UNIT 3
ENERGY TRANSFORMATION

Introduction

- Living things require energy for various essential processes that sustain life.
- Living things extract energy from their environment through various mechanisms.

- Autotrophy and heterotrophy are the two main strategies for obtaining energy.
- The set of enzyme-mediated chemical reactions that occur within living organisms to maintain life is **Metabolism**.
  - Metabolism is the sum of chemical reactions that takes place within each cell of an organism.

Energy

- In cells, energy refers to the capacity to do work.
- Cells produce energy for vital processes and also synthesize new organic materials.
- Metabolic reactions can be divided into catabolic reactions and anabolic reactions.

a. Anabolism

- It is the constructive phase of metabolism.
- It is the process whereby simpler substances are joined together to form complex macromolecules.
- The process requires energy to construct substances.
- It is an endergonic (energy-absorbing) reaction.
- It occurs during photosynthesis.

b. Catabolism

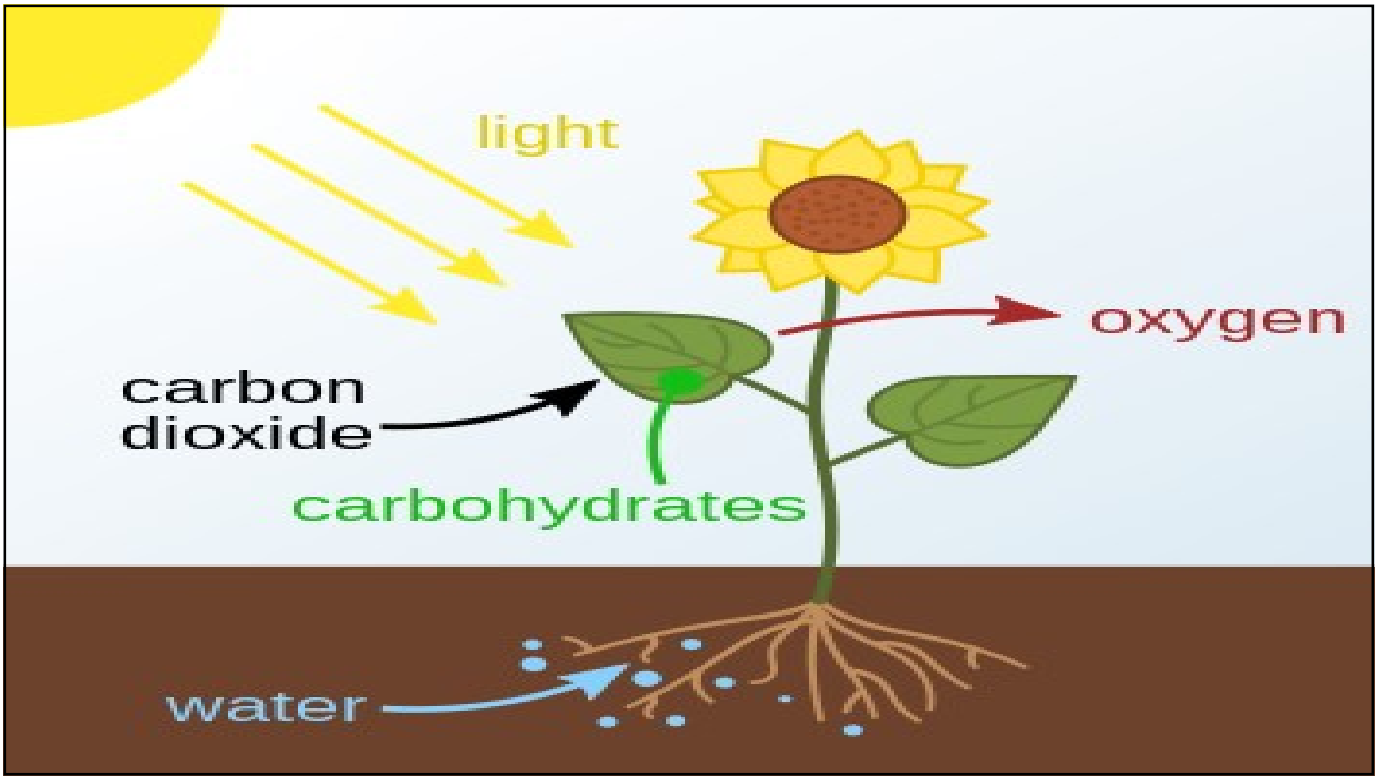
- It is the destructive phase of metabolism.
- It is the process whereby complex macromolecules are broken down to form simpler substances.
- The process releases energy as a result of the breakdown of molecules.
- It is an exergonic (energy-releasing) reaction.
- It occurs during cellular respiration.

PHOTOSYNTHESIS

- It is a series of chemical reactions that use light energy to assemble CO_2 into glucose and other carbohydrates.
- Water is used in the process and O_2 is released as a byproduct.

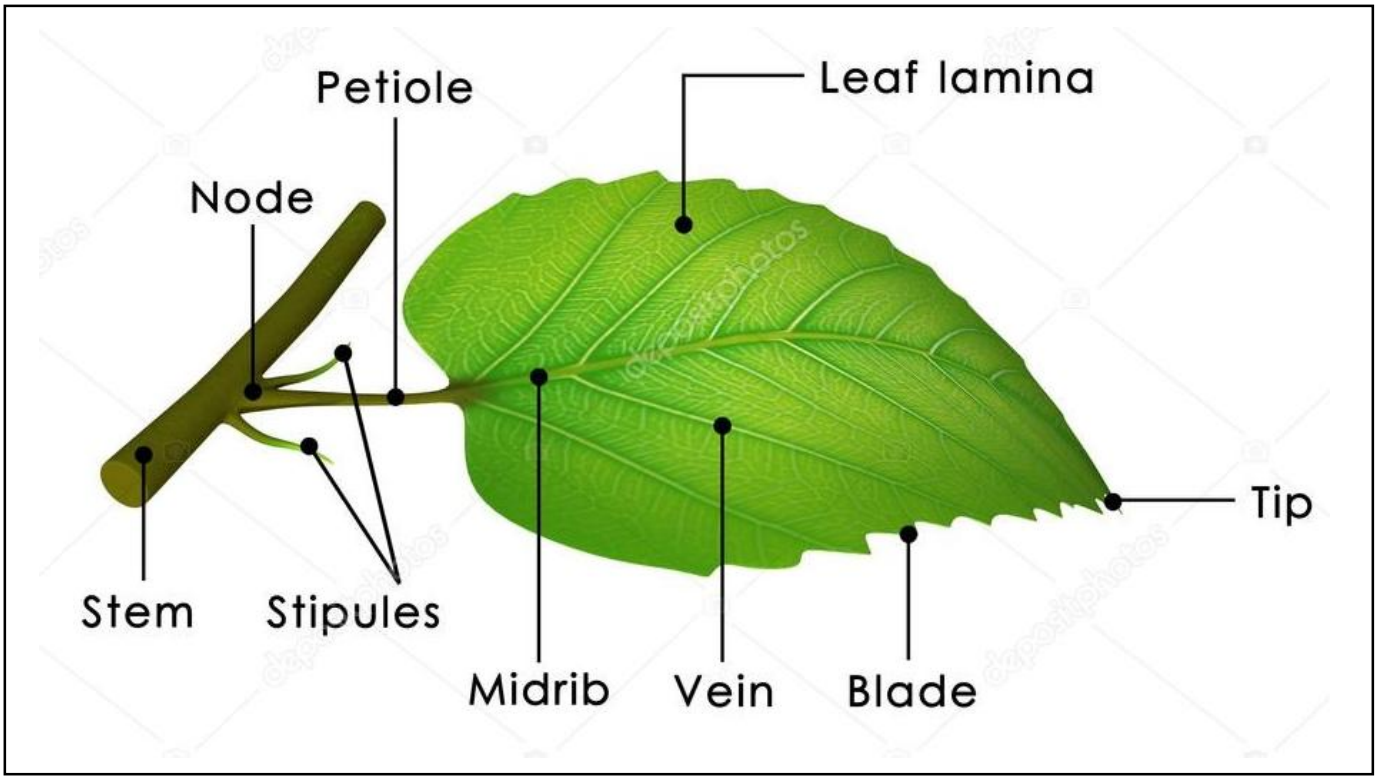
$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

- It is an efficient way to convert solar energy into chemical energy.
- It is the process that forms the basis of life on Earth.
- It provides food for the photosynthetic organisms.
- It provides energy, raw materials, and O_2 to support most heterotrophs.
- It contributes to the carbon cycle.



External and Internal structure of the leaf

- Leaves are the primary organs involved in photosynthesis in most plants.
- A leaf has three main parts:
  1. Leaf base,
  2. Petiole, and
  3. Leaf lamina.



- The leaf base is the lower part of a leaf where it attaches to the stem or the branch.
  - In many plants, the leaf base transitions into a structure called the petiole.
- Petiole is a stalk that connects the leaf blade to the stem.
- The leaf lamina (blade) is the flat, expanded part of a leaf that is typically involved in photosynthesis.

a. Epidermis

- It is the outer leaf layer and secrets a waxy coating called the **cuticle**.
  - Cuticle is waterproof and helps the plant retain water.
- It protects the plant organs from drying out and from infection.
- It is a continuous layer on the outside of the plant.
- It is one cell thick and provides protection.

b. Stomata

- Stomata (singular: stoma) are tiny pores found on the surfaces of leaves.
- They play a crucial role in the exchange of gases, particularly carbon dioxide and oxygen, as well as in the regulation of water vapor.
- Stomata are essential for photosynthesis in plants.

c. The mesophyll

- It is made up of specilalised parenchyma cells found between the lower and upper epidermis of the leaf.
  - Parenchyma cells are versatile and play essential roles in plant structure and function. They are characterized by their relatively thin cell walls and the absence of secondary walls.

