

Brahmavart P.G. College, Mandhana, Kanpur

Department of Botany

Question Bank

Section-A

B.Sc. 5th Semester

*Title: Plant Physiology, Metabolism
&
Biochemistry*

Course Code: B040501T

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Question Bank (Section-A)

Q. 1. Explain the importance of water in plants.

Ans: Importance of Water in Plants

Water is an essential substance for the survival, growth and development of plants. It is involved in almost every physiological process of a plant.

Major Importance of Water

1. Constituent of protoplasm:

Water is a major component of protoplasm and helps maintain the structure and activity of living cells.

2. Essential for photosynthesis:

Water is an important raw material for photosynthesis. It provides hydrogen for the synthesis of carbohydrates.

3. Absorption and transport:

Water dissolves mineral salts present in the soil and helps their absorption by roots. It also transports minerals through the **xylem** from roots to aerial parts.

4. Maintains turgidity:

Water maintains **turgor pressure** in plant cells. Turgidity provides mechanical support to soft tissues and helps maintain the shape of leaves and young stems.

5. Helps in transpiration:

Water is lost from aerial parts through transpiration. Transpiration helps in the cooling of plants and contributes to the upward movement of water and minerals.

6. Medium for metabolic reactions:

Many biochemical and enzymatic reactions in plant cells occur in an aqueous medium. Water also participates directly in reactions such as hydrolysis.

7. Seed germination and growth:

Water is necessary for seed germination. It activates enzymes, promotes cell expansion and supports plant growth and development.

Thus, water is indispensable for plants because it is required for **photosynthesis, mineral absorption, transport, turgidity, transpiration, metabolism, germination and growth**. A shortage of water causes wilting, reduced growth and, under severe conditions, death of the plant.

Q. 2. Write a note on transpiration and its significance.

Ans: **Transpiration**

Transpiration is the process by which plants lose excess water in the form of **water vapour** from their aerial parts, mainly through the leaves. It occurs primarily through **stomata**, but may also occur through the cuticle and lenticels.

Types of Transpiration

1. **Stomatal transpiration:**

Loss of water vapour through the stomata of leaves. It accounts for the major portion of transpiration.

2. **Cuticular transpiration:**

Loss of water vapour through the cuticle covering the epidermis.

3. **Lenticular transpiration:**

Loss of water vapour through **lenticels** present in the stems and other woody parts.

Significance of Transpiration

1. **Cooling of plants:**

Evaporation of water produces a cooling effect and helps regulate plant temperature.

2. **Transpiration pull:**

It creates a negative pressure or **transpiration pull**, which helps in the upward movement of water and minerals through the xylem.

3. **Mineral transport:**

The continuous movement of water from roots to leaves facilitates the transport of mineral nutrients.

4. **Maintains water movement:**

Transpiration helps maintain a continuous **water column** from roots to aerial parts of the plant.

5. **Helps in absorption of water:**

The loss of water from leaves creates a water deficit, which promotes further absorption of water by roots.

6. **Maintains plant water balance:**

Proper transpiration contributes to the regulation of water relations and helps maintain normal physiological activities.

Transpiration is an unavoidable process in plants. Although excessive transpiration can cause water loss and wilting, **moderate transpiration is important for water and mineral transport, cooling, and normal plant functioning.**

Q. 3. What is root pressure? Explain its mechanism and significance.

Ans: Root Pressure:

Root pressure is the positive pressure developed in the **xylem of roots** due to the active absorption and accumulation of mineral ions and water in the root xylem. It can push water upward through the xylem, particularly when transpiration is low.

Mechanism of Root Pressure

1. Active absorption of minerals:

Root cells actively absorb mineral ions from the soil and transport them into the xylem.

2. Accumulation of solutes in xylem:

The concentration of mineral salts in the xylem becomes higher than that of the surrounding soil solution.

3. Osmotic movement of water:

Due to the difference in water potential, water enters the root and moves into the xylem by **osmosis**.

4. Development of pressure:

Continuous entry of water into the xylem produces **positive hydrostatic pressure**, called root pressure.

5. Upward movement of water:

Root pressure can push water upward through the xylem. Its effect is more noticeable when transpiration is low, such as at night or under humid conditions.

Significance of Root Pressure

- It helps in the **upward movement of water and dissolved minerals** through the xylem.
- It contributes to the maintenance of water supply to aerial parts when transpiration is low.
- It is responsible for phenomena such as **guttation**, in which water droplets appear at leaf margins through hydathodes.
- It may cause **bleeding or exudation of xylem sap** from cut stems.
- It demonstrates the role of **osmotic processes in water absorption by roots**.

Root pressure is an important physiological force produced in roots due to the accumulation of solutes and osmotic entry of water into the xylem. However, it **cannot by itself account for the ascent of sap in tall plants**; transpiration pull is considered the major force responsible for long-distance water transport.

Q. 4. Write a short note on guttation.

Ans: Short Note on Guttation

Guttation is the process by which **liquid water droplets** are exuded from the margins or tips of leaves through special structures called **hydathodes**. It generally occurs when **soil water is abundant, humidity is high, and transpiration is low**, usually at night or early morning.

Mechanism of Guttation

1. **Absorption of water:** Roots absorb water actively from the soil.
2. **Development of root pressure:** Accumulation of minerals in the xylem causes osmotic entry of water and development of root pressure.
3. **Movement of water:** The positive pressure pushes water upward through the xylem towards the leaves.
4. **Exudation through hydathodes:** When transpiration is low, excess water is forced out through hydathodes present mainly at the leaf margins and tips.

Significance of Guttation

- It helps the plant **remove excess water** when transpiration is low.
- It demonstrates the role of **root pressure** in the upward movement of water.
- The guttation fluid may contain **dissolved mineral salts and other substances**.
- It is commonly observed in plants such as **grasses, wheat, maize and garden plants**.

Guttation vs. Transpiration

Guttation	Transpiration
Water is lost as liquid droplets .	Water is lost mainly as water vapour .
Occurs through hydathodes .	Occurs mainly through stomata .
Usually occurs when transpiration is low.	Usually occurs during active transpiration.
Mainly associated with root pressure .	Mainly associated with transpiration pull .

Guttation is an important phenomenon associated with root pressure, in which excess water is exuded as liquid droplets through hydathodes, especially under conditions of high soil moisture and low transpiration.

Q. 5. Describe the role of essential mineral elements in plants.

Ans: Role of Essential Mineral Elements in Plants

Mineral elements are inorganic nutrients absorbed by plants mainly from the soil. They are essential for **normal growth, development, metabolism and reproduction**. They are broadly classified into **macronutrients** and **micronutrients** according to the quantity required by plants.

1. Macronutrients

- **Nitrogen (N):**
It is an important component of **amino acids, proteins, nucleic acids and chlorophyll**. It promotes vegetative growth.
- **Phosphorus (P):**
It is a component of **ATP, nucleic acids and phospholipids**. It plays an important role in energy transfer, root development and flowering.
- **Potassium (K):**
It regulates **stomatal opening and closing**, enzyme activity and water balance. It also improves resistance to environmental stresses.
- **Calcium (Ca):**
It is important for **cell wall formation**, cell membrane stability and normal growth of roots and young tissues.
- **Magnesium (Mg):**
It is the central element of the **chlorophyll molecule** and also activates several enzymes.
- **Sulphur (S):**
It forms part of certain **amino acids and proteins** and is involved in enzyme activity.

2. Micronutrients

Micronutrients are required in very small quantities but are essential for normal plant growth.

- **Iron (Fe):** Essential for chlorophyll synthesis and electron transport.
- **Manganese (Mn):** Involved in photosynthesis and enzyme activation.
- **Zinc (Zn):** Required for enzyme activity and synthesis of growth-regulating substances.
- **Copper (Cu):** Involved in electron transport and various enzyme reactions.
- **Boron (B):** Important for cell division, cell wall formation and reproductive growth.
- **Molybdenum (Mo):** Essential for nitrogen metabolism and nitrate reduction.
- **Chlorine (Cl):** Helps in osmotic balance and photosynthesis.
- **Nickel (Ni):** Required for the proper functioning of the enzyme **urease**.

Thus, essential mineral elements perform diverse functions such as **formation of cellular components, photosynthesis, respiration, enzyme activation, energy transfer, water balance and reproduction**. Deficiency of any essential element can cause characteristic symptoms and adversely affect plant growth and development.

Q. 6. Write a note on symptoms of mineral deficiency in major crops.

Ans: Symptoms of Mineral Deficiency in Major Crops

Mineral elements are essential for the normal growth and development of plants. When a required mineral is absent or present in insufficient quantity, plants show characteristic

deficiency symptoms. These symptoms may appear as chlorosis, necrosis, stunted growth, premature leaf fall, or poor development of roots, flowers and fruits.

Important Mineral Deficiency Symptoms

Mineral element	Major deficiency symptoms	Common crops affected
Nitrogen (N)	Older leaves become pale or yellow (chlorosis); plants show stunted growth and poor yield.	Wheat, rice, maize
Phosphorus (P)	Poor root growth, stunted plants; leaves may develop dark green or purplish coloration.	Wheat, maize, rice
Potassium (K)	Yellowing and browning of leaf margins; older leaves may develop marginal scorching .	Potato, rice, banana
Calcium (Ca)	Death of growing points; young leaves become distorted and root growth is affected.	Tomato, groundnut
Magnesium (Mg)	Interveinal chlorosis first appears in older leaves because magnesium is mobile in plants.	Cotton, maize
Sulphur (S)	General yellowing of younger leaves and reduced growth.	Mustard, wheat
Iron (Fe)	Interveinal chlorosis mainly in young leaves ; severe deficiency makes leaves almost white.	Rice, citrus, soybean
Zinc (Zn)	Shortened internodes, small leaves and chlorosis; plants may show stunted growth .	Rice, maize
Boron (B)	Death of growing points, poor flowering and abnormal development of fruits and roots.	Cauliflower, sunflower
Manganese (Mn)	Interveinal chlorosis with small necrotic spots on leaves.	Wheat, rice
Molybdenum (Mo)	Reduced growth and chlorosis; in cauliflower, leaves may become narrow and malformed.	Cauliflower, pulses

General Classification of Symptoms

1. **Chlorosis:** Yellowing of leaves due to reduced chlorophyll formation, commonly seen in nitrogen, magnesium and iron deficiency.
2. **Necrosis:** Death of tissues, producing brown or dead patches on leaves.
3. **Stunted growth:** Reduced shoot and root growth, commonly associated with nitrogen, phosphorus and zinc deficiency.
4. **Leaf deformation:** Young leaves may become distorted due to calcium or boron deficiency.
5. **Poor flowering and fruiting:** Deficiencies of phosphorus, boron and other elements can adversely affect reproductive development.

Mineral deficiency symptoms provide useful indications of the nutritional status of crops. Correct identification of these symptoms helps in **diagnosing nutrient deficiencies and applying appropriate fertilizers** to improve crop growth and yield.

Q. 7. Explain active and passive transport of ions across the cell membrane.

Ans: Active and Passive Transport of Ions Across the Cell Membrane

The cell membrane controls the movement of ions and other substances between the cell and its surroundings. Ion transport occurs mainly by **active transport** and **passive transport**.

1. Active Transport

Active transport is the movement of ions across the cell membrane **against their electrochemical gradient**, requiring energy, usually in the form of **ATP**.

Main features:

- Requires metabolic energy.
- Ions move from a region of **lower electrochemical potential to higher electrochemical potential**.
- It occurs through specific **carrier proteins or membrane pumps**.
- It helps plants accumulate essential mineral ions even when their concentration is higher inside the cell.

Example:

The **H⁺-ATPase proton pump** in the plasma membrane uses ATP to pump H⁺ ions out of the cell. This creates an electrochemical gradient that drives the uptake of other mineral ions.

2. Passive Transport

Passive transport is the movement of ions across the membrane **down their electrochemical gradient**, without direct expenditure of metabolic energy.

Main features:

- Does not directly require ATP.
- Ions move from a region of higher electrochemical potential to lower electrochemical potential.
- It occurs through **ion channels or carrier proteins**.
- The direction of movement depends on the concentration gradient and electrical potential across the membrane.

Example:

When suitable ion channels are open, ions such as **K⁺** may move across the membrane according to their electrochemical gradient.

Difference Between Active and Passive Transport

Feature	Active Transport	Passive Transport
Energy	Requires metabolic energy	Does not directly require ATP
Direction	Against electrochemical gradient	Along electrochemical gradient
Proteins involved	Pumps/carriers	Channels/carriers
Purpose	Accumulation and regulation of ions	Movement towards equilibrium
Example	H ⁺ -ATPase	Ion-channel-mediated K ⁺ movement

Active and passive transport are essential for maintaining **ion concentration, membrane potential, nutrient uptake and cellular homeostasis** in plants. Active transport establishes ion gradients, while passive transport allows ions to move along those gradients.

Q. 8. Describe the composition and functions of phloem sap.

Ans: Composition and Functions of Phloem Sap

Phloem sap is the liquid transported through the **phloem** from source tissues, mainly mature leaves, to sink tissues such as roots, fruits, seeds and growing regions. It carries organic nutrients and other substances required for plant growth and metabolism.

Composition of Phloem Sap

Phloem sap mainly contains the following substances:

1. **Sugars:**
Sucrose is the principal sugar transported in most plants. It may also contain small amounts of other sugars.
2. **Amino acids and amides:**
These are transported from source tissues and are used for **protein synthesis and growth**.
3. **Mineral ions:**
Phloem sap contains minerals such as **potassium, magnesium, phosphate and nitrate** in varying amounts.
4. **Organic acids:**
Compounds such as organic acids are present and participate in various metabolic processes.
5. **Proteins and enzymes:**
Phloem sap contains certain proteins and enzymes involved in transport and regulation of plant processes.
6. **Plant hormones:**
Hormones such as **auxins, cytokinins, gibberellins and abscisic acid** may be transported through the phloem.

7. **Other substances:**

Phloem sap may contain **RNA, ATP, vitamins and other signalling molecules.**

Functions of Phloem Sap

1. **Transport of food:**

It transports mainly sucrose from **source to sink** tissues. This process is called **translocation.**

2. **Distribution of organic nutrients:**

It supplies carbohydrates and nitrogenous compounds to growing and storage organs.

3. **Growth and development:**

Transported sugars, amino acids and hormones support **cell division, growth and differentiation.**

4. **Storage-organ development:**

It supplies nutrients to storage organs such as **roots, tubers, bulbs, fruits and seeds.**

5. **Signalling:**

Phloem can transport hormones, proteins and nucleic acids that participate in **long-distance communication and regulation.**

Phloem sap is a complex solution rich in **sugars, amino acids, minerals, hormones and other organic compounds.** Its major role is the **translocation and distribution of photosynthetic products and other substances from source to sink tissues**, thereby supporting plant growth, storage and development.

Q. 9. Differentiate between active and passive transport.

Ans: Difference Between Active and Passive Transport

Active and passive transport are two important mechanisms by which ions and molecules move across the cell membrane.

Basis	Active Transport	Passive Transport
Definition	Movement of substances against their electrochemical gradient.	Movement of substances along their electrochemical gradient.
Energy requirement	Requires metabolic energy, usually ATP.	Does not require direct expenditure of ATP.
Direction	From lower to higher electrochemical potential.	From higher to lower electrochemical potential.
Proteins involved	Mainly membrane pumps and carrier proteins.	Mainly ion channels and carrier proteins.
Concentration	Can accumulate ions against their concentration gradient.	Cannot normally move ions against their gradient.

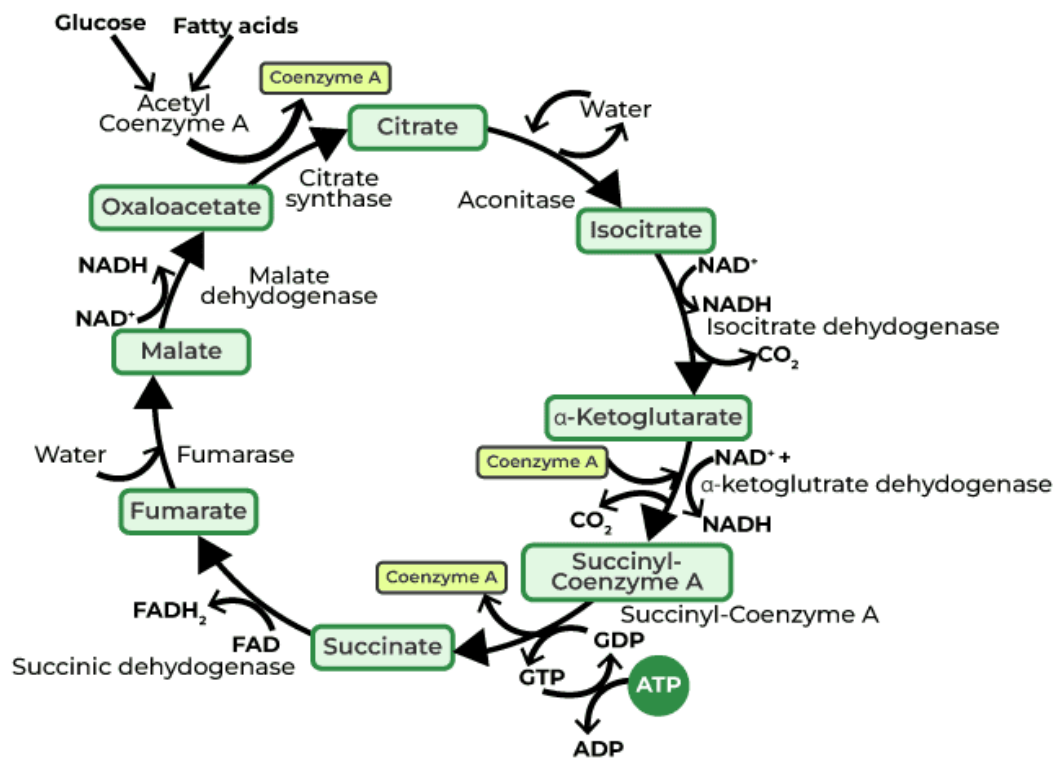
Basis	Active Transport	Passive Transport
Purpose	Helps in active uptake and maintenance of ion gradients.	Helps ions move toward electrochemical equilibrium.
Example	H⁺-ATPase pumping H ⁺ ions across the plasma membrane.	Movement of K⁺ ions through ion channels down their electrochemical gradient.

