CHAPTER-14

RESPIRATION IN PLANTS

Introduction

All of us breathe to live.

All living organisms need energy for carrying out daily life activities, be it absorption, transport, movement, reproduction, or even breathing.

We eat food for energy – but how is this energy taken from food?

And micro-organisms – for their energy requirements, do they eat 'food'?

But in reality, the process of breathing is very much connected to the process of release of energy from food.

All the energy required for 'life' processes is obtained by oxidation of some macromolecules that we call 'food'. Only green plants and cyanobacteria can prepare their food; by the process of photosynthesis, they trap light energy and convert it into chemical energy that is stored in the bonds of carbohydrates like glucose, sucrose, and starch. We must remember that in green plants too, not all cells, tissues, and organs photosynthesize; only cells containing chloroplasts, that are most often located in the superficial layers, carry out photosynthesis. Hence, even in green plants all other organs, tissues, and non-green cells need food for oxidation. Hence, food has to be translocated to all non-green parts.

Animals are heterotrophic, i.e., they obtain food from plants directly (herbivores) or indirectly (carnivores). Saprophytes like fungi are dependent on dead and decaying matter. Ultimately all the food that is respired for life processes comes from photosynthesis.

The cellular respiration or the mechanism of breakdown of food materials within the cell to release energy, and the trapping of this energy for the synthesis of ATP.

Photosynthesis, of course, takes place within the chloroplasts (in the eukaryotes), whereas the breakdown of complex molecules to yield energy takes place in the cytoplasm and the mitochondria (also only in eukaryotes). The breaking of the C-C bonds of complex compounds through oxidation within the cells, leading to the release of a considerable amount of energy is called respiration.

The compounds that are oxidized during this process are known as respiratory substrates. Usually, carbohydrates are oxidized to release energy, but proteins, fats, and even organic acids

can be used as respiratory substances in some plants, under certain conditions. During oxidation within a cell, all the energy contained in respiratory substrates is not released free into the cell, or in a single step. It is released in a series of slow step-wise reactions controlled by enzymes, and it is trapped as chemical energy in the form of ATP. Hence, it is important to understand that the energy released by oxidation in respiration is not (or rather cannot be) used directly but is used to synthesize ATP, which is broken down whenever (and wherever) energy needs to be utilized.

Hence, ATP acts as the energy currency of the cell. This energy trapped in ATP is utilized in various energy-requiring processes of the organisms, and the carbon skeleton produced during respiration is used as precursors for biosynthesis of other molecules in the cell.

Respiration	Photosynthesis
Respiration takes place in all living cells, including green (Chlorophylls) and non – green.	Photosynthesis takes place only in the case of Chlorophylls cells.
It occurs both in night and day and includes Glycolysis – in the cytoplasm, Krebs cycle/ Citric acid cycle – in the mitochondrial matrix and Electron transport chain, and oxidative phosphorylation in the inner mitochondrial membrane.	Photosynthesis occurs only in light and includes Light reaction – in grana of the chloroplast, Calvin cycle or dark reaction – in the stroma of chloroplast and Photolysis or water splitting complex in the thylakoid lumen
O_2 is utilized and CO_2 and H_2O are formed	CO_2 and water is used and O_2 is released
It is a catabolic process that includes the destruction of food.	It is an anabolic process which includes the manufactured food.
Oxygen is absorbed and carbohydrate is oxidized.	Oxygen is liberated and carbohydrate is synthesized.
It is an exothermic process and energy is released during respiration.	It is an endothermic process and energy is stored during the process.
The dry weight of the plant decreases and potential energy is transformed into kinetic energy.	In this case, the dry weight of the plant increases, and light energy is converted into potential energy.

DO PLANTS BREATHE?

Plants need oxygen for respiration but at the same time they also give out carbon dioxide. Thus, plants have a proper system to ensure the availability of oxygen.

Unlike animals, plants do not possess any specialized organs for the exchange of gases but they have lenticels and stomata (present in stems and leaves respectively) that carry out the function of gaseous exchange.

Plants do not have any specialized organ to respire and exchange gases because each part of the plant takes care of the need of gases themselves. The parts of the plant do not display any great demand for the exchange of gases. Added to this, stems, leaves, and roots respire at a very lower rate as compared to animals.

But during the process of photosynthesis, a large exchange of gases takes place and each part of the plant is well adapted to fulfil its need for gases. The availability of oxygen is not a problem during photosynthesis because the cells release oxygen within cells.

It is important to note that each living cell in a plant is located quite close to the surface of the plant and in the case of stems, the living cells are arranged in the form of thin layers beneath and inside the bark and have openings which are referred as lenticels. Thereby, the respiration and translocation take place at every part of the plant.

The complete combustion of glucose produces **H_2O** and **CO_2** as end products and release energy in the form of heat. In case, this energy is required by the cell, it will utilize accordingly. The following reaction explains the entire process:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + Energy

During the process of respiration, **O_2** is utilized and carbon dioxide, energy, and water are released as products. There is also a situation when then the oxygen is not available. For instance, the first cell on this planet must have carried out a reaction in the absence of oxygen, and even in the current living world, we are aware of several living organisms adapted to anaerobic conditions. Some of these organisms are facultative and some are obligate. In any of these cases, all living organisms retain enzymatic machinery to partially oxidize glucose in the absence of oxygen. This process is also called **Glycolysis** which includes breaking down glucose to **Pyruvic Acid**.

