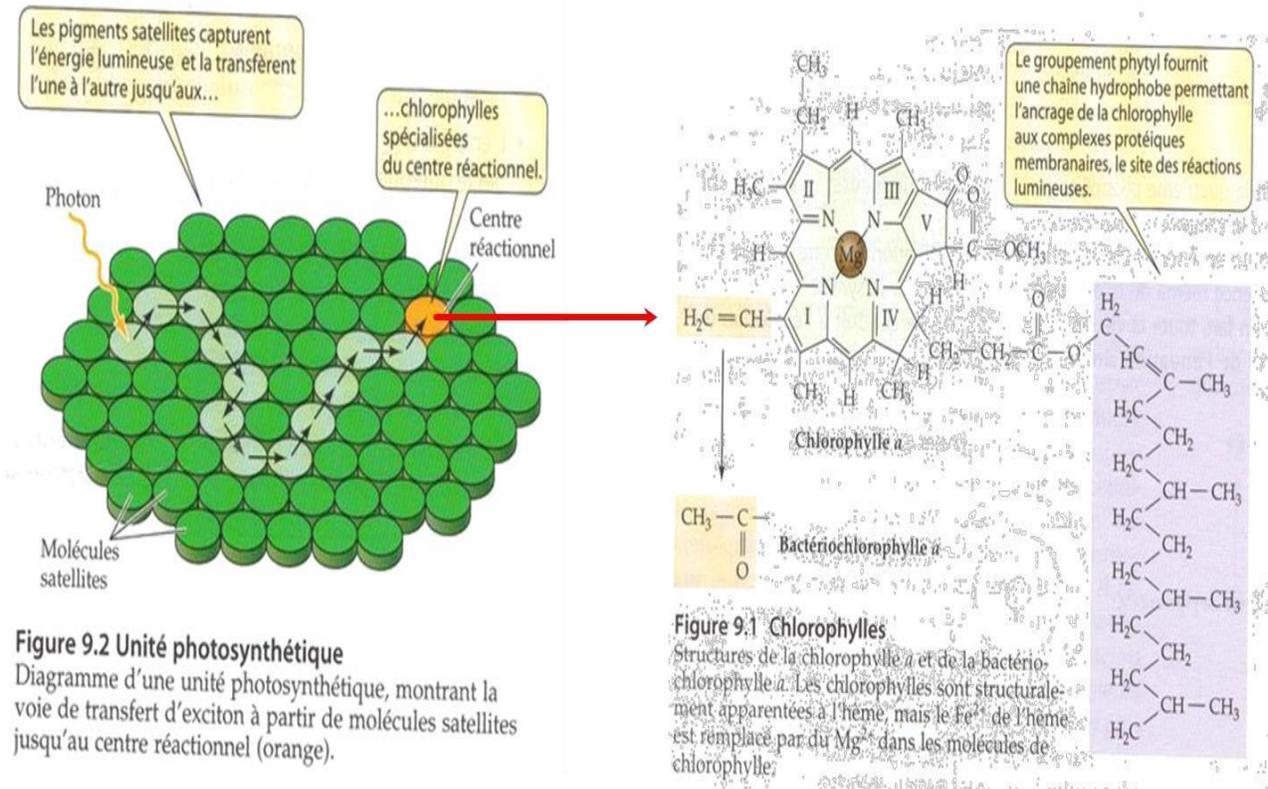


Figure 03: Example of a photosynthetic unit and the chemical structure of chlorophyll *a* and bacteriochlorophyll *a*.

The photosynthesis process includes two stages: **light phase** and **dark phase**.

- **Light Phase (Photophosphorylation):** this leads to the formation of ATP and is an energy-generating reaction usable by the cell. This phase requires the presence of pigments such as chlorophyll, and the nature of the pigments varies according to the type of phototrophic organism.