Q. 10. Describe the Krebs cycle with a suitable diagram.

Ans: Krebs Cycle (TCA Cycle/Citric Acid Cycle)

The **Krebs cycle**, also called the **citric acid cycle (TCA cycle)**, is a series of enzymatic reactions by which **acetyl-CoA is oxidized to CO₂**. It occurs mainly in the **mitochondrial matrix** of eukaryotic plant cells. The cycle produces reduced coenzymes **NADH and FADH₂**, which subsequently generate ATP through the electron transport chain.

Suitable Diagram



Steps of the Krebs Cycle

1. **Formation of citrate:**
Acetyl-CoA combines with oxaloacetate to form **citrate (6C)**.
2. **Formation of isocitrate:**
Citrate is converted into **isocitrate**.
3. **Oxidative decarboxylation:**
Isocitrate is oxidized to **α -ketoglutarate (5C)**, producing **NADH and CO_2** .
4. **Formation of succinyl-CoA:**
 α -Ketoglutarate is further oxidized to **succinyl-CoA (4C)**, producing another **NADH and CO_2** .
5. **Formation of succinate:**
Succinyl-CoA is converted into **succinate**, producing **ATP/GTP** by substrate-level phosphorylation.
6. **Formation of fumarate:**
Succinate is oxidized to **fumarate**, producing **FADH_2** .
7. **Formation of malate:**
Fumarate combines with water to form **malate**.
8. **Regeneration of oxaloacetate:**
Malate is oxidized to **oxaloacetate**, producing **NADH**. Oxaloacetate then combines with another acetyl-CoA to continue the cycle.

Yield of One Krebs Cycle

For **one molecule of acetyl-CoA**, the cycle produces:

- **3 NADH**
- **1 FADH_2**
- **1 ATP (or GTP)**
- **2 CO_2**

Thus, the Krebs cycle is an important central pathway of respiration because it provides **energy-rich reducing equivalents (NADH and FADH_2)** for ATP production and also supplies intermediates required for various biosynthetic processes.

Q. 11. Describe the fate of pyruvate under aerobic and anaerobic conditions.

Ans: Fate of Pyruvate Under Aerobic and Anaerobic Conditions

Pyruvate is the end product of glycolysis. One molecule of glucose produces **two molecules of pyruvate** in the cytoplasm. The fate of pyruvate depends mainly on the availability of oxygen.

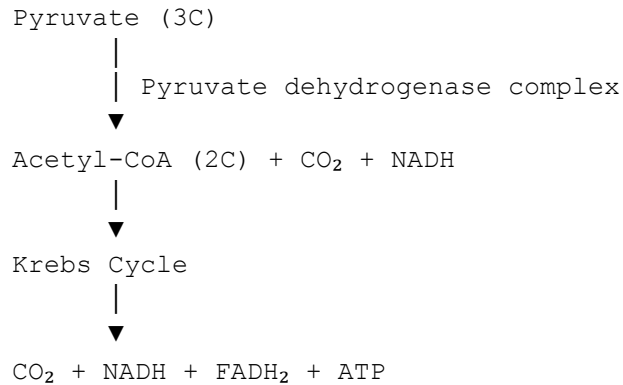
1. Fate of Pyruvate Under Aerobic Conditions

When sufficient **oxygen is available**, pyruvate enters the mitochondria and undergoes **oxidative decarboxylation**.

- Pyruvate (3C) is converted into **acetyl-CoA (2C)**.

- One molecule of **CO₂** is released.
- **NAD⁺ is reduced to NADH.**
- Acetyl-CoA enters the **Krebs cycle**, where it is completely oxidized to CO₂.
- NADH and FADH₂ produced during respiration transfer electrons to the **electron transport chain**, resulting in ATP production.

Reaction:

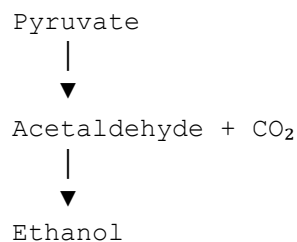


2. Fate of Pyruvate Under Anaerobic Conditions

When oxygen is absent or insufficient, pyruvate does not undergo oxidative decarboxylation. Instead, it undergoes **fermentation**.

(a) Alcoholic Fermentation

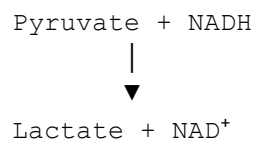
In many plant tissues, yeasts and other microorganisms, pyruvate is converted into **ethanol and CO₂**.



The process regenerates **NAD⁺**, allowing glycolysis to continue.

(b) Lactic Acid Fermentation

Under certain anaerobic conditions, pyruvate may be reduced to **lactate**, regenerating NAD⁺.



Comparison

Aerobic condition

Oxygen is available.

Pyruvate → Acetyl-CoA.

Krebs cycle operates.

Anaerobic condition

Oxygen is absent or insufficient.

Pyruvate undergoes fermentation.

Krebs cycle is not used for complete oxidation of pyruvate.

Aerobic condition

Complete oxidation ultimately produces CO_2 and H_2O .

Large amount of ATP is produced.

Anaerobic condition

Products include ethanol + CO_2 or lactate.

Only a small amount of ATP is obtained, mainly from glycolysis.

Thus, under **aerobic conditions**, pyruvate is converted into acetyl-CoA and completely oxidized through the Krebs cycle and electron transport chain. Under **anaerobic conditions**, it undergoes fermentation, mainly producing **ethanol and CO_2 in plants**, while regenerating NAD^+ so that glycolysis can continue.

Q. 12. Write a note on fermentation in plants.**Ans: Fermentation in Plants**

Fermentation is an anaerobic process in which organic compounds, mainly glucose, are incompletely broken down to release a small amount of energy. In plants, fermentation generally occurs when **oxygen is unavailable or insufficient**, such as in waterlogged roots and tissues.

Alcoholic Fermentation in Plants

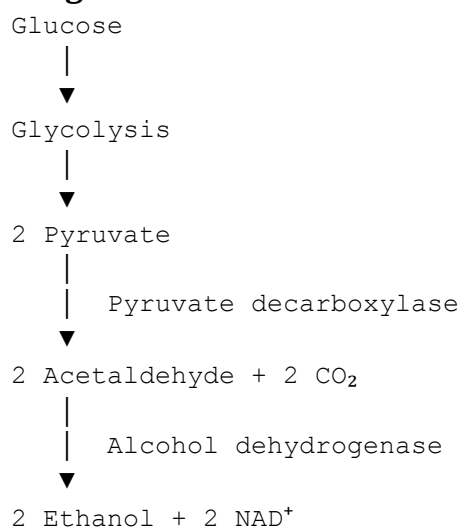
The most common type of fermentation in plants is **alcoholic fermentation**. It occurs mainly in two steps:

1. Formation of acetaldehyde:

Pyruvate formed during glycolysis is decarboxylated to form acetaldehyde, releasing CO_2 .

2. Formation of ethanol:

Acetaldehyde is reduced to ethanol by alcohol dehydrogenase, using NADH. This regenerates NAD^+ , allowing glycolysis to continue.

Diagram

Overall Reaction

Glucose $\rightarrow$ 2 Ethanol + 2 CO₂ + Energy (2 ATP)

Significance of Fermentation

1. **Provides energy under anaerobic conditions:**

Fermentation allows plants to obtain a small amount of energy when oxygen is limited.

2. **Regenerates NAD⁺:**

NAD⁺ is regenerated during fermentation, which is essential for the continuation of glycolysis.

3. **Helps plants tolerate temporary oxygen deficiency:**

It is important in tissues subjected to **waterlogging or flooding**.

4. **Produces useful end products:**

Ethanol and other fermentation products have biological and industrial importance.

Limitations

Fermentation produces much less energy than aerobic respiration. Prolonged anaerobic conditions can result in accumulation of ethanol and other toxic products, which may damage plant cells.

Fermentation is an important **anaerobic metabolic pathway** in plants. It enables ATP production through glycolysis and maintains NAD⁺ availability when oxygen is insufficient, but prolonged fermentation cannot sustain normal plant growth because of its low energy yield and accumulation of toxic products.

Q. 13. Describe the oxidative pentose phosphate pathway.

Ans: Oxidative Pentose Phosphate Pathway

The **oxidative pentose phosphate pathway (OPPP)**, also called the **pentose phosphate pathway** or **HMP pathway**, is an alternative pathway of glucose metabolism. It occurs mainly in the **cytoplasm** of plant cells and is particularly active in tissues involved in biosynthesis and growth.

The major functions of the pathway are the production of **NADPH** and **pentose sugars**, especially ribulose-5-phosphate.

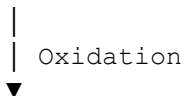
Main Steps

The pathway consists of two phases:

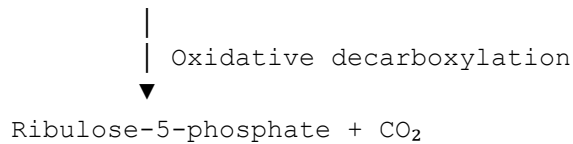
1. Oxidative Phase

Glucose-6-phosphate is oxidized through a series of reactions.

Glucose-6-phosphate



6-Phosphogluconate



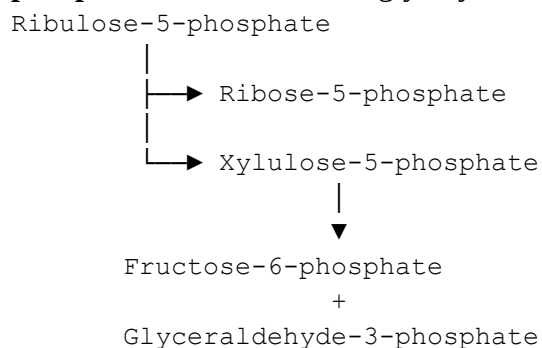
During these reactions:

- **2 NADPH** molecules are produced.
- **1 CO₂** molecule is released.
- Ribulose-5-phosphate is formed.

2. Non-Oxidative Phase

Ribulose-5-phosphate is converted into other pentose phosphates such as **ribose-5-phosphate** and **xylulose-5-phosphate**.

These sugars are then rearranged to form **fructose-6-phosphate** and **glyceraldehyde-3-phosphate**, which can enter glycolysis.



Importance of OPPP

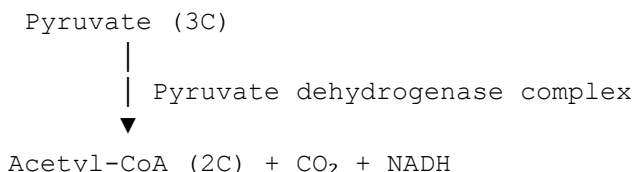
1. **Production of NADPH:**
NADPH provides reducing power for **fatty acid, lipid and other biosynthetic reactions**.
2. **Formation of pentose sugars:**
Ribose-5-phosphate is required for the synthesis of **nucleotides and nucleic acids**.
3. **Provides metabolic intermediates:**
The pathway produces compounds that can enter **glycolysis** and other metabolic pathways.
4. **Antioxidant defence:**
NADPH helps maintain cellular antioxidant systems, particularly the regeneration of **reduced glutathione**, which protects cells from oxidative damage.
5. **Active in growing tissues:**
The pathway is important in tissues where active biosynthesis and cell division occur.

The oxidative pentose phosphate pathway is an important alternative route of glucose metabolism. Unlike glycolysis, its major products are **NADPH and pentose phosphates rather than ATP**. It therefore plays an important role in **biosynthesis, nucleic acid formation and protection against oxidative stress** in plants.

Q. 14. Explain oxidative decarboxylation of pyruvate.

Ans: Oxidative Decarboxylation of Pyruvate: Oxidative decarboxylation of pyruvate is the process in which pyruvate, the end product of glycolysis, is converted into acetyl-CoA before entering the Krebs cycle. In eukaryotic plant cells, this process occurs mainly in the mitochondrial matrix.

Reaction



Mechanism

The reaction is catalysed by the **pyruvate dehydrogenase complex (PDC)**, which consists of three main enzymes:

1. **Pyruvate dehydrogenase (E_1):**
Pyruvate loses one carbon atom as CO_2 . The remaining two-carbon fragment is oxidized.
2. **Dihydrolipoyl transacetylase (E_2):**
The two-carbon acetyl group is transferred to **CoA**, forming **acetyl-CoA**.
3. **Dihydrolipoyl dehydrogenase (E_3):**
Electrons are transferred to NAD^+ , producing **NADH** and regenerating the oxidized enzyme complex.

Overall Reaction



Since one glucose molecule produces **two pyruvate molecules**, oxidative decarboxylation of one glucose produces:

- 2 Acetyl-CoA
- 2 CO_2
- 2 NADH

Importance

- It provides the **link between glycolysis and the Krebs cycle**.
- It converts pyruvate into **acetyl-CoA**, which enters the Krebs cycle.
- It produces **NADH**, which contributes to ATP production through the electron transport chain.
- It releases **CO_2** as a product of respiratory metabolism.
- Acetyl-CoA also serves as an important starting material for several **biosynthetic pathways**.

Oxidative decarboxylation is an essential step in aerobic respiration in which **pyruvate is converted into acetyl-CoA with the release of CO_2 and formation of NADH**. It connects glycolysis with the Krebs cycle and prepares carbon molecules for further oxidation.

Q. 15. Explain the mitochondrial electron transport system.

Ans: Mitochondrial Electron Transport System (ETS)

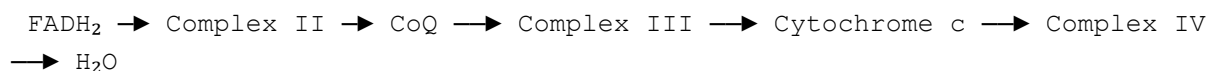
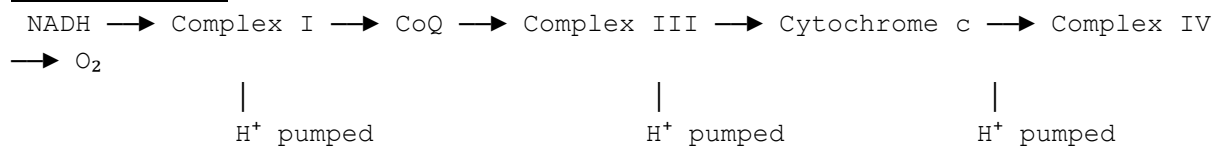
The **mitochondrial electron transport system (ETS)** is a series of electron carriers located in the **inner mitochondrial membrane**. It is the final stage of aerobic respiration. Electrons from **NADH and FADH₂** are transferred through a series of complexes to oxygen, and the energy released is used to synthesize **ATP**.

Components of Electron Transport System

The mitochondrial ETS consists mainly of **four protein complexes**, along with mobile electron carriers:

1. **Complex I – NADH dehydrogenase:**
Accepts electrons from NADH and transfers them to **ubiquinone (CoQ)**. Energy released is used to pump H⁺ ions across the inner membrane.
2. **Complex II – Succinate dehydrogenase:**
Receives electrons from FADH₂ produced during the Krebs cycle and transfers them to CoQ. It does **not** pump protons.
3. **Coenzyme Q (Ubiquinone):**
A mobile electron carrier that transfers electrons from Complex I and II to Complex III.
4. **Complex III – Cytochrome bc₁ complex:**
Transfers electrons from CoQ to **cytochrome c** and pumps protons across the membrane.
5. **Cytochrome c:**
A mobile protein that carries electrons from Complex III to Complex IV.
6. **Complex IV – Cytochrome c oxidase:**
Transfers electrons to molecular oxygen. Oxygen combines with electrons and H⁺ to form **water**. This complex also contributes to proton pumping.

Electron Flow



Chemiosmotic Mechanism

As electrons pass through the electron transport chain, **Complexes I, III and IV pump H⁺ ions** from the mitochondrial matrix into the intermembrane space. This creates a **proton gradient** across the inner mitochondrial membrane.

H⁺ ions then flow back into the matrix through **ATP synthase (Complex V)**. The energy released during this movement drives the formation of **ATP from ADP and inorganic phosphate (Pi)**. This process is called **oxidative phosphorylation**.

Significance

- Produces most of the **ATP** during aerobic respiration.
- Oxidizes NADH and FADH₂ back to **NAD⁺** and **FAD**, allowing metabolic pathways to continue.
- Molecular oxygen acts as the **final electron acceptor**.
- Produces **water** as the final product of electron transfer.
- Provides energy required for various cellular activities.

The mitochondrial ETS is an essential part of aerobic respiration. It transfers electrons from **NADH and FADH₂ to oxygen** through a series of electron carriers and uses the released energy to generate a proton gradient and ultimately **ATP through oxidative phosphorylation**.

Q. 16. What is oxidative phosphorylation? Explain its mechanism.

Ans: Oxidative Phosphorylation:

Oxidative phosphorylation is the process by which **ATP is synthesized from ADP and inorganic phosphate (Pi)** using the energy released during the transfer of electrons through the **mitochondrial electron transport system (ETS)**.

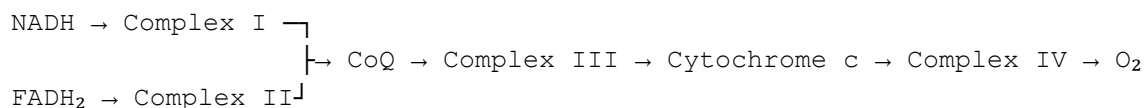
It occurs mainly on the **inner mitochondrial membrane** of eukaryotic plant cells. It is the major mechanism of ATP production during aerobic respiration.

Mechanism of Oxidative Phosphorylation

The mechanism can be explained in the following steps:

1. Transfer of electrons:

NADH and FADH₂ donate electrons to the electron transport system.