Respiration in Plants

Plants perform photosynthesis to create sugars (such as glucose), this, along with oxygen is used to produce energy that is used in the plant's growth. This process of respiration is essentially the process of photosynthesis but in reverse.

Respiration In Roots

The process of respiration in roots is carried out in the following manner:

Air occurs in several interspaces of soil. The hairs of the roots are in direct contact with them.

The oxygen of the soil gets diffused via root hairs and reaches all internal cells of the root for respiration.

Carbon dioxide produced during the diffusion is released in the opposite direction.
In the condition of waterlogging, the air gets deficient in the soil, and in this case, the metabolic activity of the roots declines.

Respiration in Stems

The stems of herbaceous plants possess stomata and the air gets diffused via it and reaches the cells for respiration.

The carbon dioxide produced during the process gets diffused in the air via stomata.
When the stems are woody, this gaseous exchange is carried out by lenticels.

Respiration in Leaves

Leaves of the plants have tiny pores which are referred to as stomata. The exchange of gases takes place by the process of diffusion via stomata. The stomata are present in large numbers on the lower surface of the leaves of the plant. Each stoma is surrounded and controlled by **Guard Cells** (two kidney-shaped cells). Then the stoma, open gaseous exchange takes place between the **Atmosphere** and **Interior of Leaves**.

Glycolysis

Glycolysis is the only process in respiration taking place in anaerobic organisms. This process takes place in the cytoplasm of the cell and is found in all the living entities wherein glucose undergoes partial oxidation forming two molecules of pyruvic acid.

“Glycolysis is the metabolic process that breaks down glucose into pyruvic acid.”

Glycolysis is the process in which glucose is broken down to produce energy. It produces two molecules of pyruvate, ATP, NADH, and water. The process takes place in the cytosol of the cell cytoplasm, in the presence or absence of oxygen.

Glycolysis is the primary step of cellular respiration. In the absence of oxygen, the cells take small amounts of ATP through the process of fermentation.

This metabolic pathway was discovered by three German biochemists- Gustav Embden, Otto Meyerhof, and Jakub Karol Parnas in the early 19th century and are known as the EMP pathway (Embden–Meyerhof–Parnas).

Stage 1

A phosphate group is added to glucose in the cell cytoplasm by the action of enzyme hexokinase.

In this, a phosphate group is transferred from ATP to glucose forming glucose,6-phosphate.

Stage 2

Glucose-6-phosphate is isomerized into fructose,6-phosphate by the enzyme phosphoglucomutase.

Stage 3

The other ATP molecule transfers a phosphate group to fructose 6-phosphate and converts it into fructose 1,6-bisphosphate by the action of enzyme phosphofructokinase.

Stage 4

The enzyme aldolase breaks down fructose 1,6-bisphosphate into glyceraldehyde 3-phosphate and dihydroxyacetone phosphate, which are isomers of each other.

Step 5

Triose-phosphate isomerase converts dihydroxyacetone phosphate into glyceraldehyde 3-phosphate which is the substrate in the successive step of glycolysis.

Step 6

This step undergoes two reactions: The enzyme glyceraldehyde 3-phosphate dehydrogenase transfers 1 hydrogen molecule from glyceraldehyde phosphate to nicotinamide adenine dinucleotide to form NADH + H^+.

Glyceraldehyde 3-phosphate dehydrogenase adds a phosphate to the oxidized glyceraldehyde phosphate to form 1,3-bisphosphoglycerate.

Step 7

Phosphate is transferred from 1,3-bisphosphoglycerate to ADP to form ATP with the help of phosphoglycerokinase. Thus two molecules of phosphoglycerate and ATP are obtained at the end of this reaction.

Step 8

The phosphate of both the phosphoglycerate molecules is relocated from the third to the second carbon to yield two molecules of 2-phosphoglycerate by the enzyme phosphoglyceromutase.

Step 9

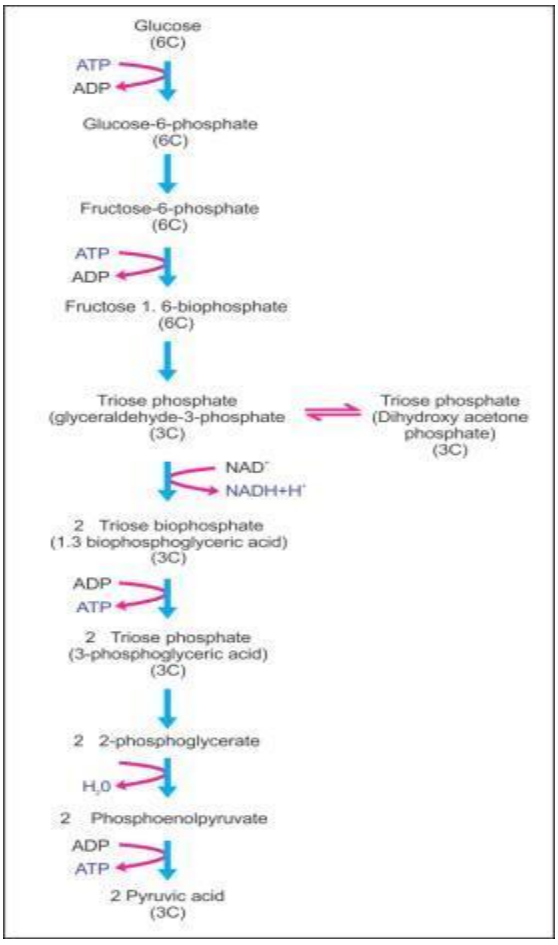
The enzyme enolase removes a water molecule from 2-phosphoglycerate to form phosphoenolpyruvate.