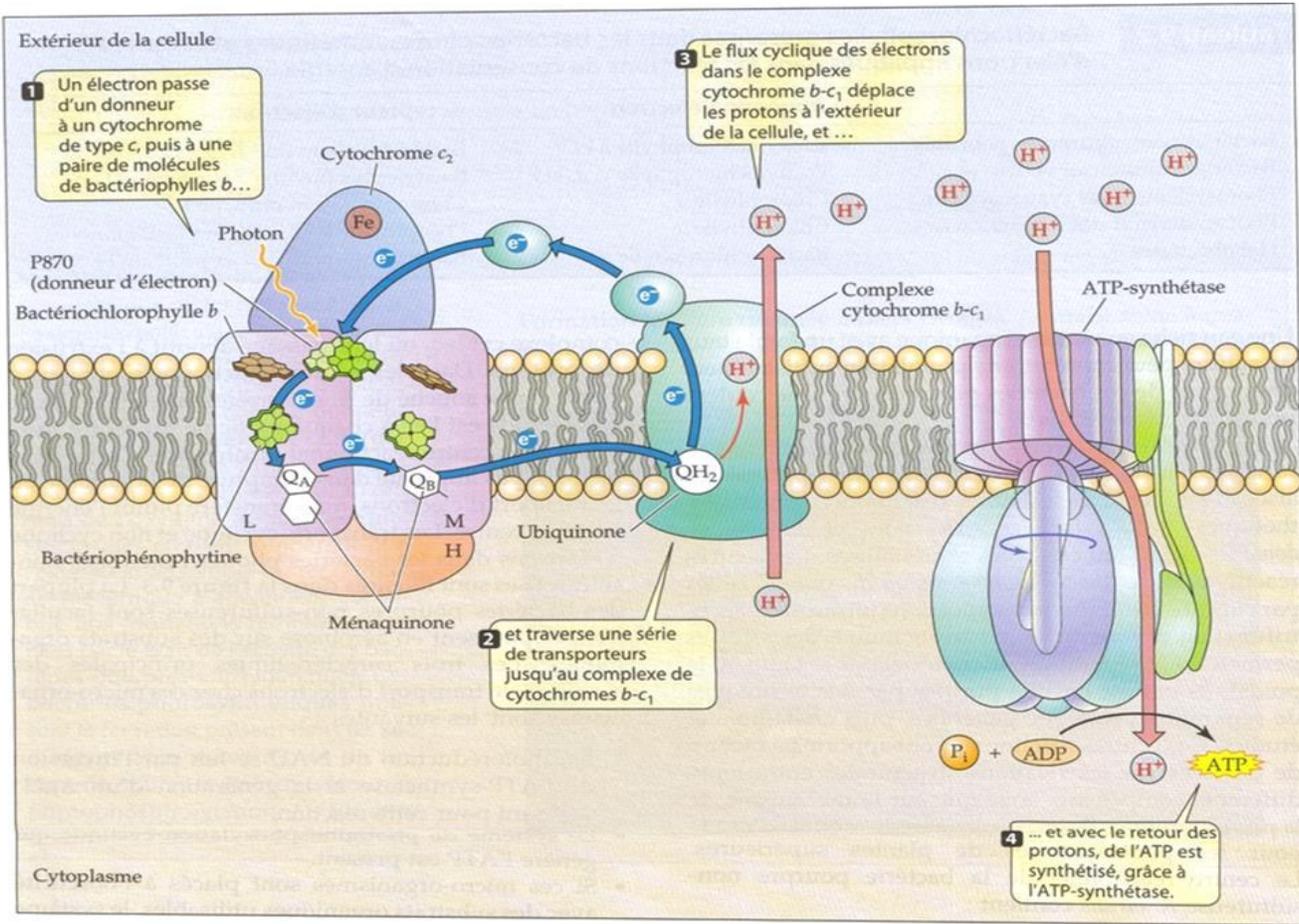


Figure 9.3 Centre réactionnel des bactéries pourpres non-sulfureuses
 Arrangement des transporteurs d'électrons et flux d'électron dans le centre réactionnel de *Rhodospseudomonas viridis*. Les sous-unités (polypeptides) du centre réactionnel sont indiquées légères (L), moyennes (M), et lourdes (H), selon leurs tailles relatives.

Figure 04: Example of the reaction center of purple non-sulfur bacteria.

There are two types of photophosphorylation (Fig. 05):

1. **Cyclic Photophosphorylation** produces only ATP.
2. **Non-cyclic Photophosphorylation** produces both ATP and "reducing power" and requires the presence of an electron donor (and protons).

