Photosynthesis in Higher Plants

INTRODUCTION

- Green plants and some chlorophyll bearing bacteria are autotrophic and synthesise organic compounds by using simple inorganic compounds in the presence of sunlight.
- All the heterotrophic organisms are dependent on the food prepared by autotrophs for survival.
- All life forms on earth are dependent on sunlight for energy directly or indirectly.
- Thus, the use of energy from sunlight by the plants to do photosynthesis is the basis of life on earth.

Definition

Photosynthesis: It is a physico-chemical (anabolic) process by which plants and certain other organisms use light energy and synthesise their own organic food.

Previous Year's Question

Chlorophyll a is found in all
(1) O_2 liberating photosynthetic organisms
(2) Autotrophs
(3) Higher plants
(4) Algae

SIMPLE EXPERIMENTS RELATED TO PHOTOSYNTHESIS

- Photosynthesis occurs in green parts of the plants in the presence of sunlight and starch is manufactured after the process. It can be demonstrated as follows:
  - A small potted plant is placed in dark for 72 hours to get its leaves destarched.

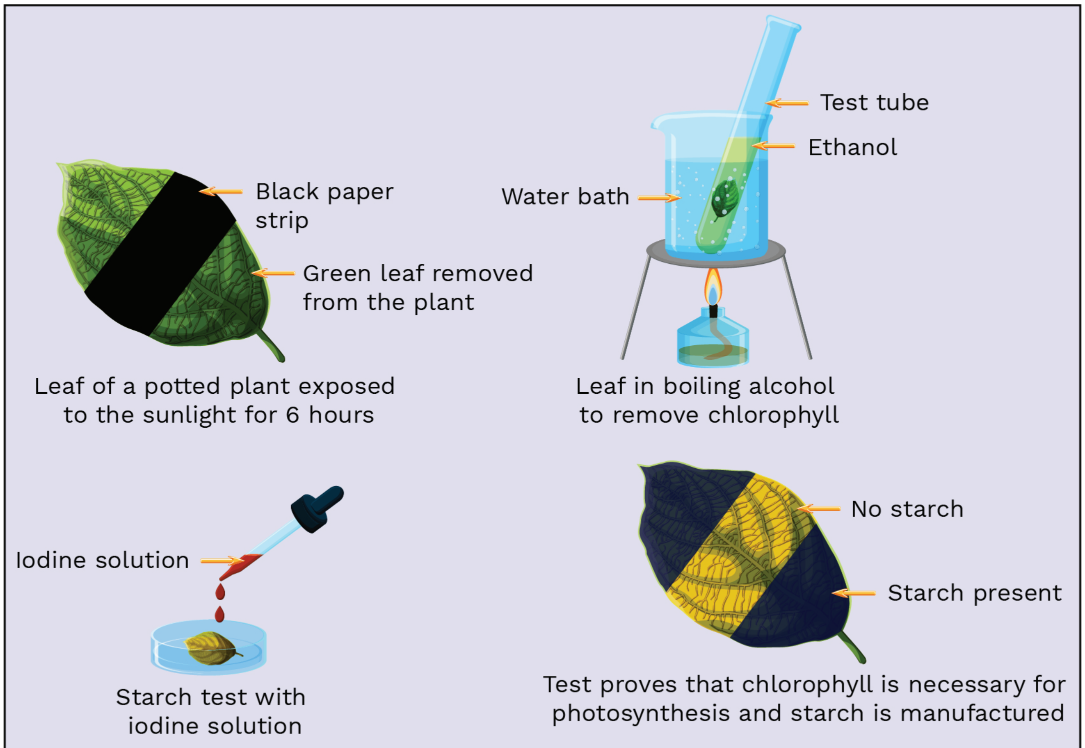


FIG. LEAF — CHLOROPHYLL AND STARCH TEST

- Green parts of the plant when exposed to sunlight show blue-black colour with iodine solution while the part of the leaf covered with black strip shows negative starch test.
- Iodine solution is used to test the presence of starch in any plant part or item. Iodine gives blue-black colour if starch is present in the experimental part or substance.

- **Carbon dioxide is essential for photosynthesis:**
  - One leaf of a destarched plant (as shown in the figure) is placed half inside a bottle containing KOH. KOH absorbs CO_2 and this part of the leaf (after 6 hours) on testing for the presence of starch shows negative result.

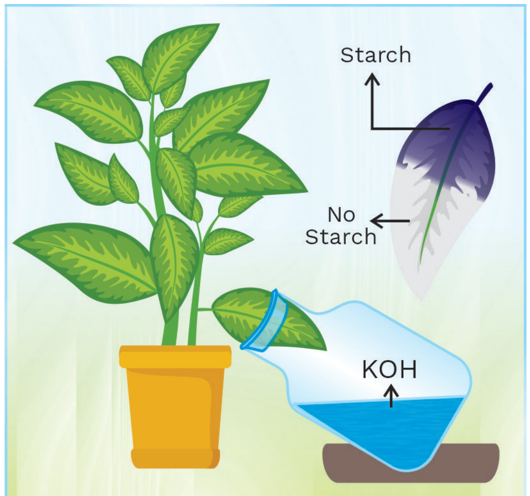


FIG. CARBON DIOXIDE IS ESSENTIAL FOR PHOTOSYNTHESIS

PHOTOSYNTHESIS

- It is a physico-chemical process by which green plants use light energy to synthesise organic compounds.
- Photosynthesis is important for two reasons:
  - It is the primary source of food for all living organisms.
  - It is the only process responsible for the release of oxygen into the atmosphere by green plants.

EARLY EXPERIMENTS

Joseph Priestley (1733–1804)

- He performed a series of experiments (1770), that revealed the essential role of air in the growth of plants.
- He observed that a candle burning in a closed space (say a bell jar), gets extinguished in a very short time.
- Similarly, a mouse kept in a closed space, the bell jar would suffocate soon.
- He concluded that a burning candle or an animal that breathes the air, somehow damage the air.
- But when he placed a mint plant in the same bell jar, it was observed that the mouse stayed alive and the candle continued to burn.

Previous Year's Question

The major portion of dry weight of plants comprises of

(1) Carbon, hydrogen and oxygen
(2) Nitrogen, phosphorus and potassium
(3) Calcium, magnesium and sulphur
(4) Carbon, nitrogen and hydrogen

Previous Year's Question

The core metal of chlorophyll is

(1) Ni
(2) Cu
(3) Fe
(4) Mg

- So, Priestley hypothesised that **plants restore to the air whatever breathing animals and burning candle remove.**

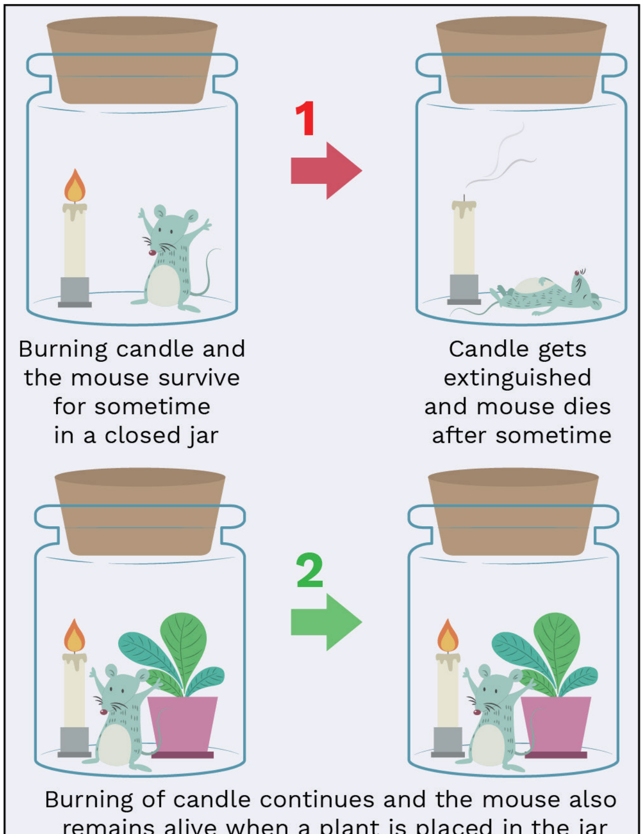


FIG. PRIESTLEY'S EXPERIMENT – PLANT RESTORE AIR (O_2) WHICH THE BURNING CANDLE AND BREATHING ANIMALS REMOVE

Jan Ingenhousz (1730–1799)

- He conducted an experiment similar to Priestley's experiment with an aquatic plant, once kept in bright sunlight and then in the dark.
- He showed that when the plant that was kept in light, **small bubbles were formed around the green parts,** while no bubbles appeared when the same plant was kept in the dark.
- Later these bubbles have been identified as oxygen bubbles.

Rack Your Brain

Glucose is the product of photosynthesis which consists of three elements. What is the source of oxygen in it?

Rack Your Brain

What was proved by Joseph Priestley in 1770 w.r.t. photosynthesis?

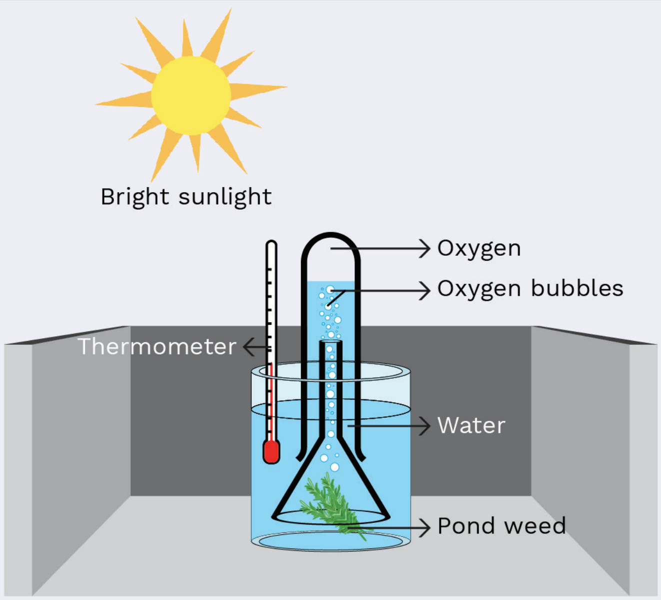
Rack Your Brain

To prove that carbon dioxide is essential for photosynthesis which chemical is used that stops CO_2 to reach the experimental plant parts.

Rack Your Brain

Who discovered that green parts of the plant release oxygen during the day?

- Thus, he showed that only **the green parts of the plants could release oxygen.**



$$\text{Carbon dioxide + water} \xrightarrow[\text{Light energy}]{\text{Chlorophyll}} \text{Glucose + } \textbf{Oxygen}$$

$$6CO_2 + 6H_2O \xrightarrow[\text{Light energy}]{\text{Chlorophyll}} C_6H_{12}O_6 + \mathbf{6O_2}$$

FIG. INGENHOUSZ'S EXPERIMENT (OXYGEN PRODUCTION DURING PHOTOSYNTHESIS)

Julius von Sachs

- He showed that the green substance (chlorophyll) is located in special bodies (chloroplasts).
- He provided evidence (1854) for the production of glucose when plants grow and **glucose is stored in the form of starch.**
- He found that green parts of the plants are the places where glucose is made.