Step 10

A phosphate from phosphoenolpyruvate is transferred to ADP to form pyruvate and ATP by the action of pyruvate kinase. Two molecules of pyruvate and ATP are obtained as the end products.

Key Points of Glycolysis

- It is the process in which a glucose molecule is broken down into two molecules of pyruvate.
- The process takes place in the cytoplasm of plant and animal cells.
- Six enzymes are involved in the process.
- The end products of the reaction include 2 pyruvate, 2 ATP,substrate-level, and 2 NADH molecules.



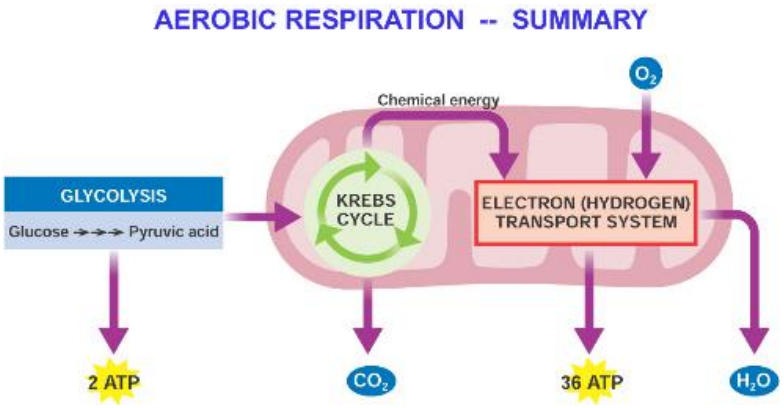
Glycolysis vs Krebs Cycle

Glycolysis	Krebs Cycle
It is the first step in respiration in which glucose is broken down into two molecules of pyruvate	Krebs Cycle is the second step of respiration in which it degrades pyruvate into inorganic substances (water and carbon dioxide)
Occurs inside the cytoplasm	Occurs inside the mitochondria
No carbon dioxide evolved	Carbon dioxide evolved
One molecule of glucose liberates 4 ATP molecules through substrate-level phosphorylation	Two acetyl residues liberate two ATP and GTP molecules through substrate-level phosphorylation
Oxygen not required for glycolysis	Oxygen is required for Krebs Cycle
Occurs as a linear sequence	Occurs as a cyclic sequence
Consumes 2 molecules of ATP for initial phosphorylation of substance molecules	Doesn't consume ATP
Two molecules of ATP and two molecules of NADH gained for every molecule of glucose broken down	Six molecules of NADH and two molecules of FADH2 for every acetyl-CoA oxidized

Types of Respiration

Respiration is of two types:

- **Aerobic Respiration:** In this type of respiration, the food substances are completely oxidized into **H_2O** and **CO_2** with the release of energy. It requires atmospheric oxygen and all higher organisms respire aerobically. The following figure shows the steps included in **Aerobic Respiration**.



- **Anaerobic Respiration:** In this type of respiration, partial oxidation of food takes place and energy is released in the absence of oxygen. This type of respiration occurs in prokaryotic organisms like bacteria and yeast. Ethyl alcohol and carbon dioxide are formed in this process.

Fermentation

In this process, incomplete oxidation of glucose is obtained under anaerobic conditions by a set of reactions resulting in the conversion of carbon dioxide to ethanol, reactions catalyzed by enzymes – alcohol dehydrogenase, pyruvic acid decarboxylase.

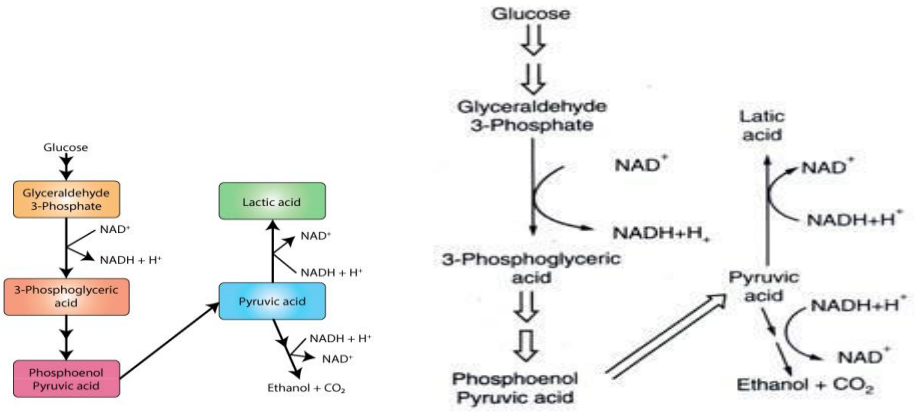
In fermentation, say by yeast, the incomplete oxidation of glucose is achieved under anaerobic conditions by sets of reactions where pyruvic acid is converted to CO2 and ethanol. The enzymes, pyruvic acid decarboxylase, and alcohol dehydrogenase catalyze these reactions. Other organisms like some bacteria produce lactic acid from pyruvic acid.

In animal cells also, like muscles during exercise, when oxygen is inadequate for cellular respiration pyruvic acid is reduced to lactic acid by lactate dehydrogenase. The reducing agent is NADH+H+ which is reoxidized to NAD+ in both the processes.