In plants, algae, and cyanophytes, the proton (and electron) donor involved in the synthesis phase is H₂O, leading to the release of O₂.

In bacteria, there is never the release of O₂ (H₂O cannot be a donor) except *Cyanobacteria*. The electron and proton donor can be a mineral compound like H₂S in the *Thiorhodaceae* and

Chlorobacteriaceae (photolithotrophic or photoautotrophic organisms), or an organic compound like succinic acid in the *Athiorhodaceae* (photoorganotrophic or photoheterotrophic organisms).

Most photosynthetic bacteria can also use molecular hydrogen. The electron and proton acceptor is NADP^+ , which, after reduction, forms NADPH , H^+ .

The balance of the light phase is summarized by the following equation:

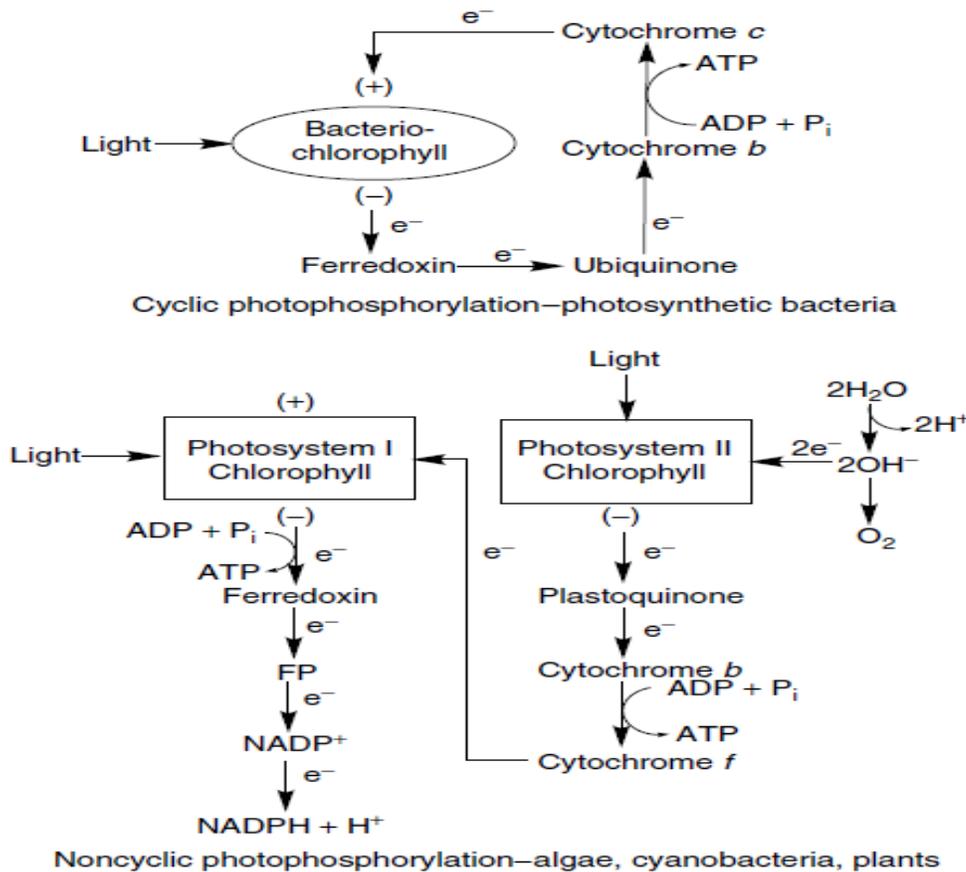
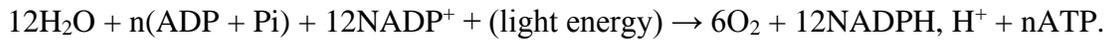


Figure 05: Comparison between cyclic and non-cyclic photophosphorylation.

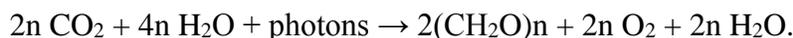
(In cyclic photophosphorylation, ATP is produced, but no reducing power is generated. In the non-cyclic pathway, two molecules of ATP are produced, a reduced NADP is generated, and oxygen is produced by the photolysis of water).

