CHAPTER 14: RESPIRATION IN PLANTS

"Biological oxidation of organic food molecules like glucose into simpler inorganic compounds like CO₂ and H₂O, with the release of energy in the form of ATP molecules is called cellular respiration".

Respiration is a catabolic process that takes place in each and every living cells of an organism.

Aerobic Respiration
Break down of glucose in the presence of molecular oxygen is called aerobic respiration E.g. All higher plants and animal cells.

\[ \text{C}_6\text{H}_12\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + 36\text{ATP} \]

“The breaking of C-C bonds of complex compounds through oxidation within the cells, leading to release of considerable amount of energy is called respiration”.

* The compound that oxidized during this process is known as respiratory substrates.
* In the process of respiration the energy is released in a series of slow step-wise reactions controlled by enzymes and is trapped in the form of ATP.
* ATP acts as the energy currency of the cell.

The overall mechanism of aerobic respiration can be studied under the following steps :
- Glycolysis (EMP pathway)
- Oxidative Decarboxylation
- Krebs’s cycle (TCA-cycle)
- Oxidative phosphorylation

Glycolysis (EMP Pathway or Embden-Meyerhof-Paranus pathway)

* The term has originated from the Greek word, glyco =glucose, lysis = splitting or breakdown means breakdown of glucose molecule.
* It is common in both aerobic and anaerobic respiration.
* It takes place outside the mitochondria, in the cytoplasm.

1. Breakdown of glucose in the cytoplasm of the cell is called glycolysis.
2. One molecule of glucose (Hexose sugar) ultimately produces two molecules of pyruvic acid through glycolysis.
3. A molecule of glucose is phosphorylated into glucose-6-phosphate by utilizing a molecule of ATP.
4. Glucose-6-phosphate is isomerizes into fructose-6-phosphate which is again phosphorylated to form fructose-1,6 diphosphate. Here another molecule of ATP is utilized.
5. Fructose-1,6 diphosphate cleaves into two compounds such as phospho- glyceraldehyde and dihydroxy acetone phosphate which are the isomers and inter convertible.
6. A molecule of phosphoglyceraldehyde is oxidized to 1,3 Diphosphoglyceric acid by loosing hydrogen molecules which are accepted by NAD and reduced to NADH₂
7. 1,3 Diphosphoglyceric acid is converted into 3 phosphoglyceric acid. Here a molecule of ADP is phosphorylated to ATP.
8. 3 phosphoglyceric acid undergo structural re arrangement to form 2 phosphoglyceric acid which in turn undergo dehydration to form phosphoenol pyruvic acid.
9. PEP is converted into a molecule of pyruvic acid by losing phosphate which is accepted by ADP and phosphorylated to ATP.
10. Dihydroxy acetone phosphate is again converted into its isomer phosphoglyceraldehyde that results in the formation of another molecule of pyruvic acid. Hence during glycolysis one molecule of glucose yields two molecules of pyruvic acid, 2 NADH₂ and 2 ATP

\[ \text{Glucose} \rightarrow 2\text{Pyruvic acid} +2\text{NADH}_2+2\text{ATP} \]

9. This biochemical pathway was traced by three German biochemists namely, Embden, Mayorhoff and Parnas. Hence glycolysis is also known as EMP path way.
10. So formed pyruvic acids are pumped into mitochondrial matrix for Kreb’s cycle.
Glucose
ATP ↓
ADP ↓
Glucose-6-Phosphate

↓

Fructose-6-phosphate
ATP ↓
ADP ↓
Fructose-1,6-Diphosphate

Phosphoglyceraldehyde ⇌ Dihydroxy acetone phosphate

NAD ↓
NADH₂ ↓
1,3 Diphosphoglyceric acid

ADP + Pi
ATP

3 Phosphoglyceric acid

2 Phosphoglyceric acid
H₂O
Phoshoenol Pyruvic acid

ADP + Pi
ATP

Energy yield during glycolysis

Pyruvic acid

1 NADH₂ X 2 = 6 ATP (1 NADH₂ = 3 ATP)
2 ATP X 2 = 4 ATP
10 ATP

Utilized = 2 ATP
Net energy = 8 ATP

Oxidative decarboxylation:

- Pyruvic acid formed in the cytoplasm enters into mitochondria.
- Pyruvic acid is converted into Acetyl CoA in presence of pyruvate dehydrogenase complex.
- The pyruvate dehydrogenase catalyses the reaction require several coenzymes, including NAD⁺ and Coenzyme A.
- During this process two molecules of NADH are produced from metabolism of two molecules of pyruvic acids (produced from one glucose molecule during glycolysis).
- The Acetyl CoA (2c) enters into a cyclic pathway, tricarboxylic acid cycle.