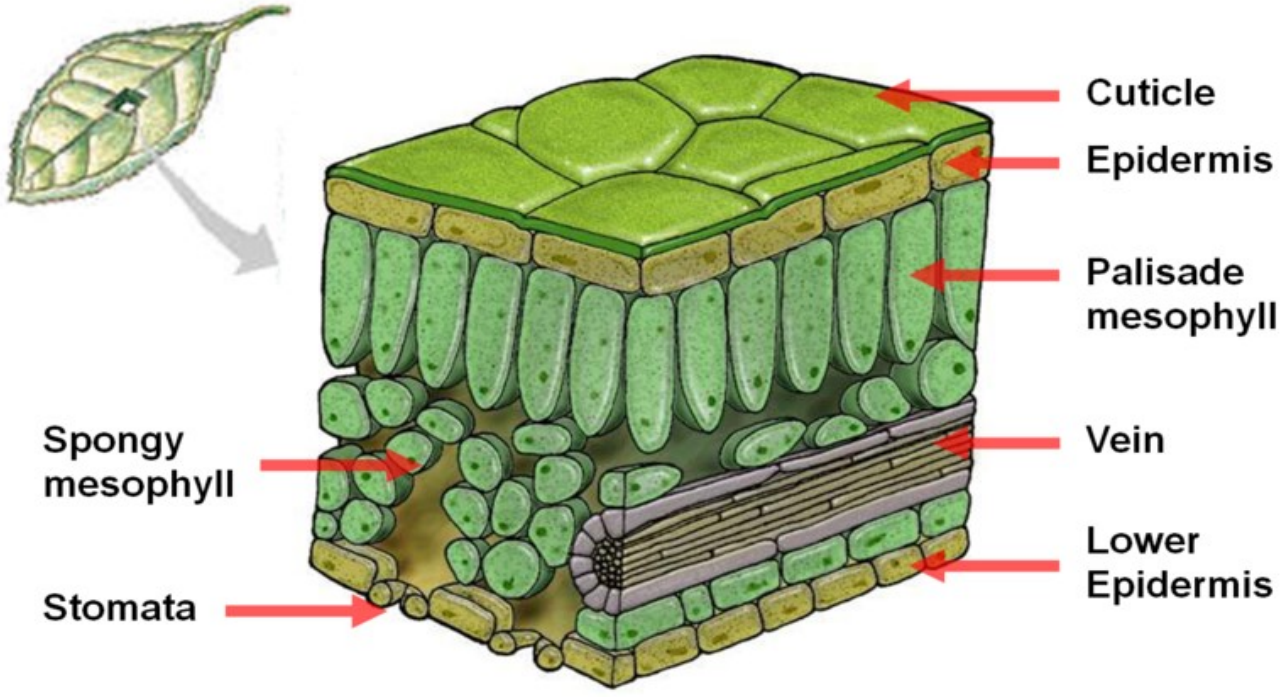
- The mesophyll is a critical tissue in leaves, providing a specialized environment for the photosynthetic process.
  - They are specialised for photosynthesis and therefore contain chloroplasts.
- There are two main types of mesophyll cells: palisade mesophyll cells and spongy mesophyll cells.

i. Spongy mesophyll

- It is located beneath the palisade mesophyll.
- It consists of loosely arranged cells with large intercellular spaces.
  - These spaces create a spongy appearance when observed under a microscope.
- The cells in the spongy mesophyll are not as tightly packed as those in the palisade mesophyll.
- It plays a crucial role in gas exchange.

ii. Palisade mesophyll

- It is located beneath the upper epidermis of the leaf and above the spongy mesophyll.
- The cells in the palisade mesophyll are tightly packed and arranged vertically.
- Palisade mesophyll cells are rich in chloroplasts (high chloroplast density).
- It is the primary site of photosynthesis in the leaf.



Site of Photosynthesis

- The primary site of photosynthesis in plant cells is the **chloroplast**.
- Chloroplasts are double-membraned cellular organelles found in the cells of plants.
- Chloroplasts contain **chlorophyll**.
- Chlorophyll absorbs light energy during the light-dependent reactions of photosynthesis.

Chloroplast Structure

- The structural organization of chloroplasts allows them to carry out the complex processes of photosynthesis efficiently.

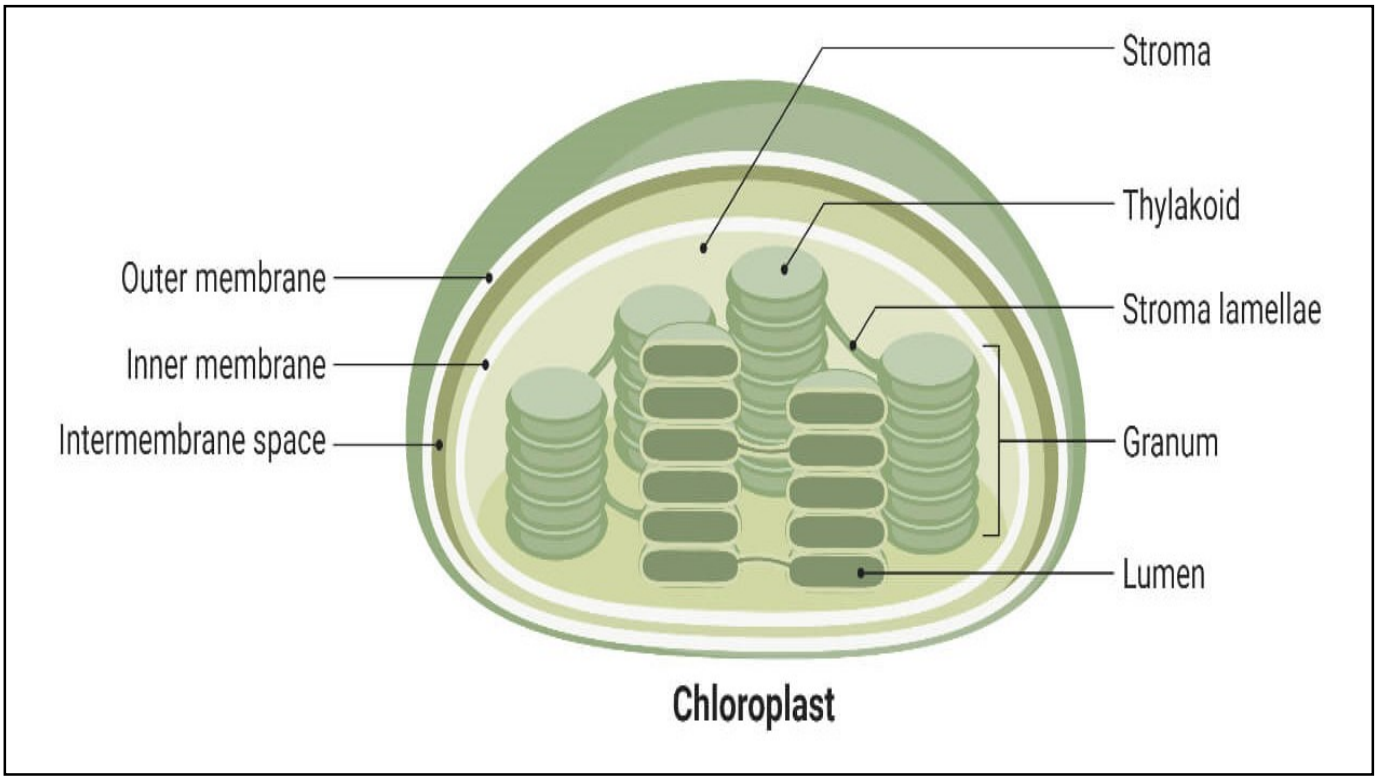
a. Thylakoids

- Internal membranes within chloroplasts where the light-dependent reactions take place are thylakoid membranes.

- Chlorophyll is a green pigment found in the thylakoid membranes of chloroplasts.
- The interior of thylakoid is called **lumen**.
- The grana consist of stacks of thylakoids.
- Chloroplasts can have from 10 to 100 grana.
- The intergranal lamellae connects all the grana present in the chloroplast.

b. Stroma

- It is the semi-fluid matrix that fills the interior of the chloroplast and it surrounds the thylakoid membranes.
- It is the site for the light-independent reactions.
- The stroma contains enzymes and proteins necessary for various metabolic pathways related to photosynthesis.



Photosynthetic Pigments

- Photosynthetic pigments are molecules that capture and absorb light energy for the process of photosynthesis.
- The primary photosynthetic pigments in plants are chlorophylls, but there are also accessory pigments that broaden the range of light absorption.

Chlorophyll-a

- It is the primary pigment involved in the light-dependent reactions of photosynthesis.
- It is directly involved in the conversion of light energy into chemical energy during photosynthesis.
- It absorbs violet-blue and reddish orange-red and reflects green light, giving plants their characteristic green color.