T. W. Engelmann (1843–1909)

- He split the light causing a prism into its component parts and illuminated a green alga, *Cladophora* placed in suspension of aerobic bacteria.

Previous Year's Question

Water soluble pigments found in plant cell vacuoles are

(1) carotenoids
(2) anthocyanins
(3) xanthophylls
(4) chlorophylls

Definitions

Photosynthetic Pigments: Pigments that absorb light of certain wavelength(s) of the visible spectrum.

Accessory Photosynthetic Pigments: These are the pigments which absorb light energy and pass it on to the main photosynthetic pigments, but do not carry out the reactions themselves.

Previous Year's Question

Which pigment absorbs the red and far red light?

(1) Cytochrome
(2) Phytochrome
(3) Carotenoids
(4) Chlorophyll

- The bacteria were used to detect the sites of oxygen evolution.
- He observed that the bacteria accumulated mainly in the region of blue and red light of the visible spectrum of light.
- Engelmann was the first to describe the action spectrum of photosynthesis; the action spectrum resembles roughly the absorption spectrum of chlorophyll a and b.

Cornelis Van Niel (1897–1985)

- Based on his experiments with purple and green bacteria, he made a contribution, a milestone, in the understanding of photosynthesis.
- He demonstrated that photosynthesis is essentially a light-dependent reaction in which hydrogen from a hydrogen-donor reduces carbon dioxide to carbohydrates.
- The present day equation has been given by him.

$$2H_2A + CO_2 \xrightarrow{\text{Light}} 2A + CH_2O + H_2O$$

- In green plants, water (H_2O) is the hydrogen donor and it is oxidised to oxygen.
- Purple and green sulphur bacteria use H_2S as the hydrogen donor and so the oxidation product is sulphur and no oxygen is produced.
- Thus, he inferred that the oxygen evolved by green plants during photosynthesis comes from water (H_2O) and not from carbon dioxide (CO_2)
- This was later proved by using radioactive isotopes of oxygen ($H_2{}^{18}O$).
- The overall correct equation for photosynthesis is as follows:

$$6CO_2 + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 + 6H_2O + 6O_2$$

SITE OF PHOTOSYNTHESIS

- Photosynthesis takes place mainly in the green leaves and to some extent in other green parts of the plant.
- It takes place in the cell organelles called chloroplasts.

Rack Your Brain

Name the experimental plant used by T. W. Engelmann to demonstrate action spectrum.

Rack Your Brain

Statement I: Red and blue light support the highest rate of photosynthesis.
Statement II: These are the only waves reaching to the plants.
Which statement/s is correct?

Previous Year's Question

Which of the following absorb light energy for photosynthesis?
(1) Chlorophyll
(2) Water molecule
(3) O_2
(4) RuBP

Rack Your Brain

Who discovered that oxygen released during photosynthesis comes from the breakdown of the water molecules?

- The chloroplasts are found in large number in the mesophyll cells of leaves.
- The chloroplasts align themselves along the walls of the mesophyll cells, in such a way that they get maximum quantity of incident light; they will be aligned with their flat surfaces parallel to the wall under low or optimum light intensities and perpendicular to the walls when the intensity goes very high.
- There is a clear division of labour within the chloroplasts. The membrane system is responsible for the photo-chemical phase, where synthesis of ATP and NADPH occurs, whereas the stroma has enzymes for the reduction of carbon dioxide into carbohydrates and formation of sugars.
- The pigments are distributed in the membrane system.

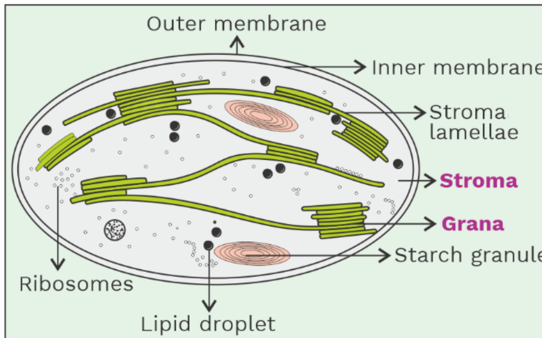


FIG. DIAGRAMMATIC REPRESENTATION OF AN ELECTRON MICROGRAPH OF SECTION OF CHLOROPLAST

Gray Matter Alert!!!

The —CH_3 (methyl group) in chlorophyll a is replaced by —CHO (aldehyde group) in chlorophyll b.

PIGMENTS INVOLVED IN PHOTOSYNTHESIS

- There are four pigments: chlorophyll a, chlorophyll b, carotene and xanthophyll (carotenoids).

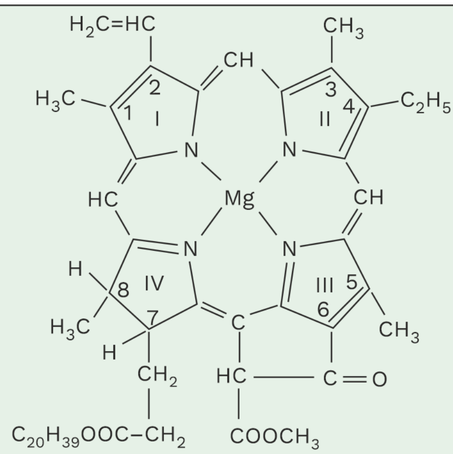


FIG. STRUCTURE OF CHLOROPHYLL A

- Chlorophyll a ($C_{55}H_{72}O_5N_4Mg$) — Bright green or bluish green.
- Chlorophyll b ($C_{55}H_{70}O_6N_4Mg$) — Yellowish green.
- Xanthophyll (e.g., Lutein $C_{40}H_{56}O_2$) — Yellow.
- Carotene ($C_{40}H_{56}$) — Yellow-orange or reddish.

Previous Year's Question

In chloroplasts, chlorophyll is present in the
(1) Inner membrane
(2) Thylakoid
(3) Stroma
(4) Outer membrane

Previous Year's Question

Which element is located at the centre of the porphyrin ring of chlorophyll?
(1) Magnesium (2) Calcium
(3) Manganese (4) Potassium

- **Chief or main pigment** associated with photosynthesis — Chlorophyll a.
- **Accessory pigments —** Chlorophyll b, carotenoids (carotenes and xanthophylls).
- The accessory pigments help in two ways:
  - Thylakoid pigments like xanthophylls and carotenes also absorb light from the mid-part of visible light spectrum. Thus, widen the absorption of spectrum.
  - Chlorophyll b, xanthophylls and carotenes also protect chlorophyll a from photo-oxidation.

Note: Photosynthetic bacteria possess two types of photosynthetic pigments, e.g., bacteriochlorophyll (it is of several types) and bacterioviridin (chlorobium chlorophyll). Bacteriochlorophyll has an empirical formula of $C_{55}H_{74}O_6N_4Mg$.

Note: Phycobillins is the group of photosynthetic pigments found in red algae and cyanobacteria (blue-green algae).

ABSORPTION SPECTRUM

- The curve showing the amount of different wavelengths of light absorbed by photosynthetic pigments.
- Chlorophyll a and b absorb maximum light in blue-violet and red wavelengths.

ACTION SPECTRUM

- The curve depicting the relative rates of photosynthesis at different wavelengths of light.
- It shows maximum photosynthesis in blue-violet and red part of visible light spectrum.

Note: Plants absorb 400 – 700 nm light for photosynthesis. The best wavelength is 425 – 460 nm (blue range) & 600 – 700 nm (red range).

Previous Year's Question

Which fraction of visible spectrum of solar radiations are primarily absorbed by carotenoids of the higher plants?
(1) Violet and blue
(2) Blue and green
(3) Green and red
(4) Red and violet

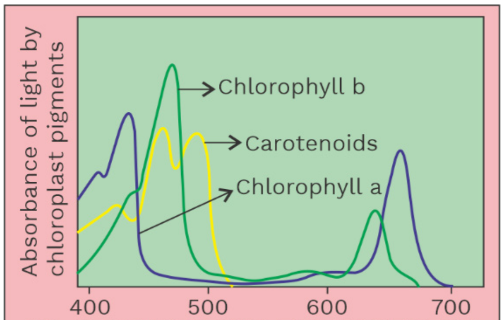


FIG. GRAPH SHOWING THE ABSORPTION SPECTRUM OF CHLOROPHYLL A, B AND THE CAROTENOIDS

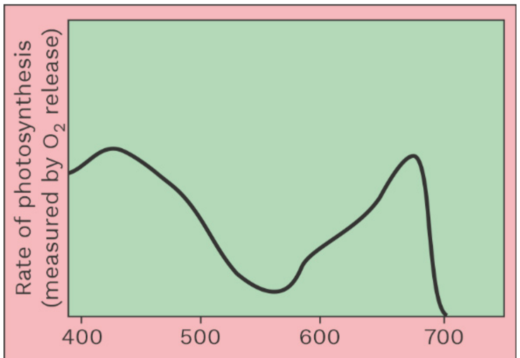


FIG. GRAPH SHOWING ACTION SPECTRUM OF PHOTOSYNTHESIS

- The absorption spectrum and action spectrum coincide closely showing that photosynthesis is maximum at the blue and red regions of the spectrum.

EMERSON'S EFFECT

- Emerson *et. al.* (1957) exposed unicellular alga *Chlorella* to monochromatic light (i.e., only one wavelength of light at a time) and measured the photosynthetic yield in terms of quantum yield (i.e., the number of O_2 molecules evolved per light quanta absorbed).
- It was observed that the quantum yield of photosynthesis decreased very sharply towards far red (above 680 nm) region of the spectrum. The fall in photosynthetic yield beyond red region of the spectrum is called **Emerson's first effect or red drop.**
- In another experiment Emerson *et. al.* observed that the quantum yield is enhanced if monochromatic lights of longer wavelength (i.e., 680 nm and above) and shorter wavelength (below 680 nm) were given simultaneously.
- It was observed that the photosynthetic yield was higher than the sum total of the photosynthetic yields of the two types of waves given separately. The enhancement in photosynthetic yield by combined effect of short and long wave-lengths of light is known as **Emerson's second effect or Emerson enhancement effect'.**
- It is due to:
  - Presence of different types of harvesting molecules around a trap centre in a photosynthetic unit.
  - Presence of two interconnected pigment systems with some common pigments.