• **Dark Phase:** this corresponds to a phase of organic compound synthesis, resulting in the formation of carbohydrate reserves by using CO_2 , as well as the reducing power and ATP formed during the light phase. This synthesis occurs through a series of reactions known as the Calvin cycle (Fig. 06), which is summarized by the formula:



SUMMARY of Photosynthesis Types in Microorganisms.

There are two main types of photosynthesis: *oxygenic* (the type that generates O₂) and *anoxygenic* (the type that does not generate O₂) (Tab. 01). *Oxygenic photosynthesis* is used by Cyanobacteria, algae, and plants. In oxygenic photosynthesis, water is the electron donor, whose dissociation releases oxygen while water is reformed from an oxygen atom of carbon dioxide:



The equation is generally simplified by eliminating 2n H₂O from both terms, which gives:



Anoxygenic photosynthesis uses compounds other than water as the electron donor. It occurs without oxygen production and is practiced under anaerobic conditions. It is mainly used by purple sulfur bacteria, green sulfur bacteria, non-sulfur green bacteria, *Heliobacteria*, and Acidobacteria.

Thus, purple sulfur bacteria use hydrogen sulfide H₂S:

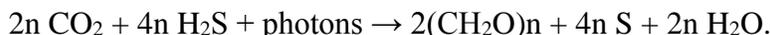


Table 01: Examples of photosynthetic microorganisms.

	Anoxygenic Photosynthesis					Oxygenic Photosynthesis
Group	Purple Bacteria			Green Bacteria		Cyanobacteria
Family	Sulfur Purple Bacteria		Non-Sulfur Purple Bacteria	Green Sulfur Bacteria	Multicellular filamentous green bacteria (Green Non-Sulfur Bacteria)	
	Chromatiaceae	Ectothiorhodospiraceae				
Genus	<i>Chromatium,</i> <i>Thiocystis,</i> <i>Thiospirillum,</i> <i>Thiocapsa,</i> <i>Lamprobacter,</i> <i>Lamprocystis,</i> <i>Thiodictyon,</i> <i>Amocobacter,</i> <i>Thiopedia</i>	<i>Ectothiorhodospira</i>	<i>Rhodospirillum,</i> <i>Rhodopil,</i> <i>Rhodobacter,</i> <i>Rhodopseudomonas,</i> <i>Rhodomicrobium,</i> <i>Rhodocyclus</i>	<i>Chlorobium</i> <i>Prosthecochloris</i> <i>Pelodictyon</i> <i>Ancalochloris</i> <i>Chloroherpeton</i>	<i>Chloroflexus</i> <i>Heliobacter</i> <i>Oscillochloris</i> <i>Chloronema</i>	<i>Anabaena</i> <i>Oscillatoria</i> <i>Microcystis</i>

Green sulfur bacteria, for example, are capable of using hydrogen sulfide H_2S (e.g., *Chlorobium*), thiosulfate $S_2O_3^{2-}$, and elemental sulfur S^0 as electron donors, while non-sulfur green bacteria can use hydrogen H_2 (e.g., *Chloronema*).

In general, in prokaryotes, the electron donor (RH_2) is not water, as is the case in plants.