Chlorophyll-b

- It expands the overall range of light wavelengths that a plant can absorb for photosynthesis.
- It captures wavelengths that chlorophyll-a cannot efficiently absorb.
- It absorbs mostly blue and yellow light.

Carotenoids

- Carotenoids are pigments which exhibit yellow, orange, red and purple colors.
- They absorb in the blue-green region of the solar spectrum.
- Carotenoids can be further categorized into two classes – xanthophylls and carotenes.

Xanthophylls

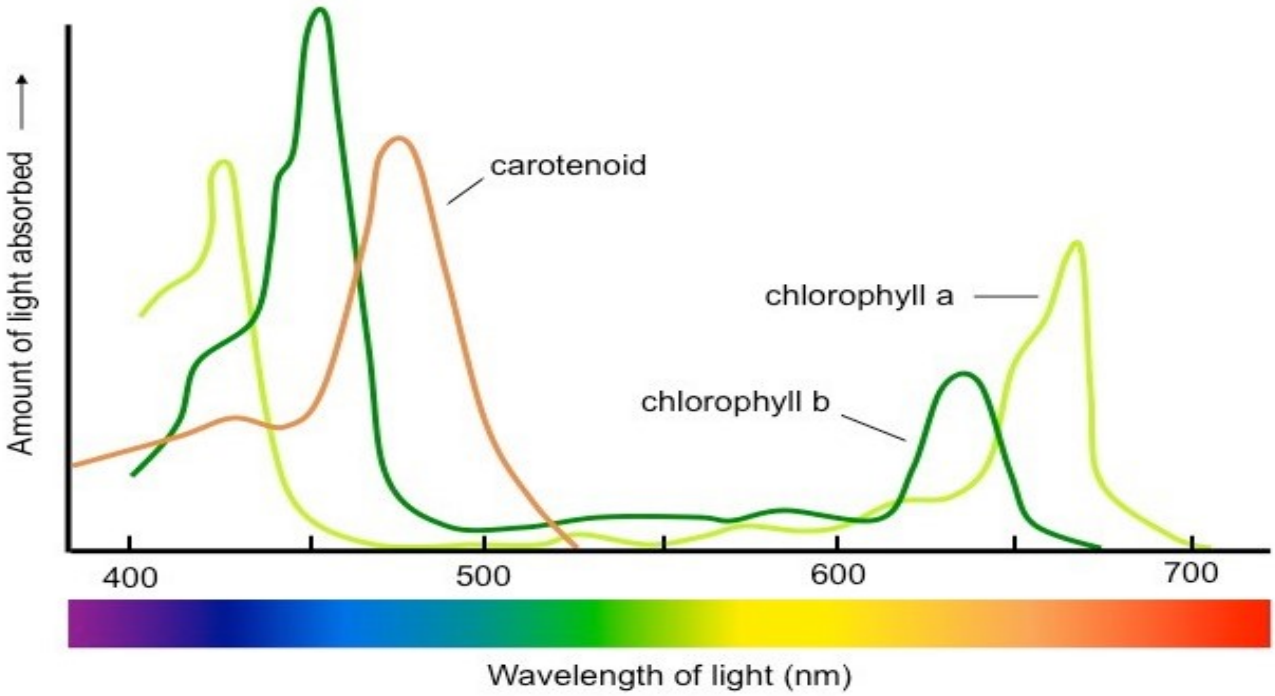
- Xanthophylls are typically yellow to orange pigments.
- They absorb light energy in the blue and green regions of the spectrum, which complements the absorption spectra of chlorophylls.

Fucoxanthin

- It is a brownish-yellow pigment found in the chloroplasts of brown algae.
- It is responsible for the characteristic brown or olive-green color of brown algae.
- It has absorption peaks in the blue-green range.

Phycobilins

- They are water-soluble pigments found in Cyanobacteria & Red Algae.
- They are found in the cytoplasm (Cyanobacteria) or in the stroma of the chloroplast (Rhodophyta).
- They absorb light in the blue and red regions.
- Phycobilins are localized in specialized structures called **phycobilisomes**.



Light-dependent and Light-independent reactions

1. Light-dependent reactions (cyclic and noncyclic photophosphorylation)

- It converts solar energy to chemical energy.
- Water is split and O_2 is released as a byproduct.
- Transfer of electrons and hydrogen ions from water to $NADP^+$

- Reduction of $NADP^+$ to NADPH by addition of a pair of electrons along with H^+.
- Generation of ATP using chemiosmosis (photophosphorylation)
- The light reactions do not produce sugar

Comparison of Non-cyclic photophosphorylation and cyclic photophosphorylation

Feature	Noncyclic Photophosphorylation	Cyclic Photophosphorylation
Occurrence	Occurs in both photosystem I and II	Occurs specifically in photosystem I (PSI)
Electron Flow	Electrons flow linearly from PSII to PSI	Electrons follow a cyclic pathway and return to PSI
Purpose	Generates both ATP and NADPH for the synthesis of organic molecules	Generates ATP for cellular energy needs
Production of ATP	Produces ATP and NADPH for the Calvin Cycle	Produces ATP, contributing to ATP synthesis
Oxygen Production	Releases oxygen gas as a byproduct	Does not result in the release of oxygen gas
Electron Donors	Electrons are donated by water molecules, splitting in PSII	Electrons are donated by PSI's chlorophylls
Last Electron Acceptor	NADP+ (Reduced to NADPH)	PSI's chlorophylls (Cyclic process, no final electron acceptor)

Photosystems

- Photosystems are functional and structural units of protein complexes involved in photosynthesis.
- Photosystems are found in the thylakoid membranes of the chloroplasts in plant cells.
- There are two kinds of photosystems: PSI and PSII.

- Each photosystem has two parts: a reaction center and an antenna complex.
- The two photosystems work together to capture and convert light energy into chemical energy during the light-dependent reactions of photosynthesis.

Photosystem I and II

- Photons of light are absorbed by chlorophyll and other pigments.
- The absorbed light energy excites electrons in the chlorophyll molecules.
- The excited electrons are donated to the primary electron acceptor (pheophytin), leaving P680 in an oxidized state.

- To replenish the electrons lost from chlorophyll, water molecules are split in a process called **photolysis**.
- Electrons from water are used to replace the lost electrons in the chlorophyll, and oxygen is released as a byproduct.

- The excited electrons from the primary electron acceptor move through a series of proteins in the thylakoid membrane, known as the **electron transport chain (ETC).**
  - This chain pumps protons (H^+ ions) across the thylakoid membrane into the thylakoid space.

- The flow of protons back into the stroma through ATP synthase drives the synthesis of ATP from ADP and inorganic phosphate (P_i) in a process known as **chemiosmosis.**
- The electrons from the ETC are eventually transferred to photosystem I (PSI) via a protein called plastocyanin.

- PSI absorbs light and re-energizes the electrons.
- The energized electrons are then transferred to $NADP^+$, reducing it to NADPH.

2. Light-independent reactions (Calvin cycle)

- They are a series of chemical reactions that take place in the stroma of chloroplasts during photosynthesis.
- They do not directly rely on light.
- It is purely enzymatic and slower than light reaction.

- It uses the products of the light-dependent reactions (ATP and NADPH) to convert carbon dioxide into glucose or other sugars.
- In the stroma, in addition to CO_2, two other components are present to initiate the light-independent reactions: RuBisCO and RuBP.
- It has 3 basic stages:

1. Carbon fixation

- It is a biochemical process in which CO_2 is converted into organic compounds.
- 3 molecules of CO_2 are combined with 3 molecules of ribulose-1,5-bisphosphate (RuBP) with the help of ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO).

- The combination of CO_2 and RuBP forms an unstable six-carbon compound that immediately breaks down into two molecules of 3-phosphoglycerate (3-PGA).

2. Reduction

- It refers to the chemical process in which 3-PGA is converted into glyceraldehyde-3-phosphate (G3P).
- It involves the addition of electrons and protons to 3-PGA and it is an energy-requiring step.