Tri Carboxylic Acid Cycle (Krebs cycle) or Citric acid Cycle:

1. Pyruvic acid synthesized during glycolysis is pumped into the mitochondrial matrix where Kreb’s cycle operates.
2. A molecule of pyruvic acid combine with coenzyme ‘A’ to undergo de-hydrogenation and de-carboxylation to produce acetyl Co A. Here NAD is reduced to NADH₂ and a molecule of CO₂ is liberated.
3. Acetyl Co A combine with Oxalo acetic acid to form Citric acid by losing coenzyme A.
4. Citric acid undergoes dehydration to form Cis-aconitic acid which in turn hydrated to form Isocitric acid.
5. Isocitric acid undergoes dehydrogenation to form Oxalo Succinic acid. Here NAD reduced to NADH₂.
6. Oxalo Succinic acid is decarboxylated to form α-Ketoglutaric acid. Here another molecule of CO₂ is liberated.
7. α-Ketoglutaric acids undergo dehydrogenation and de-carboxylation to form succinyl CoA. Here NAD is reduced to NADH₂ and one more molecule of CO₂ is liberated.
8. Succinyl Co A is converted into succinic acid by loosing a phosphate molecule which is accepted by GDP and phosphorylated to GTP (Guanosine triphosphate).
9. Succinic acid undergoes dehydrogenation to produce Fumaric acid. Here FAD (Flavin Adenine Dinucleotide) is reduced to of FADH₂.
10. Fumaric acid is hydrated to form malic acid which in turn dehydrogenated to form Oxalo-acetic acid. Here NAD is reduced to NADH₂.
11. OAA combine with another molecule of Acetyl Co A formed by the second molecule of pyruvic acid to produce Citric acid again. Hence Kreb’s cycle is also known as Citric acid cycle. Since Citric acid has there carboxylic groups. Hence it is also known as TCA cycle (Tricarboxylic acid cycle).

Total energy yielded during Kreb’s cycle.

4NADH₂ × 2 = 8 NADH₂ = 24 ATP
1 FADH₂ × 2 = 2 FADH₂ = 4 ATP
1 GTP × 2 = 2 GTP = 2 ATP

From glycolysis 8 ATP

Total 38 ATP/Glucose

➢ The products during Krebs cycle from one molecule of pyruvic acid are:
   o 2 molecule of CO₂
   o 3 NADH₂
   o 1 FADH₂
   o 1 GTP

➢ During the whole process of oxidation of glucose produce:
   o 6 CO₂
   o 10 NADH₂
   o 2 FADH₂
Electron transport system and oxidative phosphorylation:

- The metabolic pathway, through which the electron passes from one carrier to another, is called **Electron transport system**.
- It is present in the inner mitochondrial membrane.
- ETS comprises of the following:
  - Complex I – NADH Dehydrogenase.
  - Complex II – Succinate dehydrogenase.
  - Complex III – Cytochromes bc1
  - Complex IV – Cytochromes a-a3 (cytochromes c oxidase).
  - Complex V – ATP synthase.
- NADH₂ produced in the citric acid cycle oxidized by NADH Dehydrogenase, and electrons are then transferred to ubiquinone located in the inner membrane.
- FADH₂ is oxidized by succinate dehydrogenase and transferred electrons to ubiquinone.
- The reduced ubiquinone is then oxidized with transfer of electrons to cytochrome c via cytochromes bc1 complex.
- Cytochrome c is a small protein attached to the outer surface of the inner membrane and acts as a mobile carrier for transfer electrons from complex III and complex IV.
- When electrons transferred from one carrier to another via complex I to IV in the electron transport chain, they are coupled to ATP synthase for the synthesis of ATP from ADP and Pi.
- One molecule of NADH₂ gives rise to 3 ATP.
- One molecule of FADH₂ gives rise to 2ATP.
- Oxygen plays a vital role in removing electrons and hydrogen ion finally production of H₂O.
- Phosphorylation in presence of oxygen is called oxidative phosphorylation.

**Total number of ATP produced during aerobic respiration:**

- Glycolysis 2ATP + 2NADH₂ (6ATP) = 8ATP
- Oxidative decarboxylation 2NADH₂ (6ATP) = 6ATP
- Krebs’s Cycle 2GTP (2ATP) + 6NADH₂ (18ATP) + 2FADH₂ (4ATP) = 24 ATP
- Energy production in prokaryotes during aerobic respiration = 38 ATP
- 2ATP are used up in transporting 2 molecule of pyruvic acid in mitochondria. 38 – 2 = 36 ATP
- Energy production in eukaryotes during aerobic respiration = 36 ATP

**FERMENTATION:**

**Anaerobic Respiration**

Break down of glucose molecules in the absence of molecular oxygen is called anaerobic respiration. Eg., Micro organisms like bacteria and yeast.