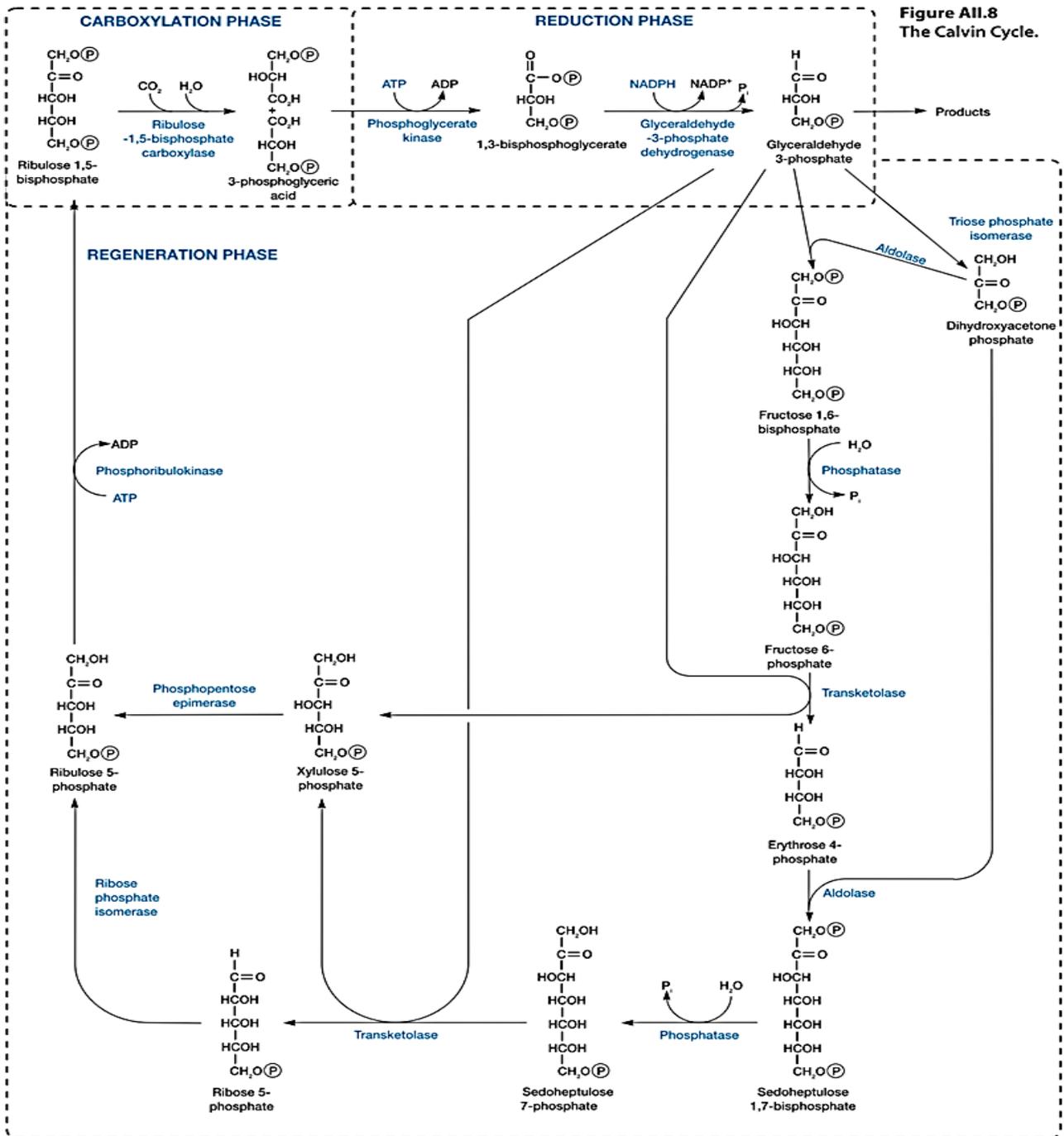


Figure 06: Calvin Cycle.

1.3.1. Photolithotrophic Microorganisms

Photolithotrophic microorganisms use radiant energy from the sun as an energy source, atmospheric CO₂ as a carbon source, and a mineral compound as a source of H⁺ and electrons (sulfides or H₂). In Thiobacterial species = Green sulfur bacteria (*Chlorobium*) or non-sulfur (*Chloronema*), the donor of H⁺ and electrons is hydrogen sulfide (hydrogen sulfide) H₂S in the first case, atmospheric dihydrogen H₂ in the second case. Photosynthesis occurs without oxygen production (anoxygenic photosynthesis). Purple photosynthetic bacteria living in sulfurous waters or mud (*Thiorhodobacteria* = Purple sulfur bacteria: *Thiospirillum*) or non-sulfur (*Rhodobacter*) perform anoxygenic photosynthesis (neither water oxidation nor oxygen production). These cells contain, in addition to bacteriochlorophylls, carotenoids that mask the green color and give the cells a purple hue. The assimilatory pigments are located in a membrane system dependent on the plasma membrane.