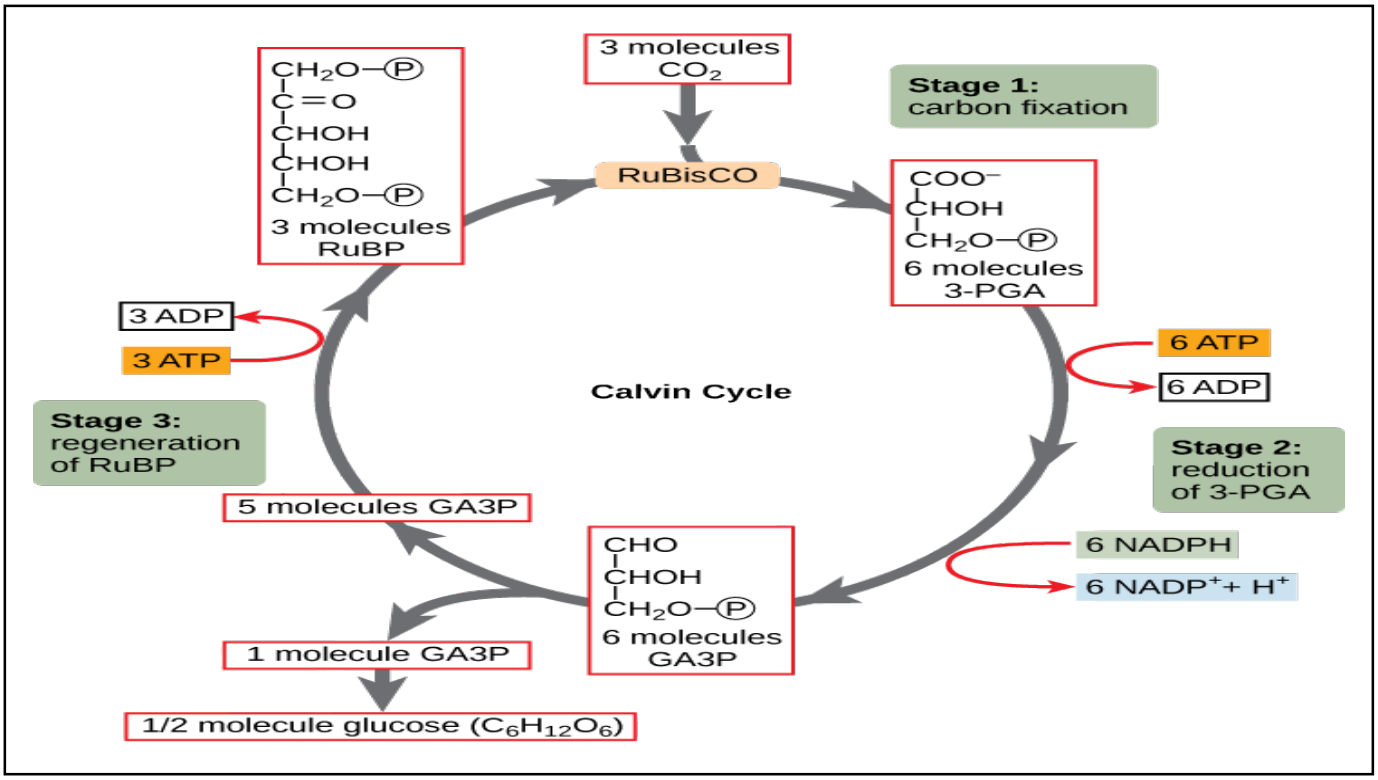
- 6 ATP and 6 NADPH provide the energy and electrons needed to convert six molecules of 3-PGA into six molecules of G3P.

$$\text{3-PGA} + \text{ATP} + \text{NADPH} \rightarrow \text{G3P} + \text{ADP} + \text{NADP}^+ + P_i$$

- The enzyme that plays a crucial role in this conversion is called glyceraldehyde-3-phosphate dehydrogenase (GAPDH).

3. Regeneration of RuBP

- Some of the G3P molecules are used to regenerate RuBP, ensuring the continuity of the Calvin cycle.
- Out of the six G3P molecules produced, only one is directly used for the synthesis of glucose.
- 3 ATP molecules are consumed during various steps of the regeneration phase.



Photosynthetic Pathways

a. C3 Photosynthesis

- Most plants, including crops like wheat, rice, rye, oats and soybeans, use C3 photosynthesis.
- It takes place in mesophyll cells of leaves.
- The first stable compound formed during carbon fixation is 3-PGA (a three-carbon compound).

- It is efficient under moderate temperatures and normal atmospheric conditions.
- It is less efficient in hot and dry conditions due to photorespiration.

b. C4 Photosynthesis

- Certain plants, especially those in hot and arid regions, use C4 photosynthesis.
- It involves spatial separation with initial carbon fixation occurring in mesophyll cells and the Calvin cycle in bundle sheath cells.

- The first stable compound formed during carbon fixation is a four-carbon compound, oxaloacetate.
- C4 plants are adapted to high temperatures and can minimize water loss.
- They show reduced photorespiration making them efficient in arid environments.
- Examples include maize, sorghum, and sugarcane.

Steps

1. fixation of CO_2 by carboxylation of PEP in mesophyll cells to form oxaloacetic acid.
2. Transport of oxaloacetic acid to bundle sheath cells
   - The absence of thylakoids in bundle sheath chloroplasts is an adaptation that minimizes photorespiration

3. Decarboxylation of C4 acids within the bundle sheath cells and generation of CO_2 and pyruvate.
4. Transport of C3 acid to the mesophyll and regeneration of PEP.

c. CAM photosynthetic pathway

- CAM photosynthesis is employed by succulent plants like cacti.
- CAM plants open stomata at night and fix CO_2 into organic acids, storing them in vacuoles.
- The Calvin cycle occurs during the day.

- Initial carbon fixation produces a four-carbon organic acid (oxaloacetate).
- CAM plants are adapted to arid environments and reduce water loss by opening stomata at night when temperatures are lower.
- This pathway allows for CO_2 uptake during the night and minimizes water loss during the day.

Steps

- During the night, CAM plants open their stomata to allow the entry of CO_2.
- CO_2 taken in during the night is fixed into oxaloacetate.
  - ➢ This initial carbon fixation occurs in mesophyll cells of the plant.

- PEP carboxylase is a key enzyme involved in the initial fixation of CO_2 during CAM photosynthesis.
- Phosphoenolpyruvate (PEP) is the substrate for PEP carboxylase.
  - ➢ PEP is a three-carbon compound.

Phosphoenolpyruvate (PEP) + CO_2 → Oxaloacetate

- Oxaloacetate is reduced to malate in a reaction catalyzed by malate dehydrogenase.
- Malate is a four-carbon organic acid, and it is stored in vacuoles within the plant cells.
- During the day, CAM plants close their stomata to minimize water loss through transpiration.

- The malate produced during the night serves as a storage form of carbon.
- Malate is stored in vacuoles until it is needed for the Calvin cycle.
- During the day, malate is transported out of vacuoles to the chloroplasts where decarboxylation occurs.

- Malic enzyme catalyzes the conversion of malate to pyruvate and releases CO_2 in the process.

$$\text{Malate} \rightarrow \text{Pyruvate} + CO_2$$

- The released CO_2 is then used in the Calvin cycle to drive photosynthesis.

Photorespiration

- It is the oxidation of organic compounds in plants by oxygen in the presence of light.
- It releases CO_2 but no ATP.
  - ➢ It is a wasteful process because it can reduce the efficiency of photosynthesis.

- RuBisCO can also catalyze the oxygenation of RuBP.
  - formation of one molecule of 3-PGA and one molecule of phosphoglycolate.
- It is common in C3 plants but highly reduced in C4 and absent in CAM plants.

- The compensation point occurs when the rate of CO_2 uptake through photosynthesis equals the rate of CO_2 release through photorespiration.
  - At this point, there is neither a net gain nor a net loss of carbon by the plant.

Contributions of photosynthesis

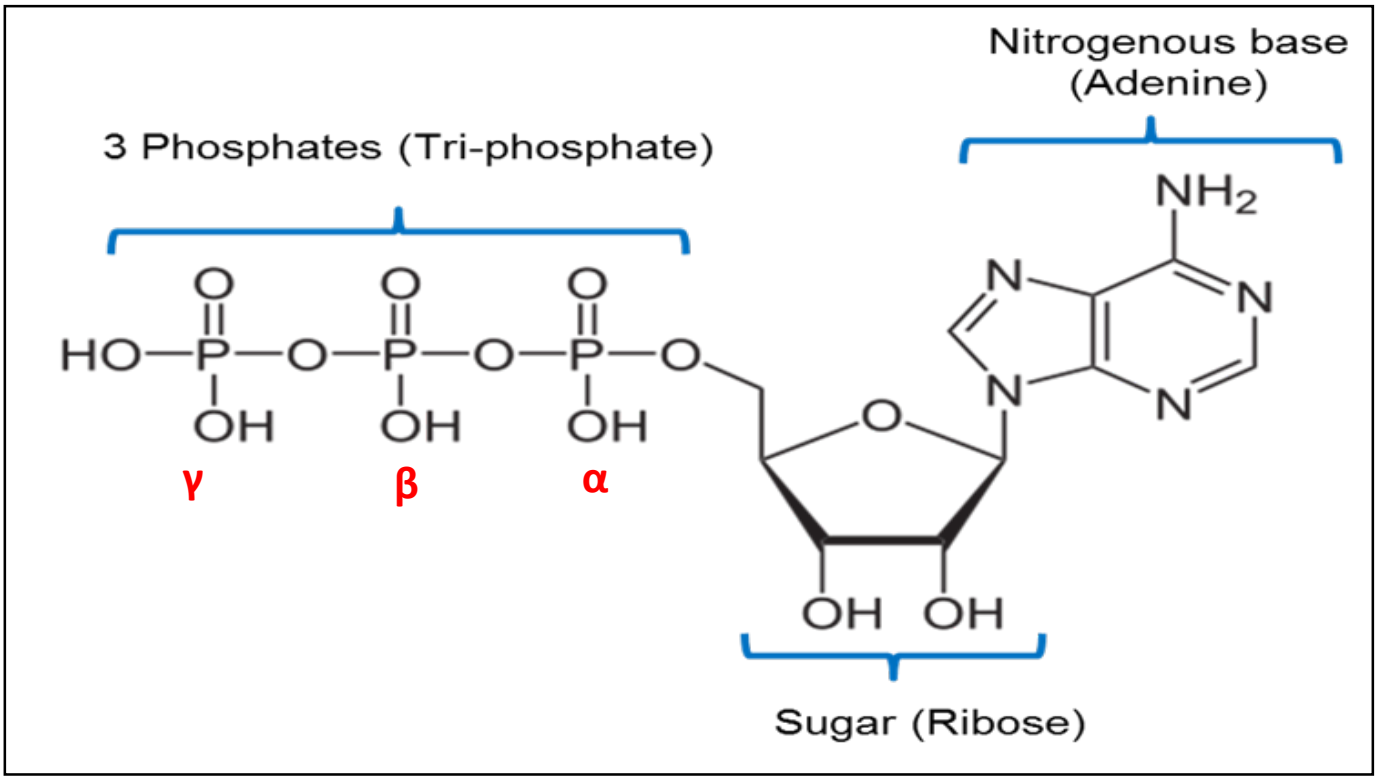
- Photosynthesis is the primary process responsible for the production of oxygen in the atmosphere.
- It converts CO_2 from the atmosphere into organic compounds, such as glucose.
- The glucose synthesized during photosynthesis serve as a primary source of energy for organisms.