PHOTOSYSTEMS

- The pigments are organised on the inner side of thylakoid membranes into two discrete photosystems:

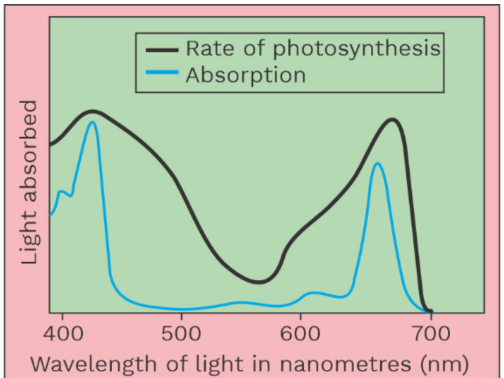


FIG. GRAPH SHOWING ACTION SPECTRUM OF PHOTOSYNTHESIS SUPERIMPOSED ON ABSORPTION SPECTRUM OF CHLOROPHYLL A

Previous Year's Question

Which pigment absorbs the blue-violet light?
(1) Cytochrome (2) Phytochrome
(3) Carotenoids (4) Chlorophyll

Rack Your Brain

What is meant by red drop in photosynthesis?

Previous Year's Question

Chlorophylls absorb light of wavelengths
(1) 400–500 nm
(2) 400–500 nm and 600–700 nm
(3) 600–800 nm
(4) 300–400 nm

- Photosystem I (PS I)
- Photosystem II (PS II)

- Each photosystem has one specific chlorophyll a and many other pigments bound by proteins.
- The chlorophyll a forms the reaction centre, where the actual reactions take place, while the other pigment molecules from the light harvesting complex (LHC), also called as antenna.

Photosystem I

- In PS I, the reaction centre is P_{700}, which is a chlorophyll a molecule that absorbs light at 700 nm.
- Electron carriers in PS I are ferredoxin, cytochrome complex, plastoquinone, cytochrome f and plastocyanin.
- PS I participates in cyclic photophosphorylation as well as in non-cyclic photophosphorylation.

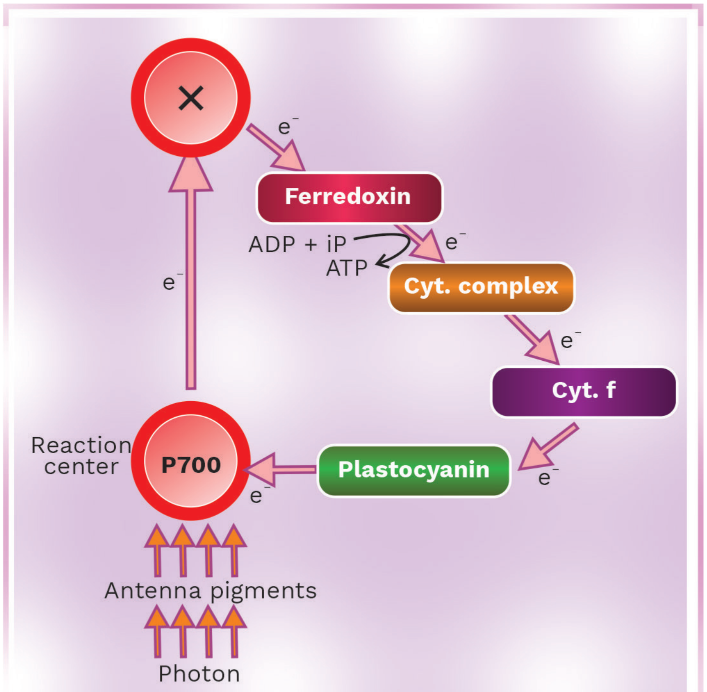


FIG. PHOTOSYTEM I

Rack Your Brain

Light reaction is concerned with the generation of ___________ and ATP.

Definition

Photosystem I (PS I): The photocentre P_{700} along with the other pigment molecules which absorbs light at or below 700 nm.

Rack Your Brain

All pigments except ___________ are called accessory photosynthetic pigments in higher plants.

Previous Year's Question

Constituents of PS I are located in

(1) granal thylakoids
(2) stromal thylakoids
(3) outer surface of granal and stromal thylakoids
(4) stroma

Photosystem II

- In PS II, the reaction centre is P_{680}, a chlorophyll a molecule that absorbs light at 680 nm.
- The electron carriers in Photosystem II are quinone, pheophytin, plastoquinone, cytochrome complex and plastocyanin (common in both PS I and PS II).

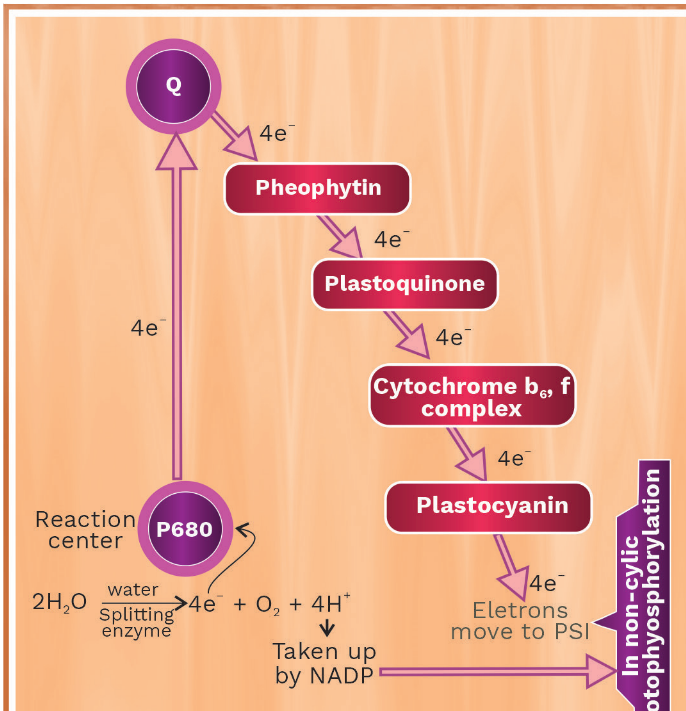


FIG. PHOTOSYSTEM II

Definition

Photosystem II (PS II): The photocentre P_{680} along with the other pigment molecules which absorbs light at or below 680 nm.

Rack Your Brain

Electron ejected by PS II is initially accepted by __________.

Previous Year's Question

Energy change in photosynthesis is

(1) Electrical → Chemical

(2) Chemical → Light → Electrical

(3) Light → Chemical

(4) Light → Electrical → Chemical

LIGHT GATHERING—ENERGY CAPTURE—ENERGY TRANSFER

- Photosynthetic organisms perform the following basic functions of the light gathering, or better termed light harvesting structures, in maximizing the conversion of light quanta into different chemical intermediates of higher energy order:
  - **Light absorption:** The energy of the photon is captured by an antenna pigment molecule and an electron is excited thereof.
  - **Energy transfer:** The excitation energy is transferred through the antenna to a reaction

Rack Your Brain

How does bacteriochlorophyll differ from chlorophyll of higher plants?

centre, which is a specialised form of pigment, from which an electron is excited.

- **Energy transfer:** The energised electron from the reaction centre is accepted by a chemical acceptor; the oxidized reaction centre is reduced by an electron either from inorganic (water) or organic molecules.

- The pigment antenna is a mechanism for gathering quanta in low light to drive a process which requires several quanta. This helps the reaction centre to gather maximum light from the visible spectrum.

ELECTRON AND PROTON TRANSPORT IN OXYGENIC PHOTOSYNTHESIS IN PLANTS

- The electron flow is relatively complex and involves the following events:
  - Water splitting complex (in the lumen of thylakoids)
  - PS II complex
  - Electron carrier intermediate
  - PS I complex
  - Electron carrier which reduce the NADP to NADPH + H^+.

PHOTOSYNTHETIC UNIT

- The assemblage of chlorophylls, other accessory photosynthetic pigments and reaction centre constitute the photosynthetic unit.

PHOTOSYNTHETIC REACTION CENTRE

- It is a complex of several proteins, a chlorophyll a molecule and co-factors.
  - It helps in conversion of light energy (energy of photons) into chemical energy (ATPs) in stepwise manner.
  - Reaction centre gathers excitation energy from light-harvesting antenna system and pass it through various electron acceptors.
  - Reaction centre of PS I is P_{700}.
  - Reaction centre of PS II is P_{680}.

Rack Your Brain

What is meant by P_{700} and P_{680}?

Previous Year's Question

The chloroplasts contain maximum quantity of
(1) RuBP carboxylase
(2) Hexokinase
(3) Pyruvic carboxylase
(4) None of the above

Rack Your Brain

Which of the following processes occur in the lumen of thylakoids?
(i) Cyclic photophosphorylation
(ii) Non-cyclic photophosphorylation
(iii) Photolysis of water

Previous Year's Question

Besides water and carbon dioxide, which is more essential raw material for food formation?
(1) Light
(2) Oxygen
(3) NAD
(4) Minerals

LIGHT HARVESTING COMPLEX (LHC)

- It is made up of 250–400 pigment molecules bound to proteins. These are predominantly chlorophyll b, xanthophylls and carotenes with one chlorophyll a molecule.
- LHC is present in both PS I and PS II.
- LHC helps in absorbing different wavelengths of light. Thus, help in making photosynthesis more efficient.

Definition

Light harvesting complex (LHC/Antenna): All the pigments of the photosystem (chlorophyll b and carotenoids) bound with proteins except the pigment molecule (Chl. a) that forms the reaction centre.

MECHANISM OF PHOTOSYNTHESIS

- Photosynthesis occurs in two steps:
  - Light reaction or photochemical phase
  - Dark reaction or biosynthetic phase

Light Reaction (Photochemical Phase)	Dark Reaction (Biosynthetic Phase)
It is directly dependent on sunlight (light).	It is not directly dependent on sunlight (light) but is dependent on the products of light reaction.
ATP and $NADPH_2$ are generated.	ATP and $NADPH_2$ are consumed.
Photolysis of water occurs and oxygen is liberated.	Reduction of carbon dioxide occurs and carbohydrate is formed.
It occurs in the grana of chloroplast.	It occurs in the stroma of chloroplast.

PHOTOLYSIS OF WATER (Hill's Reaction)

- Robert Hill (1939) was the first person to formulate the light driven reactions of photosynthesis referred as electron transport chain.
- This light-dependent splitting of the water molecule is called photolysis of water.
- This process takes place in the lumen of thylakoids.
- When P_{680} absorbs sufficient light energy, it is excited and it transfer electrons to an electron acceptor.
- So, P_{680} becomes a strong oxidising agent and splits a molecule of water to release oxygen.
- Manganese, Chloride and Calcium ions play important roles in photolysis of water.

Definition

Photolysis of water: It is the process of breakdown of water into H^+ and OH^- ions by the chlorophyll molecules making use of solar energy.

Previous Year's Question

Ferredoxin is a component of

(1) P_{680} (2) Hill reaction
(3) Photosystem I (4) Photosystem

- The electrons generated in this process are used to replace the electrons lost by P_{680}.
- The protons are used for reducing NADP to NADPH.
- Oxygen is liberated as a by-product of photosynthesis.

$$2H_2O \xrightarrow[Mg^{+2},\ Ca^{+2},\ Cl^-]{\text{Water splitting enzyme}} 4H^+ + O_2 + 4e^-$$

- P_{680} is a strong oxidising agent which splits water into its components.