What is the net ATPs that is synthesized (calculate how many ATP are synthesized and deduct the number of ATP utilized during glycolysis) when one molecule of glucose is fermented to alcohol or lactic acid. Yeasts poison themselves to death when the concentration of alcohol reaches about 13 per cent.

In both alcohol and lactic acid fermentation, very little energy is released. Both these processes are hazardous because alcohol or acid is produced during the process. The fermentation process is used in our daily life such as in the formation of curd, vinegar, bread, and alcoholic drinks.

The various steps involved in fermentation are as follows:



Aerobic Respiration

For aerobic respiration to take place within the mitochondria, the final product of glycolysis, pyruvate is transported from the cytoplasm into the mitochondria.

The crucial events in aerobic respiration are:

• The complete oxidation of pyruvate by the stepwise removal of all the hydrogen atoms, leaving three molecules of CO2 .

• The passing on of the electrons removed as part of the hydrogen atoms to molecular cO2 with a simultaneous synthesis of ATP.

This entire process is catalyzed by pyruvic dehydrogenase and this reaction requires the involvement of several coenzymes such as Coenzyme A and NAD^+.

$$\text{Pyruvic acid} + \text{CoA} + \text{NAD}^+ \xrightarrow[\text{Pyruvate dehydrogenase}]{Mg^{2+}} \text{Acetyl CoA} + CO_2 + \text{NADH} + H^+$$

The first process takes place in the matrix of the mitochondria while the second process is located on the inner membrane of the mitochondria. Pyruvate, which is formed by the glycolytic catabolism of carbohydrates in the cytosol, after it enters the mitochondrial matrix undergoes oxidative decarboxylation by a complex set of reactions catalyzed by pyruvic dehydrogenase. The reactions catalyzed by pyruvic dehydrogenase require the participation of several coenzymes, including NAD+ and Coenzyme A.

During this process, two molecules of NADH are produced from the metabolism of two molecules of pyruvic acid (produced from one glucose molecule during glycolysis). The acetyl CoA then enters a cyclic pathway, the tricarboxylic acid cycle, more commonly called as Krebs' cycle after the scientist Hans Krebs who first elucidated it.

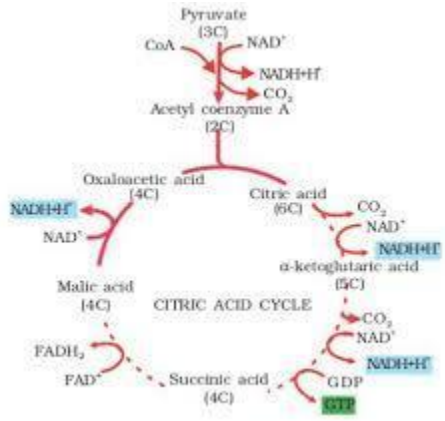
Tricarboxylic Acid Cycle

It is the second stage of cellular respiration. It plays an integral role in the catabolism of the breaking down of organic fuel molecule i.e. glucose, sugar, fatty acid, and amino acids. The cycle starts with the condensation of acetyl group with oxaloacetic acid and water to release citric acid.

The overall reaction of Krebs cycle is –

2 acetyl CoA + $6NAD^+$ + 2FAD + 2ADP + $2P_i$ → 4 CO_2 + 6 NADH + $6H^+$ + 2 $FADH_2$ + 2ATP

This reaction is catalyzed by citrate synthase enzyme and a molecule of CoA is released. This citrate is then isomerized to isocitrate followed by decarboxylation that results in the formation of α-ketoglutaric acid and succinyl-CoA. Then succinyl-CoA is oxidized to OAA allowing the cycle to continue. During this conversion of succinyl-CoA to succinic acid one molecule of GTP is synthesized.



In a coupled reaction GTP is converted to GDP along with the synthesis of ATP from ADP. Added to this, at three places in the entire cycle, NAD^+ is reduced to NADH + H^+ and at one point FAD^+ is reduced to $FADH_2$.

Furthermore, the continued oxidation of acetic acid oxidized in this cycle requires continued replenishment of oxaloacetic acid, i.e. the first member of the cycle. The summary equation of the entire process is given below -

$$\text{Pyruvc acid} + 4NAD^{+} + FAD^{+} + 2H_2O + ADP + Pi \xrightarrow{\text{Mitlochondrial Matrix}} 3CO_2 + 4NADH + 4H^{+} + FADH_2 + ATP$$

Electron Transport System (ETS) and Oxidative Phosphorylation

The **electron transport chain** is a series of proteins and organic molecules found in the inner membrane of the mitochondria. Electrons are passed from one member of the transport chain to another in a series of redox reactions. The energy released in these reactions is captured as a proton gradient, which is then used to make ATP in a process called **chemiosmosis**. Together, the electron transport chain and chemiosmosis make up **oxidative phosphorylation**.

Delivery of electrons by NADH and $FADH_2$. Reduced electron carriers (NADH and $FADH_2$) from other steps of cellular respiration transfer their electrons to molecules near the beginning of the transport chain. In the process, they turn back into NAD^+ and FAD, which can be reused in other steps of cellular respiration.