- Photosynthesis is the foundation of the food web, as autotrophic organisms produce their own food through photosynthesis.
- The synthesized organic matter contributes to the formation of biomass in ecosystems.
- It regulates the concentrations of atmospheric gases, especially CO_2 and oxygen.

- Photosynthesis plays a role in regulating the Earth's climate by influencing the levels of greenhouse gases, such as CO_2.
  - The absorption of CO_2 by plants helps mitigate the greenhouse effect.
- Photosynthesis plays a crucial role in influencing global warming, as it directly affects the balance of greenhouse gases, especially CO_2.

RESPIRATION

- It is the process by which cells produce energy from glucose in the form of ATP for various cellular activities.
  - ATP is a nucleotide consisting of an adenine base attached to a ribose sugar, which is attached to three phosphate groups.



- The three phosphate groups of ATP are linked to one another by two high-energy bonds called phosphoanhydride bonds.
  - When one phosphate group is removed by breaking a phosphoanhydride bond in a process called hydrolysis energy is released, and ATP is converted to ADP.

- Energy is also released when a phosphate is removed from ADP to form AMP.
- The free energy from the breaking of phosphoanhydride bond can be transferred to other molecules to make unfavorable reactions in a cell favorable.
- AMP, ADP, and ATP are constantly interconverted as they involve in biological reactions.

Coupled Reactions

- A biochemical concept where the energy released during one chemical reaction is used to drive another reaction.
- The energy produced by an exergonic reaction is harnessed to fuel an endergonic reaction.

- ATP is often the key molecule involved in coupling reactions.
- An example of a coupled reaction is the hydrolysis of ATP and the contraction of muscle tissue.
  - The energy released during the hydrolysis of ATP is utilized to power muscle contraction.

- Another example of a coupled reaction is the hydrolysis of creatine phosphate to release energy which in turn is used for the formation of more ATP.
  - The hydrolysis of creatine phosphate involves the transfer of a phosphate group from creatine phosphate to ADP, forming ATP.

The Site of Cellular Respiration

- Cellular respiration is carried out by both prokaryotic and eukaryotic cells.
- In prokaryotes, such as bacteria and archaea, cellular respiration occurs in the cytoplasm.
  - The electron transport chain and oxidative phosphorylation in prokaryotes take place on the cell membrane.

- In eukaryotic cells, cellular respiration occurs in the the cytoplasm and mitochondria.
  - Glycolysis occurs in the cytoplasm.
  - The site of pyruvate oxidation is the mitochondria.
  - The mitochondria play a central role in the generation of ATP through the citric acid cycle and the electron transport chain.

Stages of respiration

- The stages of cellular respiration are glycolysis, transition reaction (pyruvate oxidation), the Krebs cycle (citric acid cycle), and oxidative phosphorylation through the elctron transport chain.

1. Glycolysis

- It occurs in the cytosol of the cell in anaerobic condition.
- It is the common pathway of both aerobic and anaerobic respiration.
- It begins cellular respiration by breaking glucose into two molecules of pyruvate.

- Glycolysis occurs in the cytoplasm and consists of 10 enzyme-catalyzed steps.

Step 1: Glucose Phosphorylation

- Glucose is phosphorylated by ATP to form glucose-6-phosphate.

Step 2: Isomerization

- Glucose-6-phosphate is converted to its isomer, fructose-6-phosphate.

Step 3: Phosphorylation

- Fructose-6-phosphate is phosphorylated by ATP to form fructose-1,6-bisphosphate.

Step 4: Cleavage

- Fructose-1,6-bisphosphate is cleaved into two three-carbon compounds: dihydroxyacetone phosphate (DHAP) and glyceraldehyde-3-phosphate (G3P).

Step 5: Isomerization

- DHAP is isomerized to form another molecule of G3P.

Step 6: Oxidation and Phosphorylation

- G3P is oxidized, and NAD+ is reduced to form NADH.
- Inorganic phosphate is added to G3P, forming 1,3-bisphosphoglycerate.

Step 7: Phosphorylation

- 1,3-bisphosphoglycerate is converted to 3-phosphoglycerate by transferring a phosphate group to ADP, forming ATP.

Step 8: Isomerization

- 3-phosphoglycerate is isomerized to form 2-phosphoglycerate.

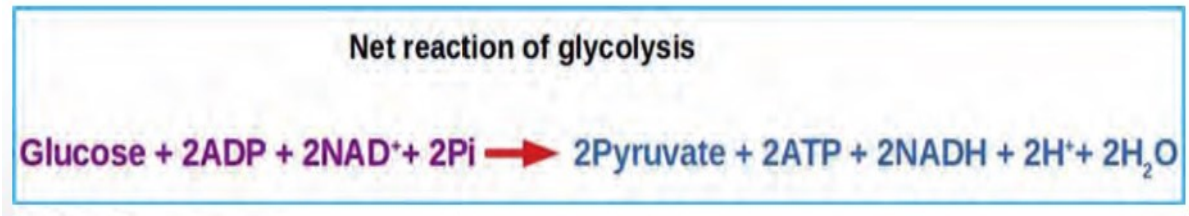
Step 9: Dehydration

- 2-phosphoglycerate undergoes dehydration to form phosphoenolpyruvate (PEP).

Step 10: Phosphorylation

- PEP is converted to pyruvate by transferring its phosphate group to ADP, forming ATP.

- At the end of glycolysis, one molecule of glucose is converted into two molecules of pyruvate, and a net gain of two molecules of ATP and two molecules of NADH are achieved.



2. Pyruvate Oxidation (The link reaction)

- It is a crucial step in cellular respiration, linking glycolysis to the citric acid cycle.
- Pyruvate undergoes a series of enzymatic reactions that result in the production of acetyl coenzyme A (acetyl CoA).
- It takes place in the mitochondrial matrix in eukaryotic cells.

The key steps involved in pyruvate oxidation

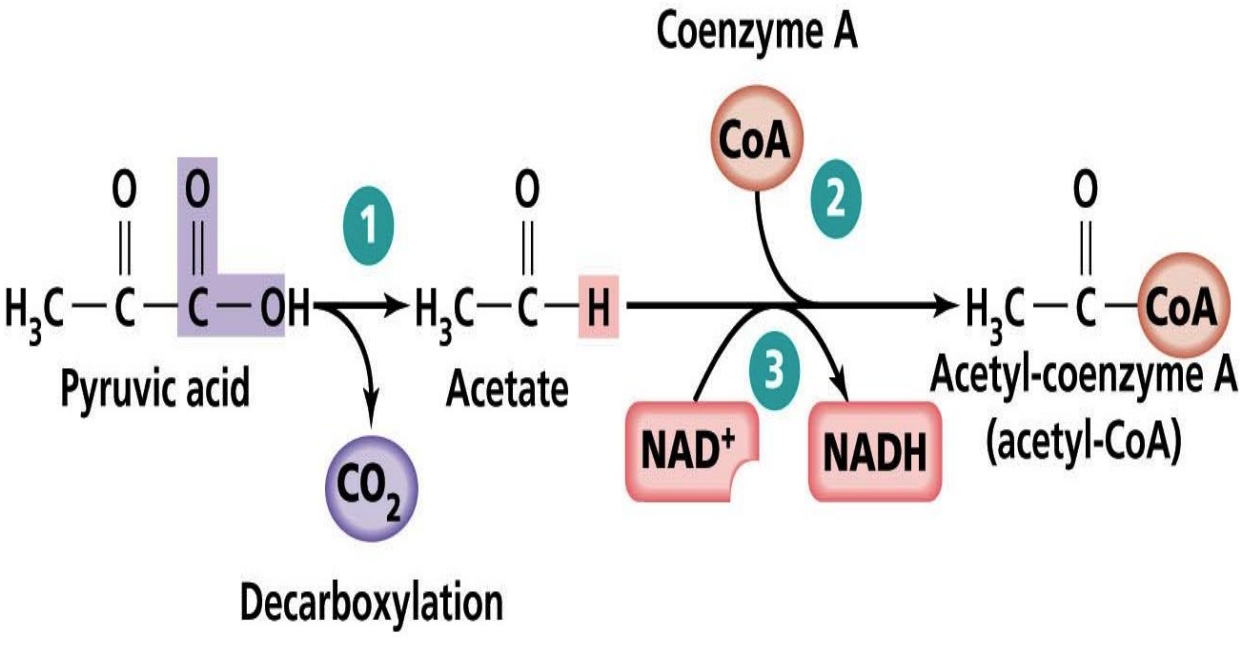
Step 1: A carboxyl group is removed from pyruvate, releasing a molecule of carbon dioxide into the surrounding medium.

