TOPIC: CELL RESPIRATION

Key Knowledge:

- General structure of the biochemical pathways in cell respiration from initial reactant to final product
- The main inputs, outputs and locations of glycolysis, Krebs Cycle and electron transport chain including ATP yield (details of biochemical pathway mechanisms are not required)
- The location, inputs and the difference in outputs of anaerobic fermentation in animals and yeasts
- Uses and applications of anaerobic fermentation of biomass for biofuel production
- Factors affecting the rate of cell respiration (temperature, glucose availability and O_2 concentration)

CELL RESPIRATION

Cellular respiration is the controlled release of energy from the breakdown of organic compounds. These compounds are produced by autotrophs (via photosynthesis) or can be synthesised from other pre-existing molecules within the cell (e.g. excess glucose can be converted to fats). Usable carbon compounds include:

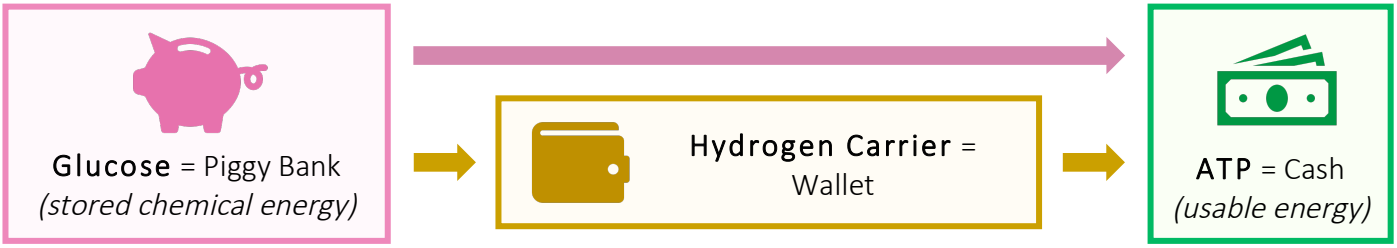
- **Carbohydrates:** The main organic molecule used in cell respiration is the monomer **glucose** ($C_6H_{12}O_6$)
- **Triglycerides:** Fats produce more energy per gram than sugars, but are harder to transport and digest
- **Proteins:** Not a primary source as produces nitrogenous by-products (which are toxic if not excreted)

ENERGY CONVERSIONS

Organic molecules store energy in their chemical bonds – but this energy is not easily accessible for use by the cell. Cell respiration transfers this stored energy into **coenzymes**. Two types of coenzymes are used:

- **ATP:** Immediately available energy source (energy is released for use when ATP is hydrolysed to ADP)
- **Hydrogen carriers:** Transitional energy source (carries high energy electrons and protons for transfer)

ATP can be produced directly from organic molecules via substrate level phosphorylation (**pink arrow**) or it can be indirectly synthesised by hydrogen carriers (needs O_2) via oxidative phosphorylation (**yellow arrow**).



TYPES OF CELL RESPIRATION

Cellular respiration can involve one of two reaction pathways: anaerobic respiration or aerobic respiration

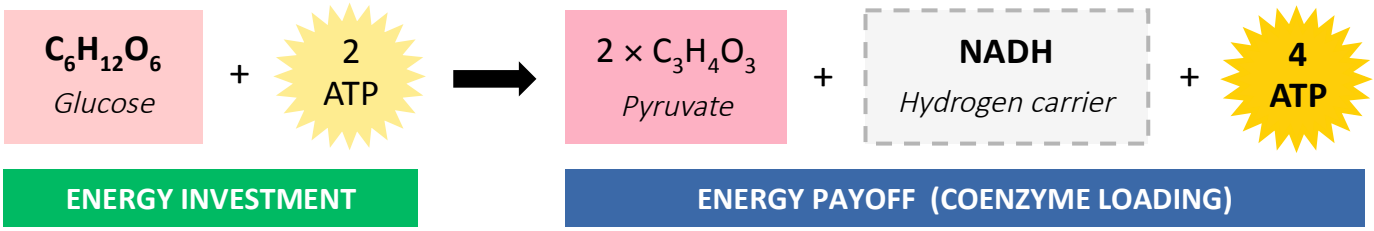
ANAEROBIC RESPIRATION	AEROBIC RESPIRATION
Partial breakdown of glucose	**Complete** breakdown of glucose
Oxygen is **not** required for a **small** ATP yield	Oxygen **is** required for a **large** ATP yield
Occurs entirely in the **cytosol**	Occurs in the **mitochondria**
Involves glycolysis and fermentation	Involves glycolysis, Krebs cycle and ETC
Products: Lactic acid / Ethanol + CO_2	**Products:** Carbon dioxide and water

ANAEROBIC RESPIRATION

Anaerobic respiration involves the partial breakdown of carbohydrates (glucose) in the absence of oxygen. It occurs in the **cytosol** and results in a low yield of ATP (net production = 2 ATP). This ATP is produced via substrate level phosphorylation. The process of anaerobic respiration involves glycolysis and fermentation.