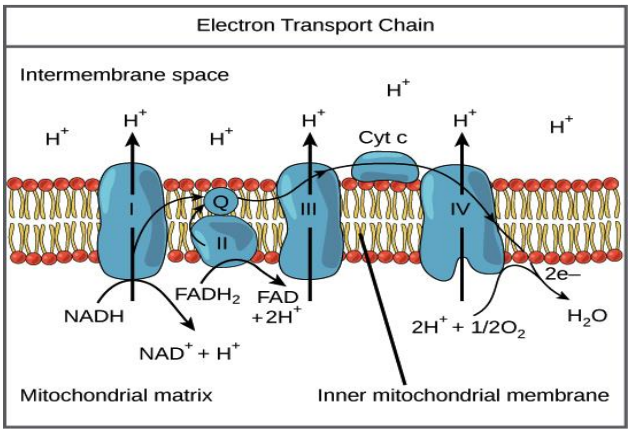
Electron transfer and proton pumping. As electrons are passed down the chain, they move from a higher to a lower energy level, releasing energy. Some of the energy is used to pump H+, moving them out of the matrix and into the intermembrane space. This pumping establishes an electrochemical gradient.

Splitting of oxygen to form water. At the end of the electron transport chain, electrons are transferred to molecular oxygen, which splits in half and takes up H^+ to form water.

Gradient-driven synthesis of ATP. As H^+, end superscript ions flow down their gradient and back into the matrix, they pass through an enzyme called ATP synthase, which harnesses the flow of protons to synthesize ATP.

The **electron transport chain** is a collection of membrane-embedded proteins and organic molecules, most of them organized into four large complexes labelled I to IV. In eukaryotes, many copies of these molecules are found in the inner mitochondrial membrane. In prokaryotes, the electron transport chain components are found in the plasma membrane.

As the electrons travel through the chain, they go from a higher to a lower energy level, moving from less electron-hungry to more electron-hungry molecules. Energy is released in these "downhill" electron transfers, and several of the protein complexes use the released energy to pump protons from the mitochondrial matrix to the intermembrane space, forming a proton gradient.



All of the electrons that enter the transport chain come from NADH and $FADH_2$, molecules produced during earlier stages of cellular respiration: glycolysis, pyruvate oxidation, and the citric acid cycle.

NADH is very good at donating electrons in redox reactions (that is, its electrons are at a high energy level), so it can transfer its electrons directly to complex I, turning back into NAD+. As electrons move through complex I in a series of redox reactions, energy is released, and the complex uses this energy to pump protons from the matrix into the intermembrane space.
$FADH_2$ is not as good at donating electrons as NADH (that is, its electrons are at a lower energy level), so it cannot transfer its electrons to complex I. Instead, it feeds them into the transport chain through complex II, which does not pump protons across the membrane.
Because of this "bypass," each $FADH_2$, end subscript molecule causes fewer protons to be pumped (and contributes less to the proton gradient) than an NADH.

Beyond the first two complexes, electrons from NADH and $FADH_2$, travel the same route. Both complex I and complex II pass their electrons to a small, mobile electron carrier called **ubiquinone** (U**Q**), which is reduced to form QH_2 and travels through the membrane, delivering the electrons to complex III. As electrons move through complex III, more H^+ ions are pumped across the membrane, and the electrons are ultimately delivered to another mobile carrier called **cytochrome C** (**Cyt C**). Cyt C carries the electrons to complex IV, where a final batch of H^+ ions is pumped across the membrane. Complex IV passes the electrons to O_2, which splits into two oxygen atoms and accepts protons from the matrix to form water. Four electrons are required to reduce each molecule of O_2, and two water molecules are formed in the process.

It has two important functions:

Regenerates electron carriers. NADH and $FADH_2$, end subscript pass their electrons to the electron transport chain, turning back into NAD^+, end superscript, and FAD. This is important

because the oxidized forms of these electron carriers are used in glycolysis and the citric acid cycle and must be available to keep these processes running.

Makes a proton gradient. The transport chain builds a proton gradient across the inner mitochondrial membrane, with a higher concentration of H^+ in the intermembrane space and a lower concentration in the matrix. This gradient represents a stored form of energy, and, as we'll see, it can be used to make ATP.

When the electrons pass from one carrier to another via complex I to IV in the electron transport chain, they are coupled to ATP synthase (complex V) for the production of ATP from ADP and inorganic phosphate. The number of ATP molecules synthesized depends on the nature of the electron donor. Oxidation of one molecule of NADH gives rise to 3 molecules of ATP, while that of one molecule of

FADH2 produces 2 molecules of ATP. Although the aerobic process of respiration takes place only in the presence of oxygen, the role of oxygen is limited to the terminal stage of the process. Yet, the presence of oxygen is vital, since it drives the whole process by removing hydrogen from the system. Oxygen acts as the final hydrogen acceptor. Unlike photophosphorylation where it is the light energy that is utilized for the production of proton gradient required for phosphorylation, in respiration, it is the energy of oxidation-reduction utilized for the same process. It is for this reason that the process is called oxidative phosphorylation.

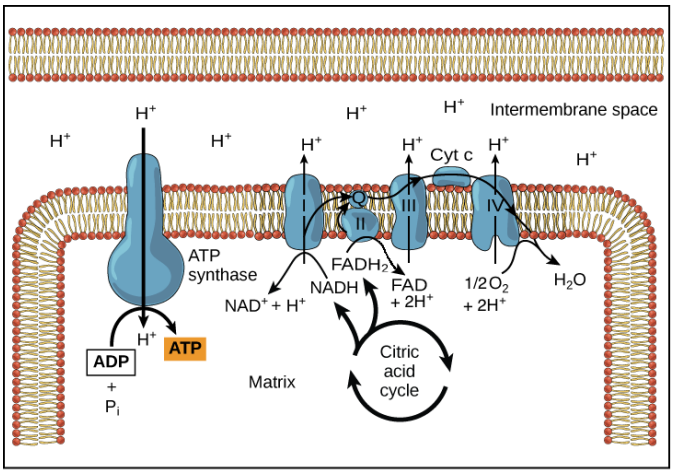
Chemiosmosis

Complexes I, III, and IV of the electron transport chain are proton pumps. As electrons move energetically downhill, the complexes capture the released energy and use it to pump H^+ ions from the matrix to the intermembrane space. This pumping forms an electrochemical gradient across the inner mitochondrial membrane. The gradient is sometimes called the **proton-motive force**, and you can think of it as a form of stored energy, kind of like a battery.