Step 2: The hydroxyethyl group is oxidized to an acetyl group, and the electrons are picked by NAD^+, forming NADH.

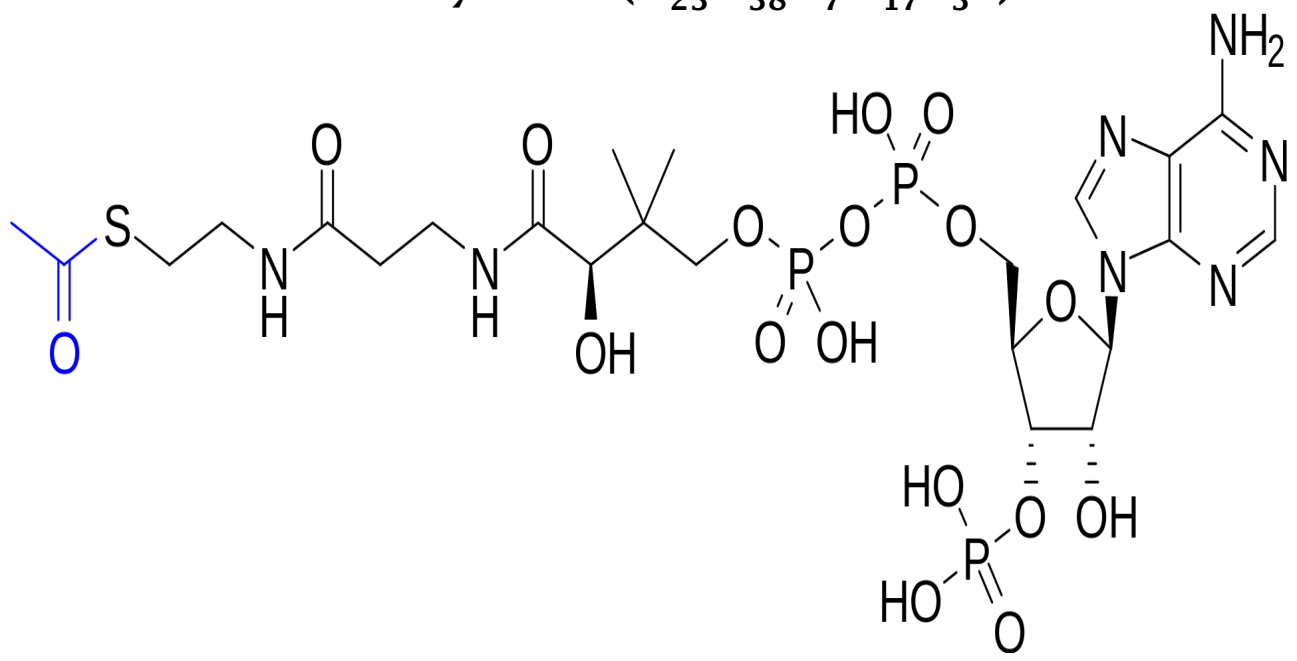
Step 3: The enzyme-bound acetyl group is transferred to CoA, producing a molecule of acetyl CoA.

$$2\text{pyruvate} + 2\text{NAD+} + 2\text{ CoA} \rightarrow 2\text{ acetyl-CoA} + 2\text{NADH} + 2\text{H+} + 2\text{CO2}$$

- The acetyl-CoA enter the Krebs cycle, NADH goes to ETC to produce ATP. CO_2 diffuses out of the cell as a waste product. The protons ($2H^+$) stay in the matrix.



Acetyl-CoA ($C_{23}H_{38}N_7O_{17}P_3S$)



3. Kreb Cycle

- It takes place in the mitochondria of eukaryotic cells and the cytoplasm of prokaryotic cells.
- It is also known as the citric acid cycle or tricarboxylic acid (TCA) cycle.
- It completes the breakdown of carbohydrates, fats, and proteins.

- It plays a crucial role by providing electrons to the electron transport chain.

The key steps of the Krebs Cycle

1. Citrate formation

- The Acetyl-CoA formed from the breakdown of carbohydrates, fats, or proteins enters the cycle by combining with oxaloacetate (4C), forming citrate (6C).

2. Citrate isomerization

- Citrate undergoes isomerization to isocitrate.

3. α-Ketoglutarate formation

- Isocitrate is converted to α-ketoglutarate, releasing CO_2 and producing NADH.

4. Succinyl-CoA formation

- α-ketoglutarate is transformed into succinyl-CoA, releasing another molecule of carbon dioxide and producing NADH.

5. Succinate formation

- Succinyl-CoA is converted to succinate with the release of GTP and the conversion of a NAD^+ to NADH.

6. Fumarate formation

- Succinate is oxidized to fumarate, producing $FADH_2$.

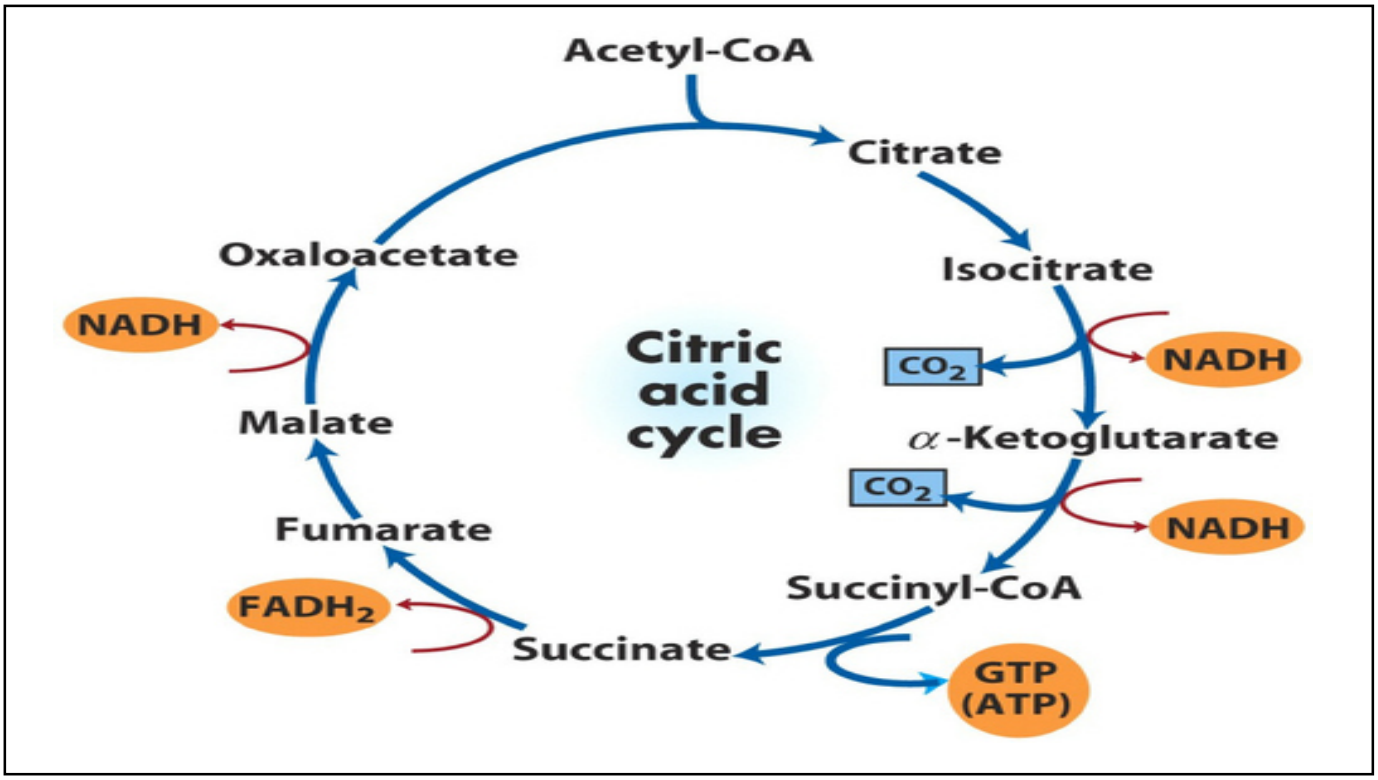
7. Malate formation

- Fumarate is further transformed into malate.

8. Regeneration of Oxaloacetate

- Malate is converted back to oxaloacetate, and the cycle can start again.

- In a single turn of the cycle,
  - 2 CO_2 are released
  - 3 NADH and 1 $FADH_2$ are generated
  - 1 GTP (ATP) is produced.
- The Krebs cycle makes a lot of ATP indirectly, by way of the NADH and $FADH_2$ it generates.



