

Chapter 2
Energy Metabolism of Microorganisms

Before you start — 3 key words

- **Energy source:** where the cell gets its power — light, or a chemical reaction.
- **Electron (hydrogen) donor:** the molecule that gives away electrons — the one that “pays”.
- **Carbon source:** where the cell gets carbon atoms to build its own molecules (CO₂ or organic matter).

1. Trophic Types

The words “**heterotrophic**” and “**autotrophic**” were first used to describe plants and animals, but microorganisms are far more diverse. Microbiologists classify them using three criteria instead: their **energy source**, their **electron (hydrogen) donor**, and their **carbon source**.

Every microorganism needs chemical energy (mostly stored as **ATP**) to build new cell material. This energy can come from two places:

- **Light → chemical energy:** called **phototrophs** (photosynthetic organisms).
- **Chemical → chemical energy:** called **chemotrophs**.

Separately, the electron donor can be organic (**organotrophs**) or inorganic — such as NH₃, H₂S, S, CO₂, Fe²⁺ (these organisms are called **lithotrophs**).

Energy Source	Electron Source	Carbon Source	Type of Organism	Examples
Light	Inorganic	CO ₂	Photoautotroph	Cyanobacteria, green sulfur bacteria
	Organic	Organic compounds	Photoheterotroph	Purple non-sulfur bacteria, green non-sulfur bacteria
Chemical	Inorganic	CO ₂	Chemoautotroph (Chemolithoautotroph)	Nitrosomonas, Thiobacillus
	Organic	Organic compounds	Chemoheterotroph (Chemoorganoheterotroph)	Most bacteria, fungi, animals

Table 1 — The main microbial trophic types, classified by energy source, electron source and carbon source.

Concrete examples

- **Cyanobacteria** (algae blooms): light + CO₂ → *photoautotrophs*, just like plants.
- **Nitrosomonas** (soil bacteria): oxidizes ammonia (NH₃) for energy → *chemolithoautotroph*.
- **The bacteria in yogurt or in your gut**: eat sugars (organic matter) → *chemoheterotrophs*, the same category as humans and animals.

2. Autotrophic and Heterotrophic Concepts

These two words have a **narrow, precise meaning**: they only describe the **carbon source**, nothing else.

- **Autotrophic**: gets almost all its cellular carbon by fixing CO₂.
- **Heterotrophic**: gets its cellular carbon from organic compounds made by other organisms.
- **Mixotrophic**: can use either mineral or organic carbon, while keeping the same metabolic machinery.

Prokaryotes are the **only** organisms capable of **chemolithotrophic** and **photoorganotrophic** metabolism. This classification is **not** the same as taxonomy — many bacteria can switch between two or even three metabolic types depending on the conditions around them.

Type	Carbon source	Simple example
Autotroph	CO ₂ (mineral)	Cyanobacteria, green plants
Heterotroph	Organic compounds	Most bacteria, fungi, animals, humans
Mixotroph	CO ₂ or organic (flexible)	Some algae and purple bacteria

3. Types of Respiration — Where Do the Electrons Go?

Oxidizing an organic compound means **transferring electrons** away from it, usually together with hydrogen atoms (this is called **dehydrogenation**).

Simple analogy

Picture the electrons as a hot potato being passed from player to player. The **donor** throws it away (it is *oxidized*); the **acceptor** catches it (it is *reduced*). Where the potato finally lands decides which type of metabolism we are looking at.

Several words are used as synonyms :

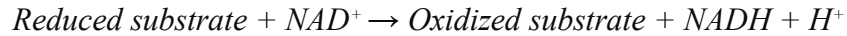
- hydrogen donor = electron donor
- hydrogen acceptor = electron acceptor

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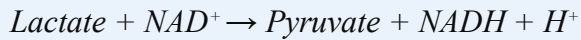
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- oxidation = dehydrogenation
- reduction = hydrogenation

The enzymes that carry out this transfer are called **dehydrogenases**; they hand the hydrogen to **NAD** or **NADP**.



Worked example — lactate oxidation



- **Oxidation = dehydrogenation:** lactate loses a hydrogen atom.
- **Reduction = hydrogenation:** NAD^+ gains that hydrogen and becomes NADH.