1.3.2. Photoorganotrophic Microorganisms

Photoorganotrophic microorganisms use radiant energy from the sun as an energy source, CO₂ as a carbon source, and an organic compound (alcohol, acid, etc.) as a source of H⁺ and electrons. There are no strictly photoorganotrophic organisms; this metabolism is always practiced temporarily by organisms of another trophic type under strong demands.

Example: *Rhodopseudomonas viridis*: non-sulfur purple bacteria (*Rhodospirillaceae*).

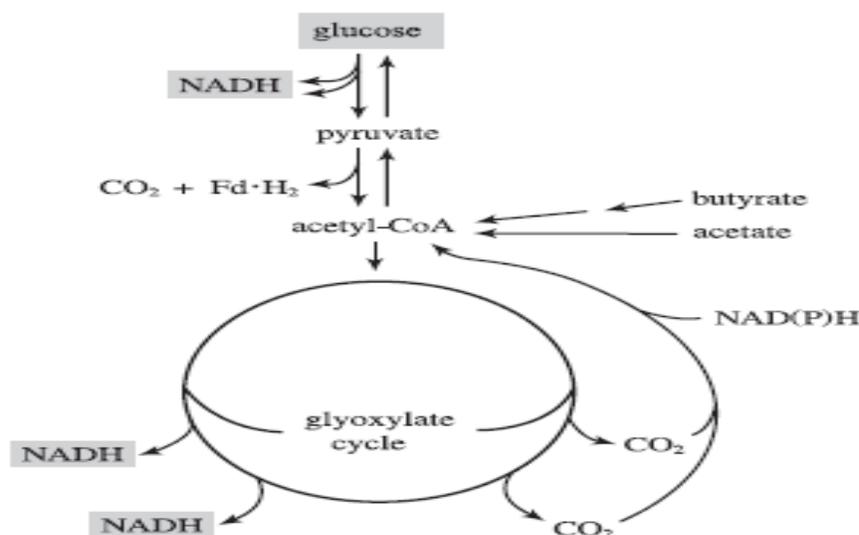


Figure 07: Photo-organotrophic metabolism in purple bacteria.

1.4. Chemotrophic Microorganisms (Chemotrophy)

Chemotrophic bacteria use chemical energy (energy "contained" in the bonds between atoms) released during oxidation reactions of reduced substrates (RH₂), known as *energy substrates* (or *energy sources*).

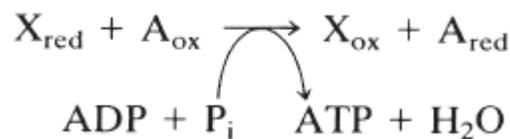
Yeasts, molds, and most bacteria are unable to perform photosynthesis. These microorganisms use the energy released during chemical reactions.

Oxidation reactions occur in several ways:

<p>- Electron loss</p> $\text{Fe}^{++} \rightarrow \text{Fe}^{+++} + \text{e}^- + \text{energy}$	<p>- Dehydrogenation</p> $\text{R-CH}_2\text{OH} \rightarrow \text{R-CHO} + 2\text{H}^+ + 2\text{e}^- + \text{energy}$
<p>- Hydration-dehydrogenation</p> $\text{R-CHO} + \text{H}_2\text{O} \rightarrow \text{R-COOH} + 2\text{H}^+ + 2\text{e}^- + \text{energy}$	<p>- Dehydrogenation coupled with decarboxylation</p> $\text{R-CO-COOH} + \text{H}_2\text{O} \rightarrow \text{R-COOH} + \text{CO}_2 + 2\text{H}^+ + 2\text{e}^- + \text{energy}$

Inside the cell, the oxidation of a reduced compound is always accompanied by the reduction of another oxidized molecule, which acts as a transient or final electron acceptor. Transient electron acceptors, known as *electron carriers*, are often *coenzymes* that shift from the oxidized to the reduced state, and then back to the oxidized state during successive oxidation-reduction reactions until the electrons are fixed onto a final acceptor.

Reoxidation of a molecule that has just been reduced allows the release of energy, which can participate in the formation of high-energy chemical bonds, such as the phosphoanhydride bonds of ATP.