2. Pumping of protons:

As electrons pass through the ETS, energy is released. Complexes **I, III and IV** use this energy to pump H^+ ions from the mitochondrial matrix into the intermembrane space.

3. Formation of proton gradient:

The accumulation of H^+ ions in the intermembrane space creates an **electrochemical proton gradient** across the inner mitochondrial membrane.

4. Chemiosmosis:

H^+ ions flow back into the mitochondrial matrix through the enzyme **ATP synthase (Complex V)**. The movement of protons provides energy for ATP synthesis.

5. Formation of ATP:

ATP synthase uses this energy to combine ADP with inorganic phosphate:

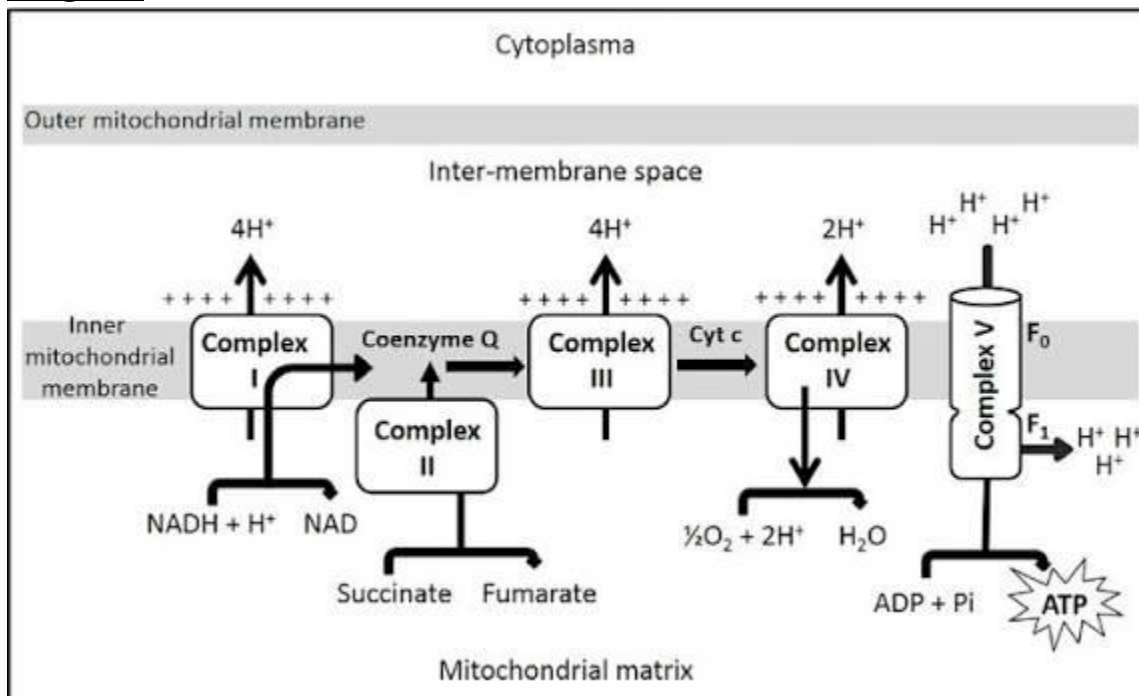


6. Formation of water:

At the end of the electron transport chain, **oxygen acts as the final electron acceptor**. It combines with electrons and H^+ ions to form water.



Diagram



Significance

- Produces **ATP**, the major energy currency of the cell.
- Reoxidizes **NADH and $FADH_2$** to NAD^+ and FAD .
- Uses oxygen as the **final electron acceptor**.
- Produces water as the end product of electron transfer.
- Provides energy required for **growth, active transport, biosynthesis and other cellular activities**.

Oxidative phosphorylation is the final energy-producing stage of aerobic respiration. It is based on the **electron transport chain, proton gradient and ATP synthase**, and is explained by the **chemiosmotic theory**.

Q. 17. Explain the chemiosmotic mechanism of ATP synthesis.

Ans: Chemiosmotic Mechanism of ATP Synthesis

The **chemiosmotic mechanism** explains how ATP is synthesized using the energy stored in a **proton (H^+) gradient** across the inner mitochondrial membrane. This mechanism was proposed by **Peter Mitchell** and forms the basis of **oxidative phosphorylation**.

Mechanism

The process occurs in the following steps:

1. Electron transport:

NADH and FADH₂ donate electrons to the **mitochondrial electron transport chain**. Electrons pass through different electron carriers and finally reach oxygen.

2. Proton pumping:

The energy released during electron transfer is used by **Complexes I, III and IV** to pump H⁺ ions from the mitochondrial matrix into the intermembrane space.

3. Formation of proton gradient:

As H⁺ ions accumulate in the intermembrane space, a difference in proton concentration and electrical charge develops across the inner mitochondrial membrane. This is called the **proton motive force (PMF)**.

4. Movement of protons through ATP synthase:

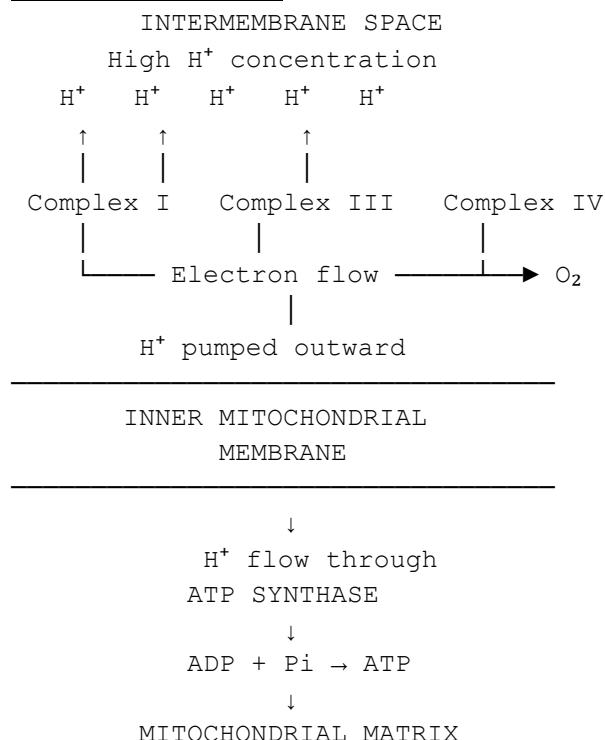
The inner mitochondrial membrane is largely impermeable to H⁺ ions. Therefore, protons return to the matrix mainly through **ATP synthase (Complex V)**.

5. ATP synthesis:

The flow of H⁺ through ATP synthase provides energy for the phosphorylation of ADP:



Suitable Diagram



Importance

- It is the major mechanism of **ATP production during aerobic respiration**.
- It converts the energy of electron transport into **chemical energy in ATP**.

- It explains the role of the **proton gradient** in oxidative phosphorylation.
- It also helps maintain the energy balance required for various cellular activities.

According to the chemiosmotic mechanism, **electron transport creates a proton gradient across the inner mitochondrial membrane, and the return flow of H^+ through ATP synthase provides the energy for ATP formation.** Thus, the proton motive force links electron transport with ATP synthesis.

Q. 18. Write a short note on cyanide-resistant respiration.

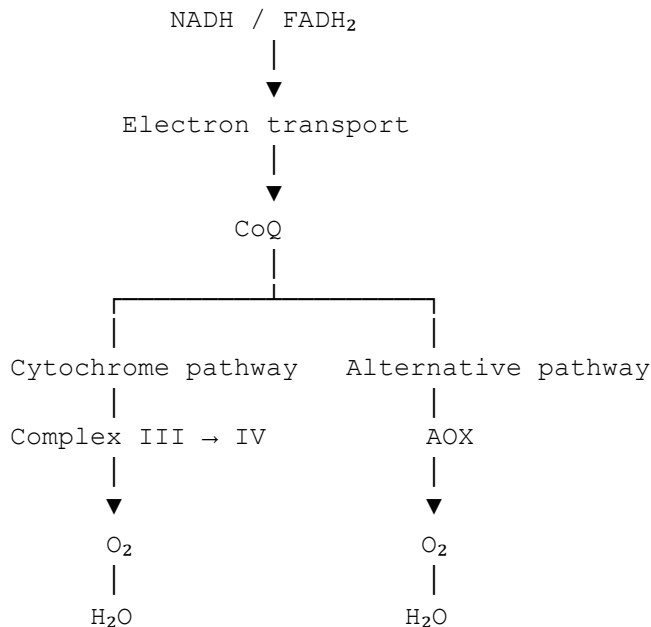
Ans: Cyanide-Resistant Respiration

Cyanide-resistant respiration is an alternative pathway of respiration found mainly in **plants**, in which electron transport and oxygen consumption continue even in the presence of cyanide. It is also called the **alternative respiratory pathway**.

In normal mitochondrial respiration, cyanide inhibits **cytochrome c oxidase (Complex IV)**. However, in the alternative pathway, electrons are transferred to oxygen through an alternative terminal oxidase called **alternative oxidase (AOX)**.

Mechanism

The alternative pathway branches from the normal electron transport chain at the level of the **ubiquinone (CoQ) pool**.



In the alternative pathway, electrons bypass **Complexes III and IV** and are transferred directly from the ubiquinone pool to oxygen through AOX.

Characteristics

1. **Cyanide resistant:**

The pathway is not blocked by cyanide because it bypasses cytochrome c oxidase.

2. **Alternative oxidase:**

AOX acts as the terminal electron acceptor pathway and transfers electrons to oxygen.

3. **Less ATP production:**

Since electrons bypass Complexes III and IV, fewer protons are pumped across the mitochondrial membrane. Therefore, **less ATP is produced**.

4. **Heat production:**

Much of the energy that would otherwise be conserved as ATP is released as **heat**.

Significance in Plants

- It helps maintain **respiration and electron flow** when the cytochrome pathway is restricted.
- It helps prevent excessive reduction of the electron transport chain.
- It can reduce the formation of harmful **reactive oxygen species (ROS)** under certain stress conditions.
- It is particularly well known in some **thermogenic plants**, where heat production helps volatilize floral odors and attract pollinators.

Cyanide-resistant respiration is an important alternative respiratory pathway in plants. It uses **alternative oxidase (AOX)** to transfer electrons to oxygen while bypassing the cyanide-sensitive cytochrome pathway. Although it produces less ATP, it provides flexibility in plant mitochondrial respiration and can contribute to stress responses and heat production.

Q. 19. Differentiate between aerobic respiration and fermentation.

Ans: Difference Between Aerobic Respiration and Fermentation

Aerobic respiration and fermentation are two different pathways of glucose breakdown. Aerobic respiration occurs in the presence of oxygen, whereas fermentation occurs when oxygen is absent or insufficient.

Basis	Aerobic Respiration	Fermentation
Oxygen	Requires oxygen.	Occurs in the absence or deficiency of oxygen.
Breakdown of glucose	Glucose is completely oxidized .	Glucose is partially broken down .
Main products	CO ₂ and H ₂ O.	Ethanol + CO ₂ in alcoholic fermentation, or lactate in lactic acid fermentation.
Site	Glycolysis occurs in cytoplasm; Krebs	Mainly occurs in the cytoplasm.

Basis	Aerobic Respiration	Fermentation
	cycle and ETS occur mainly in mitochondria.	
Krebs cycle	Operates after glycolysis.	Does not operate for the fermentation process.
Electron transport chain	Present and involved in ATP production.	Not involved.
ATP yield	High; approximately 30–32 ATP per glucose in many modern estimates for eukaryotic cells.	Only 2 ATP per glucose , produced during glycolysis.
End products	Stable end products: CO ₂ and H ₂ O.	Reduced organic products such as ethanol or lactate.
NAD ⁺ regeneration	NAD ⁺ is regenerated through the electron transport chain.	NAD ⁺ is regenerated during fermentation, allowing glycolysis to continue.
Efficiency	More energy is obtained from glucose.	Much less energy is obtained from glucose.

Simple Comparison

Aerobic Respiration:

Glucose → Pyruvate → Acetyl-CoA → Krebs Cycle → ETS → CO₂ + H₂O + Much ATP

Fermentation:

Glucose → Pyruvate → Ethanol + CO₂

OR

Lactate

→ Only 2 ATP

Aerobic respiration results in the complete oxidation of glucose and produces a large amount of ATP, whereas **fermentation** involves incomplete breakdown of glucose and produces only a small amount of ATP. In plants, alcoholic fermentation is particularly important under **anaerobic conditions**, such as waterlogging.

Q. 20. Explain the process of nitrate assimilation in plants.

Ans: Nitrate Assimilation in Plants

Nitrate assimilation is the process by which plants convert nitrate (NO₃⁻) absorbed from the soil into **ammonia** (NH₃/NH₄⁺) and then incorporate it into organic compounds such as amino acids and proteins. It is an important part of **nitrogen metabolism** in plants.

Steps of Nitrate Assimilation

The process occurs mainly in three stages:

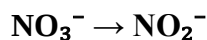
1. Absorption of Nitrate

Plants absorb nitrate ions (NO_3^-) from the soil through their roots. Nitrate is transported to the cells where it is assimilated.

2. Reduction of Nitrate to Nitrite

Nitrate is first reduced to nitrite (NO_2^-) by the enzyme **nitrate reductase**.

Reaction:

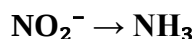


This reaction occurs mainly in the **cytoplasm** and requires reducing power, generally supplied by NADH or NADPH.

3. Reduction of Nitrite to Ammonia

Nitrite enters the **chloroplasts** of leaves or plastids of non-green tissues. It is reduced to ammonia by the enzyme **nitrite reductase**.

Reaction:



This reaction requires electrons, ultimately supplied by reduced ferredoxin.

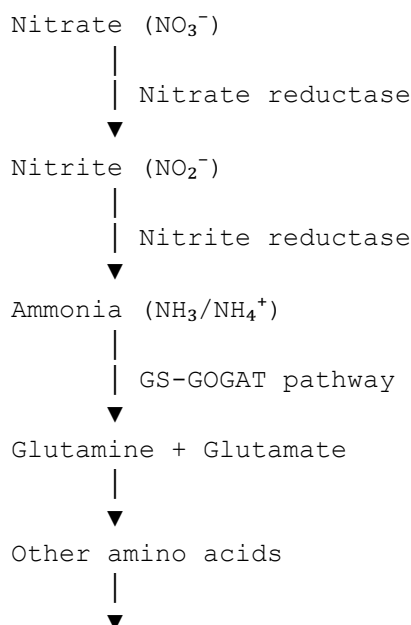
4. Incorporation of Ammonia into Organic Compounds

Ammonia is toxic if it accumulates, so it is rapidly incorporated into organic compounds. The major pathway is the **GS-GOGAT pathway**.

- **Glutamine synthetase (GS)** combines ammonia with glutamate to form **glutamine**.
- **Glutamate synthase (GOGAT)** transfers the amino group to another molecule, producing **glutamate**.

Glutamate and glutamine then serve as important nitrogen donors for the synthesis of other **amino acids, proteins, nucleic acids and other nitrogen-containing compounds**.

Suitable Flow Chart



Proteins and other
nitrogen-containing compounds

Significance

1. Provides plants with **usable nitrogen** for growth and development.
2. Helps in the synthesis of **amino acids and proteins**.
3. Supplies nitrogen for the formation of **nucleic acids, chlorophyll and enzymes**.
4. Plays an essential role in **plant growth, metabolism and reproduction**.

Nitrate assimilation converts inorganic nitrate into organic nitrogen compounds. The sequence **nitrate** → **nitrite** → **ammonia** → **amino acids** is essential for the utilization of soil nitrogen and the synthesis of important cellular components in plants.

Q. 21. What is biological nitrogen fixation? Explain its significance.

Ans: Biological Nitrogen Fixation

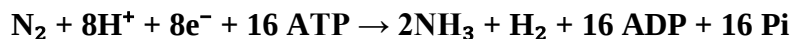
Biological nitrogen fixation is the process by which atmospheric nitrogen (N_2) is converted into ammonia (NH_3) by certain microorganisms with the help of the enzyme **nitrogenase**. Atmospheric nitrogen cannot be directly utilized by most plants, so nitrogen fixation makes it available in a usable form.

Types of Nitrogen Fixation

1. **Symbiotic nitrogen fixation:**
Nitrogen-fixing microorganisms live in association with plants. For example, **Rhizobium** forms root nodules in leguminous plants such as pea, gram and soybean.
2. **Free-living nitrogen fixation:**
Some microorganisms fix atmospheric nitrogen independently of plants, e.g. **Azotobacter** and certain cyanobacteria such as **Nostoc** and **Anabaena**.

Mechanism

The enzyme **nitrogenase** catalyses the reduction of atmospheric nitrogen to ammonia:



Nitrogenase is highly sensitive to oxygen. In legume root nodules, **leghemoglobin** helps maintain a suitable low-oxygen environment for nitrogen fixation.

Significance of Biological Nitrogen Fixation

1. **Increases soil fertility:**
It adds biologically available nitrogen to the soil.
2. **Provides nitrogen to plants:**
The fixed nitrogen is incorporated into amino acids, proteins, nucleic acids and other nitrogen-containing compounds.

3. **Important for leguminous crops:**

Symbiotic nitrogen fixation reduces the dependence of legumes on external nitrogen fertilizers.

4. **Maintains the nitrogen cycle:**

It converts atmospheric N_2 into biologically useful forms and is therefore an essential part of the **nitrogen cycle**.

5. **Agricultural importance:**

Nitrogen-fixing microorganisms can improve soil nitrogen availability and contribute to sustainable crop production.

Biological nitrogen fixation is a vital natural process in which microorganisms convert atmospheric N_2 into **ammonia**. It plays an important role in **plant nutrition, soil fertility, agriculture and maintenance of the nitrogen cycle**.

Q. 22. Describe biological nitrogen fixation in leguminous plants.

Ans: Biological Nitrogen Fixation in Leguminous Plants

Biological nitrogen fixation in leguminous plants is the conversion of atmospheric nitrogen (N_2) into ammonia (NH_3) by symbiotic bacteria of the genus **Rhizobium** living in root nodules. This process makes atmospheric nitrogen available to the plant in a usable form.