Note: Manganese is the important metal in water-splitting enzyme complex.

PHOTOPHOSPHORYLATION

- It is the process of formation of ATP in the chloroplasts, making use of the light energy.
- The protons formed during photolysis of water accumulated inside the thylakoid membrane resulting in a proton gradient.
- The energy released by the protons, when they diffuse across the thylakoid membrane into the stroma following the H^+ concentration gradient, is used for the formation of ATP.
- It occurs in two ways:
    - Non-cyclic photophosphorylation
    - Cyclic photophosphorylation

Non-cyclic Photophosphorylation

- It occurs in the membrane or lamellae of grana because both PS I and PS II as well as NADP reductase enzyme are found.
- When P_{680} (PS II) acquires sufficient amount of light energy, it becomes excited and emits electrons.
- The electrons (with high energy) run down an electron transport chain, consisting of a primary acceptor, plastoquinone, cytochrome complex and plastocyanin to P_{700}, which transfer them to ferredoxin.

Previous Year's Question

Photosynthetic pigments occur in
(1) Thylakoid matrix
(2) Matrix
(3) Thylakoid membranes
(4) Plastoglobules

Definition

Light reaction: It is a set of reactions, directly dependent on light and takes place in the grana of chloroplast.

Previous Year's Question

Structural component of chlorophyll among the following is
(1) Mg
(2) Mn
(3) Fe
(4) Zn

Definition

Non-cyclic photophosphorylation: Electrons do not move in a closed circle. Here electrons expelled from P_{680} (reaction centre) do not return to it.

- Ferredoxin in turn transfer the electrons to NADP, which along with the protons reduced to NADPH.
- The electrons lost by PS II are replaced by the electrons generated by splitting of water.
- Since the electrons lost by PS II do not come back to it, this process of ATP formation is called non-cyclic photophosphorylation.

Previous Year's Question

Photolysis of water is associated with

(1) PS I (2) PS II

(3) Cyt. b (4) Quinone

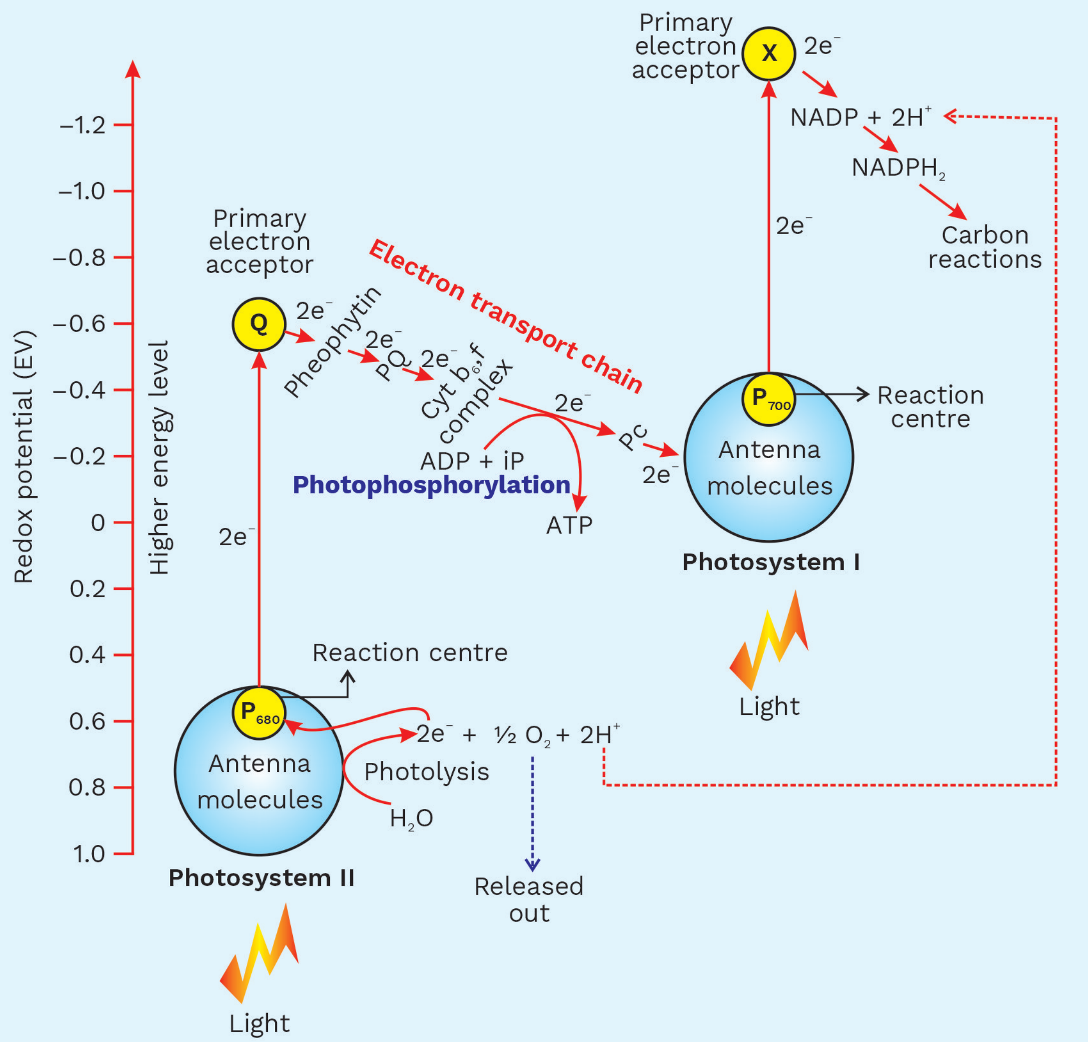


FIG. ELECTRON TRANSPORT FLOW AND NON-CYCLIC PHOTOPHOSPHORYLATION

Cyclic Photophosphorylation

- It occurs in the stroma lamellae of chloroplast because here PS II as well as NADP reductase enzyme are absent.
- When PS I (P_{700}) is activated by light, it is raised to high energy level and emits a pair of electrons.
- These electrons are captured by the primary acceptor, which passes them on to Ferredoxin, Plastoquinone, cytochrome complex and plastocyanin.
- Finally, the de-energised electrons come back to P_{700}.
- Since the electrons come back to P_{700}, this process of ATP formation is known as cyclic photophosphorylation.

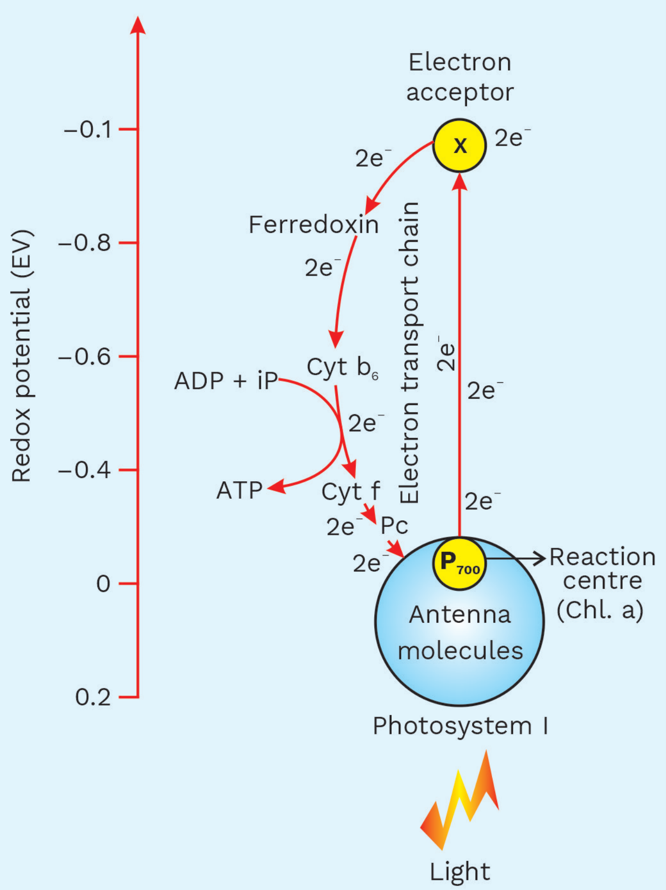


FIG. CYCLIC PHOTOPHOSPHORYLATION

Previous Year's Question

Energy is transformed from the light reaction step to the dark reaction step by

(1) Chlorophyll
(2) ADP
(3) ATP
(4) RuBP

Definition

Photocentres or reaction centres: The chlorophyll a molecules which expel electrons after excitation to electron acceptors for the generation of ATP in PS I and PS II.

Previous Year's Question

In both respiration and photosynthesis ATP synthesis is an oxidative process that uses energy of

(1) Electrons
(2) Ferredoxin
(3) Cytochromes
(4) Carbon dioxide

Definition

Non-cyclic photophosphorylation: Electrons move in a closed circle. Here electrons expelled from P_{700} (reaction centre) return to it.

CHEMIOSMOTIC HYPOTHESIS

- Chemiosmotic hypothesis has been put forward to explain the mechanism of ATP synthesis.
- ATP synthesis is linked to the development of a proton gradient across the membranes of thylakoids.
- When electrons are transported through the electrons transport system (ETS), the protons accumulate inside the thylakoid membranes.
- Since the splitting of the water molecules or photolysis takes place on the inner side of the thylakoid membrane, protons produced accumulate within the lumen of the thylakoids.
- As electrons are passed through photosystems, protons are transported across the membrane.
- This happens because protons are removed from the stroma for the following reasons:
    - The primary electrons acceptor is located towards the outer side of the membrane and transfer its electrons to the H carrier; so this molecule removes a proton from the stroma while transporting an electron and releases it into the lumen or inner side of the membrane.
    - The enzyme NADP–reductase is located on the stroma side of the membrane; along with the electrons coming from the PS I, protons are also needed to reduce NADP and so these protons are also removed from the stroma.
- As a result, the protons in the stroma decrease in number, while the protons in the lumen, increase in number, thus creating a proton gradient across the thylakoid membrane.
- This gradient is important because energy is released by the breakdown of this gradient.
- The gradient is broken down due to the movement of protons across the membrane through transmembrane channel of the F_0 of the ATP synthetase; the other portion of ATP synthetase called F_1 undergoes conformational changes with the energy provided by the breakdown of proton gradient and synthesis several molecules of ATP.

Gray Matter Alert!!!

Chemiosmosis was first hypothesized by British biochemist Peter Dennis Mitchell.

Rack Your Brain

Where does chemiosmosis occur in a prokaryotic cell?

Previous Year's Question

The rate of photosynthesis is higher in

(1) very high light
(2) continuous light
(3) red light
(4) green light

Rack Your Brain

What is the term for ATP synthesis in mitochondria by using the process of chemiosmosis?