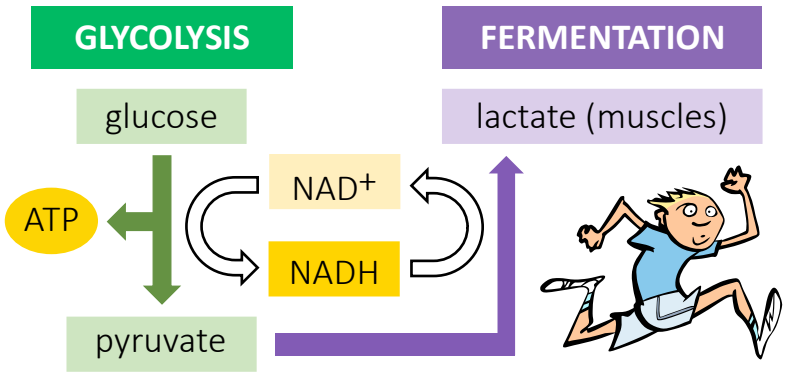
GLYCOLYSIS

Both anaerobic and aerobic respiration begins with the breakdown of glucose in the cytosol via glycolysis. Glycolysis splits glucose into two molecules of **pyruvate** in a process that consumes two molecules of ATP. However, four molecules of ATP are produced via substrate level phosphorylation, resulting in a **net gain** of **two ATP** molecules. Additionally, the coenzyme NAD is loaded with hydrogen to form molecules of **NADH**.



FERMENTATION

In the presence of oxygen, the hydrogen carriers produced by glycolysis may be used by the mitochondria to produce large amounts of ATP (via oxidative phosphorylation). However, in the absence of oxygen the hydrogen carriers must be unloaded to allow for glycolysis to continue (NADH must be unloaded to NAD). Fermentation involves the conversion of pyruvate via a reaction that unloads hydrogen carriers to restore stocks of NAD. In plants and yeasts, pyruvate is irreversibly converted into **ethanol** and **carbon dioxide**. In animals, pyruvate is converted into **lactic acid** (however, this reaction can be reversed if oxygen is present).



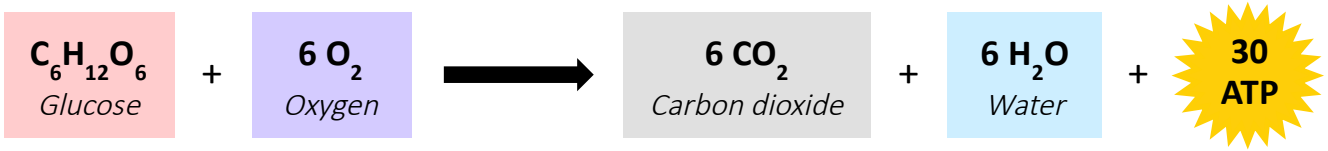
Fermentation is **reversible** in animals *(but is irreversible in plants or yeast)*

This means that lactic acid can be **converted back** into pyruvate when exercise is over and the pyruvate can then be digested **aerobically** to make ATP *(via oxidative phosphorylation)*

AEROBIC RESPIRATION

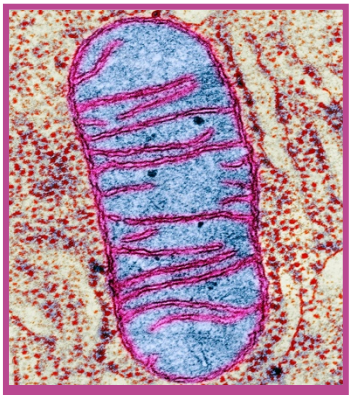
Aerobic respiration completes the breakdown of glucose begun by glycolysis. This process requires oxygen and occurs within the **mitochondrion**. Aerobic respiration occurs via two distinct reactions:

- **Krebs Cycle:** Pyruvate is broken down to make carbon dioxide and large amounts of hydrogen carriers
- **Electron Transport Chain:** Hydrogen carriers are unloaded to produce ATP *(oxidative phosphorylation)*