Mechanism of Nitrogen Fixation

1. Recognition between plant and bacterium:

Chemical substances released by legume roots attract compatible *Rhizobium* bacteria. The bacteria recognize the host plant and attach to the root hairs.

2. Root hair infection:

The bacteria enter the root hair through an **infection thread**, which develops inward toward the root cortex.

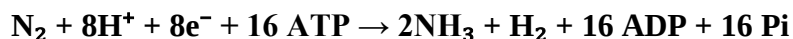
3. Formation of root nodules:

Bacterial infection stimulates division of cortical cells, leading to the formation of **root nodules**. The bacteria differentiate into nitrogen-fixing forms called **bacteroids**.

4. Role of nitrogenase:

Inside the nodule, the enzyme **nitrogenase** reduces atmospheric nitrogen to ammonia. The reaction requires a large amount of ATP and reducing power.

Overall reaction:



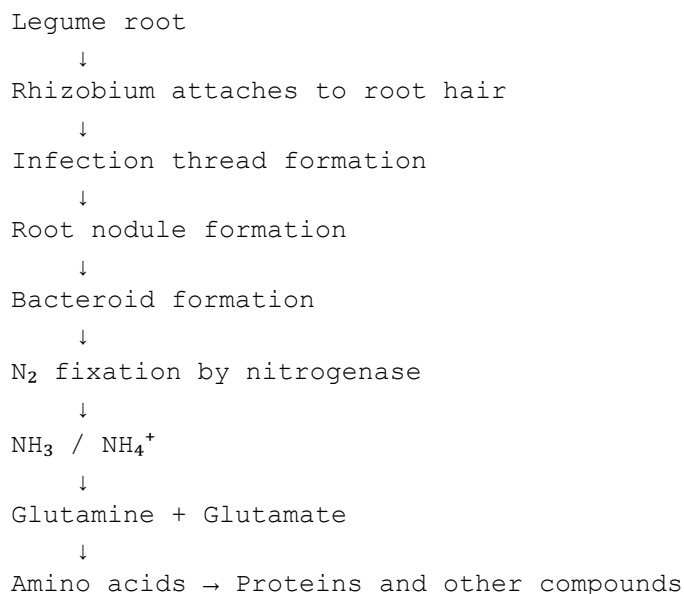
5. Role of leghemoglobin:

Root nodules contain **leghemoglobin**, which helps regulate oxygen concentration. This protects the oxygen-sensitive nitrogenase enzyme while allowing respiration to provide ATP.

6. Assimilation of ammonia:

The ammonia formed is rapidly incorporated into organic compounds, particularly **glutamine and glutamate**, which are used to synthesize other amino acids and nitrogen-containing compounds.

Simple Flow Diagram



Significance

- Provides the legume with a source of **biologically available nitrogen**.
- Improves **soil nitrogen status** through nitrogen fixation and subsequent return of nitrogen to the soil.
- Reduces dependence on external nitrogen fertilizers.
- Supports synthesis of **proteins, nucleic acids, chlorophyll and other nitrogen-containing compounds**.
- Has considerable importance in **agriculture and sustainable crop production**.

Biological nitrogen fixation in legumes is a highly specialized **symbiotic association between leguminous plants and *Rhizobium***. Formation of root nodules provides a suitable environment for nitrogenase to convert atmospheric nitrogen into ammonia, which is subsequently assimilated into organic nitrogen compounds.

Q. 23. Explain the physiology and biochemistry of nitrogen fixation.

Ans: Physiology and Biochemistry of Nitrogen Fixation

Nitrogen fixation is the process by which atmospheric nitrogen (N_2) is converted into ammonia (NH_3), a form that can be utilized by plants. Atmospheric nitrogen is abundant but cannot be directly used by most plants because the $N \equiv N$ triple bond is very strong. Biological nitrogen

fixation is mainly carried out by microorganisms such as **Rhizobium**, **Azotobacter**, **cyanobacteria** and some other bacteria.

Physiology of Nitrogen Fixation

In biological nitrogen fixation, microorganisms obtain energy from respiration and use it to reduce atmospheric nitrogen.

1. Association with the host plant

In legumes, *Rhizobium* bacteria enter the root through root hairs and stimulate the formation of **root nodules**. Inside the nodules, bacteria differentiate into **bacteroids**, which carry out nitrogen fixation.

2. Role of root nodules

Root nodules provide a suitable environment for nitrogen fixation. They contain **leghemoglobin**, which maintains a low concentration of free oxygen. This is important because the nitrogenase enzyme is highly sensitive to oxygen.

3. Energy requirement

Nitrogen fixation is an energy-intensive process. Large amounts of **ATP** are supplied through respiration and photosynthesis-derived carbohydrates of the host plant.

4. Assimilation of fixed nitrogen

The ammonia produced during fixation is rapidly incorporated into organic compounds such as **glutamine and glutamate**. These compounds subsequently provide nitrogen for the synthesis of amino acids, proteins, nucleic acids and other nitrogen-containing substances.

Biochemistry of Nitrogen Fixation

The biochemical reduction of nitrogen is carried out by the enzyme complex **nitrogenase**.

Nitrogenase complex

Nitrogenase consists mainly of two components:

1. **Fe-protein (Fe protein):** Transfers electrons to the Mo-Fe protein and binds ATP.
2. **Mo-Fe protein:** Contains the active site where atmospheric N_2 is reduced.

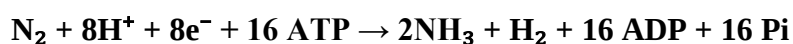
Mechanism

The process occurs approximately as follows:

Reducing agent $\rightarrow$ Fe-protein $\rightarrow$ Mo-Fe protein $\rightarrow$ N_2 $\rightarrow$ NH_3

1. Electrons are supplied by reducing substances such as **ferredoxin**.
2. The Fe-protein receives electrons and binds ATP.
3. ATP hydrolysis provides energy for electron transfer.
4. Electrons are transferred to the Mo-Fe protein.
5. N_2 binds at the active site and is progressively reduced.
6. Finally, ammonia is produced.

The overall reaction is:



Thus, nitrogen fixation requires **nitrogenase, electrons, protons and a large supply of ATP**.

Assimilation of Ammonia

The ammonia produced is quickly incorporated into organic molecules, mainly through the **GS-GOGAT pathway**:

$\text{NH}_4^+ \rightarrow \text{Glutamine} \rightarrow \text{Glutamate} \rightarrow \text{Other amino acids} \rightarrow \text{Proteins and other nitrogen compounds}$

Factors Affecting Nitrogen Fixation

- Adequate supply of carbohydrates and energy
- Suitable temperature and pH
- Availability of phosphorus, molybdenum and iron
- Adequate but controlled oxygen supply
- Presence of effective nitrogen-fixing microorganisms
- Proper functioning of nitrogenase

Significance

- Converts atmospheric N_2 into biologically useful nitrogen.
- Increases the nitrogen supply available to plants.
- Improves soil fertility, particularly through legume–*Rhizobium* associations.
- Reduces dependence on chemical nitrogen fertilizers.
- Provides nitrogen required for synthesis of proteins, nucleic acids, chlorophyll and other compounds.

Nitrogen fixation is an important physiological and biochemical process in which atmospheric nitrogen is converted into ammonia by nitrogen-fixing microorganisms. **Nitrogenase** performs the central biochemical reaction, while ATP, reducing power and a controlled oxygen environment are essential for the process. The fixed nitrogen is subsequently assimilated into organic compounds and becomes available for plant growth and metabolism.

Q. 24. Explain ammonia assimilation in plants.

Ans: Ammonia Assimilation in Plants

Ammonia assimilation is the process by which ammonia ($\text{NH}_3/\text{NH}_4^+$) is incorporated into organic compounds such as amino acids. Ammonia is produced in plants mainly through **nitrate reduction, biological nitrogen fixation, photorespiration and amino acid metabolism**. Since free ammonia can be toxic at high concentrations, plants rapidly assimilate it into amino acids.

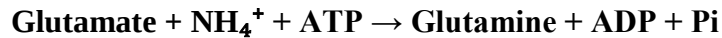
The major pathways of ammonia assimilation are:

1. **Glutamine synthetase (GS) pathway**
2. **Glutamate synthase (GOGAT) pathway**
3. **Glutamate dehydrogenase (GDH) pathway**

1. Glutamine Synthetase (GS) Pathway

Glutamine synthetase is an important enzyme involved in the initial assimilation of ammonium.

It catalyses:



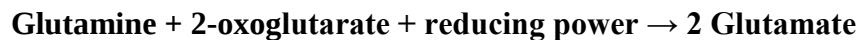
Thus, ammonium is incorporated into glutamate to form **glutamine**.

GS occurs in different cellular compartments, particularly in the **cytosol and chloroplasts**.

2. Glutamate Synthase (GOGAT) Pathway

Glutamine produced by GS is converted into glutamate by **glutamate synthase (GOGAT)**.

The reaction can be represented as:



GOGAT uses reducing power in the form of **ferredoxin or NADH**, depending on the form of the enzyme.

The GS-GOGAT cycle is considered the **major pathway of ammonia assimilation in plants**.

GS-GOGAT cycle



↓



↓ (*Glutamine synthetase*)



↓ (*GOGAT + 2-oxoglutarate*)



↓

Other amino acids

3. Glutamate Dehydrogenase (GDH) Pathway

Glutamate dehydrogenase can also incorporate ammonium into glutamate:



GDH may have an important role under certain physiological conditions, particularly when ammonium concentration is high, although the **GS-GOGAT pathway is generally the principal route of primary ammonium assimilation**.

Importance of Ammonia Assimilation

- Converts potentially toxic ammonium into organic nitrogen compounds.
- Produces **glutamine and glutamate**, which act as major nitrogen donors.
- Provides nitrogen for synthesis of **amino acids and proteins**.
- Contributes to the synthesis of **nucleic acids, chlorophyll and other nitrogen-containing compounds**.
- Helps recycle ammonium released during processes such as photorespiration.
- Maintains nitrogen balance and supports plant growth and development.

Ammonia assimilation is an essential step in plant nitrogen metabolism. The **GS-GOGAT pathway** is the major pathway through which NH_4^+ is incorporated into glutamine and glutamate. These compounds then serve as nitrogen donors for the synthesis of other amino acids and nitrogen-containing biomolecules.

Q. 25. Explain the importance of nitrogen metabolism in plants.

Ans: Nitrogen metabolism refers to the uptake, assimilation, conversion, utilization and recycling of nitrogen compounds in plants. Nitrogen is one of the most important mineral nutrients required for normal plant growth and development. Plants obtain nitrogen mainly in the form of nitrate (NO_3^-) and ammonium (NH_4^+) and convert it into organic compounds.

Importance of Nitrogen Metabolism

1. Synthesis of Amino Acids

Nitrogen metabolism is essential for the formation of **amino acids**, which are the basic building blocks of proteins. Ammonium is incorporated into compounds such as glutamine and glutamate, which act as nitrogen donors for the synthesis of other amino acids.

2. Protein Synthesis

Nitrogen is an essential component of **proteins and enzymes**. Therefore, proper nitrogen metabolism is necessary for the synthesis of structural proteins, enzymes and other functional proteins involved in plant metabolism.

3. Formation of Nucleic Acids

Nitrogen is an important constituent of the nitrogenous bases present in **DNA and RNA**. Proper nitrogen metabolism is therefore essential for DNA replication, RNA synthesis, cell division and genetic processes.

4. Chlorophyll Formation

Nitrogen is a component of **chlorophyll molecules**. Adequate nitrogen metabolism is necessary for chlorophyll formation and consequently for efficient **photosynthesis**. Nitrogen deficiency commonly causes yellowing or chlorosis of leaves.

5. Synthesis of Plant Hormones and Other Compounds

Nitrogen is involved in the formation of several biologically important compounds, including certain **plant hormones, alkaloids, vitamins and coenzymes**. These compounds regulate various physiological activities of plants.

6. Plant Growth and Development

Nitrogen promotes **cell division, cell enlargement and formation of new tissues**. Adequate nitrogen availability supports healthy vegetative growth, leaf development and overall plant productivity.

7. Energy and Metabolic Processes

Many nitrogen-containing compounds function as **enzymes, cofactors and electron carriers**. Nitrogen metabolism therefore supports respiration, photosynthesis and several other biochemical reactions.

8. Nitrogen Recycling

Plants continuously recycle nitrogen through the breakdown and resynthesis of amino acids and proteins. This recycling helps maintain an adequate supply of nitrogen within plant tissues.

9. Crop Productivity

Efficient nitrogen metabolism contributes to **higher biomass production, better leaf development, improved photosynthesis and increased crop yield**. Therefore, nitrogen management is important in agriculture.

Flow Chart

Nitrate (NO_3^-) / Ammonium (NH_4^+)

↓

Nitrogen assimilation

↓

Glutamine + Glutamate

↓

Amino acids

↓

Proteins + Nucleic acids + Chlorophyll + Other nitrogen compounds

↓

Growth and development

Nitrogen metabolism is fundamental to plant life because it provides nitrogen for the synthesis of **amino acids, proteins, nucleic acids, chlorophyll and many other essential compounds**. Efficient nitrogen metabolism is therefore essential for photosynthesis, growth, development, reproduction and crop productivity.

Q. 26. Lipid Metabolism.

Ans: Lipid metabolism refers to the synthesis, breakdown and utilization of lipids in plants. Lipids include fats, oils, phospholipids, glycolipids and fatty acids. They serve as important energy reserves and are essential components of cell membranes.

In plants, lipid metabolism involves two major processes:

1. Lipid synthesis (lipogenesis)
2. Lipid breakdown (lipolysis and β -oxidation)

1. Lipid Synthesis

Lipid synthesis mainly occurs in plastids and the endoplasmic reticulum.

Formation of fatty acids

Acetyl-CoA acts as the starting material for fatty acid synthesis.

Acetyl-CoA $\rightarrow$ Malonyl-CoA $\rightarrow$ Fatty acids

The enzyme **acetyl-CoA carboxylase** converts acetyl-CoA into malonyl-CoA. Fatty acid synthase then adds two-carbon units repeatedly to form long-chain fatty acids.

Formation of triglycerides

Fatty acids combine with **glycerol-3-phosphate** to form triacylglycerols (fats and oils).

Glycerol + Fatty acids $\rightarrow$ Triacylglycerol

These are commonly stored in **oil bodies** or lipid droplets, particularly in seeds.

2. Lipid Breakdown

Stored lipids are mobilized when energy and carbon skeletons are required, especially during **seed germination**.

Lipolysis

The enzyme **lipase** hydrolyses stored triacylglycerols into:

Triacylglycerol → Glycerol + Fatty acids

β-Oxidation of Fatty Acids

Fatty acids undergo **β-oxidation**, mainly in **peroxisomes/glyoxysomes** in germinating oil-rich seeds.

During each cycle of β-oxidation, a fatty acid is shortened by two carbon atoms and produces **acetyl-CoA**.

Fatty acid → Acetyl-CoA + reducing equivalents

The acetyl-CoA can then enter the **glyoxylate cycle** and subsequently contribute to the formation of carbohydrates.

3. Glyoxylate Cycle

The glyoxylate cycle is particularly important in germinating oil seeds. It occurs in specialized peroxisomes called **glyoxysomes**.

The cycle converts acetyl-CoA derived from fatty acids into compounds that can ultimately be used for **sugar synthesis**.

Fatty acids → β-oxidation → Acetyl-CoA → Glyoxylate cycle → Succinate → Glucose

This conversion allows stored oil in seeds to support the growth of the young seedling before it becomes photosynthetically independent.

Functions of Lipid Metabolism

- Provides **energy** through oxidation of fatty acids.
- Provides long-term **energy storage**, especially in seeds.
- Produces components required for **cell membranes**.
- Provides precursors for several important plant compounds.
- Supports **seed germination and early seedling growth**.
- Helps in the synthesis of phospholipids, glycolipids and other cellular lipids.

Flow Chart

Stored lipids

↓ (*lipase*)

Glycerol + Fatty acids

↓

β-oxidation

↓

Acetyl-CoA

↓

Glyoxylate cycle

↓

Organic acids / sugars

↓

Growth and development

Lipid metabolism is an essential part of plant metabolism. It includes the **synthesis, storage and degradation of lipids**. In oil-rich seeds, breakdown of stored fats through **lipolysis, β-oxidation**

and the glyoxylate cycle provides carbon and energy needed for germination and early seedling development.

Q. 27. Explain the glyoxylate cycle and its significance.

Ans: Glyoxylate Cycle and Its Significance

The **glyoxylate cycle** is a modified form of the Krebs cycle that enables plants, fungi and some microorganisms to convert **acetyl-CoA derived from fats into carbohydrates**. In plants, it occurs mainly in specialized peroxisomes called **glyoxysomes**, particularly in germinating oil-rich seeds.

The cycle is important because plants cannot convert acetyl-CoA into carbohydrates through the normal Krebs cycle alone.

Steps of the Glyoxylate Cycle

The cycle begins with **acetyl-CoA**, produced mainly from fatty acids through β -oxidation.

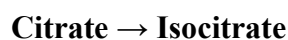
1. Formation of Citrate

Acetyl-CoA combines with **oxaloacetate** to form citrate.



2. Formation of Isocitrate

Citrate is converted into **isocitrate** through the intermediate cis-aconitate.



3. Cleavage of Isocitrate

This is the characteristic step of the glyoxylate cycle. The enzyme **isocitrate lyase** cleaves isocitrate into:



No CO_2 is released in this step.

4. Formation of Malate

Glyoxylate combines with another molecule of acetyl-CoA to form malate.



The enzyme involved is **malate synthase**.

5. Regeneration of Oxaloacetate

Malate is converted into oxaloacetate.



Oxaloacetate can then enter another turn of the cycle.