Like many other ions, protons can't pass directly through the phospholipid bilayer of the membrane because its core is too hydrophobic. Instead, H^+ ions can move down their concentration gradient only with the help of channel proteins that form hydrophilic tunnels across the membrane.

In the inner mitochondrial membrane, H^+ ions have just one channel available: a membrane-spanning protein known as **ATP synthase**. Conceptually, ATP synthase is a lot like a turbine in a

hydroelectric power plant. Instead of being turned by water, it's turned by the flow of H^+ ions moving down their electrochemical gradient. As ATP synthase turns, it catalyzes the addition of a phosphate to ADP, capturing energy from the proton gradient as ATP.



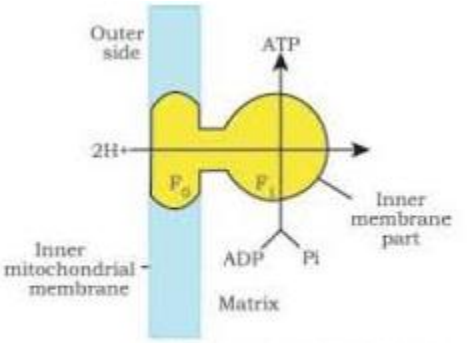
Overview diagram of oxidative phosphorylation.

This process, in which energy from a proton gradient is used to make ATP, is called **chemiosmosis**. More broadly, chemiosmosis can refer to any process in which energy stored in a proton gradient is used to do work. Although chemiosmosis accounts for over 80% of ATP made during glucose breakdown in cellular respiration, it's not unique to cellular respiration. For instance, chemiosmosis is also involved in the light reactions of photosynthesis.

It would be released as heat, and interestingly enough, some types of cells deliberately use the proton gradient for heat generation rather than ATP synthesis. This might seem wasteful, but it's an important strategy for animals that need to keep warm. For instance, hibernating mammals (such as bears) have specialized cells known as brown fat cells. In the brown fat cells, **uncoupling proteins** are produced and inserted into the inner mitochondrial membrane. These proteins are simply channels that allow protons to pass from the intermembrane space to the matrix without travelling is through ATP synthase. By providing an alternate route for protons to flow back into the matrix, the uncoupling proteins allow the energy of the gradient to be dissipated as heat.

The electron transport system is utilized in synthesizing ATP with the help of ATP synthase (complex V). This complex consists of two major components, F1 and F0. The F1 headpiece is a peripheral membrane protein complex and contains the site for synthesis of ATP from ADP and inorganic phosphate. F0 is an integral membrane protein complex that forms the channel through which protons across the inner membrane. The passage of protons through the channel is coupled to the catalytic site of the F1 component for the production of ATP. For each ATP

produced, 2H+ passes through F0 from the intermembrane space to the matrix down the electrochemical proton gradient.



Diagramatic presentation of ATP synthesis in mitochondria

ATP yield

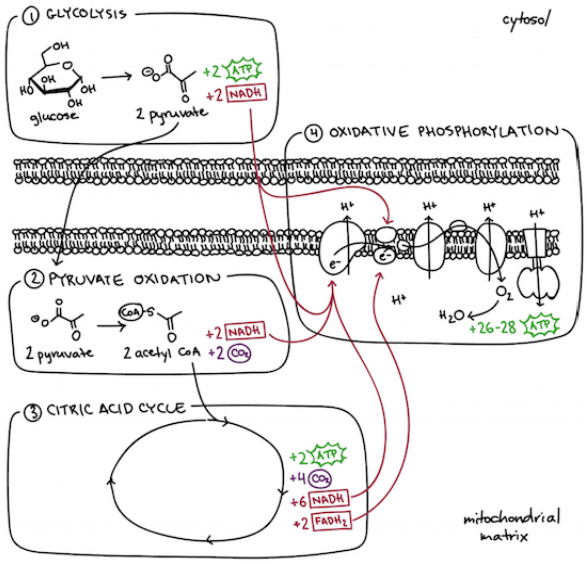
However, most current sources estimate that the maximum ATP yield for a molecule of glucose is around 30-32 ATP. This range is lower than previous estimates because it accounts for the necessary transport of ADP into, and ATP out of, the mitochondrion.

Two net ATP is made in glycolysis, and another two ATP (or energetically equivalent GTP) are made in the citric acid cycle. Beyond those four, the remaining ATP all comes from oxidative phosphorylation. Based on a lot of experimental work, it appears that four H^+ ions must flow back into the matrix through ATP synthase to power the synthesis of one ATP molecule. When electrons from NADH move through the transport chain, about 10 H^+ ions are pumped from the matrix to the intermembrane space, so each NADH yields about 2.5 ATP. Electrons from $FADH_2$, end subscript, which enter the chain at a later stage, drive pumping of only 6 H^+, leading to the production of about 1.5 ATP.