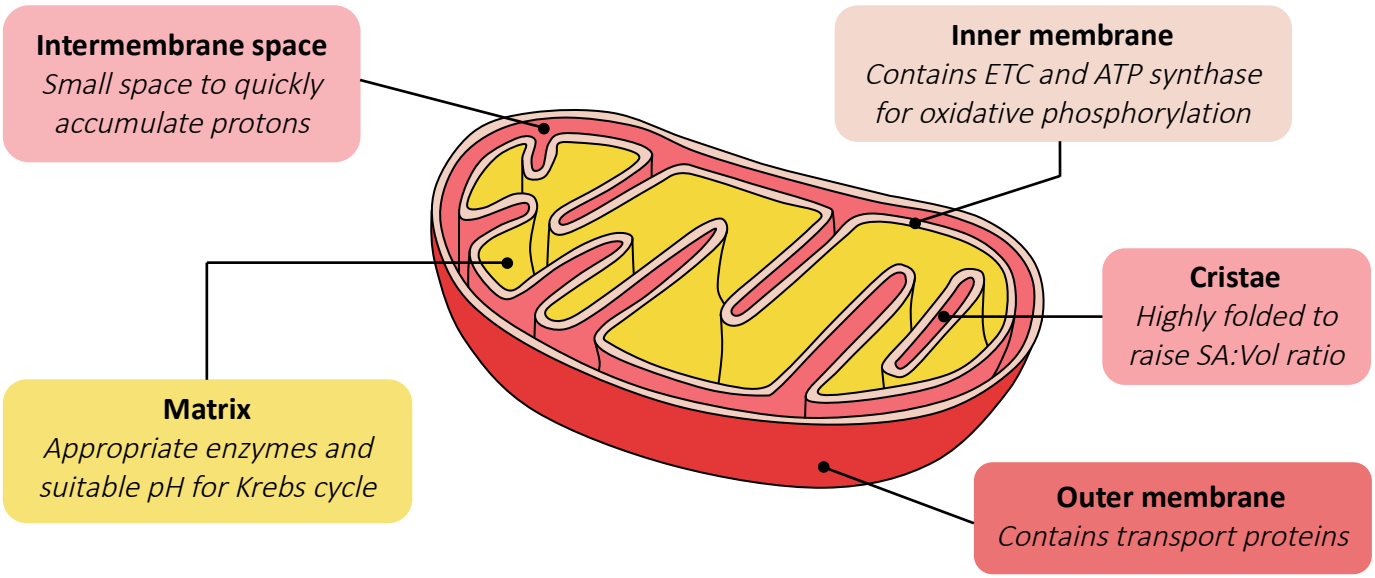


MITOCHONDRIA

The mitochondrion is an organelle in eukaryotic cells that is responsible for aerobic respiration. It is believed to have evolved via endosymbiosis, when an aerobic bacterium was engulfed by another prokaryotic cell. Evidence for this endosymbiotic origin includes the fact that the mitochondrion possesses circular DNA, 70S ribosomes has a double membrane. In terms of structure, the central region is called the **matrix** and is the location of the Krebs cycle. Mitochondria contain an **inner membrane** that is highly folded into **cristae**. The cristae are the site of the electron transport chain. By folding the inner membrane, the SA:Vol ratio is increased, which optimises electron transport.



