Microbial Metabolism

- **Microbial metabolism** is the means by which a microbe **obtains the energy and nutrients** (e.g. carbon) it needs to live and reproduce.

- Microbes use many **different types of metabolic strategies** and species can often be **differentiated** from each other based on metabolic characteristics.

- The **specific** metabolic properties of a microbe are the major factors in determining that microbe's **ecological niche**.

All microbial metabolisms can be arranged according to **three** principles:

1. **How the organism obtains carbon for synthesizing cell mass**
2. **How the organism obtains reducing equivalents* used either in energy conservation or in biosynthetic reactions**
3. **How the organism obtains energy for living and growth (increase in number)**

- **reducing equivalent** refers to any of a number of chemical species which transfer the equivalent of one electron in redox reactions, e.g. an electron, H+, etc.

1. How the organism obtains carbon for synthesizing cell mass:

- **autotrophic** – carbon is obtained from carbon dioxide (CO_2).
- **heterotrophic** – carbon is obtained from organic compounds.
- **mixotrophic** – carbon is obtained from both organic compounds and by fixing carbon dioxide.

2. How the organism obtains reducing equivalents used either in energy conservation or in biosynthetic reactions:

There are two types:

- **lithotrophic** – reducing equivalents are obtained from inorganic compounds.

- **organotrophic** – reducing equivalents are obtained from organic compounds.

3. How the organism obtains energy for living and growth:

- **chemotrophic** – energy is obtained from external chemical compounds.

- **phototrophic** – energy is obtained from light.

In practice, these terms are almost **freely combined**. Typical examples are:

Chemolithoautotrophs obtain energy from the oxidation of inorganic compounds and carbon from the fixation of carbon dioxide.

Examples: Nitrifying bacteria, Sulfur-oxidizing bacteria, Iron-oxidizing bacteria.

Photolithoautotrophs obtain energy from light and carbon from the fixation of carbon dioxide, using reducing equivalents from inorganic compounds.

Examples: Cyanobacteria

Heterotrophic microbial metabolism

- **Heterotrophic metabolism** is the **biologic oxidation of organic compounds**, such as glucose, to yield **ATP** and simpler organic (or inorganic) compounds, which are **needed by the bacterial cell for biosynthetic or assimilatory reactions**.

- Most **pathogenic** bacteria can be viewed as **heterotrophic parasites** of humans or the other eukaryotic species they affect.

- Heterotrophic microbes are **extremely abundant** in nature and are responsible for the **breakdown of large organic polymers** such as cellulose, chitin or lignin which are generally indigestible to larger animals.

- Biochemically, **prokaryotic** heterotrophic metabolism is much **more versatile** than that of **eukaryotic** organisms.

- Many prokaryotes share the most basic metabolic models with eukaryotes, e. g. **glycolysis** and **citric acid cycle**.

- However, many bacteria and archaea utilize **alternative** metabolic pathways other than glycolysis and the citric acid cycle.

Fermentation

- Most microbes **respire** (use an electron transport chain), although oxygen is not the **only** terminal electron acceptor that may be used.

- Fermentation is a **specific** type of heterotrophic metabolism that uses **organic carbon instead of oxygen** as a terminal electron acceptor.

- As oxygen is not required, fermentative organisms are **anaerobic**.

- However, many organisms can use **fermentation under anaerobic conditions** and **aerobic respiration when oxygen is present**.

- These organisms are **facultative anaerobes**.

- Instead of using an **ATP synthase**, ATP in fermentative organisms is produced by **substrate-level phosphorylation** where a phosphate group is transferred from a high-energy organic compound to ADP to form ATP.

- Fermentative organisms are very important **industrially** and are used to make many **different types of food products**.

Syntrophy

- Syntrophy, in the context of microbial metabolism, refers to the **pairing of multiple species** to achieve a chemical reaction that, on its own, would be energetically unfavorable.

- The best studied example of this process is the **oxidation of fermentative end products** (such as acetate, ethanol and butyrate) by organisms such as *Syntrophomonas*.

Anaerobic respiration

- While aerobic organisms use oxygen as a terminal electron acceptor during respiration, **anaerobic organisms use other electron acceptors.**

- These inorganic compounds have a **lower redox potential** than oxygen, meaning that respiration is less efficient in these organisms and leads to **slower growth** rates than aerobes.

- **Redox potential** is the tendency of a chemical species to either be reduced by accepting electrons or oxidized by donating electrons

Denitrification – nitrate as electron acceptor

- Denitrification is the utilization of **nitrate (NO_3)** as a terminal electron acceptor.

- It is a widespread process that is used by many members of the **Proteobacteria** (Gram negative; includes pathogens like *Salmonella, Vibrio* and *E.coli*).

- Many facultative anaerobes use denitrification because nitrate, like oxygen, has a **high reduction (redox) potential**.

Sulfate reduction – sulfate as electron acceptor

- Sulfate reduction is a relatively **energetically poor** process used by many Gram-negative and Gram-positive organisms.
- **Hydrogen sulfide (H_2S)** is produced as a metabolic end product.
- For sulfate reduction **electron donors and energy** are needed.
- Many sulfate reducers are **organotrophic**, using carbon compounds such as lactate and pyruvate (among many others) as electron donors, while others are **lithotrophic**, using hydrogen gas (H_2) as an electron donor.