- The overall reaction of the Krebs cycle is:

$$\text{Acetyl-CoA} + 3NAD^+ + 1FAD + 1ADP + 1P_i \rightarrow 2CO_2 + 3NADH + 3H^+ + 1FADH_2 + 1ATP$$

4. Oxidative Phosphorylation

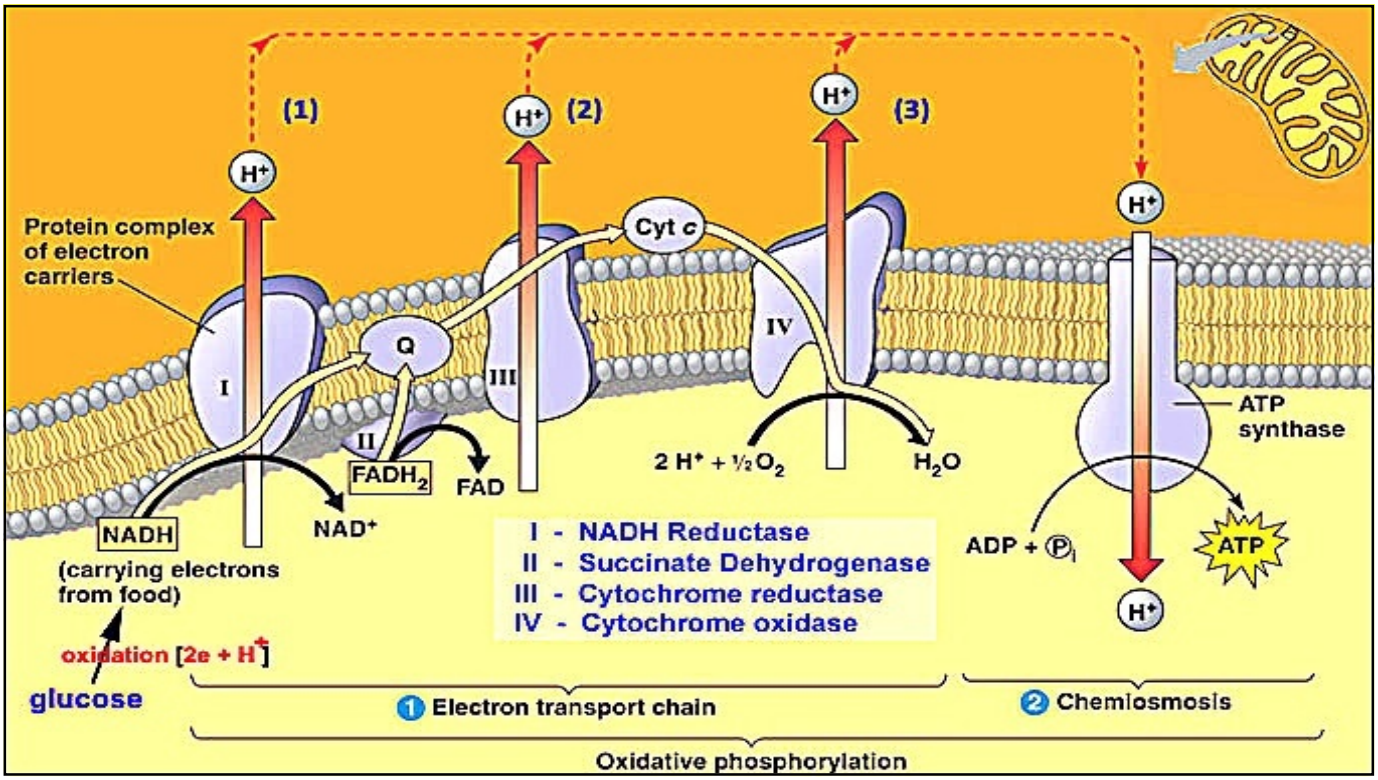
- It is the process in which ATP is formed as a result of the transfer of electrons from NADH or $FADH_2$ to O_2 by a series of electron carriers.
- It is a highly efficient process for ATP production.
- It takes place in the inner mitochondrial membrane of eukaryotic cells and the plasma membrane of prokaryotic cells.

- It involves the transfer of electrons through a series of protein complexes known as the electron transport chain (ETC) and the synthesis of ATP through the process of chemiosmosis.
- In the inner mitochondrial membrane, there are protein complexes (Complex I, II, III, and IV) that make up the electron transport chain.

- The protein complexes contain electron carriers that pass electrons from one to another.
- Electrons are initially donated by molecules such as NADH and $FADH_2$.
- As electrons move through the ETC, they lose energy, which is used to actively pump protons (H^+ ions) from the mitochondrial matrix into the intermembrane space.

- The pumping of protons creates a proton gradient, with a higher concentration of protons in the intermembrane space compared to the mitochondrial matrix.
- ATP synthase allows protons to flow back into the mitochondrial matrix, and as they do so, ATP synthase harnesses the energy released to synthesize ATP from ADP & inorganic phosphate.

- The flow of protons through ATP synthase is coupled with the synthesis of ATP, a process known as oxidative phosphorylation.
- At the end of the electron transport chain, oxygen serves as the terminal electron acceptor.
  - Oxygen combines with electrons and protons to form water.



- ETC is composed of four protein complexes:
  - i. **Complex I:** NADH dehydrogenase, FMN, and an iron-sulphur protein.
  - ii. **Complex II:** Succinate dehydrogenase, FAD, and an iron-sulphur protein.
  - iii. **Complex III:** Cytochrome b and cytochrome c_1.
  - iv. **Complex IV:** Cytochrome a and cytochrome a_3.

- ❖ Coenzyme Q shuttles electrons from Complex I and Complex II to Complex III.
- ❖ After receiving electrons from Complex III, cytochrome c carries the electrons to Complex IV.
- The flow of electrons in ETC is as follows:

Complex I → Complex II → Coenzyme Q → Complex III → Cytochrome c → Complex IV → Oxygen

- The chemiosmotic process in mitochondria involves the following steps:
  - ➢ Electrons are provided to the electron transport chain via NADH and $FADH_2$.
  - ➢ NADH provides electrons to Complex I of the ETC while $FADH_2$ provides electrons to Complex II.
  - ➢ The electrons then move down the electron transport chain liberating a considerable amount of energy.

- The energy liberated from electrons moving down the ETC is used to pump protons, creating a proton gradient.
- The proton gradient serves as the driving force for ATP synthesis.
- Protons flow back into the mitochondrial matrix through ATP synthase.
- The flow of protons induces a rotary motion in ATP synthase, leading to the synthesis of ATP from ADP and inorganic phosphate.

- The oxidation of 1 NADH leads to the synthesis of 3 ATP and the oxidation of 1 $FADH_2$ leads to the synthesis of 2 ATP.
- The difference in ATP yields between NADH and $FADH_2$ is a consequence of their entry points into the ETC and the number of protons pumped during the electron transport process.
  - NADH contributes to more proton-pumping events.

The energy budget of one glucose molecule

Stage	ATP	NADH	$FADH_2$	CO_2
Glycolysis	2	2	0	0
Link reaction	0	2	0	2
Krebs cycle	2	6	2	4
Total	4	10 (30 ATP)	2 (4 ATP)	6

- The standard Gibbs free energy change (ΔG°) for the hydrolysis of one mole of ATP is approximately -30.5 kJ/mol.
- The standard enthalpy change (ΔH^o) for the complete combustion of one mole of glucose is approximately -2800 kJ/mol.
- The estimated efficiency of aerobic respiration is approximately 39.2%.

Energy from non-carbohydrate sources

- Energy can be derived from non-carbohydrate sources through various metabolic pathways.
- While carbohydrates are a primary source of energy, alternative sources such as fats and proteins can also contribute to energy production.

1. Fats (Triglycerides)

- Fats are a major storage form of energy in the body.
- Triglycerides can be broken down through a process called **lipolysis**.
  - Lipolysis is a crucial process during times of energy demand.
- The breakdown of triglycerides releases fatty acids and glycerol.

- Fatty acids can enter the mitochondria and undergo **beta–oxidation.**
  - It is a process that generates acetyl–CoA.
  - If the fatty acid is an odd-numbered chain, the final product will be propionyl–CoA, which will be converted into succinyl–CoA and enters the TCA cycle.
  - NADH and $FADH_2$ are also generated during beta–oxidation.

- The complete oxidation of fatty acids in the Krebs cycle and subsequent electron transport chain contributes to the production of ATP.
- A gram of fat oxidized by respiration produces more than twice as much ATP as a gram of carbohydrate.

2. Glycerol

- Glycerol is a simple polyol (sugar alcohol) compound with the chemical formula $C_3H_8O_3$.
- Glycerol can be converted to glyceraldehyde-3-phosphate, an intermediate of glycolysis, and continue through the remainder of the cellular respiration breakdown pathway.

3. Amino Acids

- They are the building blocks of proteins and their catabolism is essential for energy production.
- Excess amino acids are converted to intermediates of glycolysis and the Krebs cycle.
- Deamination occurs during amino acid catabolism which is the removal of an amino group from a molecule.

- When an amino group ($-NH_2$) is removed from an amino acid, the resulting molecule is called an α-keto acid.
- The α-keto acid can enter various metabolic pathways depending on the specific amino acid from which it originated.
- The amino group is converted into NH_3 and needs to be safely eliminated from the body.

Anaerobic Pathway

- In anaerobic respiration, a molecule other than oxygen is used as the terminal electron acceptor.
  - Some organisms use an organic molecule (commonly pyruvate) as a final electron acceptor through a process called **fermentation**.

- In fermentation, the only energy extraction pathway is glycolysis, with one or two extra reactions tacked on at the end.
- Fermentation does not involve an electron transport system.
- It does not directly produce any additional ATP beyond that produced during glycolysis.
- The purpose of fermentation is to regenerate NAD^+ from the NADH produced in glycolysis.