Simplified Flow Chart

Fatty acids

↓ β -oxidation

Acetyl-CoA

↓

Citrate

↓

Isocitrate

↓ (*isocitrate lyase*)

Succinate + Glyoxylate

↓

Malate

↓

Oxaloacetate

↓

Gluconeogenesis

↓

Glucose / Sucrose

Significance of the Glyoxylate Cycle

1. Conversion of Fats into Carbohydrates

Its most important function is to allow the carbon of stored fatty acids to be converted into **carbohydrates** through gluconeogenesis.

2. Important During Seed Germination

Oil-rich seeds such as **castor, sunflower and groundnut** depend heavily on stored lipids during early germination. The glyoxylate cycle helps convert these stored oils into soluble sugars needed by the growing seedling.

3. Avoids Carbon Loss

Unlike the Krebs cycle, the glyoxylate cycle bypasses the two decarboxylation steps. Therefore, carbon from acetyl-CoA is conserved rather than being lost as CO₂.

4. Provides Precursors for Biosynthesis

The succinate and malate produced can contribute to the formation of compounds required for **respiration, gluconeogenesis and other metabolic processes**.

5. Supports Early Seedling Growth

Before young seedlings develop sufficient photosynthetic capacity, carbohydrates produced through this pathway provide substrates for **respiration and growth**.

The glyoxylate cycle is an important metabolic pathway in plants, especially in germinating oil-rich seeds. By using the enzymes **isocitrate lyase and malate synthase**, it converts acetyl-CoA from fatty acid breakdown into four-carbon compounds that can ultimately be used to synthesize carbohydrates. Thus, it provides an important link between **lipid metabolism and carbohydrate metabolism**.

Q. 28. Write a note on the mobilization of stored lipids during seed germination.

Ans: Mobilization of Stored Lipids During Seed Germination

Introduction

Many seeds, particularly **oil-rich seeds** such as castor, groundnut and sunflower, store large quantities of lipids in the form of **triacylglycerols (TAGs)**. During seed germination, these stored lipids are mobilized and converted into soluble carbohydrates and energy required for the growth of the embryo and young seedling.

The major steps involved are:

Lipolysis → β -oxidation → Glyoxylate cycle → Gluconeogenesis → Sugars

1. Hydrolysis of Stored Lipids

After germination begins, stored triacylglycerols present in **oil bodies** are hydrolysed by lipolytic enzymes, mainly **lipases**.

Triacylglycerol → Glycerol + Fatty acids

The glycerol and fatty acids are then utilized through different metabolic pathways.

2. Utilization of Glycerol

Glycerol is converted into **glycerol-3-phosphate** and subsequently into glycolytic intermediates such as **dihydroxyacetone phosphate (DHAP)**.

Glycerol → Glycerol-3-phosphate → DHAP → Carbohydrate metabolism

Thus, glycerol can contribute to respiration or carbohydrate synthesis.

3. β -Oxidation of Fatty Acids

Fatty acids undergo **β -oxidation**, mainly in **glyoxysomes/peroxisomes** in germinating oil seeds.

During β -oxidation, fatty acids are progressively broken down into **acetyl-CoA**, while producing reduced electron carriers.

Fatty acid → β -oxidation → Acetyl-CoA

Acetyl-CoA is the major carbon product of fatty acid breakdown.

4. Glyoxylate Cycle

The acetyl-CoA enters the **glyoxylate cycle** in glyoxysomes.

Two important enzymes of this pathway are:

- **Isocitrate lyase**
- **Malate synthase**

The cycle converts acetyl-CoA into four-carbon compounds such as **succinate and malate**, without the carbon loss that occurs in the decarboxylation steps of the Krebs cycle.

5. Gluconeogenesis

The succinate and other four-carbon compounds produced by the glyoxylate cycle are converted through metabolic reactions into **phosphoenolpyruvate and other gluconeogenic intermediates**.

These ultimately lead to the formation of **glucose and sucrose**.

Fatty acids → Acetyl-CoA → Glyoxylate cycle → Four-carbon compounds → Gluconeogenesis → Sugars

The sugars are transported to growing tissues and used as substrates for respiration and biosynthesis.

Flow Chart

Stored triacylglycerols in oil bodies
↓ (*lipase*)
Glycerol + Fatty acids
↓
Fatty acids → β-oxidation → Acetyl-CoA
↓
Glyoxylate cycle
↓
Succinate / Malate
↓
Gluconeogenesis
↓
Glucose / Sucrose
↓
Respiration + Growth of seedling

Significance

1. Provides **energy** for germination and early seedling growth.

2. Converts stored lipids into **soluble carbohydrates** that can be transported to growing tissues.
3. Supplies carbon skeletons for the synthesis of cellular components.
4. Supports seedling growth before sufficient photosynthesis begins.
5. Establishes an important metabolic connection between **lipid and carbohydrate metabolism**.

Mobilization of stored lipids is essential during the early stages of germination in oil-rich seeds. Stored triacylglycerols are hydrolysed, fatty acids undergo **β -oxidation**, and the resulting acetyl-CoA enters the **glyoxylate cycle**. The products are subsequently used in gluconeogenesis to produce sugars, providing the young seedling with energy and carbon for growth and development.

Q. 29. Describe the major photosynthetic pigments.

Ans: Major Photosynthetic Pigments

Photosynthetic pigments are coloured substances present in the chloroplasts and other photosynthetic organisms that absorb light energy and convert it into chemical energy during photosynthesis. They are mainly present in the **thylakoid membranes** of chloroplasts.

The major photosynthetic pigments are:

1. **Chlorophyll a**
2. **Chlorophyll b**
3. **Carotenoids**
4. **Phycobilins** in cyanobacteria and red algae

1. Chlorophyll a

- Chlorophyll a is the **principal photosynthetic pigment** found in oxygenic photosynthetic organisms.
- It is blue-green in colour.
- It is present in **higher plants, green algae and cyanobacteria**.
- It directly participates in the photochemical reactions of photosynthesis.
- Its major absorption peaks are approximately **430 nm and 662 nm**.
- Chlorophyll a is the main pigment of the **reaction centres of Photosystem I and Photosystem II**.

Function: It converts absorbed light energy into chemical energy during the light reaction.

2. Chlorophyll b

- Chlorophyll b is a **yellow-green accessory pigment**.
- It is mainly found in higher plants and green algae.
- It absorbs light mainly around **453 nm and 642 nm**.
- It broadens the range of light wavelengths that can be used for photosynthesis.
- It transfers the absorbed energy to chlorophyll a.

Function: It acts mainly as an **accessory pigment** and increases the efficiency of light absorption.

3. Carotenoids

Carotenoids are accessory pigments that are generally **yellow, orange or red**.

They are mainly of two types:

(a) Carotenes

These are **hydrocarbon carotenoids**, such as **β -carotene**.

(b) Xanthophylls

These contain oxygen in their structure. Examples include **lutein, zeaxanthin and violaxanthin**.

Functions of carotenoids:

- Absorb wavelengths of light that chlorophylls absorb less efficiently.
- Transfer some of the absorbed energy to chlorophyll.
- Protect the photosynthetic apparatus from **excess light and photo-oxidative damage**.
- Participate in **non-photochemical quenching** and photoprotection.

4. Phycobilins

Phycobilins are accessory pigments found mainly in **cyanobacteria and red algae**.

Important phycobilins include:

- **Phycoerythrin** – reddish pigment
- **Phycocyanin** – bluish pigment
- **Allophycocyanin** – blue pigment

They are associated with protein complexes called **phycobiliproteins**, which form **phycobilisomes**.

Function: They absorb light in regions of the spectrum that are poorly absorbed by chlorophyll and transfer the energy to chlorophyll a.

Comparison of Major Photosynthetic Pigments

Pigment	Colour	Major occurrence	Main function
Chlorophyll a	Blue-green	Higher plants, algae, cyanobacteria	Primary photochemical pigment
Chlorophyll b	Yellow-green	Green plants and green algae	Accessory pigment
Carotenes	Yellow-orange	Plants and algae	Light absorption and photoprotection
Xanthophylls	Yellow	Plants and algae	Accessory pigment and photoprotection
Phycoerythrin	Red	Red algae, cyanobacteria	Accessory light absorption
Phycocyanin	Blue	Cyanobacteria, red algae	Accessory light absorption

Significance of Photosynthetic Pigments

The combined action of different pigments:

- Broadens the range of wavelengths absorbed by plants.
- Increases the efficiency of photosynthesis.

- Transfers light energy to reaction-centre chlorophyll.
- Protects chloroplasts from excessive light energy.
- Helps plants and algae adapt to different light environments.

Photosynthetic pigments are essential for the capture and utilization of light energy. **Chlorophyll a** is the principal photochemical pigment, while chlorophyll b, carotenoids and phycobilins act mainly as accessory pigments. Together, they maximize light absorption and ensure efficient photosynthesis.

Q. 30. Write a note on the enhancement effect in photosynthesis.

Ans: Enhancement Effect in Photosynthesis

The **enhancement effect** is the phenomenon in which the rate of photosynthesis becomes significantly higher when light of **two different wavelengths is supplied simultaneously** than when either wavelength is supplied separately.

This phenomenon provided important evidence for the existence of **two photosystems** in oxygenic photosynthesis.

The enhancement effect was demonstrated by **Robert Emerson and his co-workers** through experiments on photosynthesis using different wavelengths of light.

Emerson observed that:

- Red light of a longer wavelength alone produced a certain rate of photosynthesis.
- Far-red light alone also produced a lower rate.
- When **red light and far-red light were supplied together**, the rate of photosynthesis was greater than the sum of their individual effects.

This is known as the **Emerson enhancement effect** or **Emerson effect**.

Experimental Observation

The experiment showed that photosynthetic activity increases sharply when light of approximately **680 nm** is combined with light of wavelengths above **680 nm**, particularly far-red light.

Simplified representation

Red light (~680 nm) alone

↓

Moderate photosynthetic rate

Far-red light (>680 nm) alone

↓

Lower photosynthetic rate

Red + Far-red light simultaneously

↓

Enhanced photosynthetic rate

Explanation of the Enhancement Effect

The enhancement effect is explained by the cooperation of **two photosystems**:

Photosystem II (PS II)

- Has a reaction centre called **P680**.
- Absorbs light most effectively around 680 nm.
- Involved in water splitting and electron supply.

Photosystem I (PS I)

- Has a reaction centre called **P700**.
- Absorbs light most effectively around 700 nm.
- Participates in the transfer of electrons toward NADP^+ and formation of NADPH.

When only one wavelength is supplied, one photosystem may be preferentially excited. When **both red and far-red wavelengths are supplied together**, PS II and PS I are excited simultaneously and cooperate in electron transport.

PS II → Electron carriers → PS I → NADP^+ → NADPH

This cooperation increases the efficiency of the overall photosynthetic electron transport and produces the enhancement effect.

Significance

1. Provided strong evidence for the existence of **two photosystems**.
2. Demonstrated the cooperation between **PS I and PS II**.
3. Helped in understanding the mechanism of **non-cyclic electron transport**.
4. Supported the concept of the **Z-scheme of photosynthetic electron transport**.
5. Established that different wavelengths of light can act cooperatively during photosynthesis.

The Emerson enhancement effect is an important phenomenon in photosynthesis in which simultaneous illumination with **red and far-red light** produces a greater photosynthetic response than either light alone. It provided crucial experimental evidence for the **two-photosystem concept** and their cooperation in the light reactions of photosynthesis.

Q. 31. Describe photophosphorylation.

Ans: Photophosphorylation

Photophosphorylation is the process of formation of **ATP from ADP and inorganic phosphate (Pi)** using light energy during the light reactions of photosynthesis. It occurs in the **thylakoid membranes of chloroplasts**.

$\text{ADP} + \text{Pi} + \text{Light energy} \rightarrow \text{ATP}$

Photophosphorylation is mainly of two types:

1. **Cyclic photophosphorylation**
2. **Non-cyclic photophosphorylation**

1. Cyclic Photophosphorylation

Cyclic photophosphorylation involves mainly **Photosystem I (PS I)** and its reaction centre **P700**.

Mechanism

1. Light excites chlorophyll molecule P700.
2. The excited electron is transferred to an electron acceptor.
3. The electron passes through a series of electron carriers.
4. During electron transport, energy is used to establish a **proton gradient** across the thylakoid membrane.
5. The proton gradient drives **ATP synthase**, resulting in ATP formation.
6. The electron finally returns to P700; hence, the pathway is called **cyclic**.

Features

- Mainly involves **PS I**.
- Produces **ATP only**.
- **NADPH is not produced**.
- **O₂ is not released**.
- Water is not split.
- It helps supply additional ATP required for photosynthetic carbon fixation.

Flow:

P700 → Electron acceptor → Electron carriers → ATP formation → P700

2. Non-Cyclic Photophosphorylation

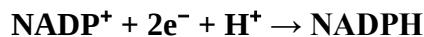
Non-cyclic photophosphorylation involves **both Photosystem II (PS II) and Photosystem I (PS I)**. It is also called the **linear electron flow**.

Mechanism

1. Light excites **P680** of PS II.
2. Water undergoes photolysis to replace the electrons lost by PS II.



3. Electrons pass through carriers such as plastoquinone, cytochrome complex and plastocyanin.
4. Their movement contributes to the formation of a proton gradient.
5. The proton gradient drives ATP synthase and produces ATP.
6. Electrons reach PS I and are re-excited by light.
7. Finally, electrons are transferred to **ferredoxin and NADP⁺**, resulting in the formation of **NADPH**.



Features

- Involves **PS II and PS I**.
- Produces **ATP and NADPH**.
- **O₂ is released** as a by-product.
- Electrons do not return to their original reaction centre.

Difference Between Cyclic and Non-Cyclic Photophosphorylation

Feature	Cyclic	Non-cyclic
Photosystems involved	Mainly PS I	PS I and PS II
Reaction centre	P700	P680 and P700
ATP	Produced	Produced
NADPH	Not produced	Produced
O ₂	Not released	Released
Electron flow	Cyclic	Linear
Water splitting	Absent	Present

Significance

- Provides **ATP** required for the Calvin cycle.
- Non-cyclic photophosphorylation provides both **ATP and NADPH**.
- Cyclic photophosphorylation helps balance the ATP requirement of the chloroplast.
- Provides reducing power needed for the synthesis of carbohydrates.
- Forms an essential part of the **light reactions of photosynthesis**.

Photophosphorylation is the light-dependent synthesis of ATP in chloroplasts. **Cyclic photophosphorylation** involves mainly PS I and produces ATP, whereas **non-cyclic photophosphorylation** involves both photosystems and produces ATP, NADPH and O₂. Together, they provide the energy and reducing power required for the light-independent reactions of photosynthesis.

Q. 32. Explain the C₃ photosynthetic pathway.

Ans: Photophosphorylation

Photophosphorylation is the process of formation of **ATP from ADP and inorganic phosphate (Pi)** using light energy during the light reactions of photosynthesis. It occurs in the **thylakoid membranes of chloroplasts**.



Photophosphorylation is mainly of two types:

1. **Cyclic photophosphorylation**
2. **Non-cyclic photophosphorylation**

1. Cyclic Photophosphorylation

Cyclic photophosphorylation involves mainly **Photosystem I (PS I)** and its reaction centre **P700**.

Mechanism

1. Light excites chlorophyll molecule P700.
2. The excited electron is transferred to an electron acceptor.
3. The electron passes through a series of electron carriers.

4. During electron transport, energy is used to establish a **proton gradient** across the thylakoid membrane.
5. The proton gradient drives **ATP synthase**, resulting in ATP formation.
6. The electron finally returns to P700; hence, the pathway is called **cyclic**.

Features

- Mainly involves **PS I**.
- Produces **ATP only**.
- **NADPH is not produced**.
- **O₂ is not released**.
- Water is not split.
- It helps supply additional ATP required for photosynthetic carbon fixation.

Flow:

P700 → Electron acceptor → Electron carriers → ATP formation → P700

2. Non-Cyclic Photophosphorylation

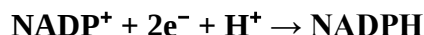
Non-cyclic photophosphorylation involves **both Photosystem II (PS II) and Photosystem I (PS I)**. It is also called the **linear electron flow**.

Mechanism

1. Light excites **P680** of PS II.
2. Water undergoes photolysis to replace the electrons lost by PS II.



3. Electrons pass through carriers such as plastoquinone, cytochrome complex and plastocyanin.
4. Their movement contributes to the formation of a proton gradient.
5. The proton gradient drives ATP synthase and produces ATP.
6. Electrons reach PS I and are re-excited by light.
7. Finally, electrons are transferred to **ferredoxin and NADP⁺**, resulting in the formation of **NADPH**.



Features

- Involves **PS II and PS I**.
- Produces **ATP and NADPH**.
- **O₂ is released** as a by-product.
- Electrons do not return to their original reaction centre.

Difference Between Cyclic and Non-Cyclic Photophosphorylation

Feature	Cyclic	Non-cyclic
Photosystems involved	Mainly PS I	PS I and PS II
Reaction centre	P700	P680 and P700
ATP	Produced	Produced
NADPH	Not produced	Produced

Feature	Cyclic	Non-cyclic
O ₂	Not released	Released
Electron flow	Cyclic	Linear
Water splitting	Absent	Present

Significance

- Provides **ATP** required for the Calvin cycle.
- Non-cyclic photophosphorylation provides both **ATP and NADPH**.
- Cyclic photophosphorylation helps balance the ATP requirement of the chloroplast.
- Provides reducing power needed for the synthesis of carbohydrates.
- Forms an essential part of the **light reactions of photosynthesis**.

Photophosphorylation is the light-dependent synthesis of ATP in chloroplasts. **Cyclic photophosphorylation** involves mainly PS I and produces ATP, whereas **non-cyclic photophosphorylation** involves both photosystems and produces ATP, NADPH and O₂. Together, they provide the energy and reducing power required for the light-independent reactions of photosynthesis.