- Thus, chemiosmosis requires:
  - a membrane
  - a proton pump
  - a proton gradient
  - ATP synthase
- Energy is used to pump protons across the membrane, to create a gradient or high concentration of protons with the lumen of the thylakoid.
- ATP synthase has a channel that allows the diffusion of protons back across the membrane which releases energy.
- This energy activates ATP synthase enzyme that catalyses the formation of ATP.

Previous Year's Question

Translocation of carbohydrates (photosynthetic product) in flowering plants occurs in the form of

(1) Glucose

(2) Sucrose

(3) Fructose

(4) Starch

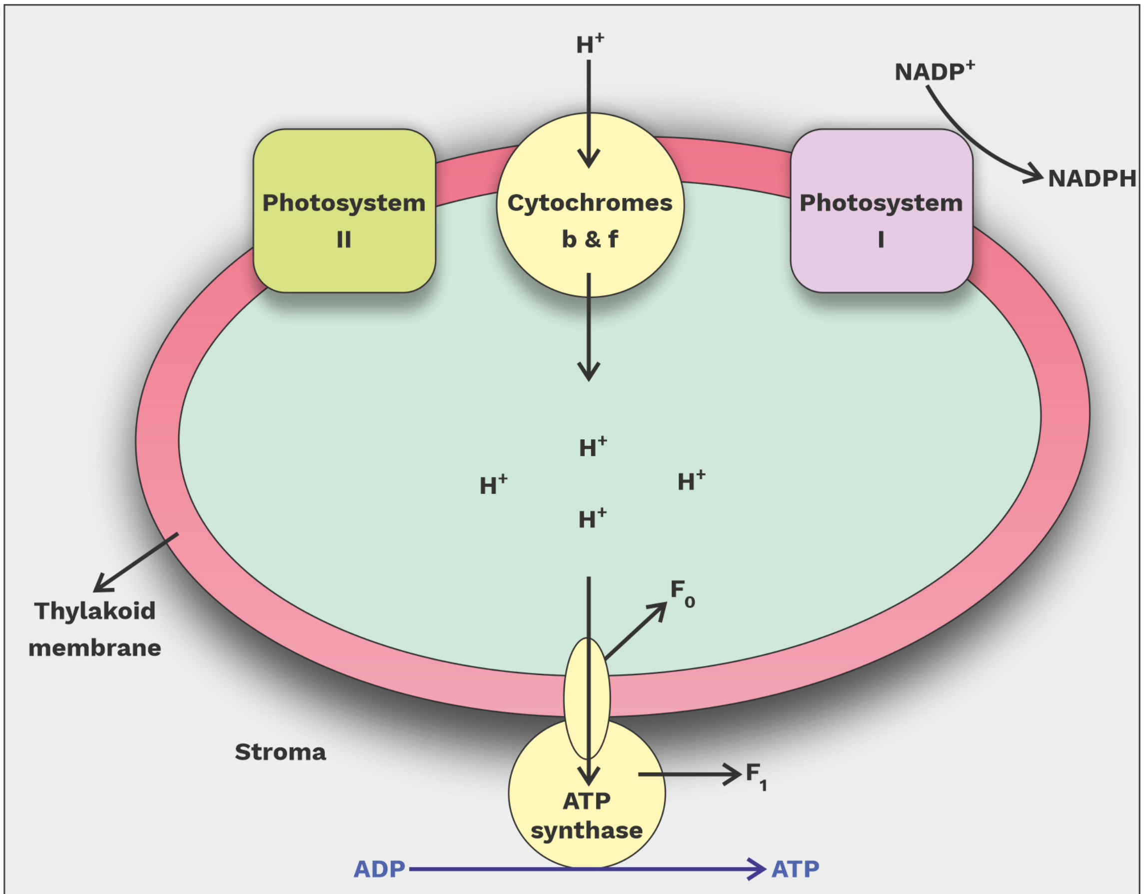


FIG. ATP SYNTHESIS THROUGH CHEMIOSMOSIS

BIOSYNTHETIC PHASE (DARK REACTION)

- The process by which carbon dioxide is reduced to carbohydrates is called carbon fixation which occurs in the stroma.
- The process makes use of the ATP and NADPH produced in the photochemical phase.

C_3 Pathway or Calvin Cycle

- The path of carbon in the dark reaction was traced by Melvin Calvin through a technique called autoradiography, using ^{14}C, hence this pathway is termed as Calvin cycle
- Calvin cycle consists of three phases namely:
  - Carboxylation
  - Reduction
  - Regeneration of RuBP

Carboxylation

- Six molecules of Ribulose 1, 5 bisphosphate react with six molecules of carbon dioxide to form six molecules of a short-lived 6C-compound.
- The reaction is catalysed by RuBP-carboxylase (Rubisco).
- The six molecules of the 6C-compound break into 12 molecules of 3-phosphoglyceric acid (PGA), 3C-compound.
- PGA is the first stable compound in this pathway.

Reduction

- 12 molecules of phosphoglyceric acid are converted into 12 molecules of 1, 3-diphosphoglycerate and then reduced to phosphoglyceraldehyde (PGAL).
- Two molecules of PGAL are diverted for the synthesis of sugar and then starch.

Regeneration of RuBP

- For the cycle to continue, the primary acceptor of carbon dioxide, i.e., RuBP has to be regenerated.
- 10 molecules of PGAL, carry a series of complex reactions and are converted into 6 molecules of 5C-compound, RuBP.

Definition

C_3 pathway: The photosynthetic pathway where the first stable product of C-fixation is a three-carbon (3C) compound i.e., 3-PGA.

Previous Year's Question

In C_3 plants, the first stable product of photosynthesis during the dark reaction is

(1) OAA (2) 3-PGA
(3) PGAL (4) Malic acid

Rack Your Brain

Why is photosynthetic product translocated in the form of sucrose instead of glucose?

Previous Year's Question

Calvin cycle is

(1) Dependent on light
(2) Not dependent on light
(3) Inhibited by light
(4) Partly dependent on light

Note: Input and output in Calvin cycle.

Input — $6CO_2$, 18ATP, 12NADPH

Output — $C_6H_{12}O_6$, 18ADP, 12NADP

To make one molecule of glucose 6 turns of Calvin cycle are required.

- The formation of 6 molecules of RuBP requires six ATP molecules.

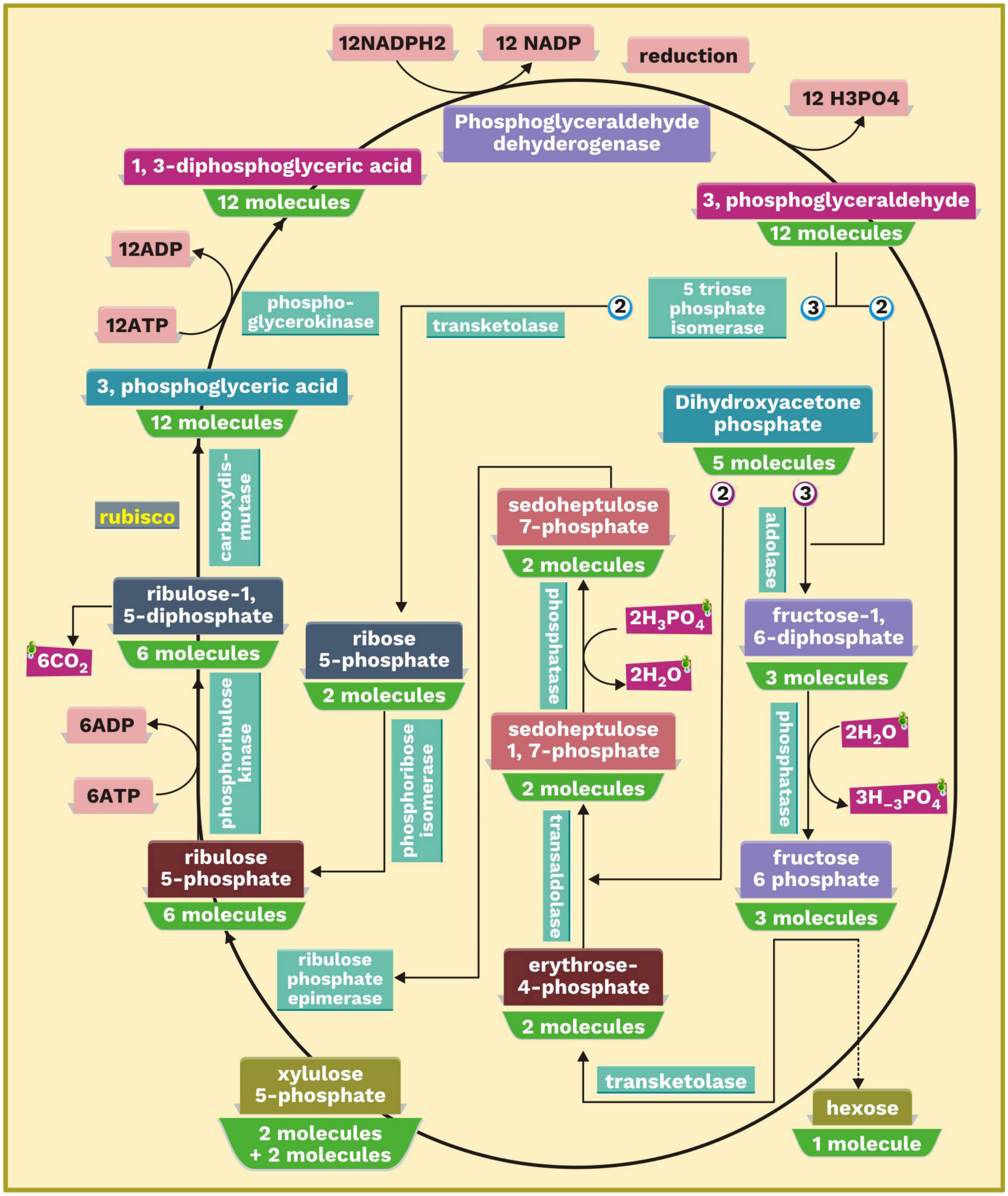


FIG. DETAILED SCHEME OF CALVIN CYCLE

PHOTORESPIRATION

- In C_3 plants, RuBP-carboxylase which is the main enzyme of photosynthesis, functions as oxygenase at high temperature and high oxygen concentration.
- It catalyses the oxidation of RuBP into one molecule of a 3C-compound, phosphoglycerate and one molecule of a 2C-compound, phosphoglycerate.
- Phosphoglycerate is quickly converted into glycolate and transported to peroxisomes.