Anaerobic respiration is also referred to as fermentation, during which glucose molecules undergo incomplete or partial oxidation to yield two ATP molecules. Glycolysis is the common process in both aerobic and
anaerobic respiration. The fate of pyruvic acid produced during glycolysis is determined by the type of end products where it is converted either into ethyl alcohol or lactic acid.

a) Alcoholic Fermentation

When the micro organism is the yeast cell, glucose molecule undergo glycolysis to produce two molecules of pyruvic acid, two NADH and 2ATP. Pyruvic acid is then converted into acetaldehyde by loosing CO₂. Acetaldehyde combines with NADH to produce ethyl alcohol (C₂H₅OH).

\[
\text{Glucose} \rightarrow 2 \text{Pyruvic acid} + 2 \text{NADH} + 2 \text{ATP}
\]

\[
2 \text{Pyruvic acid} \rightarrow 2 \text{Acetaldehyde} + 2\text{CO}_2
\]

\[
2 \text{Acetaldehyde} + 2 \text{NADH} \rightarrow 2 \text{Ethyl Alcohol}
\]

\[
\text{Glucose} \rightarrow 2 \text{Ethyl Alcohol} + 2\text{CO}_2 + 2 \text{ATP}
\]

b) Lactic Acid Fermentation

When the micro organism is the Lactobacillus bacteria, lactose which is the milk sugar is converted into lactic acid.

\[
\text{Lactose} \rightarrow \text{glucose} + \text{galactose}
\]

\[
\text{Glucose} \rightarrow 2 \text{Pyruvic acid} + 2 \text{NADH} + 2 \text{ATP}
\]

\[
2 \text{Pyruvic acid} + 2 \text{NADH} \rightarrow 2 \text{Lactic Acid}
\]

\[
\text{Glucose} \rightarrow 2 \text{Lactic Acid} + 2 \text{ATP}
\]

Differences between Aerobic and Anaerobic respiration

<table>
<thead>
<tr>
<th></th>
<th>Aerobic</th>
<th>Anaerobic</th>
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<tbody>
<tr>
<td>1</td>
<td>Takes place in the presence of molecular oxygen</td>
<td>Takes place in the absence of oxygen.</td>
</tr>
<tr>
<td>2</td>
<td>Takes place in higher plants and animals</td>
<td>Takes place in lower organisms like yeast and bacteria.</td>
</tr>
<tr>
<td>3</td>
<td>Glucose undergoes complete oxidation</td>
<td>Glucose undergoes incomplete oxidation.</td>
</tr>
<tr>
<td>4</td>
<td>One molecule of glucose yield 38 ATP</td>
<td>One molecule of glucose yield 2 ATP</td>
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<tr>
<td>5</td>
<td>Takes place in cytoplasm and mitochondria</td>
<td>Takes place only in cytoplasm.</td>
</tr>
<tr>
<td>6</td>
<td>Kreb’s cycle and terminal oxidation are present</td>
<td>These steps are absent</td>
</tr>
<tr>
<td>7</td>
<td>The end products are CO₂ &amp; H₂O</td>
<td>The end products are Ethyl alcohol or Lactic acid and CO₂</td>
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Amphibolic Pathway

“The respiratory pathway is involved in both anabolism and catabolism, respiratory pathway is called **amphibolic pathway**”. Breaking down processes within the living organism is catabolism, and synthesis is anabolism.

a) Glucose is the favoured substrate for respiration. All carbohydrates are usually first converted into glucose before they are used for respiration.
b) 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.

(c) 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.

d) Since respiration involves breakdown of substrates, the respiratory process has traditionally been considered a catabolic process and the respiratory pathway as a catabolic pathway.

e) Hence, fatty acids would be broken down to acetyl CoA before entering the respiratory pathway when it is used as a substrate.

f) But when the organism needs to synthesise fatty acids, acetyl CoA would be withdrawn from the respiratory pathway for it.

g) Hence, the respiratory pathway comes into the picture both during breakdown and synthesis of fatty acids.

h) Similarly, during breakdown and synthesis of protein too, respiratory intermediates form the link.

**Respiratory Quotient**

“It is the ratio of amount of CO₂ liberated to the amount of O₂ utilized”.

\[
RQ = \frac{\text{CO}_2 \text{ released}}{\text{O}_2 \text{ utilized}}
\]

RQ value depends on the type of respiratory substrate.

1. RQ = 1
Eg: Carbohydrates

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + 38 \text{ATP} \]
(Glucose)
RQ = 6/6 = 1

2. RQ < 1

Eg: Proteins, fats and Oils

\[ 2\text{C}_{51}\text{H}_{96}\text{O}_6 + 145\text{O}_2 \rightarrow 102 \text{CO}_2 + 98 \text{H}_2\text{O} + \text{ATP} \]
(Tripalmitin)
RQ = 102/145 = 0.4

3. RQ > 1

Eg: Organic Acid

\[ 2(\text{COOH}_2) + \text{O}_2 \rightarrow 4\text{CO}_2 + 2\text{H}_2\text{O} + \text{ATP} \]
(Oxalic Acid)
RQ = 4/1 = 4

Abbreviations:

* ATP – Adenosine tri phosphate
* ADP – Adenosine di phosphate
* NAD – Nicotinamide Adenine dinucleotide
* NADP – Nicotinamide Adenine dinucleotide Phosphate
* NADH – Reduced Nicotinamide Adenine dinucleotide
* PGA – Phosphoglyceric acid
* PGAL – Phospho glyceraldehyde
* FAD – Flavin adenine dinucleotide
* ETS – Electron transport system
* ETC – Electron transport chain
* TCA – Tricarboxylic acid
* OAA – Oxalo acetic acid
* FMN – Flavin mono nucleotide
* PPP – Pentose phosphate pathway