As with phototrophic bacteria, chemotrophic bacteria can be classified as:

1.4.1. Chemolithotrophic Microorganisms

Chemolithotrophic bacteria derive their energy from the oxidation of mineral compounds, use CO₂ as a carbon source, various mineral compounds as reducing power sources, H⁺ and electrons (substrates to oxidize = fuel), and various electron acceptors (acceptors to reduce = fuel). The reducing power of

inorganic ions is too weak to be used for CO₂ reduction, so these bacteria all possess membrane enzymes such as NADH dehydrogenase.

The flow of electrons donated by inorganic ions causes H⁺ to be pumped out of the cell (creating a **Proton Motive Force**); their return to the cell activates both ATP synthase and NADH-DHase (reduction of NAD⁺ or NADP⁺ through electrons from the reverse flow activated by the H⁺ gradient). The final acceptor is often O₂ (aerobic species), but **also NO₃⁻** in the case of anaerobic species (e.g., *Thiobacillus denitrificans*, *Pseudomonas*), this is known as "**nitrate respiration.**"

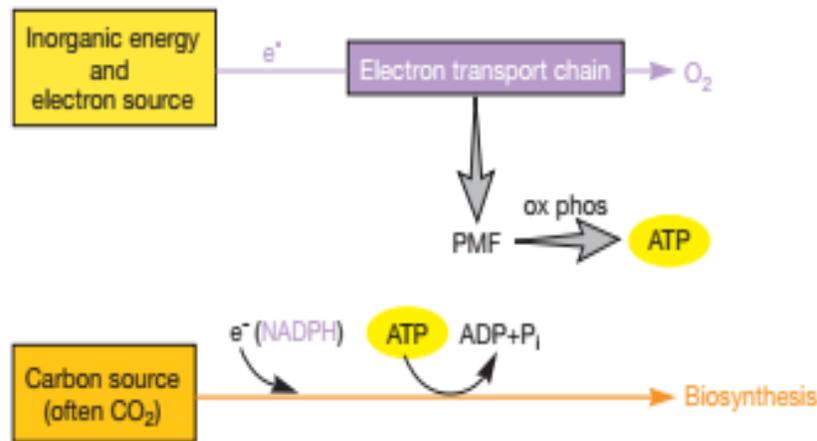


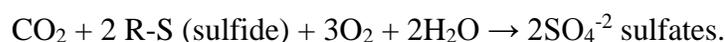
Figure 08: Energy supply process in chemolithotrophs.

(Chemolithotrophic bacteria and archaea oxidize inorganic molecules (e.g., H₂S and NH₃), which serve as energy and electron sources. The released electrons pass through an electron transfer system, generating a proton motive force (PMF). ATP is synthesized by oxidative phosphorylation (Phos-Ox). Most chemolithotrophs use O₂ as the final electron acceptor. Some, however, can use other exogenous molecules as final acceptors. Note that a molecule other than the energy source provides the carbon for biosynthesis. Many chemolithotrophs are autotrophic).

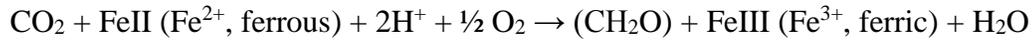
Examples of some chemolithotrophs:

- **Nitrifying bacteria** use various nitrogen compounds, they participate in protein mineralization that occurs step-by-step in the soil. They can use ammonium or nitrite as the sole energy source and perform autotrophic CO₂ fixation via the Calvin cycle. All nitrifying bacteria belong to one of the following genera: *Nitrobacter*, *Nitromonas*, *Nitrococcus*, *Nitrospina*, and *Nitrospira*.

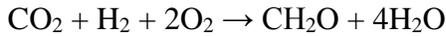
- **Sulfobacteria**, free or symbiotic, use sulfur compounds and produce sulfates (Sulfur-oxidizing bacteria or sulfobacteria):



• **Siderobacteria**, also called iron bacteria, are part of the normal microflora of groundwater. They use ferrous compounds, FeII (Fe²⁺):



• **Hydrogenomonas** use atmospheric dihydrogen:



1.4.2. Chemo-organotrophic Microorganisms

Chemo-organotrophic microorganisms use pre-existing organic matter as both an energy source, carbon source, and reducing power. Bacteria of this type are the most numerous and differ in their relationship with dioxygen and the origin of the organic matter they use.