With this information, we can do a little inventory for the breakdown of one molecule of glucose:

Stage	Direct products (net)	Ultimate ATP yield (net)
Glycolysis	2 ATP	2 ATP
	2 NADH	3-5 ATP
Pyruvate oxidation	2 NADH	5 ATP
Citric acid cycle	2 ATP/GTP	2 ATP
	6 NADH	15 ATP

	2 $FADH_2$	3 ATP
Total		**30-32 ATP**



One number in this table is still not precise: the ATP yield from NADH is made in glycolysis. This is because glycolysis happens in the cytosol, and NADH can't cross the inner mitochondrial membrane to deliver its electrons to complex I. Instead, it must hand its electrons off to a molecular "shuttle system" that delivers them, through a series of steps, to the electron transport chain.

Some cells of your body have a shuttle system that delivers electrons to the transport chain via $FADH_2$. In this case, only 3 ATP are produced for the two NADH of glycolysis.
Other cells of your body have a shuttle system that delivers the electrons via NADH, resulting in the production of 5 ATP.
In bacteria, both glycolysis and the citric acid cycle happen in the cytosol, so no shuttle is needed and 5 ATP are produced.

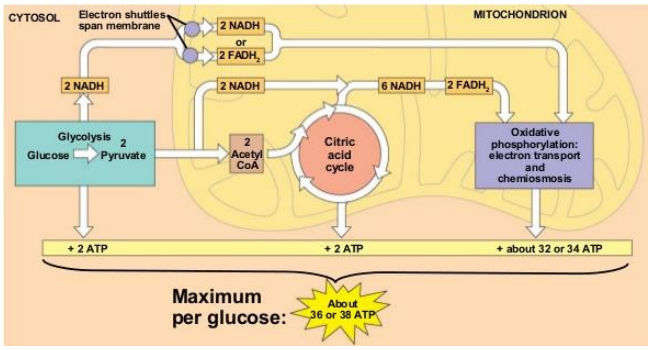
30-32 ATP from the breakdown of one glucose molecule is a high-end estimate, and the real yield may be lower. For instance, some intermediates from cellular respiration may be siphoned off by the cell and used in other biosynthetic pathways, reducing the number of ATP produced. Cellular respiration is a nexus for many different metabolic pathways in the cell, forming a network that's larger than the glucose breakdown pathways alone.

The Respiratory Balance Sheet

Theoretically, we can calculate the net gain of ATP for every molecule of oxidized glucose and this calculation is based on the following assumptions –

- There is an orderly and sequential functioning of the pathway; with one substrate forming the next with glycolysis, Krebs cycle, and Electron Transport System following one after another.
- The NADH formed during glycolysis is transferred into mitochondria and oxidative phosphorylation takes place.
- None of the intermediates in any process is utilized to synthesize any other compound.
- No alternative substrates except glucose are respired.

All of the pathways work simultaneously but none of the above-mentioned assumptions is valid in the living system. The substrate that enters the pathways are extracted as and when required, ATP is utilized as and when required, the rate of the enzyme is controlled by several means. On the other hand, doing this exercise is important as it appreciates the efficiency and beauty of the living system in extracting and storing energy. Thus, there can be a net gain of 36 ATP molecules from one molecule of glucose in case of aerobic respiration.



Comparison between Fermentation and Aerobic Respiration

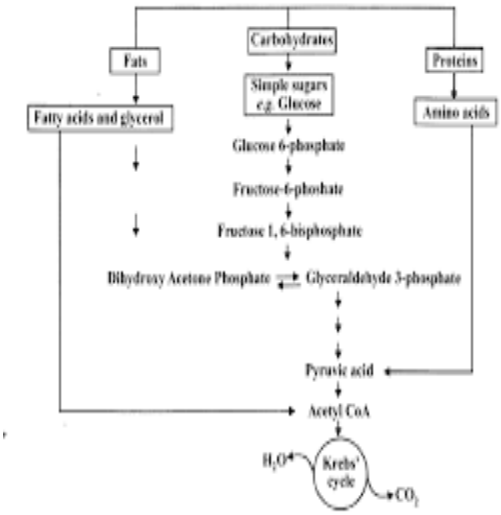
- Where aerobic respiration is the complete degradation of carbon dioxide and water, fermentation results in the partial breakdown of glucose only
- Aerobic conditions lead to the formation of several molecules of ATP whereas the net gain of only two molecules of ATP is observed for each molecule of glucose degraded to pyruvic acid in the process of fermentation
- In fermentation, NADH is oxidized to NAD+ slowly whereas this same reaction is vigorous under aerobic conditions

Amphibolic Pathway

The term amphibolic is used to explain the *"biological pathway that involves both catabolism and anabolism."*
Glucose is the favoured substrate for respiration. All carbohydrates are usually first converted into glucose before they are used for respiration. Other substrates can also be respired.

Fats would need to be broken down into glycerol and fatty acids first. If fatty acids were to be respired they would first be degraded to acetyl CoA and enter the pathway. Glycerol would enter the pathway after being converted to PGAL. The proteins would be degraded by proteases and the individual amino acids (after deamination) depending on their structure would enter the pathway at some stage within the Krebs' cycle or even as pyruvate or acetyl CoA. Since respiration involves the breakdown of substrates, the respiratory process has traditionally been considered a catabolic process and the respiratory pathway as a catabolic pathway.