Q. 33. Differentiate between C₃ and C₄ photosynthesis.

Ans: Difference Between C₃ and C₄ Photosynthesis

Plants use different pathways for the fixation of atmospheric CO₂. The **C₃ pathway** is the Calvin cycle in which the first stable product is a three-carbon compound, whereas **C₄ photosynthesis** involves an initial four-carbon CO₂ fixation followed by the Calvin cycle.

Differences Between C₃ and C₄ Photosynthesis

Feature	C ₃ Photosynthesis	C ₄ Photosynthesis
1. First stable product	3-phosphoglycerate (3-PGA), a 3-carbon compound	Oxaloacetate (OAA), a 4-carbon compound
2. Initial CO₂ acceptor	RuBP	Phosphoenolpyruvate (PEP)
3. Initial CO₂-fixing enzyme	RuBisCO	PEP carboxylase
4. Site of initial CO₂ fixation	Mesophyll cells	Mesophyll cells
5. Site of Calvin cycle	Mesophyll chloroplasts	Mainly bundle-sheath chloroplasts
6. Kranz anatomy	Generally absent	Usually present
7. Photorespiration	Relatively high	Very low or effectively suppressed
8. CO₂ concentration mechanism	No special CO ₂ -concentrating mechanism	Has a CO ₂ -concentrating mechanism

Feature	C ₃ Photosynthesis	C ₄ Photosynthesis
9. Efficiency at high temperature	Generally lower	Generally higher
10. Water-use efficiency	Lower	Higher
11. Light saturation	Usually lower	Usually higher
12. ATP requirement	Lower; about 3 ATP and 2 NADPH per CO ₂ fixed	Higher; about 5 ATP and 2 NADPH per CO ₂ fixed
13. Examples	Rice, wheat, potato, soybean	Maize, sugarcane, sorghum, millet
14. Major advantage	Efficient under moderate temperature and light conditions	Efficient under high light, high temperature and relatively dry conditions

C₃ Pathway

CO₂ → RuBP → 3-PGA → Calvin cycle → Carbohydrates

The enzyme **RuBisCO** fixes CO₂ directly in mesophyll chloroplasts.

C₄ Pathway

The C₄ pathway involves two major stages:

CO₂ → PEP → OAA → C₄ acids → CO₂ release in bundle sheath → Calvin cycle

PEP carboxylase initially fixes CO₂, and the released CO₂ is subsequently fixed by RuBisCO through the Calvin cycle.

Simplified Comparison

C₃ plants:

CO₂

↓

RuBisCO

↓

3-PGA

↓

Calvin cycle

C₄ plants:

CO₂

↓

PEP carboxylase

↓

OAA / C₄ acids

↓

CO₂ released in bundle sheath

↓

RuBisCO + Calvin cycle

Significance

C₃ plants are well adapted to conditions where temperature and light intensity are moderate. C₄ plants have adaptations that improve **CO₂ concentration, water-use efficiency and photosynthetic performance under high temperature and intense light.**

The major difference between C₃ and C₄ photosynthesis is the **initial method of CO₂ fixation.** C₃ plants directly fix CO₂ through RuBisCO, whereas C₄ plants first fix CO₂ through PEP carboxylase into four-carbon compounds and then use the Calvin cycle. The C₄ mechanism minimizes photorespiration and is particularly advantageous under hot, bright conditions.

Q. 34. What is CAM photosynthesis? Explain its significance.

Ans: CAM Photosynthesis and Its Significance

CAM (Crassulacean Acid Metabolism) is a special type of photosynthetic pathway found mainly in plants adapted to **dry and water-limited environments.** It is named after the family **Crassulaceae**, in which this pathway was first studied extensively.

Examples of CAM plants include **Opuntia, Agave, Aloe, pineapple and many other succulents.**

The main feature of CAM photosynthesis is the **temporal separation of CO₂ fixation and the Calvin cycle.**

Mechanism of CAM Photosynthesis

CAM plants perform different steps of carbon fixation during **night and day.**

1. During the Night

At night, stomata open to reduce water loss.

1. Atmospheric CO₂ enters the leaf through open stomata.
2. CO₂ is converted into bicarbonate.
3. **PEP carboxylase** fixes CO₂ using phosphoenolpyruvate (PEP).
4. Oxaloacetate (OAA) is formed.
5. OAA is converted into **malate (malic acid).**
6. Malic acid is stored in the vacuole.

CO₂ → OAA → Malic acid → Vacuole

2. During the Day

During the day, stomata remain mostly closed to minimize water loss.

1. Malic acid moves out of the vacuole.
2. It is decarboxylated, releasing CO₂.
3. The released CO₂ is concentrated around **RuBisCO.**

4. CO₂ enters the **Calvin cycle** and is converted into carbohydrates using ATP and NADPH generated by the light reactions.

Malic acid → CO₂ → Calvin cycle → Carbohydrates

Simplified Flow Chart

Night: Stomata open

CO₂

↓

PEP carboxylase

↓

OAA

↓

Malic acid

↓

Stored in vacuole

Day: Stomata closed

Malic acid

↓

CO₂ released

↓

RuBisCO

↓

Calvin cycle

↓

Carbohydrates

Significance of CAM Photosynthesis

1. Water Conservation

The most important advantage is **reduced water loss**. Stomata open mainly at night when evaporation is lower and remain closed during the hot daytime.

2. Adaptation to Dry Environments

CAM allows plants to survive in **arid and semi-arid habitats**, where water availability is limited.

3. High Water-Use Efficiency

CAM plants produce relatively more carbon gain per unit of water lost compared with many non-CAM plants.

4. Reduced Photorespiration

CO₂ released from stored malic acid during the day increases the internal CO₂ concentration around RuBisCO. This helps suppress the oxygenase activity of RuBisCO and therefore reduces **photorespiration**.

5. Survival Under Environmental Stress

CAM metabolism helps plants tolerate **drought, high temperature and water scarcity**. It is particularly important in succulent plants that store water in their tissues.

Difference from C₃ and C₄ Pathways

The special feature of CAM is that the two stages occur at different **times**:

- **Night:** Initial CO₂ fixation by PEP carboxylase.
- **Day:** CO₂ is released from malate and used in the Calvin cycle.

Thus, CAM shows **temporal separation**, whereas C₄ photosynthesis generally shows **spatial separation** between mesophyll and bundle-sheath cells.

CAM photosynthesis is a specialized adaptation that enables plants to conserve water while carrying out carbon fixation. By opening stomata mainly at night and storing CO₂ as **malic acid**, CAM plants can maintain photosynthesis during the day with their stomata largely closed. Therefore, CAM is especially important for plant survival in **dry and water-deficient environments**.

Q. 35. Describe the physiological roles of auxins.

Ans: Physiological Roles of Auxins

Auxins are a group of plant growth regulators that play important roles in plant growth and development. The naturally occurring auxin is **indole-3-acetic acid (IAA)**. Auxins are mainly synthesized in **shoot apices, young leaves, developing seeds and fruits**.

Their effects depend on concentration, plant organ and environmental conditions.

Physiological Roles of Auxins

1. Cell Elongation

Auxins promote **cell elongation**, particularly in young shoots. They stimulate proton pumps in the plasma membrane, leading to cell-wall loosening and increased water uptake.

Thus, auxins are important for the elongation and growth of stems and shoots.

2. Apical Dominance

Auxin produced in the **shoot apical meristem** suppresses the growth of lateral buds and promotes the growth of the main shoot. This phenomenon is called **apical dominance**.

Removal of the shoot apex often results in increased growth of lateral branches.

3. Root Initiation

Auxins promote the formation of **adventitious and lateral roots** at appropriate concentrations. Synthetic auxins such as IBA and NAA are therefore widely used for rooting of stem cuttings.

4. Tropic Responses

Auxins are involved in **phototropism and gravitropism**.

- In shoots, unequal distribution of auxin causes differential cell elongation, resulting in bending toward light.
- In roots, auxin redistribution contributes to the gravitropic response.

5. Fruit Development

Auxins promote **fruit growth and development**. Application of auxins can sometimes induce fruit development without fertilization, a phenomenon called **parthenocarpy**.

6. Prevention of Premature Fruit and Leaf Abscission

Auxins can delay **abscission** of young leaves and developing fruits by influencing the formation and activity of the abscission zone.

7. Vascular Differentiation

Auxins promote the differentiation and development of **vascular tissues**, particularly xylem. They help in the proper development of conducting tissues during plant growth.

8. Callus Formation and Tissue Culture

Auxins are important in **plant tissue culture**. In suitable concentrations, they promote cell division and callus formation. The ratio of auxin to cytokinin helps determine whether roots, shoots or callus are preferentially formed.

9. Weed Control

Synthetic auxins such as **2,4-D** can act as selective herbicides. At appropriate concentrations, they cause abnormal growth and ultimately death of many broad-leaved weeds.

Table

Physiological role	Effect of auxin
Cell elongation	Promotes shoot cell elongation
Apical dominance	Suppresses lateral buds
Root formation	Promotes lateral/adventitious roots at suitable concentrations
Tropic movements	Controls phototropism and gravitropism
Fruit development	Promotes growth and may induce parthenocarpy
Abscission	Can delay premature abscission
Vascular differentiation	Promotes vascular tissue development
Tissue culture	Promotes cell division and rooting/callus formation
Weed control	Synthetic auxins act as herbicides

Auxins are essential plant growth regulators that coordinate **cell elongation, root formation, apical dominance, tropic responses, fruit development, vascular differentiation and abscission**. Thus, auxins play a central role in regulating the growth and development of plants.

Q. 36. Explain the role of gibberellins in plant growth and development.

Ans: Role of Gibberellins in Plant Growth and Development

Gibberellins (GAs) are an important group of plant growth regulators that promote various aspects of plant growth and development. They are naturally occurring **diterpenoid compounds**. Gibberellic acid (**GA₃**) is one of the best-known gibberellins.

Gibberellins are produced mainly in **young leaves, shoot apices, developing seeds and fruits**.

Physiological Roles of Gibberellins

1. Promotion of Stem Elongation

Gibberellins promote **cell division and cell elongation**, resulting in increased length of stems and internodes. This effect is particularly prominent in genetically dwarf plants.

Gibberellin → Cell division + Cell elongation → Increased stem length

2. Breaking Seed Dormancy

Gibberellins help break **seed dormancy** and promote germination in many plants. They can overcome dormancy imposed by environmental or physiological conditions.

3. Promotion of Seed Germination

During cereal seed germination, gibberellins produced by the embryo stimulate the aleurone layer to synthesize and release hydrolytic enzymes, especially **α-amylase**.

GA → Aleurone layer → α-amylase → Starch breakdown → Sugars → Energy for embryo

The sugars provide energy and nutrients for the developing embryo.

4. Bolting

Gibberellins promote rapid elongation of the stem or flowering stalk in **rosette plants** such as cabbage, beet and related plants. This rapid internode elongation is called **bolting**.

5. Flowering

Gibberellins can promote flowering in certain plants, particularly some **long-day plants** and plants that require specific environmental conditions for flowering.

6. Fruit Growth and Development

Gibberellins promote **fruit growth** and can increase fruit size. They are used commercially in some crops to improve fruit development.

They may also induce **parthenocarpic fruit development** in certain plants.

7. Breaking Bud Dormancy

Gibberellins can help overcome dormancy in some **buds**, thereby promoting renewed growth.

8. Promotion of Enzyme Production

Gibberellins stimulate the production of hydrolytic enzymes such as **α-amylase, proteases and lipases** during seed germination. These enzymes mobilize stored food reserves.

9. Delay of Senescence

In some plant tissues, gibberellins can **delay senescence** and maintain growth and metabolic activity for a longer period.

Table

Role	Effect of Gibberellins
Stem growth	Promotes cell elongation and internode growth
Seed germination	Promotes germination and mobilization of food reserves
Seed dormancy	Helps break dormancy
Bolting	Promotes rapid stem elongation
Flowering	Promotes flowering in certain plants
Fruit growth	Promotes fruit enlargement
Enzyme production	Stimulates hydrolytic enzymes during germination
Bud growth	Can overcome dormancy in some buds
Senescence	May delay senescence in certain tissues

Gibberellins are important regulators of plant growth and development. They promote **stem elongation, seed germination, enzyme production, bolting, flowering and fruit growth**. Their role in stimulating α -amylase production during cereal seed germination is particularly important because it helps mobilize stored food reserves for the developing embryo.

Q. 37. Explain the role of abscisic acid (ABA) in plants.

Ans: Role of Absciscic Acid (ABA) in Plants

Abscisic acid (ABA) is an important plant growth regulator involved mainly in the regulation of **plant responses to environmental stress, seed dormancy, stomatal movement and growth inhibition**. It is a naturally occurring plant hormone synthesized in many plant tissues, particularly under stress conditions.

ABA is often called a **stress hormone** because its concentration increases during drought and other adverse environmental conditions.

Physiological Roles of ABA

1. Stomatal Closure

One of the most important functions of ABA is the promotion of **stomatal closure during water stress**.

During drought:

Water stress → ABA increases → Guard-cell ion efflux → Water loss from guard cells → Stomata close → Reduced transpiration

Thus, ABA helps plants conserve water.

2. Seed Dormancy

ABA promotes and maintains **seed dormancy**. It prevents premature germination and allows seeds to remain viable until suitable environmental conditions become available.

ABA generally acts antagonistically to gibberellins in the regulation of dormancy and germination.

3. Inhibition of Growth

ABA generally inhibits growth, particularly under unfavorable environmental conditions. It helps plants reduce active growth and conserve resources during stress.

4. Stress Tolerance

ABA plays a central role in plant responses to:

- Drought
- Salinity
- Cold and other environmental stresses

It activates stress-responsive genes and promotes physiological changes that improve plant survival under adverse conditions.

5. Regulation of Seed Development

ABA is important during **seed maturation**. It promotes the accumulation of storage proteins and other reserves and contributes to the acquisition of **desiccation tolerance** in developing seeds.

6. Regulation of Germination

ABA suppresses premature seed germination. A decrease in ABA levels or weakening of ABA responses, together with appropriate environmental conditions, facilitates the transition from dormancy to germination.

7. Leaf and Fruit Abscission

ABA may promote or contribute to **senescence and abscission** under certain physiological and environmental conditions, although abscission is regulated by several hormones, especially the balance between auxin and ethylene.

8. Root Responses to Water Stress

ABA helps regulate **root growth and development** during water limitation. It can modify root system responses so that plants adapt better to changing soil-water conditions.

Table

Role	Effect of ABA
Stomatal movement	Promotes stomatal closure during water stress
Seed dormancy	Promotes and maintains dormancy
Growth	Generally inhibits growth under stress
Stress response	Improves tolerance to drought, salinity and other stresses
Seed maturation	Promotes reserve accumulation and desiccation tolerance
Germination	Suppresses premature germination
Abscission/senescence	May contribute under certain conditions
Root response	Helps regulate root growth under water stress

ABA and Gibberellin Antagonism

ABA and gibberellins often have opposite effects during seed germination:

ABA → Dormancy and inhibition of germination

Gibberellin → Germination and growth

The balance between these hormones helps determine whether a seed remains dormant or germinates.

Absciscic acid is a key regulator of plant growth and development, particularly under stressful conditions. Its major functions include **stomatal closure, maintenance of seed dormancy, regulation of seed maturation, stress tolerance and control of growth**. Therefore, ABA is essential for helping plants survive unfavorable environmental conditions.

Q. 38. Describe the physiological roles of ethylene.

Ans: Physiological Roles of Ethylene

Ethylene (C₂H₄) is a gaseous plant growth regulator that plays important roles in plant growth, development, ripening and responses to environmental stress. It is produced in many plant tissues, particularly **ripening fruits, senescing leaves and flowers, and wounded or stressed tissues**.

Ethylene is unique among major plant hormones because it is a **gas** and can readily diffuse through plant tissues.

Physiological Roles of Ethylene

1. Fruit Ripening

Ethylene is a major regulator of **ripening in climacteric fruits** such as banana, apple, tomato and mango.

It promotes:

- Softening of fruits
- Conversion of starch into sugars
- Breakdown of chlorophyll
- Development of characteristic colour and aroma
- Changes in organic acids and other flavour compounds

Ethylene → Enzyme activation → Fruit ripening

2. Promotion of Senescence

Ethylene promotes **senescence of leaves, flowers and fruits**. During senescence, chlorophyll and cellular components are progressively degraded.

3. Abscission

Ethylene promotes **leaf, flower and fruit abscission**, particularly when interacting with changes in auxin levels.

It stimulates processes in the **abscission zone**, leading to separation of the organ from the plant.

4. Triple Response in Seedlings

Ethylene produces a characteristic **triple response** in young seedlings:

1. Inhibition of elongation growth

2. Increased radial thickening
3. Horizontal growth or exaggerated curvature

This response helps seedlings growing through soil or other physical obstacles.

5. Epinasty

Ethylene can cause **epinasty**, in which leaf petioles bend downward. This occurs because of differential growth on the upper and lower sides of the petiole.

6. Root Growth and Development

Ethylene influences **root growth, root hair formation and root architecture**. At suitable concentrations it can modify root growth and help plants respond to environmental conditions.

7. Response to Mechanical Stress

Ethylene production increases when plants experience **mechanical stress, wounding, flooding or other environmental stresses**. It participates in adaptive responses to these conditions.

8. Breaking Dormancy

Ethylene can help break dormancy in certain **seeds and buds** and may promote germination under some conditions.

9. Flowering

Ethylene can influence flowering in some plants. For example, it promotes **flowering in pineapple** and contributes to sex expression in certain cucurbits.

10. Stress Responses

Ethylene participates in plant responses to **flooding, pathogen attack, mechanical injury and other stresses**. Its effects depend on the plant species, tissue and environmental conditions.

Table

Physiological role	Effect of ethylene
Fruit ripening	Promotes ripening of climacteric fruits
Senescence	Promotes senescence of leaves and flowers
Abscission	Promotes leaf, flower and fruit abscission
Seedling growth	Produces triple response
Epinasty	Causes downward bending of leaves
Root development	Modifies root growth and architecture
Dormancy	Can help break dormancy in some tissues
Flowering	Promotes flowering in some plants
Stress response	Helps regulate responses to flooding, wounding and pathogens

Ethylene is an important gaseous plant hormone that regulates **fruit ripening, senescence, abscission, seedling growth, root development and stress responses**. Its effects often depend on the concentration, developmental stage and environmental conditions of the plant.