Mitochondrion



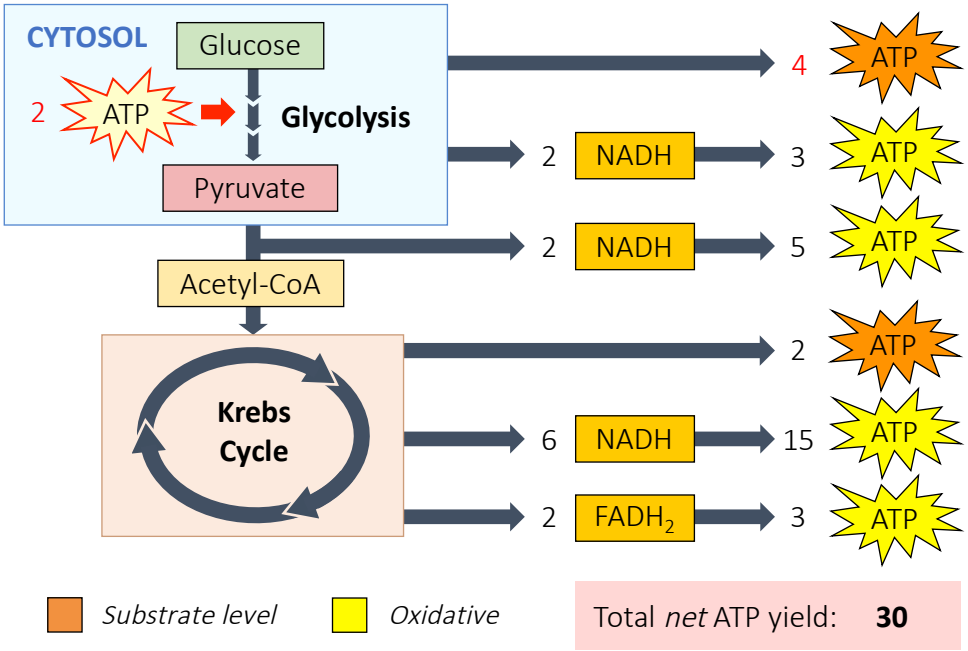
KREBS CYCLE

Pyruvate from glycolysis is transported into the mitochondrion and converted into **acetyl CoA**. It is then completely broken down via a series of reactions collectively called the Krebs cycle (or citric acid cycle). The breakdown of one pyruvate produces three **carbon dioxide** molecules, as well as one **ATP** molecule via substrate level phosphorylation (as glucose produces **two** pyruvate molecules, the Krebs cycle will produce 6 × CO_2 molecules and 2 × ATP **per glucose**). It will also result in the mass production of large quantities of **hydrogen carriers** (mainly NADH). These hydrogen carriers are unloaded via the electron transport chain.

ELECTRON TRANSPORT CHAIN

Hydrogen carriers (formed in glycolysis and the Krebs cycle) are unloaded to release protons and electrons. The high-energy electrons move through an electron transport chain, which essentially syphons this energy to synthesise **ATP**. This method of ATP production is known as **oxidative phosphorylation** as it requires the unloading of hydrogen (i.e. protons and electrons) from the hydrogen carriers. The de-energised electrons are taken up by **oxygen**, which combines with the protons to form **water**. The electron transport chain can only continue to unload hydrogen carriers if oxygen is present to accept the de-energised electrons, hence aerobic respiration will **not** occur in the absence of oxygen. Unloading all the hydrogen carriers produced by one molecule of glucose will result in the production of 26 molecules of ATP. If oxygen is not available, the hydrogen carriers can be unloaded anaerobically via fermentation, however this will not produce any additional ATP (this is why aerobic respiration has a much higher ATP yield than anaerobic respiration).

OVERVIEW OF AEROBIC RESPIRATION



Aerobic Stages:

Glycolysis
Glucose → Pyruvate
Substrate Level: 2 ATP

Krebs Cycle
Pyruvate → CO_2
Substrate Level: 2 ATP

Electron Transport
Oxygen → Water
Oxidative: 26 ATP

Intermediates:

NADH = NAD + H^+ + e^-

ANAEROBIC VERSUS AEROBIC

Cell respiration involves the partial (anaerobic) or complete (aerobic) digestion of glucose to produce ATP for use by the cell. Both pathways begin with the initial breakdown of glucose (by glycolysis) to form two molecules of pyruvate. In anaerobic respiration, this pyruvate is converted within the cytosol into either lactic acid (animals) or ethanol and carbon dioxide (plants and yeast). In aerobic respiration, the pyruvate is converted into carbon dioxide and water within the mitochondrion. Aerobic respiration requires oxygen to proceed and produces a larger yield of ATP (oxidative phosphorylation utilises the hydrogen carriers).

TYPE OF CELL RESPIRATION	ATP YIELD		
	Glycolysis	Krebs Cycle	Electron Transport Chain
Aerobic Cell Respiration	2 × ATP	2 × ATP	26 × ATP
Anaerobic Fermentation	2 × ATP		

BIOFUELS

Biofuels are an energy source produced from the anaerobic fermentation of **biomass** (i.e. organic material from plants or animals). Biofuels are a renewable resource and are typically associated with a lower carbon footprint (because biomass is typically produced via photosynthesis, which uses CO_2 as an input). Biomass has historically been produced from agricultural feedstocks (edible crops), which requires large amounts of arable land and drives up local food prices (as less crops are being used as a food source). Biomass can also be produced from non-edible plant components and certain municipal wastes; however, these sources are associated with higher costs of production. More recently, algae has been used as a source of biomass. The algae can photosynthesise at low costs and does not require large quantities of land (can be maintained in a photobioreactor). **Bioethanol** is a common biofuel that can be used to supplement or replace traditional fossil fuels (i.e. petrol) in fuel tanks. Drawbacks of bioethanol include the fact that it has a lower energy output than fossil fuels, is harder to vaporise (more difficult to use in colder temperatures) and is more likely to corrode materials (such as car engines) upon extended exposure (i.e. higher maintenance costs).