Depending on what the **final electron acceptor** is, three situations exist:

Metabolism	Final electron acceptor	Electron transport chain?	ATP yield
Aerobic respiration	O_2 (oxygen)	Yes	High (~38 ATP / glucose)
Anaerobic respiration	NO_3^- , SO_4^{2-} , Fe^{3+} , CO_2 ...	Yes	Lower than aerobic
Fermentation	An organic molecule (e.g. pyruvate)	No	Very low (2–4 ATP)

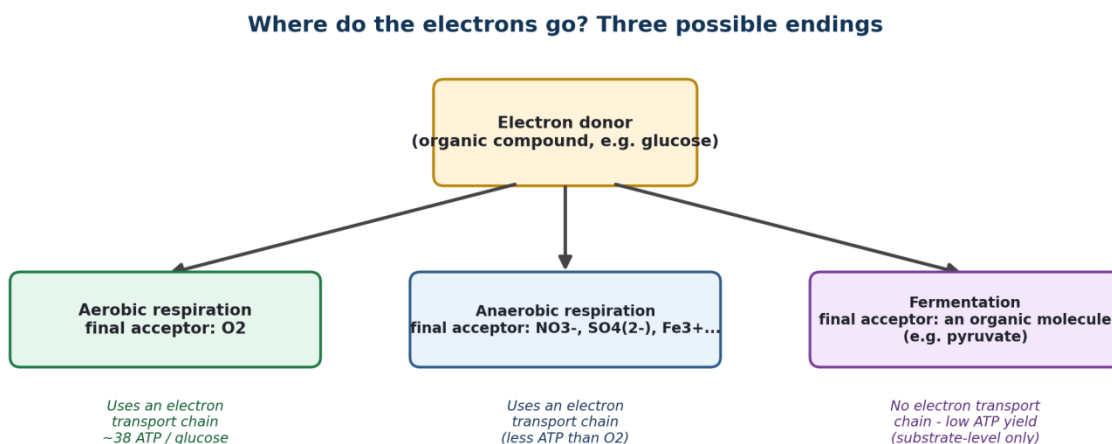


Fig. 1 — The three possible destinations for electrons removed from an organic donor.

3.1 Aerobic Respiration

When the final electron acceptor is molecular oxygen (O_2), the metabolism is **aerobic**. Electrons travel along a **transport chain** built into a membrane — the **respiratory chain** (also called the oxidative phosphorylation chain).

The energy released (equivalent to 38 ATP from one glucose molecule) is first stored as an **electrochemical gradient of H^+** across the membrane, then converted into ATP and reduced NAD(P).

Everyday example

This is essentially what happens inside your own cells when you breathe: oxygen is the final electron acceptor in your mitochondria, exactly as it is for an aerobic bacterium at its cell membrane.