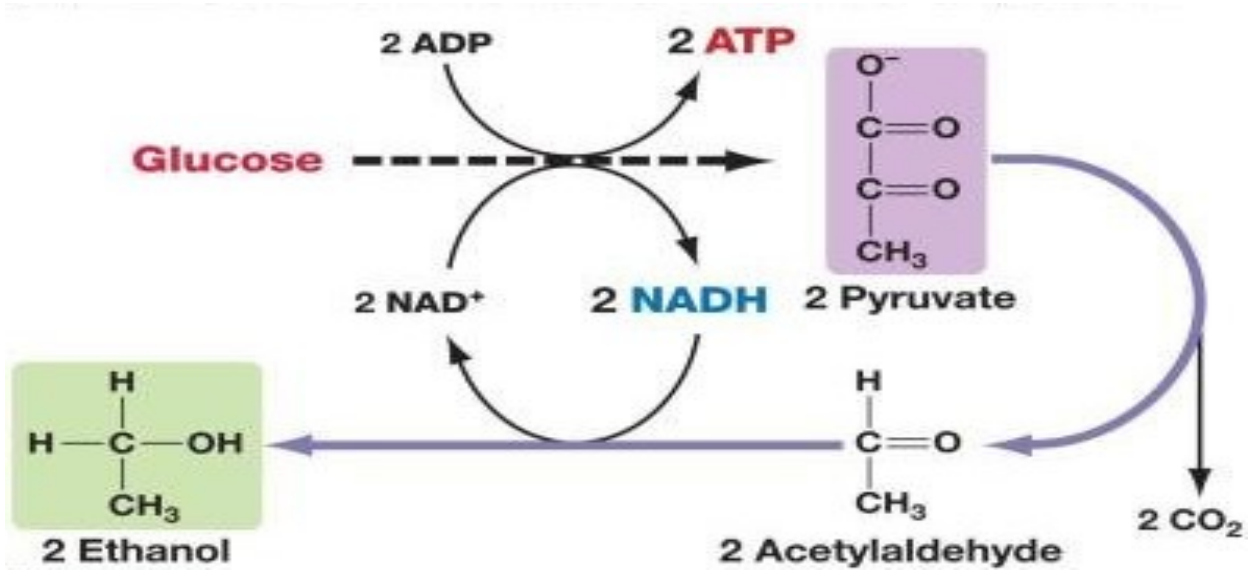
- There are two main types of anaerobic respiration, **alcoholic fermentation** and **lactic acid fermentation**.

A. Alcohol fermentation

- It is a metabolic process in which sugars are converted into ethanol and carbon dioxide.
- NADH donates its electrons to a derivative of pyruvate, producing ethanol.

- Going from pyruvate to ethanol is a two-step process.
  a) A carboxyl group is removed from pyruvate and released as carbon dioxide, producing acetaldehyde (2C).
  b) NADH passes its electrons to acetaldehyde, regenerating NAD^+ and forming ethanol.

- Alcohol fermentation by yeast produces the ethanol found in alcoholic drinks.

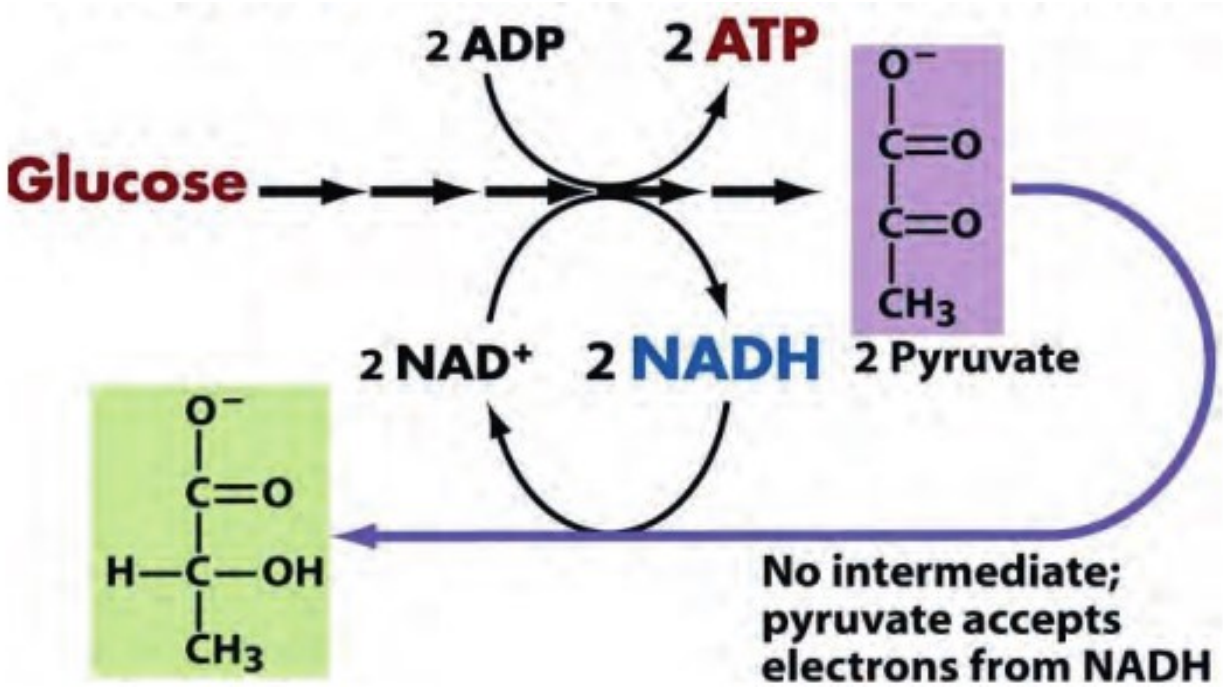


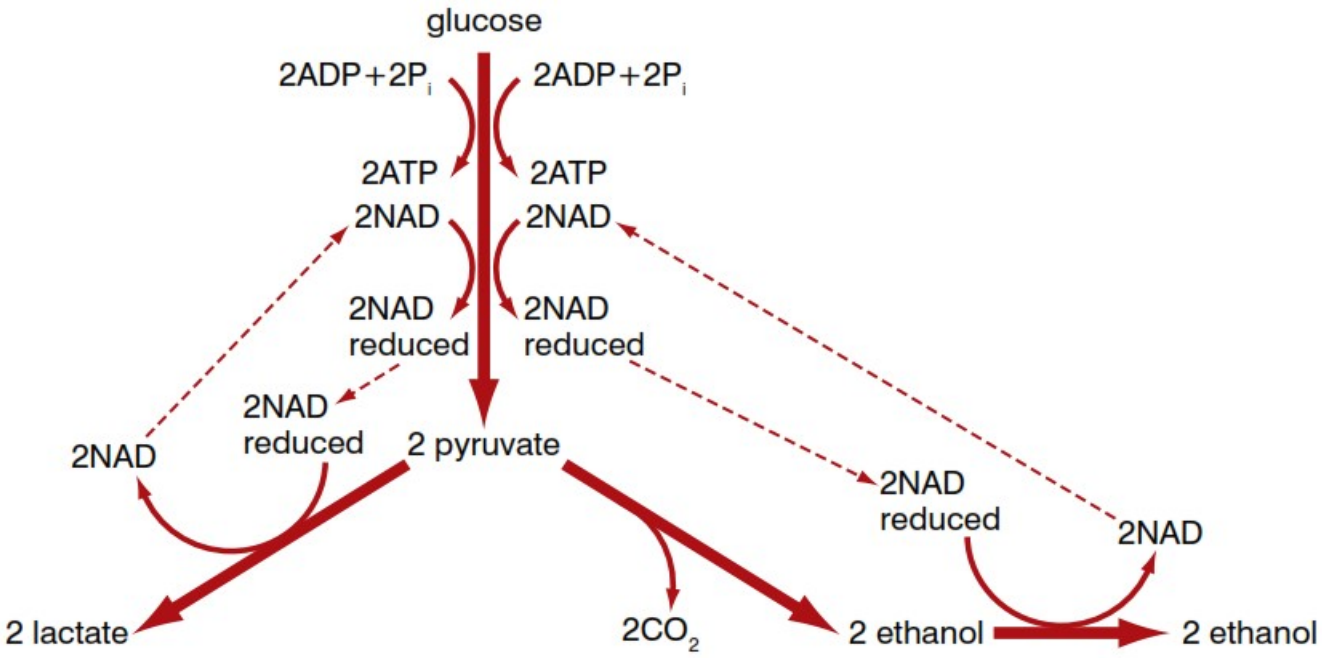
B. Lactic acid fermentation

- NADH transfers its electrons directly to pyruvate, generating lactate as a byproduct.

$$\text{Pyruvate} + \text{NADH} \rightleftharpoons \text{lactic acid} + \text{NAD}^+$$

- The bacteria that make yogurt carry out lactic acid fermentation.
- Muscle cells carry out lactic acid fermentation only when they have too little oxygen for aerobic respiration.





The fermentation processes in animal cells and yeast

Comparison of aerobic and anaerobic respiration

Features	Aerobic respiration	Anaerobic respiration
Reactants	Glucose and oxygen	Glucose
Products	ATP, H_2O and CO_2	ATP and lactic acid (animals); ATP, ethanol and CO_2 (yeast)
Location	Cytoplasm (for glycolysis) and mitochondria	Cytoplasm
Stages	Glycolysis (anaerobic), the link reaction, Krebs cycle & oxidative phosphorylation	Glycolysis, fermentation
ATP produced	Large amount (36 ATP)	Small amount (2 ATP)