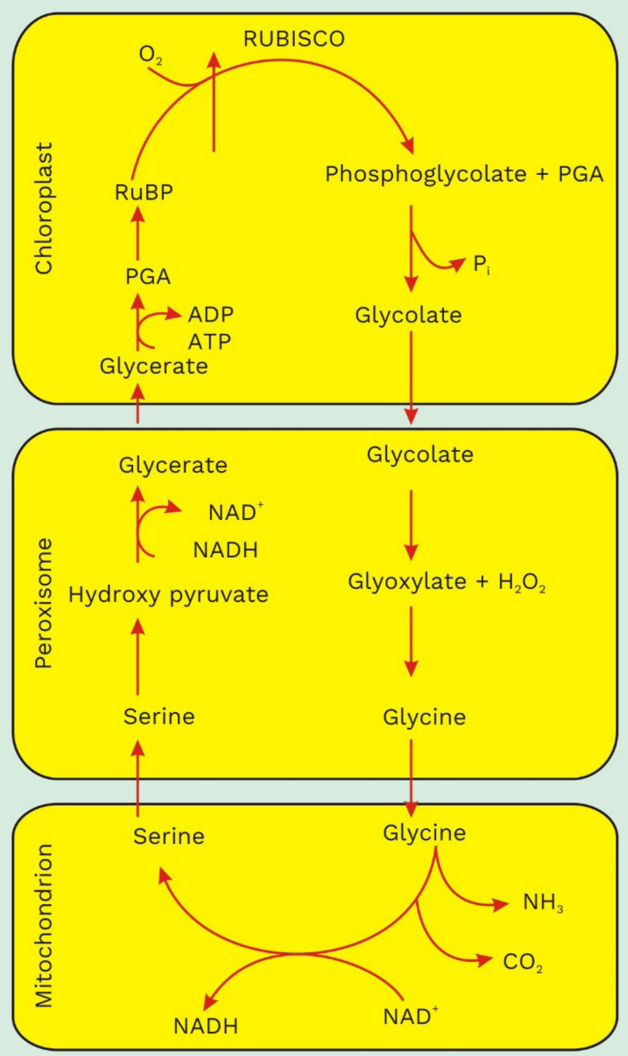


FIG. THE PHOTORESPIRATORY PATHWAY

Definition

Photorespiration: Due to high oxygen concentration RuBISCO of photosynthesising tissue start taking up oxygen and the green tissue release carbon dioxide during day.

Previous Year's Question

Photo-oxidation is
(1) photorespiration
(2) photolysis
(3) light and oxygen induced breakdown
(4) all the above

Rack Your Brain

Why photorespiration is called a wasteful process?

Previous Year's Question

Which one of the following is wrong in relation to photorespiration?
(1) It is the characteristic of C_3 plants.
(2) It occurs in chloroplasts.
(3) It occurs in day time only.
(4) It is a characteristic of C_4 plants.

- In the peroxisome, glycolate is oxidised to glyoxylate and is converted into amino acid, glycine.
- Glycine enters the mitochondria and two glycine molecules give rise to one molecule of serine and one molecule of carbon dioxide.
- Serine is picked up by peroxisomes and is converted to glycerate by a series of reactions.
- The glycerate leaves the peroxisome and enters the chloroplast, where it is phosphorylated to form PGA.
- The PGA enters Calvin cycle and thus 75% of the carbon lost during oxygenation of RuBP is recovered, but 25% is lost, as one molecule of carbon dioxide is released.
- Since there is loss of photosynthetically fixed carbon and no energy-rich compound is produced, photorespiration is considered as wasteful process.

Previous Year's Question

Photosynthate is translocated through
(1) Tracheids
(2) Vessels
(3) Sieve tubes
(4) Latex tubes

Previous Year's Question

RuBP carboxylase-oxygenase is located in
(1) Mitochondria (2) Chloroplasts
(3) Peroxisomes (4) Golgi bodies

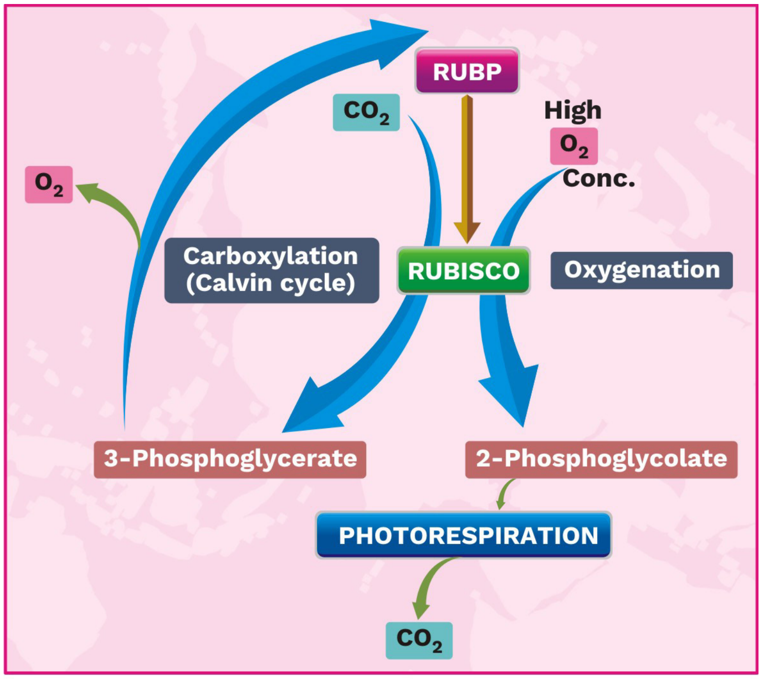


FIG. CARBOXYLATION AND OXYGENATION BY THE SAME ENZYME RUBISCO

C_4 PATHWAY OR HATCH-SLACK PATHWAY

- This pathway of carbon fixation occurs in plants like maize, sugar cane, pearl millet and amaranth.
- The plants which employ this mechanism of carbon fixation show the presence of two types of photosynthetic cells, i.e., mesophyll cells and bundle sheath cells (Kranz anatomy).
- The chloroplasts are dimorphic, i.e., those in the mesophyll cells are granal and those in the bundle sheath cells are adrenal.
- Phospho-enol-pyruvate (PEP) is the carbon dioxide acceptor, present in the mesophyll cells and the reaction is catalysed by the enzyme phosphorenol-pyruvate carboxylase (PEP-case).
- The first stable product is oxaloacetic acid (OAA), which is a 4C-compound.

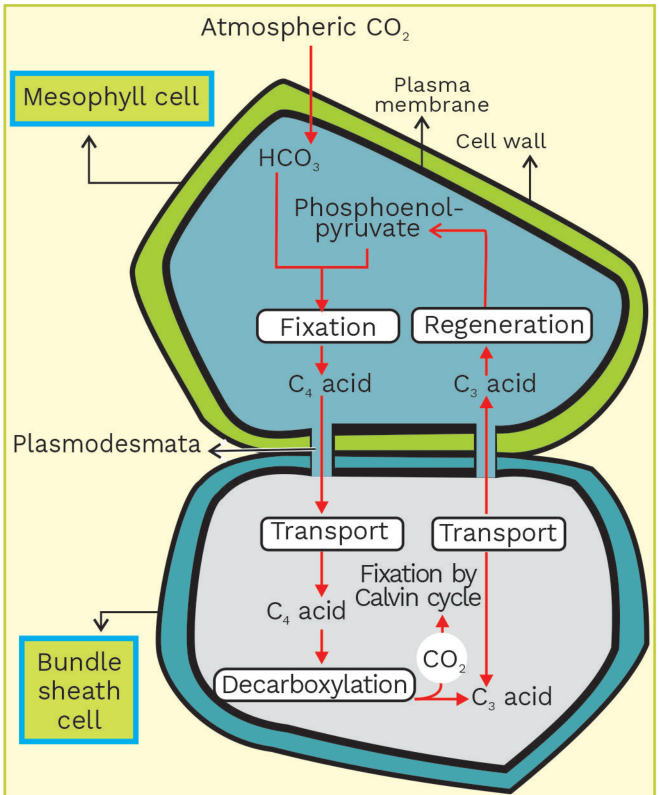


FIG. DIAGRAMMATIC REPRESENTATION OF HATCH AND SLACK PATHWAY

Note: The large cells around the vascular bundles of C_4 pathway plants are called bundle sheath cells, and the leaves which have such anatomy are said to have 'Kranz' anatomy. 'Kranz' means 'wreath' and is the reflection of the arrangement of cells. The bundle sheath cells may form several layers around the vascular bundles; they have characterised by having a large number of chloroplasts, thick walls impervious to gaseous exchange and no intercellular spaces.

Definition

C_4 pathway: The photosynthetic pathway where the first stable product of C-fixation is a four-carbon (4C) compound, oxaloacetic acid (OAA).

Rack Your Brain

Initial fixation of CO_2 in C_4 plants takes place in __________ cells.

Previous Year's Question

Kranz type of anatomy is found in
(1) C_2 plants
(2) C_3 plants
(3) C_4 plants
(4) succulents

- OAA is converted into malic acid and transported to bundle sheath cells, where it is decarboxylated into pyruvic acid.
- The carbon dioxide liberated is used for Calvin cycle in the bundle sheath cells.
- Pyruvic acid is transported back to mesophyll cell, where it is used for regeneration of PEP, utilising two molecules of ATP for each pyruvate.
- It is an adaptive mechanism to avoid photorespiration; the decarboxylation of malic acid in the bundle sheath cells maintains a high concentration of carbon dioxide near RuBisCo, so that it functions as carboxylase only and not as oxygenase.

CRASSULACEAN ACID METABOLISM (CAM)

- Among dicotyledons plants the family crassulaceae (e.g., jade plant and bryophyllum) and among cotyledonous plants the members of family Liliaceae, Orchidaceae, etc., exhibit CAM.
- The CAM plans are characterised by:
  - Succulent nature.
  - Stomata open at night and remain closed during the day.
  - CO_2 fixation occurs at night (darkness) (PEP is CO_2 acceptor).
  - Large quantities of malic acid is synthesised at night and is stored in vacuoles.
  - Decarboxylation of malic acid occurs during day and CO_2 is generated.
  - Released CO_2 enters Calvin cycle (RuBP is CO_2 acceptor) and carbohydrates (sucrose and starch) are formed.
  - Drop in stored starch and malate occurs during night and day respectively.

Note: CO_2 Compensation Point – The atmospheric concentration of CO_2 at which photosynthesis just compensates for respiration. Under such a conditions net photosynthesis is zero. It is higher in C_3 plants than in C_4 plants.