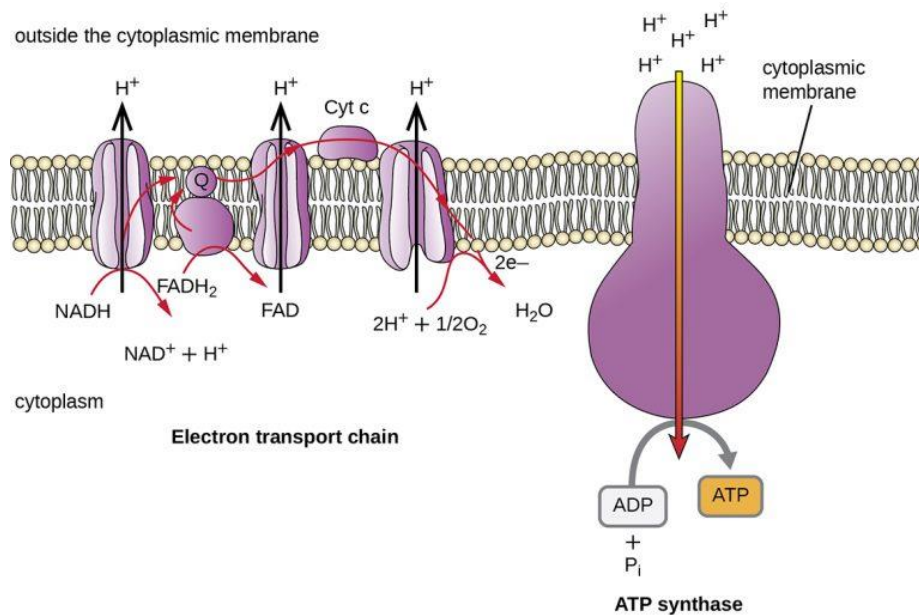


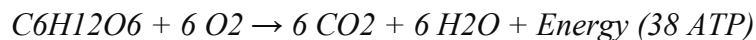
Fig. 2 — The bacterial electron transport chain pumps H^+ out of the cytoplasm; H^+ then flows back through ATP synthase, driving ATP production.

Reading the figure in 3 simple steps

1. Electrons from NADH and $FADH_2$ pass through the protein complexes (Q, Cyt c...), releasing energy.
2. That energy pumps H^+ out of the cell, like pumping water uphill — this builds up the gradient.
3. H^+ flows back down through ATP synthase, like water turning a turbine, and this turning motion makes ATP.

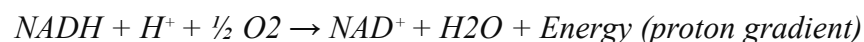
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Overall reaction of glucose oxidation:

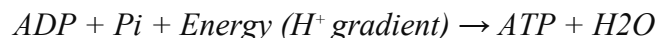


Simplified energy coupling:

1. Electron transport and proton gradient formation:



2. ATP synthesis using the gradient:



3.2 Anaerobic Respiration

Without oxygen, some microorganisms still build an electron transport chain (with cytochromes) — but they hand the electrons to a **different final acceptor**: nitrate, sulfate, carbonate, sulfide, iron, manganese, or even an organic molecule. This lets them survive and grow in oxygen-free places such as soil, sediments, or the gut.

These organisms are **facultative** or **strict anaerobes**, and include nitrate reducers, denitrifiers, sulfate reducers, sulfide reducers, methanogens, and acetogens. They play a very important ecological role.

Final acceptor	Reduced product	Example bacteria	Why it matters
Nitrate (NO ₃ ⁻)	N ₂ gas (denitrification)	Pseudomonas, Paracoccus	Removes nitrate from soil and water; part of the nitrogen cycle. Can reduce soil fertility after fertilizer use.
Sulfate (SO ₄ ²⁻)	H ₂ S (rotten-egg smell)	Desulfovibrio, Desulfotomaculum	Common in sediments and animal intestines; H ₂ S is toxic.
CO ₂ (acetogenesis)	Acetic acid (CH ₃ COOH)	Acetobacterium woodii	Recycles CO ₂ in anaerobic environments; part of the carbon cycle.
Fe ³⁺ (ferric iron)	Fe ²⁺ (ferrous iron)	Geobacter, Shewanella	Helps remove toxic metals from soil and groundwater (bioremediation).
MnO ₂	Mn ²⁺	Soil Bacillus,	Found in sediments, deep water

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Final acceptor	Reduced product	Example bacteria	Why it matters
(manganese)		Shewanella	and oxygen-free soils.
Organic acceptors (fumarate, TMAO, DMSO)	Succinate / TMA / DMS	E. coli (fumarate); marine bacteria (TMAO, DMSO)	TMA gives the “fishy” smell of old fish; DMS affects cloud formation over oceans.

Key reactions to remember

Denitrification: $2 \text{NO}_3^- + 10 \text{e}^- + 12 \text{H}^+ \rightarrow \text{N}_2 + 6 \text{H}_2\text{O}$

Sulfate reduction: $\text{SO}_4^{2-} + 8 \text{H}^+ + 8 \text{e}^- \rightarrow \text{H}_2\text{S} + 4 \text{H}_2\text{O}$

Acetogenesis: $2 \text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_3\text{COOH} + 2 \text{H}_2\text{O}$

Everyday example

Waterlogged farm soil is often low in oxygen. Instead of using O_2 , soil bacteria there use nitrate from fertilizer as their electron acceptor, releasing N_2 gas — one reason excess fertilizer can be lost from soaked fields.