Hence, fatty acids would be broken down to acetyl CoA before entering the respiratory pathway when it is used as a substrate. But when the organism needs to synthesize fatty acids, acetyl CoA would be withdrawn from the respiratory pathway for it. Hence, the respiratory pathway comes into the picture both during the breakdown and synthesis of fatty acids. Similarly, during the breakdown and synthesis of protein too, respiratory intermediates form the link. Breaking down processes within the living organism is catabolism, and synthesis is anabolism. Because the respiratory pathway is involved in both anabolism and catabolism, it would hence be better to consider the respiratory pathway is an amphibolic pathway rather than as a catabolic one.



Example of Amphibolic Pathway

Krebs cycle is an example of an Amphibolic Pathway because it includes both catabolisms of fatty acids and carbohydrates and synthesis of anabolic precursors for amino acid synthesis. Thus, the pathway with both catabolism and anabolism potential is known as the amphibolic pathway.

Respiratory Quotient

This is another aspect of respiration. *"Respiratory quotient is the ratio of CO_2 produced to O_2 consumed while food is being metabolized."*

Where RQ stands for Respiratory Quotient

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

RQ depends on the type of respiratory substrate used in respiration. When carbohydrate is used as a substrate and is completely oxidized, RQ becomes 1. It implies an equal amount of O_2 and CO_2 is consumed and evolved.

$$C_6 + H_{12}6O_2 \rightarrow 6CO_2O + \text{Energy}$$

$$RQ = \frac{6CO_2}{6O_2} = 1.0$$

In case, fats are used during the process of respiration, RQ becomes less than 1. Following equation shows the calculation for fatty acid and tripalmitin is used as a substrate –

$$2(C_{51}\ H_{98}\ O_6) + 145O_2 \rightarrow 102\ CO_2 + 98H_2O + \text{energy}$$

Tripalmitin

$$RQ = \frac{102\ CO_2}{145O_2} = 0.7$$

When protein is used as respiratory substrates the ratio comes out to be 0.9.

Factors affecting Respiration in Plants

Eight environmental factors have a significant impact on respiration in plants –

- The oxygen content of the atmosphere
- Effect of water content
- Effect of temperature
- Effect of availability of light
- Impact of respirable material
- Effect of concentration of carbon dioxide in the atmosphere
- Protoplasmic conditions, i.e. younger tissues have greater protoplasm as compared to older tissues.

- Other factors, i.e. fluorides, cyanides, azides, etc.

Important terms

Substrate

In chemistry, a substrate is typically the chemical species being observed in a chemical reaction, which reacts with a reagent to generate a product. It can also refer to a surface on which other chemical reactions are performed, or play a supporting role in a variety of spectroscopic and microscopic techniques.

Breathing

Breathing is the process of moving air into and out of the lungs to facilitate gas exchange with the internal environment, mostly by bringing in oxygen and flushing out carbon dioxide.

Cellular respiration

Cellular respiration is a set of metabolic reactions and processes that take place in the cells of organisms to convert chemical energy from oxygen molecules or nutrients into adenosine triphosphate and then release waste products.

Anaerobic respiration

Anaerobic respiration is respiration using electron acceptors other than molecular oxygen. Although oxygen is not the final electron acceptor, the process still uses a respiratory electron transport chain.

Fermentation

Fermentation is a metabolic process that produces chemical changes in organic substrates through the action of enzymes. In biochemistry, it is narrowly defined as the extraction of energy from carbohydrates in the absence of oxygen.

ATP

Adenosine triphosphate, also known as ATP, is a molecule that carries energy within cells. It is the main energy currency of the cell, and it is an end product of the processes of

photophosphorylation (adding a phosphate group to a molecule using energy from light), cellular respiration, and fermentation.S

Glycolysis

Glycolysis is the metabolic pathway that converts glucose $C_6H_{12}O_6$, into pyruvate, CH_3COCOO^-, and a hydrogen ion, H^+. The free energy released in this process is used to form the high-energy molecules ATP and NADH. Glycolysis is a sequence of ten enzyme-catalyzed reactions

Citric acid cycle

The citric acid cycle – also known as the TCA cycle or the Krebs cycle – is a series of chemical reactions used by all aerobic organisms to release stored energy through the oxidation of acetyl-CoA derived from carbohydrates, fats, and proteins.

Amphibolic

The term amphibolic is used to describe a biochemical pathway that involves both catabolism and anabolism. Catabolism is a degradative phase of metabolism in which large molecules are converted into smaller and simpler molecules, which involves two types of reactions.

ETS

The electron transport chain is a series of complexes that transfer electrons from electron donors to electron acceptors via redox reactions, and couples this electron transfer with the transfer of protons across a membrane. The electron transport chain is built up of peptides, enzymes, and other molecules.

Oxidative phosphorylation

Oxidative phosphorylation is the process in which ATP is formed as a result of the transfer of electrons from NADH or $FADH_2$ to O_2 by a series of electron carriers. This process, which takes place in mitochondria, is the major source of ATP in aerobic organisms

Respiratory quotient

A respiratory quotient is a dimensionless number used in calculations of basal metabolic rate when estimated from carbon dioxide production. It is calculated from the ratio of carbon dioxide produced by the body to oxygen consumed by the body.

Respiratory balance sheet

The respiratory balance sheet is the sheet representing the net gain of ATP for each molecule of glucose oxidized in the plants.

Flavin adenine dinucleotide-**FAD**

Nicotinamide adenine dinucleotide-**NAD**