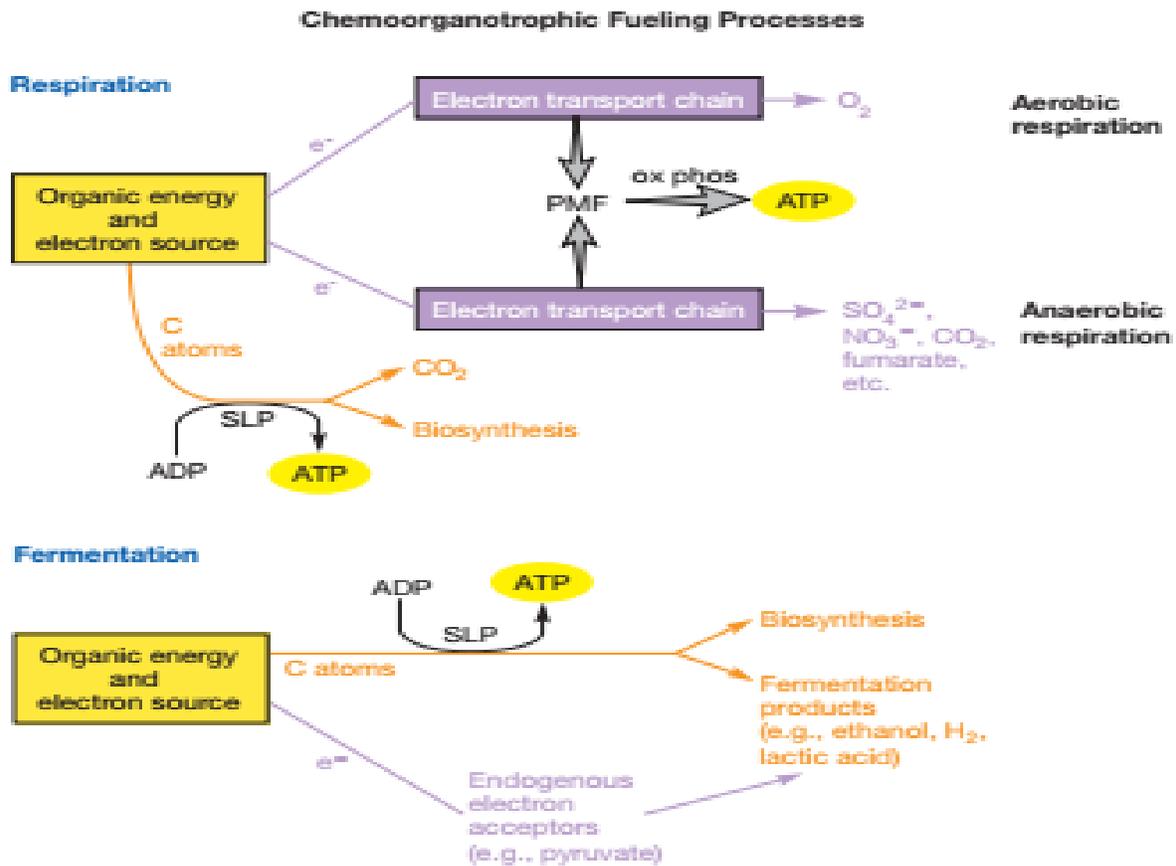


Figure 09: Energy supply process in chemo-organotrophs.

(Organic molecules serve as energy and electron sources for the three energy supply processes employed by chemo-organotrophs. In both aerobic and anaerobic respiration, electrons pass through an electron transfer system. This generates a proton motive force (PMF) that is used to synthesize most of the cellular ATP by a mechanism called substrate-level phosphorylation (SLP). In aerobic respiration, O₂ serves as the final electron acceptor. During fermentation, endogenous organic molecules act as electron acceptors, and the electron flow is not coupled with ATP synthase, which is only formed through substrate-level phosphorylation).