Q. 39. What are paratonic movements? Explain with examples.

Ans: Paratonic Movements in Plants

Paratonic movements are the movements of plant organs or parts that occur **in response to external stimuli** such as light, gravity, water, temperature, chemicals or touch.

These movements are also called **stimulus-induced movements** because they are caused by changes in the external environment.

The direction of movement may be either **towards the stimulus or away from it**.

Types of Paratonic Movements

Paratonic movements are mainly of two types:

1. Tropic Movements

These are **directional growth movements** in which the direction of movement is determined by the direction of the stimulus.

- **Phototropism:** Growth in response to light.
Example: Shoots of plants bend towards light (**positive phototropism**).
- **Geotropism (Gravitropism):** Growth in response to gravity.
Example: Roots grow downward and show **positive geotropism**, while shoots grow upward and show **negative geotropism**.
- **Hydrotropism:** Growth in response to water.
Example: Roots grow towards a region having greater moisture.
- **Chemotropism:** Growth in response to chemicals.
Example: Pollen tube grows towards the ovule due to chemical stimuli.
- **Thigmotropism:** Growth in response to touch or contact.
Example: Tendrils of pea and other climbers coil around a support.

2. Nastic Movements

These are **non-directional movements** in which the direction of movement does not depend on the direction of the stimulus.

- **Photonasty:** Movement in response to light.
Example: Opening and closing of flowers in response to light conditions.
- **Nyctinasty:** Sleep movements associated with day and night.
Example: Leaves of **Cassia** or **Mimosa** may show changes in position at night.
- **Seismonasty:** Movement caused by mechanical shock or touch.
Example: Leaves of **Mimosa pudica** fold when touched.
- **Thermonasty:** Movement in response to temperature.
Example: Opening of certain flowers at higher temperatures.

Difference Between Tropic and Nastic Movements

Tropic movement	Nastic movement
Directional movement	Non-directional movement
Direction depends on the direction of stimulus	Direction does not depend on stimulus direction
Usually involves growth	Often involves changes in turgor

Tropic movement

Example: Phototropism in shoots

Nastic movement

Example: Leaf folding in *Mimosa pudica*

Paratonic movements are important adaptations that enable plants to respond to their surroundings. They include **tropic movements**, such as phototropism and geotropism, and **nastic movements**, such as seismonasty and nyctinasty.

Q. 40. Define photoperiodism and explain its importance.

Ans: Photoperiodism

Photoperiodism is the physiological response of plants to the **relative duration of day and night**, particularly in relation to flowering.

The phenomenon was first demonstrated by **W. W. Garner and H. A. Allard (1920)**. They observed that flowering in some plants depends more on the length of the **dark period** than simply on the length of daylight.

The response to photoperiod is mainly perceived by **leaves**, and the signal responsible for flowering is transmitted to the shoot apical meristem.

Types of Photoperiodic Plants

Based on their flowering response, plants are broadly divided into three groups:

1. Short-Day Plants (SDPs)

These plants flower when the **day length is shorter than a critical photoperiod** or, more precisely, when the uninterrupted night exceeds a critical duration.

Examples: Rice, soybean, tobacco, chrysanthemum.

2. Long-Day Plants (LDPs)

These plants flower when the **day length is longer than a critical photoperiod**, usually involving a sufficiently short night.

Examples: Wheat, barley, spinach, radish.

3. Day-Neutral Plants

Flowering in these plants is **not significantly controlled by photoperiod**.

Examples: Tomato, sunflower, cucumber.

Simple Classification

Photoperiodism → Response to day/night duration

→ **Short-day plants** → Flower under shorter days

→ **Long-day plants** → Flower under longer days

→ **Day-neutral plants** → Flowering largely independent of day length

Importance of Photoperiodism

1. Regulation of Flowering

Photoperiodism is especially important in determining the **time of flowering**. Plants flower only when the appropriate photoperiodic conditions are available.

2. Adaptation to Environment

It helps plants coordinate flowering with **favourable seasonal conditions**, such as temperature, water availability and pollinator activity.

3. Geographical Distribution

Photoperiodic responses influence the **distribution of plant species** in different geographical regions because day length changes with latitude and season.

4. Agricultural Importance

Knowledge of photoperiodism helps in selecting and cultivating suitable varieties of **rice, wheat, soybean and other crops** in particular regions.

5. Controlled Flowering

Photoperiod can be manipulated artificially in greenhouses and nurseries by controlling **light and darkness**. This allows flowering to be induced or delayed at desired times.

6. Role in Plant Development

Photoperiod also influences other developmental processes such as **dormancy, tuber formation, bulb formation and seasonal growth** in some plants.

Photoperiodism is an important mechanism by which plants respond to seasonal changes in the **duration of day and night**. It plays a major role in flowering, seasonal adaptation, geographical distribution and agricultural practices.

Q. 41. Describe the role of red and far-red light in photomorphogenesis.

Ans: Role of Red and Far-Red Light in Photomorphogenesis

Photomorphogenesis refers to the regulation of plant growth and development by light. Red and far-red light are particularly important because they regulate several developmental processes through a light-sensitive pigment called **phytochrome**.

Phytochrome exists mainly in two interconvertible forms:

- **Pr (Phytochrome Red)**: absorbs red light around **660 nm**.
- **Pfr (Phytochrome Far-Red)**: absorbs far-red light around **730 nm** and is generally the physiologically active form.

Interconversion of Phytochrome

Red light (660 nm)

Pr —————→ Pfr

Far-red light (730 nm)

Pr ←———— Pfr

Thus, red and far-red light can switch phytochrome between two forms and thereby regulate plant development.

Role of Red Light

1. Seed Germination

Red light can promote germination in many **positively photoblastic seeds**. The effect is mediated by conversion of Pr into active Pfr.

2. De-etiolation

Red light promotes the transition of dark-grown seedlings from an **etiolated condition** to normal light-grown development. It promotes:

- Stem growth inhibition
- Leaf expansion
- Chlorophyll formation
- Development of chloroplasts

3. Stem and Internode Growth

Red light generally suppresses excessive elongation of stems and internodes, producing shorter and stronger seedlings.

4. Regulation of Flowering

Through phytochrome, red light can influence flowering responses in **long-day and short-day plants**.

Role of Far-Red Light

1. Reversal of Red-Light Effects

Far-red light converts **Pfr back towards Pr** and can reverse several responses induced by red light.

For example:

Red light → promotes germination

Far-red light → may inhibit/reverse the response

This reversibility is known as the **red–far-red reversibility phenomenon**.

2. Shade Avoidance Response

Vegetation absorbs much of the red light but transmits or reflects relatively more far-red light.

Therefore, a **low red:far-red ratio** indicates the presence of neighbouring plants.

Plants respond by:

- Increased stem/internode elongation
- Upward growth
- Changes in leaf angle
- Earlier flowering in some species

This is called the **shade avoidance response**.

3. Regulation of Seedling Development

Far-red light influences stem elongation, leaf development and other aspects of photomorphogenesis through changes in the Pr/Pfr ratio.

Red–Far-Red Reversibility

One of the most important characteristics of phytochrome is that some red-light responses can be reversed by far-red light.

Pr + Red light → Pfr → Response

Pfr + Far-red light → Pr → Reversal of response

This phenomenon provided important evidence for the role of **phytochrome as a photoreceptor**.

Importance

Red and far-red light help plants detect:

- Day and night conditions
- Seasonal changes
- Presence of neighbouring vegetation
- Suitable conditions for germination and growth

Red and far-red light regulate plant development mainly through the **phytochrome system**. The reversible conversion of **Pr and Pfr** allows plants to control seed germination, seedling development, stem elongation, flowering and shade responses according to environmental light conditions.

Q. 42. Define carbohydrates and explain their classification.

Ans: Carbohydrates: Definition and Classification

Carbohydrates are organic compounds mainly composed of **carbon, hydrogen and oxygen**, generally having the empirical formula $C_x(H_2O)_y$. Chemically, they are defined as **polyhydroxy aldehydes or ketones, or compounds that yield such substances on hydrolysis**.

Carbohydrates are important sources of **energy** and also serve structural and storage functions in plants.

Examples include **glucose, fructose, sucrose, starch and cellulose**.

Classification of Carbohydrates

Carbohydrates are mainly classified into:

1. Monosaccharides

Monosaccharides are the **simplest carbohydrates** that cannot be hydrolysed into smaller carbohydrate units.

They are classified according to the number of carbon atoms:

Type	Number of carbon atoms	Examples
Triose	3	Glyceraldehyde
Tetrose	4	Erythrose
Pentose	5	Ribose, Ribulose
Hexose	6	Glucose, Fructose
Heptose	7	Sedoheptulose

They may also be classified as **aldoses** and **ketoses** depending on whether they contain an aldehyde or ketone group.

Examples: Glucose is an aldohexose, while fructose is a ketohexose.

2. Oligosaccharides

Oligosaccharides are carbohydrates that yield **2–10 monosaccharide units** on hydrolysis.

They are further classified according to the number of monosaccharide units:

- **Disaccharides:** 2 units
- **Trisaccharides:** 3 units
- **Tetrasaccharides:** 4 units, and so on.

Examples:

- **Sucrose** = glucose + fructose
- **Maltose** = glucose + glucose
- **Lactose** = glucose + galactose
- **Raffinose** = three monosaccharide units

3. Polysaccharides

Polysaccharides are complex carbohydrates consisting of **many monosaccharide units** joined by glycosidic bonds.

They are mainly of two types:

A. Homopolysaccharides

They contain **only one type of monosaccharide**.

Examples:

- **Starch** – polymer of glucose; major storage carbohydrate in plants.
- **Cellulose** – polymer of glucose; important component of plant cell walls.
- **Glycogen** – glucose polymer, mainly a storage carbohydrate in animals and fungi.

B. Heteropolysaccharides

They contain **two or more different types of monosaccharides or their derivatives**.

Examples:

- **Pectin**
- **Hemicellulose**
- **Hyaluronic acid**

Simple Classification

Carbohydrates

→ **Monosaccharides** → Glucose, Fructose, Ribose

→ **Oligosaccharides** → Sucrose, Maltose, Raffinose

→ **Polysaccharides**

→ Homopolysaccharides → Starch, Cellulose

→ Heteropolysaccharides → Pectin, Hemicellulose

Carbohydrates are essential biomolecules that perform important **energy, storage and structural functions** in plants. Based on the number and type of sugar units, they are classified into **monosaccharides, oligosaccharides and polysaccharides**.

Q. 43. Describe the structure and functions of glucose.

Ans: Structure and Functions of Glucose

Glucose is a six-carbon monosaccharide and an important carbohydrate in plants. It is an **aldohexose** with the molecular formula $\text{C}_6\text{H}_{12}\text{O}_6$. It is commonly called **dextrose** and serves as a major source of energy in living organisms.

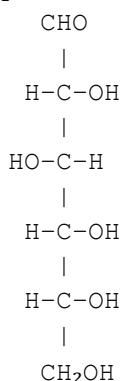
Structure of Glucose

1. Open-Chain Structure

Glucose contains:

- **Six carbon atoms**
- One **aldehyde group** ($-\text{CHO}$) at carbon-1
- Five **hydroxyl groups** ($-\text{OH}$)
- The molecular formula $\text{C}_6\text{H}_{12}\text{O}_6$

The open-chain structure can be represented as:



This structure represents **D-glucose** in its open-chain form.

2. Cyclic Structure

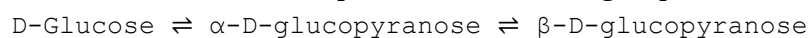
In aqueous solution, glucose mainly exists in a **cyclic form** due to the reaction between the aldehyde group at C-1 and the hydroxyl group at C-5.

It forms a six-membered ring called **glucopyranose**.

Two anomeric forms are possible:

- **α -D-glucose**
- **β -D-glucose**

These forms differ in the position of the $-\text{OH}$ group at the **anomeric carbon (C-1)**.

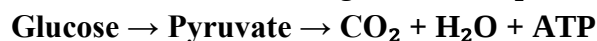


The interconversion between α and β forms in solution is called **mutarotation**.

Functions of Glucose

1. Major Source of Energy

Glucose is oxidized during **cellular respiration** to release energy.



The ATP produced is used for various metabolic activities.

2. Starting Material for Respiration

Glucose undergoes **glycolysis** in the cytoplasm and forms pyruvate. It therefore provides an important substrate for energy metabolism.

3. Formation of Starch

In plants, excess glucose is converted into **starch**, which acts as a major storage carbohydrate.

Glucose → Starch

4. Formation of Cellulose

Glucose molecules are linked together to form **cellulose**, which is a major structural component of plant cell walls.

Glucose → Cellulose → Plant cell wall

5. Precursor for Other Compounds

Glucose provides carbon skeletons for the synthesis of various important compounds, including:

- Amino acids
- Organic acids
- Nucleotides
- Other sugars

6. Role in Biosynthetic Pathways

Glucose and its derivatives participate in several metabolic pathways, including the **pentose phosphate pathway**, which provides reducing power and intermediates for biosynthesis.

7. Transport and Storage

In plants, carbohydrates derived from glucose are transported mainly in the form of **sucrose** through the phloem and stored largely as starch.

Glucose is an important **aldohexose** that exists mainly in cyclic form in solution. It has major roles as an **energy source**, **storage-material precursor**, **structural-material precursor** and **metabolic intermediate**, making it one of the most important carbohydrates in plants.

Q. 44. Explain the structure and functions of mannitol and sorbitol.

Ans: Structure and Functions of Mannitol and Sorbitol

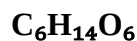
Mannitol and sorbitol are sugar alcohols, also called **polyols**. They are formed by the reduction of corresponding sugars and occur naturally in many plants. They play important roles in **carbon storage**, **transport**, **osmotic regulation** and **protection against environmental stress**.

1. Mannitol

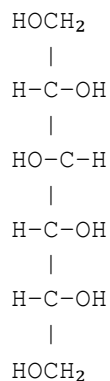
Structure of Mannitol

Mannitol is a **six-carbon sugar alcohol (hexitol)** derived from the reduction of the carbonyl group of **mannose**.

Its molecular formula is:



The open-chain structure can be represented as:



It contains **six carbon atoms and six hydroxyl (–OH) groups**, with no aldehyde or ketone group.

Functions of Mannitol

1. Osmotic Regulation

Mannitol helps maintain the **osmotic balance** of plant cells, particularly under conditions of water stress.

2. Stress Protection

It acts as an **osmoprotectant** and helps plants tolerate drought, salinity and other environmental stresses.

3. Carbon Storage and Transport

In some plants, mannitol serves as a **transportable form of reduced carbon** and can move through the phloem from source to sink tissues.

4. Protection from Reactive Oxygen Species

Mannitol can help protect cells against **oxidative stress** by scavenging certain reactive oxygen species, particularly hydroxyl radicals.

5. Reserve Food Material

It can function as a **reserve carbohydrate** in certain plants and may be metabolized when required.

2. Sorbitol

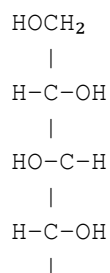
Structure of Sorbitol

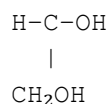
Sorbitol is another **six-carbon sugar alcohol**. It is produced by the reduction of **glucose**.

Its molecular formula is:



Its structure can be represented as:





Sorbitol contains **six carbon atoms and six hydroxyl groups**.

Functions of Sorbitol

1. Transport of Carbon

Sorbitol is an important **transport sugar alcohol** in several plants, particularly members of the **Rosaceae**, such as apple and pear.

2. Osmotic Adjustment

It contributes to the maintenance of **cellular water balance** under drought and salinity conditions.

3. Stress Tolerance

Sorbitol acts as an **osmoprotectant**, helping cells tolerate adverse environmental conditions.

4. Carbon and Energy Source

Sorbitol can be metabolized and used as a **source of carbon and energy** in plant tissues.

5. Protection of Cellular Components

It can help stabilize **proteins and membranes** during environmental stress.

Difference Between Mannitol and Sorbitol

Feature	Mannitol	Sorbitol
Type	Sugar alcohol	Sugar alcohol
Carbon atoms	6	6
Formula	$\text{C}_6\text{H}_{14}\text{O}_6$	$\text{C}_6\text{H}_{14}\text{O}_6$
Derived from	Mannose	Glucose
Major role	Osmotic regulation and stress protection	Carbon transport and osmotic regulation
Common plant association	Many plants, including some halophytes	Particularly important in Rosaceae
Storage/transport	Transport and storage in some plants	Important phloem-translocated carbohydrate

Mannitol and sorbitol are important **polyols in plants**. Besides serving as carbon compounds, they contribute to **osmotic adjustment, stress tolerance and protection of cellular structures**. Sorbitol is particularly important as a transport carbohydrate in many fruit trees, while mannitol is important in osmotic and stress regulation in several plant species.

Q. 45. What are oligosaccharides? Give examples.

Ans: Oligosaccharides:

Oligosaccharides are carbohydrates composed of a **small number of monosaccharide units**, usually **2 to 10**, joined together by **glycosidic bonds**.

On hydrolysis, oligosaccharides produce two or more monosaccharide molecules.

General Representation

The most common oligosaccharides are **disaccharides**, which contain two monosaccharide units.

Classification of Oligosaccharides

Based on the number of monosaccharide units, they are classified as:

1. **Disaccharides** – contain 2 monosaccharide units.
2. **Trisaccharides** – contain 3 monosaccharide units.
3. **Tetrasaccharides** – contain 4 monosaccharide units.
4. **Pentasaccharides** – contain 5 monosaccharide units.
5. Higher oligosaccharides may contain up to about 10 monosaccharide units.