Acetogenesis – carbon dioxide as electron acceptor

- Acetogenesis is a type of microbial metabolism that uses **hydrogen (H_2) as an electron donor** and **carbon dioxide (CO_2) as an electron acceptor** to produce acetate.

- Bacteria that can **autotrophically** synthesize acetate are called **homoacetogens**.

- Carbon dioxide reduction in all homoacetogens occurs by the **acetyl-CoA pathway**.

Organic terminal electron acceptors

- A number of organisms, instead of using inorganic compounds as terminal electron acceptors, are **able to use organic compounds** to accept electrons from respiration.

  Examples include:

  fumarate reduction to succinate

  Trimethylamine N-oxide (TMAO) reduction to trimethylamine (TMA)

Chemolithotrophy

- Chemolithotrophy is a type of metabolism where energy is obtained from the **oxidation of inorganic compounds**.

- Most chemolithotrophic organisms are **also autotrophic**.

- There are **two major objectives** to chemolithotrophy:

  the **generation of energy (ATP)**

  the **generation of reducing power (NADH)**

* NADH: nicotinamide adenine dinucleotide (NAD) + hydrogen (H)

Hydrogen oxidation

- Many organisms are capable of **using hydrogen (H_2) as a source of energy.**

- In these organisms, hydrogen is oxidized by a **membrane-bound hydrogenase** causing proton pumping via electron transfer to various **quinones** and **cytochromes**.

- In many organisms, a second **cytoplasmic hydrogenase** is used to generate reducing power in the form of NADH, which is subsequently used to fix carbon dioxide via the **Calvin cycle**.

Sulfur oxidation

- Sulfur oxidation involves the **oxidation** of reduced sulfur compounds (such as sulfide H_2S), inorganic sulfur (S), and thiosulfate (S_2O_2−3) **to form sulfuric acid (H_2SO_4).**

  A classic example of a sulfur-oxidizing bacterium is **Beggiatoa**.

- Generally, the oxidation of sulfide occurs in stages, with inorganic sulfur being stored **either inside or outside** of the cell until needed.

- Biochemically, reduced sulfur compounds are converted to sulfite (SO_3) and subsequently converted to sulfate (SO_4) by the enzyme **sulfite oxidase**.

Nitrification

- Nitrification is the process by which **ammonia (NH_3) is converted to nitrate (NO_3).**

- Nitrification is actually the net result of **two distinct processes**:

  - **oxidation of ammonia to nitrite (NO2)** by nitrosifying bacteria (e.g. Nitrosomonas)

  - **oxidation of nitrite to nitrate** by the nitrite-oxidizing bacteria (e.g. Nitrobacter).

- Both of these processes are **extremely energetically poor** leading to **very slow growth rates** for both types of organisms.

- Oxygen is required in both ammonia and nitrite oxidation, meaning that both nitrosifying and nitrite-oxidizing bacteria are **aerobes**.

Phototrophy

- Many microbes (phototrophs) are **capable of using light** as a source of energy to produce ATP and organic compounds such as carbohydrates, lipids, and proteins.

- Of these, **algae are particularly significant** because they are oxygenic (producing oxygen), using water as an electron donor for electron transfer during photosynthesis.

- Phototrophic bacteria are found in many phyla including **Cyanobacteria**.

- Along with plants these microbes are responsible for all **biological generation of oxygen gas** on Earth.

- Because chloroplasts were derived from a lineage of the Cyanobacteria, the general principles of metabolism in these bacteria can also be **applied to chloroplasts**.

- In addition to oxygenic photosynthesis, many bacteria can **also photosynthesize anaerobically**, typically **using sulfide (H_2S)** as an electron donor to produce sulfate.

- Different photosynthetic bacteria also contain different **photosynthetic pigments**, such as **chlorophylls** and **carotenoids**, allowing them to take advantage of different portions of the electromagnetic spectrum and thereby inhabit different niches.

Nitrogen fixation

- Nitrogen is an element required for growth by **all biological systems.**

- While extremely common (80% by volume) in the atmosphere, dinitrogen gas (N_2) is generally biologically **inaccessible due to its high activation energy.**

- Throughout all of nature, **only specialized bacteria** and Archaea are **capable of nitrogen fixation**, converting **dinitrogen gas into ammonia (NH_3),** which is easily assimilated by all organisms.

- These prokaryotes, therefore, are very important ecologically and are often **essential for the survival of entire ecosystems**.

- This is especially true in the ocean, where **nitrogen-fixing cyanobacteria** are often the only sources of fixed nitrogen.

- And in soils, where **specialized symbioses** exist between **legumes** and their **nitrogen-fixing partners** to provide the nitrogen needed by these plants for growth.

- Nitrogen fixation can be found distributed throughout nearly all bacterial lineages and physiological classes but is **not a universal property.**

- Because the enzyme **nitrogenase**, responsible for nitrogen fixation, is **very sensitive to oxygen** which inhibits it irreversibly, all nitrogen-fixing organisms must possess some mechanism **to keep the concentration of oxygen low**.


Thank You!