FACTORS AFFECTING RESPIRATION RATE

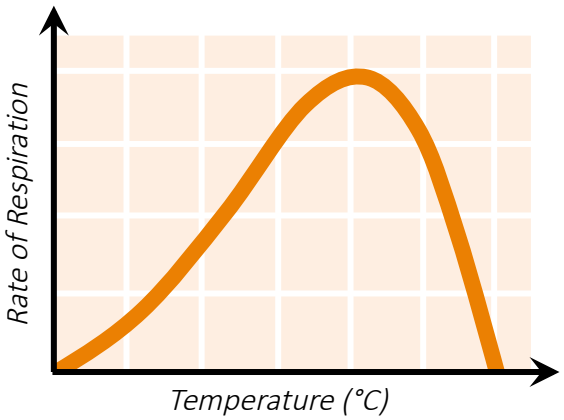
The rate of respiration can be measured by either the consumption of inputs (glucose and oxygen) or the formation of product (carbon dioxide). However, these conditions may be affected by the pathway used:

- Anaerobic respiration does **not** use oxygen and carbon dioxide is only produced as a by-product of yeast or plant fermentation (animal cells convert pyruvate into lactic acid via a reversible reaction)

Factors that affect aerobic respiration include: temperature, glucose concentration and oxygen availability

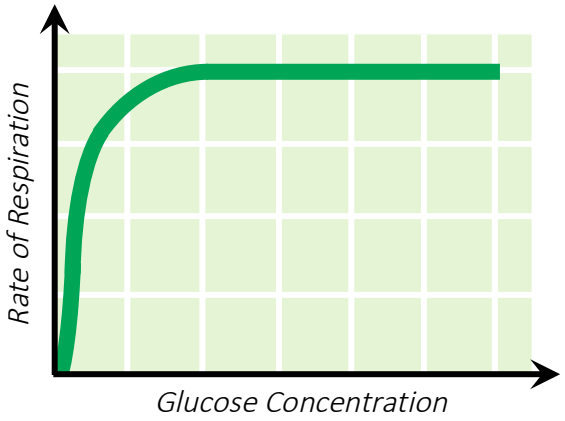
TEMPERATURE

Cell respiration is catalysed by a variety of **enzymes** and is therefore impacted by ambient temperatures. If the temperature is too low, the activation energy threshold cannot be reached. As temperatures increase, reaction rate will also increase as more kinetic energy results in more frequent enzyme-substrate collisions. At optimal temperatures, activity will peak, as higher temperatures will denature the enzymes involved in cell respiration.



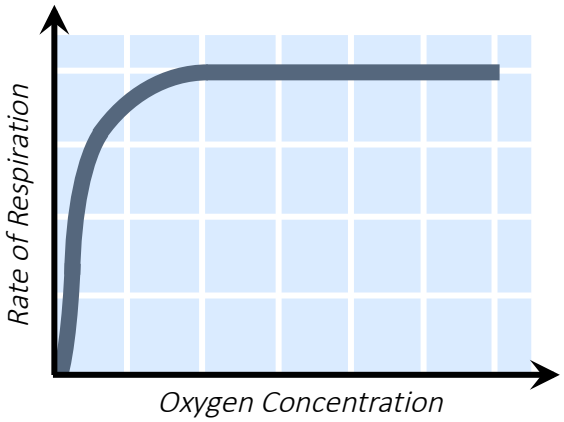
GLUCOSE CONCENTRATION

Glucose is the initial substrate for **both** pathways of respiration (anaerobic and aerobic). Higher glucose levels will result in increased frequency of collisions with glycolytic enzymes over a given period of time. Above a certain glucose level, the rate of respiration will plateau. This is because the environment is now saturated with glucose and some other condition has become the limiting factor that determines the rate.



OXYGEN AVAILABILITY

Increasing oxygen levels will result in higher rates of **aerobic** respiration. This is because oxygen is needed to maintain the functioning of the electron transport chain. Higher oxygen concentrations will increase the rate of respiration up to a certain point, above which the respiration rate will plateau as the environment is now saturated with oxygen and some other factor has become the rate-limiting factor for respiration.



EXERCISE INTENSITY

One condition that will increase the rate of cellular respiration is exercise (muscles require ATP in order to contract). Strenuous physical exertion will utilise anaerobic respiration, as ATP requirements exceed levels of oxygen intake. The resultant accumulation of lactic acid within the muscles will cause fatigue, rendering high levels of exercise unsustainable. Aerobic respiration is then used as the level of activity diminishes.