Examples

Oligosaccharide	Monosaccharide units
Sucrose	Glucose + Fructose
Maltose	Glucose + Glucose
Lactose	Glucose + Galactose
Cellobiose	Glucose + Glucose
Raffinose	Galactose + Glucose + Fructose
Stachyose	Galactose + Galactose + Glucose + Fructose

Important Examples**1. Sucrose:**

It consists of **glucose and fructose** and is the major transport sugar in many plants.

2. Maltose:

It consists of **two glucose molecules** and is produced during the breakdown of starch.

3. Raffinose:

It is a **trisaccharide** consisting of galactose, glucose and fructose. It occurs in many plant tissues and seeds.

Functions of Oligosaccharides

- Serve as **sources of energy**.
- Sucrose is an important **transport carbohydrate in plants**.
- Participate in **cell recognition and cell signalling**.
- Some oligosaccharides are involved in **plant defence and stress responses**.
- They may occur as components of **glycoproteins and glycolipids**.

Oligosaccharides are carbohydrates containing **2–10 monosaccharide units linked by glycosidic bonds**. Important examples include **sucrose, maltose, lactose, raffinose and**

stachyose. They have important roles in energy metabolism, carbohydrate transport and cellular recognition.

Q. 46. Define lipids and describe their major types.

Ans: Lipids:

Lipids are a diverse group of organic compounds that are generally **insoluble in water but soluble in non-polar organic solvents** such as ether, chloroform and benzene.

They mainly contain **carbon, hydrogen and oxygen**, and some lipids also contain phosphorus, nitrogen or sulphur.

Lipids perform important functions as **energy reserves, structural components of membranes, protective substances and signalling molecules.**

Major Types of Lipids

Lipids are broadly classified into **three major types:**

1. Simple Lipids

Simple lipids are esters of **fatty acids with alcohols.**

a. Fats and Oils

They are mainly esters of **glycerol and fatty acids**, called **triacylglycerols (triglycerides).**

- **Fats:** Usually solid at room temperature and contain a higher proportion of saturated fatty acids.
- **Oils:** Usually liquid at room temperature and generally contain more unsaturated fatty acids.

Examples: Coconut oil, mustard oil, sunflower oil, butter fat.

Functions:

- Long-term energy storage
- Provide metabolic energy
- Help in insulation and protection

b. Waxes

Waxes are esters of **long-chain fatty acids with long-chain alcohols.**

Examples: Cuticular waxes of leaves and stems, beeswax.

Functions:

- Reduce water loss
- Protect plant surfaces
- Form part of the protective cuticle

2. Compound or Complex Lipids

These lipids contain fatty acids and alcohol along with additional groups such as **phosphate, carbohydrate or protein.**

a. Phospholipids

They contain **phosphoric acid** in addition to fatty acids and alcohol.

Examples: Phosphatidylcholine (lecithin), phosphatidylethanolamine.

Functions:

- Major components of **cell membranes**
- Form the lipid bilayer
- Participate in cell signalling

b. Glycolipids

They contain a **carbohydrate group** along with lipid components.

Functions:

- Important components of biological membranes
- Involved in cell recognition and membrane interactions

3. Derived Lipids

Derived lipids are substances obtained from the **hydrolysis or modification of simple and complex lipids**.

Examples include:

- **Fatty acids**
- **Glycerol**
- **Sterols and steroids**
- **Terpenoids**

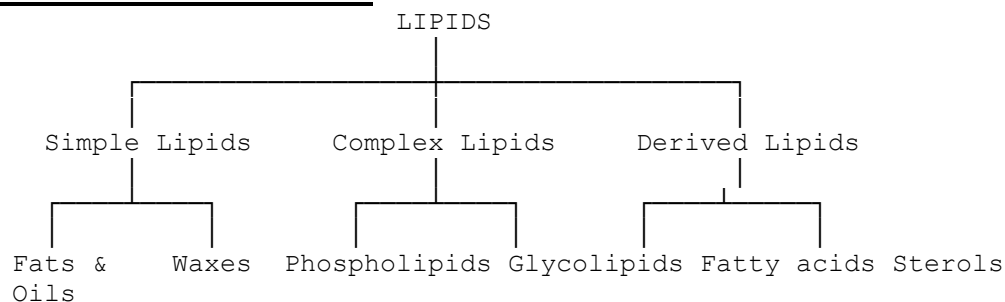
Sterols and Steroids

Sterols contain a characteristic **four-ring steroid nucleus**.

Examples: Cholesterol, phytosterols such as β -sitosterol.

Functions:

- Contribute to membrane structure
- Act as precursors of several biologically active compounds

Classification at a Glance**Biological Importance of Lipids**

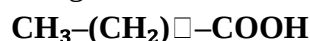
1. **Energy storage:** Triacylglycerols provide concentrated energy reserves.
2. **Membrane formation:** Phospholipids and glycolipids are important membrane components.
3. **Protection:** Waxes reduce water loss from plant surfaces.
4. **Signalling:** Some lipid-derived molecules participate in cellular signalling.
5. **Metabolic functions:** Fatty acids and other lipids act as important metabolic intermediates.

Lipids are essential biomolecules with diverse structures and functions. They are broadly classified into **simple, complex and derived lipids** and play important roles in **energy storage, membrane structure, protection and cellular regulation**.

Q. 47. Explain the structure and functions of fatty acids.

Ans: Fatty acids are **organic compounds consisting of a long hydrocarbon chain with a terminal carboxyl group (–COOH)**. They are important constituents of **fats, oils, phospholipids and other lipids**.

The general structure of a fatty acid is:



where **n** represents the number of methylene (–CH₂–) groups.

Structure of Fatty Acids

A typical fatty acid has two main parts:

1. **Hydrocarbon chain:**

It is a long, non-polar chain that is hydrophobic.

2. **Carboxyl group (–COOH):**

It is a polar, hydrophilic group present at one end of the molecule.

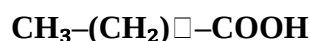
Thus, fatty acids are **amphipathic molecules**, having both hydrophobic and relatively hydrophilic regions.

Types of Fatty Acids

1. Saturated Fatty Acids

They contain **no double bonds** between carbon atoms.

General structure:



Examples:

- Palmitic acid – C_{16:0}
- Stearic acid – C_{18:0}

They generally have relatively straight chains and pack closely together.

2. Unsaturated Fatty Acids

They contain **one or more carbon-carbon double bonds**.

They are further divided into:

- **Monounsaturated fatty acids:** one double bond
Example: **Oleic acid (C_{18:1})**
- **Polyunsaturated fatty acids:** two or more double bonds
Examples: **Linoleic acid (C_{18:2})** and **Linolenic acid (C_{18:3})**

In naturally occurring plant fatty acids, double bonds are commonly in the **cis configuration**, producing bends or kinks in the hydrocarbon chain.

Functions of Fatty Acids

1. Energy Source

Fatty acids are an important source of **metabolic energy**. They are broken down by **β -oxidation** to form acetyl-CoA, which can enter the respiratory pathways.

Fatty acid $\rightarrow \beta$ -oxidation $\rightarrow$ Acetyl-CoA $\rightarrow$ ATP

2. Components of Lipids

Fatty acids combine with glycerol to form **triacylglycerols**, which are major storage lipids in seeds.

They are also components of **phospholipids and glycolipids**.

3. Membrane Structure

Fatty acids form the hydrophobic portions of membrane lipids. Their degree of saturation influences **membrane fluidity**.

- More unsaturated fatty acids $\rightarrow$ generally greater fluidity
- More saturated fatty acids $\rightarrow$ generally lower fluidity

4. Energy Storage

Plants store large amounts of fatty acids in the form of **triacylglycerols**, particularly in oil-rich seeds such as sunflower, groundnut and mustard.

5. Precursors of Signalling Molecules

Some fatty acids serve as precursors for biologically active compounds such as **jasmonates**, which participate in plant growth, development and defence responses.

6. Protection

Certain fatty acids and their derivatives contribute to the formation of **surface lipids and protective barriers**, helping plants reduce water loss and protect tissues.

7. Role in Seed Germination

During germination of oil-rich seeds, stored fatty acids are mobilized and undergo **β -oxidation**. The resulting acetyl-CoA can enter the **glyoxylate cycle** and subsequently contribute to carbohydrate formation.

Table

Feature	Fatty acids
Basic structure	Long hydrocarbon chain + $-\text{COOH}$
Saturated	No $\text{C}=\text{C}$ double bond
Unsaturated	One or more $\text{C}=\text{C}$ double bonds
Major storage form	Triacylglycerols
Major metabolic pathway	β -oxidation
Major roles	Energy, membranes, storage and signalling

Fatty acids are essential components of plant lipids. Their major functions include **energy storage and production, membrane formation, protection and signalling**. Both their chain length and degree of unsaturation influence their biological properties.

Q. 48. Explain the role of lipids as cell signals and cofactors.

Ans: Role of Lipids as Cell Signals and Cofactors

Lipids are not only important as **energy-storage and structural molecules**, but also participate in **cell signalling and enzymatic reactions**. Certain lipids and lipid-derived compounds act as signalling molecules, while some lipid-soluble compounds function as **cofactors or coenzymes** required for metabolic reactions.

1. Lipids as Cell Signals

Cell signalling involves the transmission of information within and between cells. Several lipids and their derivatives act as **signalling molecules**.

a. Phospholipid-Derived Signals

Certain membrane phospholipids can be hydrolysed to produce signalling molecules.

For example:

Phosphatidylinositol $\rightarrow$ PIP₂ $\rightarrow$ IP₃ + DAG

- **IP₃ (inositol trisphosphate)** helps release Ca²⁺ from intracellular stores.
- **DAG (diacylglycerol)** activates protein kinase C in many animal cells.

Thus, membrane lipids can participate in intracellular signal transduction.

b. Phosphoinositides

Phosphoinositides are membrane lipids that regulate:

- Cell signalling
- Membrane trafficking
- Cytoskeletal organization
- Cell growth and development

They act by recruiting or regulating specific signalling proteins.

c. Jasmonates in Plants

In plants, fatty acids such as **α -linolenic acid** are precursors of **jasmonic acid and related jasmonates**.

Jasmonates function as signalling molecules involved in:

- Wound responses
- Defence against herbivores and pathogens
- Growth and development
- Responses to environmental stress

d. Steroid Hormones

Steroid hormones are lipid-derived signalling molecules. They can pass through cell membranes and bind to **intracellular receptors**, altering gene expression.

Examples include **brassinosteroids in plants** and steroid hormones in animals.

2. Lipids as Cofactors and Coenzymes

Some lipid-derived molecules are essential for enzyme-mediated reactions and electron transport.

a. Ubiquinone (Coenzyme Q)

Ubiquinone, also called **Coenzyme Q**, is a lipid-soluble electron carrier present in respiratory membranes.

It transfers electrons between components of the **electron transport chain** and contributes to ATP production.

b. Plastoquinone

Plastoquinone is a lipid-soluble electron carrier present in the **thylakoid membranes of chloroplasts**.

It transfers electrons from **Photosystem II** towards the cytochrome complex during photosynthetic electron transport.

c. Vitamin K

Vitamin K is a lipid-soluble vitamin that functions as a cofactor in important biochemical reactions, particularly in animals.

d. Fat-Soluble Vitamins

Some lipid-soluble vitamins, including **vitamins A, D, E and K**, have important roles in metabolism, regulation and protection.

Vitamin E, for example, acts as an important **antioxidant** that helps protect membrane lipids from oxidative damage.

Lipid/lipid-derived compound	Major role
Phosphoinositides	Cell signalling
DAG and IP ₃	Intracellular signal transduction
Jasmonates	Plant defence and stress signalling
Steroid hormones	Regulation of gene expression
Ubiquinone (CoQ)	Electron transport in respiration
Plastoquinone	Electron transport in photosynthesis
Vitamin E	Antioxidant protection

Lipids have important roles beyond energy storage and membrane formation. **Phospholipids, phosphoinositides, fatty-acid derivatives and steroid-related compounds** participate in cell signalling, while lipid-soluble electron carriers such as **ubiquinone and plastoquinone** are essential for energy metabolism. Thus, lipids are vital for both **cellular communication and metabolic regulation**.

Q. 49. Describe the primary structure of proteins.

Ans: Primary Structure of Proteins

Proteins are complex biological macromolecules made up of **amino acids** joined together by **peptide bonds**. The **primary structure** of a protein refers to the **specific linear sequence and arrangement of amino acids in a polypeptide chain**.

The primary structure is the most basic level of protein organization and determines the higher levels of protein structure and ultimately its function.

Formation of Primary Structure

Amino acids are linked together by **peptide bonds** formed between:

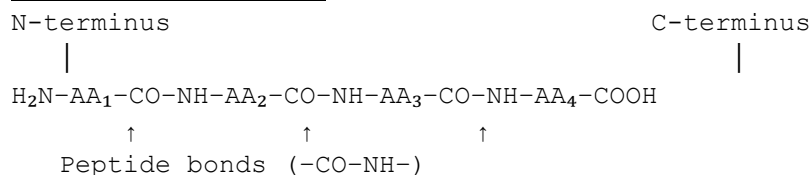
- The **carboxyl group** ($-\text{COOH}$) of one amino acid, and
- The **amino group** ($-\text{NH}_2$) of another amino acid.

A molecule of water is eliminated during peptide bond formation.

Amino acid + Amino acid $\rightarrow$ Dipeptide + H_2O

Repeated peptide bond formation produces a **polypeptide chain**.

Simplified Structure



The chain has two ends:

- **N-terminus:** End having a free amino group.
- **C-terminus:** End having a free carboxyl group.

The amino acids are conventionally written from the **N-terminus to the C-terminus**.

Important Features of Primary Structure

1. Specific Amino Acid Sequence

Each protein has a characteristic sequence of amino acids. Even a small change in this sequence can sometimes affect protein structure and function.

2. Peptide Bonds

Amino acids in the primary structure are connected by strong **covalent peptide bonds**.

3. Genetic Determination

The amino acid sequence of a protein is determined by the **nucleotide sequence of the corresponding gene** through gene expression and translation.

4. Determines Higher Structures

The primary sequence influences the formation of the protein's:

- **Secondary structure** – α -helix and β -sheet
- **Tertiary structure** – three-dimensional folding
- **Quaternary structure** – association of multiple polypeptide chains, when present

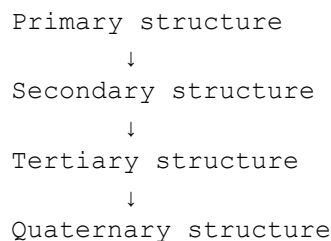
5. Functional Significance

The specific amino acid sequence determines how a protein folds and therefore contributes to its **biological activity and specificity**.

Example

Insulin is composed of two polypeptide chains, A and B, with specific amino acid sequences. The precise sequence and arrangement of amino acids are essential for its biological activity. A change in amino acid sequence can produce an altered protein with a different structure or function.

Levels of Protein Structure



The primary structure of a protein is the **linear sequence of amino acids joined by peptide bonds**. It is genetically determined and provides the basis for the formation of the protein's higher-order structures. Therefore, the primary structure is essential for determining the **shape, stability and biological function** of proteins.

Q. 50. Differentiate between the four levels of protein organization.

Ans: Four Levels of Protein Organization

Proteins have a specific three-dimensional organization that can be described at **four structural levels: primary, secondary, tertiary and quaternary structure**. Each level contributes to the final shape and function of the protein.

Difference Between the Four Levels

Feature	Primary Structure	Secondary Structure	Tertiary Structure	Quaternary Structure
Definition	Linear sequence of amino acids	Local folding of the polypeptide chain	Overall 3-D folding of a single polypeptide	Association of two or more polypeptide chains
Basic feature	Amino acid sequence	α -helix, β -sheet, turns	Complete folding into a compact structure	Arrangement of multiple subunits
Main bonds/interactions	Peptide bonds	Mainly hydrogen bonds between backbone groups	Hydrogen bonds, ionic bonds, hydrophobic interactions and	Same types of non-covalent interactions; sometimes disulfide

Feature	Primary Structure	Secondary Structure	Tertiary Structure	Quaternary Structure
			disulfide bonds	bonds
Number of chains	One polypeptide chain	Usually one chain	Usually one polypeptide chain	Two or more polypeptide chains
Example	Amino acid sequence of insulin	α -helix of keratin	Myoglobin	Hemoglobin
Importance	Determines higher structures	Provides local stability	Determines overall shape and function	Provides functional organization of multi-subunit proteins

1. Primary Structure

The **primary structure** is the specific **linear sequence of amino acids** in a polypeptide chain. Amino acids are connected by **peptide bonds**.

Example:

Amino acid 1 → Amino acid 2 → Amino acid 3 → Amino acid 4

The sequence is genetically determined and strongly influences the subsequent folding of the protein.

2. Secondary Structure

The **secondary structure** results from the regular folding of portions of a polypeptide chain.

The two major forms are:

- **α -helix**
- **β -pleated sheet**

They are stabilized mainly by **hydrogen bonds between peptide backbone groups**.

Example: α -helix is prominent in keratin.

3. Tertiary Structure

The **tertiary structure** is the complete **three-dimensional conformation of a single polypeptide chain**.

It is maintained by several interactions, including:

- Hydrogen bonds
- Ionic interactions
- Hydrophobic interactions
- Van der Waals forces
- **Disulfide bonds** between cysteine residues

Example: Myoglobin has a characteristic tertiary structure.

This level is particularly important for the formation of **active sites and functional regions** of proteins.

4. Quaternary Structure

The **quaternary structure** occurs in proteins composed of **two or more polypeptide chains (subunits)**.

The subunits associate through various non-covalent interactions and, in some proteins, disulfide bonds.

Example: Hemoglobin consists of four polypeptide subunits.

Structural Hierarchy

Primary

↓

Secondary

↓

Tertiary

↓

Quaternary

Thus, the organization progresses from a **linear amino acid sequence** → **local folding** → **complete 3-D folding** → **association of multiple subunits**.

The four levels of protein organization are closely related. The **primary structure** determines the basis for higher-order folding, while the **secondary and tertiary structures** establish the three-dimensional shape of individual polypeptide chains. The **quaternary structure** organizes multiple chains into a functional protein complex.