3.3 Fermentation — “Life Without Air”

When the final electron acceptor is an **organic compound**, we call this **fermentation**. In fermentation, the **same organic molecule** acts as both electron donor and electron acceptor. There is **no electron transport chain**, and ATP is made only by **substrate-level phosphorylation** — which is why the energy yield is much smaller than respiration.

Some fermentative microorganisms are strict anaerobes; others are facultative anaerobes, which switch to aerobic respiration whenever oxygen becomes available (oxygen actually inhibits their fermentation).

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Fermentation: two common pathways after glycolysis

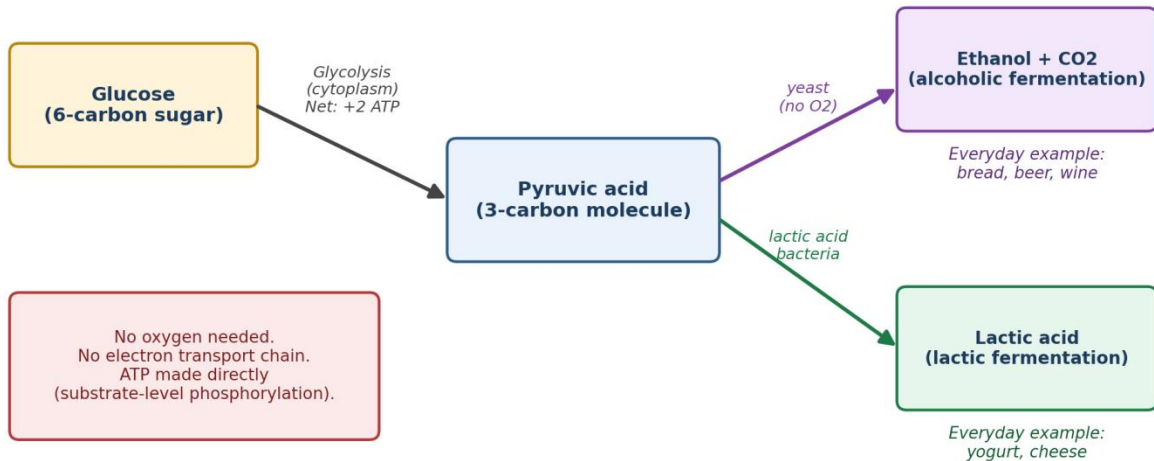


Fig. 3 — The two most common fermentation pathways: alcoholic (yeast) and lactic (lactic acid bacteria).

Fermentation type	Main product	Example microorganism	Everyday food example
Alcoholic	Ethanol + CO ₂	<i>Saccharomyces cerevisiae</i> (yeast)	Bread (CO ₂ makes it rise), beer, wine
Lactic (homolactic)	Lactic acid	<i>Lactobacillus</i> , <i>Streptococcus thermophilus</i>	Yogurt, cheese, fermented milk
Propionic	Propionic acid + CO ₂	<i>Propionibacterium</i>	The characteristic holes and flavor in Swiss-type cheese

Why this matters for food science

Fermentation is not just a textbook reaction — it is the biochemical basis of yogurt, cheese, sourdough bread, beer, wine, and many fermented beverages. The same pathways described above are what turn plain milk or dough into these everyday products.

Summary — Comparing the Three Metabolisms

	Aerobic respiration	Anaerobic respiration	Fermentation
Final electron acceptor	O ₂	NO ₃ ⁻ , SO ₄ ²⁻ , Fe ³⁺ , CO ₂ ...	An organic molecule (e.g. pyruvate)

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	Aerobic respiration	Anaerobic respiration	Fermentation
Electron transport chain	Yes	Yes	No
ATP yield (per glucose)	High (~38 ATP)	Intermediate	Low (2–4 ATP)
Oxygen required?	Yes	No	No
Everyday example	Human/animal breathing	Denitrification in soil	Yogurt, bread, beer