Previous Year's Question

In the leaves of C_4 plants, malic acid formation during CO_2 fixation occurs in the cells of
(1) bundle sheath
(2) phloem
(3) epidermis
(4) mesophyll

Previous Year's Question

Which of the following have high CO_2 compensation point?
(1) C_2 plants
(2) C_3 plants
(3) C_4 plants
(4) Alpine herbs

Previous Year's Question

CAM is the characteristic of
(1) Thin coloured leaves
(2) Flesh green leaves
(3) Thin-green reticulate veined leaves
(4) Thin green paralleled veined leaves

Previous Year's Question

Which is a C_4 plant
(1) Sugarcane
(2) Sorghum
(3) Maize
(4) All of the above

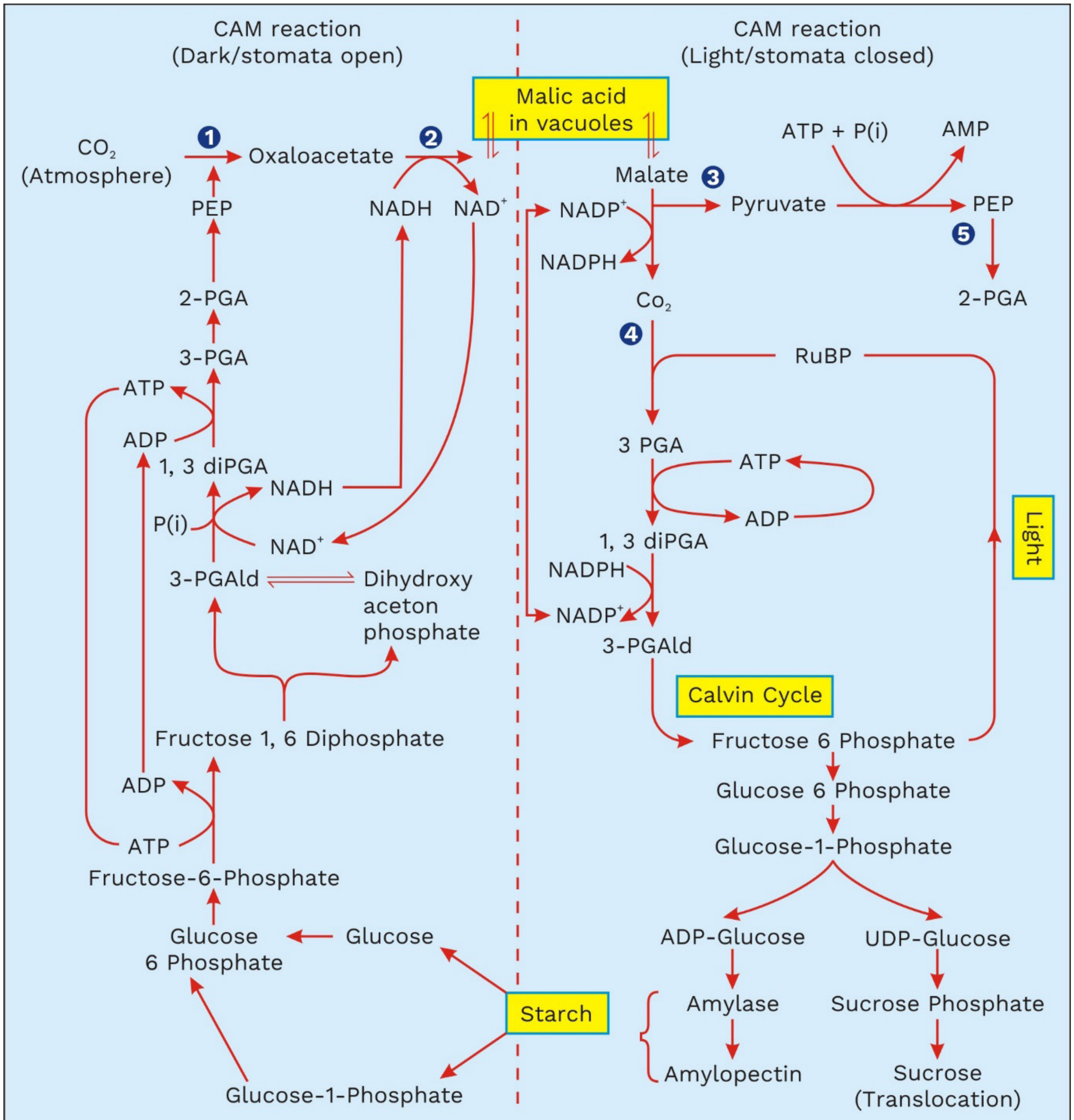


FIG. PATHWAY FOR CAM

Note: RuBISCO content of chloroplast is 16 per cent. This enzyme is found in higher percentage in the chloroplast.
In green plants for evolution of each oxygen molecule one quanta of light is required.

FACTORS AFFECTING PHOTOSYNTHESIS

Blackman's Law of Limiting Factors

- When a physiological process is controlled by a number of factors, the rate of the reaction depends on the slowest factor.
- This means that at a given time, only the factor which is the least (limiting) among all the factors, will determine the rate of the reaction.

External Factors

Light

- Light quality and light intensity influence photosynthesis.
- Light of wavelength between 400 nm and 700 nm is effective for photosynthesis and this light is known as photosynthetically active radiation (PAR).
- As the intensity of light increase the rate of photosynthesis increases.
- But at higher light intensities, the rate of photosynthesis decreases; it may be due to two reasons:
  - Other factors needed for photosynthesis may be limiting.
  - Destruction (photo-oxidation) of chlorophyll.

Temperature

- The photochemical phase remains unaffected by temperature.
- But the biosynthetic phase that involves enzyme-catalysed reactions is sensitive to temperature; it may be due to the following reasons:
  - At high temperatures, the enzymes become denatured (inactive).
  - At low temperatures, the enzymes may get inactivated.

Previous Year's Question

In sugarcane plant $^{14}CO_2$ fixed in malic acid in which the enzyme that fixes CO_2 is

(1) Fructose phosphatase
(2) Ribulose biphosphate carboxylase
(3) Phosphoenol pvruvic acid carboxylase
(4) Ribulose phosphate kinase

Previous Year's Question

In C_4 plants initial acceptor of CO_2 is

(1) RuBP
(8) PGA
(3) PEP
(4) OAA (Oxaloacetic acid)

Previous Year's Question

For each molecule of glucose formed in plants, the number of molecules of ATP and $NADPH_2$ required are respectively

(1) 15 and 10
(2) 12 and 18
(3) 18 and 12
(4) 12 and 6

Carbon Dioxide Concentration

- In C_3 plants, the rate of photosynthesis increases with increase in CO_2 concentration, up to 500 μl^{-1}.
- In C_4 plants, the saturation reaches at a concentration about 360 μl^{-1}.

Soil Water Availability

- Water influences photosynthesis in two ways:
  - If available water decreases and plants show water stress, the stomata will not open and hence there will be a decreased supply of carbon dioxide.
  - Reduced water potential in the leaf reduces leaf expansion and reduced in the photosynthetic surface area.

Previous Year's Question

Assertion: Cyclic pathway of photosynthesis first appeared in some eubacterial species.
Reason: Oxygen started accumulating in the atmosphere after the non-cyclic pathway of photosynthesis evolved.
(1) Both the statements are true, and Reason is the correct explanation of Assertion.
(2) Both the statements are true, but Reason is not the correct explanation of Assertion.
(3) Assertion is true, but Reason is a false statement.
(4) Both the statements are false.

Previous Year's Question

The factors which is not limiting in normal conditions for photosynthesis is
(1) light
(2) water
(3) chlorophyll
(4) carbon dioxide

Previous Year's Question

Photosynthesis is a process in which
(1) CO_2 is reduced to carbohydrates
(2) NAD is reduced to NADH
(3) ATP is generated
(4) Oxidative phosphorylation occurs

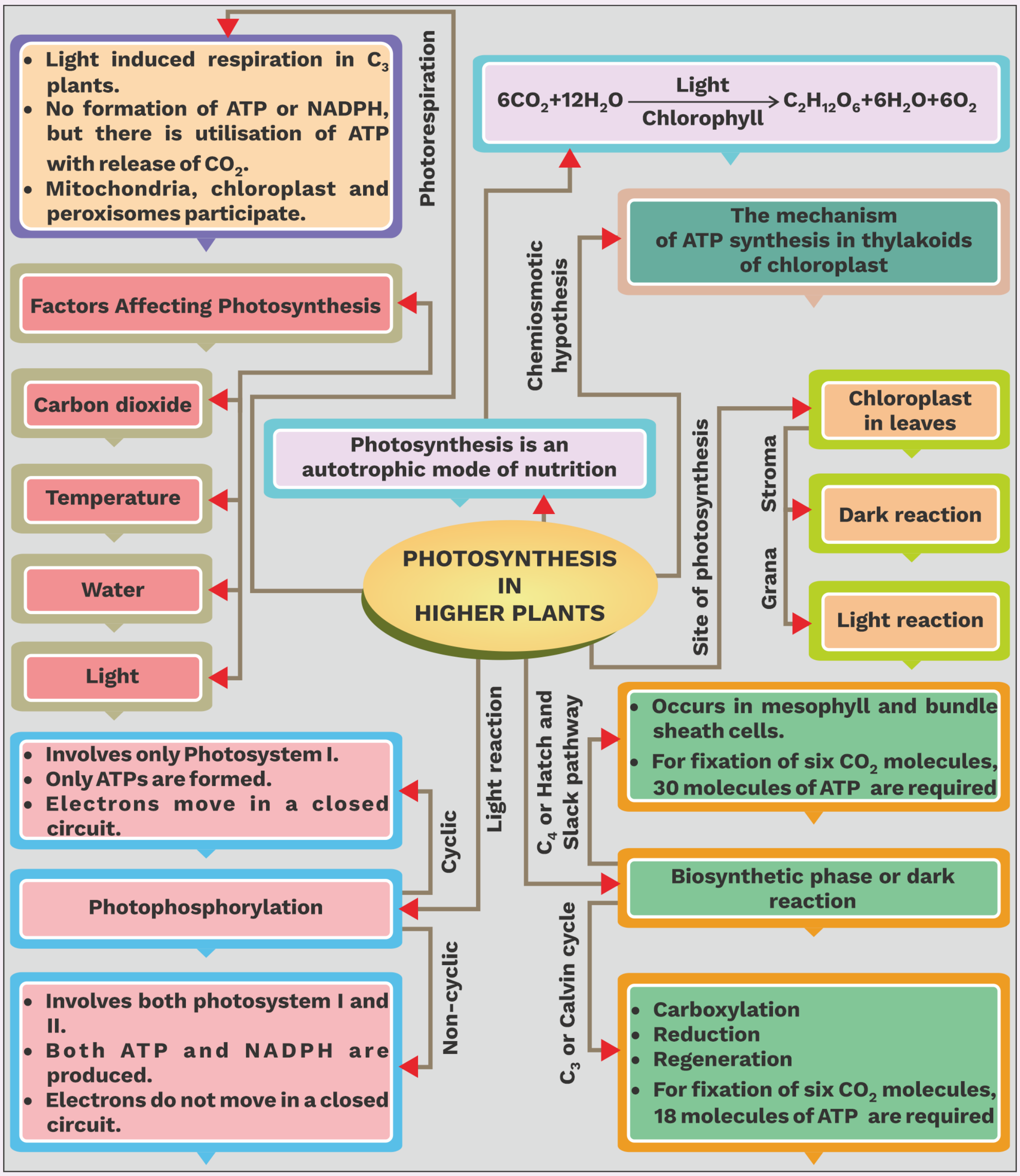
Previous Year's Question

Bacterial photosynthesis is different from photosynthesis of higher plants because
(1) Energy is not fixed
(2) Light is not required
(3) Oxygen is not released
(4) Dependence on other organisms is necessary

Summary


EARLY EXPERIMENTS TO UNDERSTAND PHOTOSYNTHESIS
Joseph Priestley (English Chemist)
1770
Experimental organisms or items
Mouse, green plant, candle bell jar
Plants restore air while animals and combustion remove air
Jan Ingenhousz (Dutch Physiologist)
1730–1799
Used aquatic plants
He used similar setup, the one used by Priestley
Setup was placed first in dark and then in sunlight
Air is purified by plants
O_2 is released from green parts of the plant
Julius von Sachs (German Botanist)
1854
Glucose, end product of photosynthesis
Chlorophyll is stored in chloroplasts
T.W. Engelmann (German Botanist)
1843–1909
Use of Prism to split spectrum
Experimental organisms
Cladophora (green alga) and aerobic bacteria
Blue and red light are the action & absorption spectrum for photosynthesis
Cornelius van Neil (Dutch American Microbiologist)
1897–1985
Experimental organisms
Purple and green bacteria
Photosynthesis is a light dependent process
H_2 comes from H_2O and reduce CO_2 to $C_6H_{12}O_6$
$2H_2A + CO_2 \xrightarrow{light} 2A + CH_2O + H_2O$

Summary


PHOTOSYNTHESIS IN HIGHER PLANTS
Photosynthesis is an autotrophic mode of nutrition
$6CO_2 + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 + 6H_2O + 6O_2$
Photorespiration
• Light induced respiration in C_3 plants.
• No formation of ATP or NADPH, but there is utilisation of ATP with release of CO_2.
• Mitochondria, chloroplast and peroxisomes participate.
Factors Affecting Photosynthesis
Carbon dioxide
Temperature
Water
Light
Chemiosmotic hypothesis
The mechanism of ATP synthesis in thylakoids of chloroplast
Site of photosynthesis
Chloroplast in leaves
Stroma
Dark reaction
Grana
Light reaction
Light reaction
Photophosphorylation
Cyclic
• Involves only Photosystem I.
• Only ATPs are formed.
• Electrons move in a closed circuit.
Non-cyclic
• Involves both photosystem I and II.
• Both ATP and NADPH are produced.
• Electrons do not move in a closed circuit.
C_4 or Hatch and Slack pathway
• Occurs in mesophyll and bundle sheath cells.
• For fixation of six CO_2 molecules, 30 molecules of ATP are required
Biosynthetic phase or dark reaction
C_3 or Calvin cycle
• Carboxylation
• Reduction
• Regeneration
• For fixation of six CO_2 molecules, 18 molecules of ATP are required

Summary

PHOTOSYNTHESIS

CALVIN CYCLE (C_3 pathway)		HATCH–SLACK CYCLE (C_4 path)
RUBP (5C compound)	Primary CO_2 acceptor	PEP (3C compound)
3, phosphoglyceraldehyde (3PGA), 3C compound	First stable compound	Oxalo acetic acid (OAA), 4C compound
Cannot operate under very low CO_2 conc.	Role of CO_2 concentration	Can operate under very low CO_2 conc.
3 ATPs per CO_2 molecule	ATP molecules requirement	5 ATPs per CO_2 molecule
CO_2 once fixed is not released	Re-releasing of CO_2	CO_2 fixed in mesophyll cells is released in bundle sheath cells
Slow	Co_2 fixation rate	Fast
20°C – 25°C	Optimum temperature	30°C – 45°C
All plants	Examples	Only in C_4 Plants

Summary

PHOTOPHOSPHORYLATION

Formation of ATP from ADP and iP in the presence of sunlight inside the chloroplasts

	Non-cyclic	Cyclic
01	Occurs in thylakoid region, both Photosystems I & II involved	Occurs in stroma lamellae, Photosystem I involved
02	Electrons expelled by the reaction centre (P_{680}) do not return to it.	Electrons expelled by the reaction centre (P_{700}) return to it
03	Photolysis of H_2O occurs and O_2 is evolved	No photolysis of H_2O and no O_2 is evolved
04	ATPs and $NADPH_2$ are synthesised	Only ATPs are synthesised
05	Ideal conditions are optimum sunlight & Co_2 and aerobic conditions	Operates under low intensity of light & CO_2 and anaerobic conditions
06	Dominant in green plants	Occurs in green plants and in photosynthetic bacteria
07	Inhibited by dichlorophenyl dimethyl urea (DCMU)	DCMU has no effect

SOLVED EXERCISE

1. **In leaves of C_4 plants malic acid synthesis during CO_2 fixation occurs in**

(1) bundle sheath **(2) guard cells**

(3) epidermal cells **(4) mesophyll cells**

Sol. **(4)**

C_4 plants show Kranz anatomy, i.e., the mesophyll is undifferentiated, and its cells occur in concentric layers around vascular bundle, which is surrounded by large sized bundle sheath cells, in a wreath like manner.

In this type of plants, the initial fixation of CO_2 occurs in mesophyll cell. The primary acceptor (phosphoenol pyruvate) combines with CO_2 to form oxaloacetic acid which later reduces to malic acid. Malic acid is then translocated to bundle sheath cell for further decarboxylation.

2. **Ferredoxin is a constituent of**

(1) PS I **(2) PS II**

(3) Hill reaction **(4) P 680**

Sol. **(1)**

In Photosystem I, the ejected electron is trapped by FRS (ferredoxin reducing substance) which is an unknown oxidation reduction system. The electron is now transferred to a non-heme iron protein called ferredoxin (Fd) from which electron is transferred to $NADP^+$ intermediate protein electron carrier ferredoxin NADP reductase. So that $NADP^+$ is reduced to $NADPH + H^+$.

3. **Photosynthetic pigments found in the chloroplasts occur in**

(1) thylakoid membranes **(2) plastoglobules**

(3) matrix **(4) chloroplast envelope**

Sol. **(1)**

Photosynthetic pigments are found in the thylakoid membrane of chloroplasts. The grana lamellae are paired to form sac like structures and form thylakoids. Chlorophylls and other photosynthetic pigments are confined to grana.

4. **'The law of limiting factors' was proposed by**

(1) Leibig **(2) Hatch and Slack**

(3) Blackman **(4) Arnon**

Sol. **(3)**

Blackman (1905) gave the law of limiting factors which states that when a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the slowest process. It is the factor which is present in minimum amount.

5. **Photorespiration is favoured by**

(1) high temperature and low O_2 **(2) high humidity and temperature**

(3) high O_2 and low CO_2 **(4) high CO_2 and low O_2**

Sol. **(3)**

Photorespiration is the light dependent process of oxygenation of ribulose biphosphate (RuBP) and release of carbon dioxide by the photosynthetic organs of a plant. It leads to oxidation of considerable amount of photosynthetic products to CO_2 and H_2O without the production of useful energy. Photorespiration occurs only in C_3 plants because at high temperature and high oxygen concentration RuBP carboxylase changes to RuBP oxygenase. Photorespiration is absent in C_4 plants. Peroxisome and mitochondria are required for completing the process.

6. **Which element is located at the centre of the porphyrin ring in chlorophyll?**

(1) Calcium **(2) Magnesium**

(3) Potassium **(4) Manganese**

Sol. **(2)**

Chlorophyll is the green pigment present in plants and some photosynthetic bacteria. The empirical formula of chlorophyll a molecule is $C_{55}H_{72}O_5N_4Mg$. It consists of a porphyrin head and a phytol tail. Porphyrin is a cyclic tetrapyrrole structure, having a magnesium atom in the centre. Tail consists of phytol alcohol, and it is attached with one of the pyrrole rings.

7. **For the synthesis of one glucose molecule the Calvin cycle operates for**

(1) 2 times **(2) 4 times**

(3) 6 times **(4) 8 times.**

Sol. **(3)**

Photosynthesis is oxidation reduction process in which water is oxidised and CO_2 is reduced to carbohydrates. The reduction of CO_2 to carbohydrates needs assimilatory powers, i.e., ATP and $NADPH_2$. The process of photosynthesis involves two steps–

(i) Light dependent phase or photochemical reaction.

(ii) Light independent phase or dark reaction. In Calvin cycle, CO_2 acceptor molecule is RuBP or RuDP. The enzyme catalysing this reaction is RuBP carboxylase/oxygenase (RuBisCO). As Calvin cycle takes in only one carbon (as CO_2) at a time, so it takes six turns of the cycle to produce a net gain of six carbons (i.e., hexose or glucose). In this cycle, for formation of one mole of hexose sugar (Glucose), 18 ATP and 12 $NADPH_2$ are used. For 6 molecules of $CO_{2,}$ it needs 18 ATP and 12 $NADPH_2$ molecules so for assimilation of one molecule of CO_2 it needs 3 ATP and 2 $NADPH_2$ molecules.

8. **In C_4 plants, Calvin cycle operates in the**

(1) stroma of bundle sheath chloroplasts

(2) grana of bundle sheath chloroplasts

(3) grana of mesophyll chloroplasts

(4) stroma of mesophyll chloroplasts

Sol. **(1)**

The C_4 plants have a characteristic leaf anatomy called Kranz anatomy. Here two types of chloroplasts are present — bundle sheath chloroplasts and mesophyll chloroplasts. In C_4 plants, there are two carboxylation reactions which occur first in mesophyll chloroplasts and then in bundle sheath chloroplasts. CO_2 acceptor molecule in mesophyll chloroplasts is PEP (Phospho-enol pyruvate) and not Ribulose 1, 5 biphosphate. Further it has enzyme PEP carboxylase for initial CO_2 fixation. RuBP carboxylase is absent in mesophyll chloroplasts but is present in bundle sheath chloroplasts. The first product formed is oxaloacetic acid and hence it is known as C_4 cycle. Bundle sheath cells fix CO_2 through C_3 cycle.

9. **The primary acceptor, during CO_2 fixation in C_3 plants, is**

(1) phosphoenolpyruvate (PEP)
(2) ribulose 1, 5 biphosphate (RuBP)
(3) phosphoglyceric acid (PGA)
(4) ribulose monophosphate (RMP)

Sol. **(2)**

In C_3 plants, CO_2 primary acceptor molecule is RuBP or RuDP (i.e., Ribulose 1, 5 biphosphate or Ribulose 1, 5-diphosphate). There occurs covalent bonding of CO_2 to RuBP and the enzyme catalyzing this reaction is RuBP carboxylase or RuBP oxygenase (RuBisCO).

10. **$NADPH_2$ is generated through**

(1) photosystem II
(2) anaerobic respiration
(3) glycolysis
(4) photosystem I

Sol. **(4)**

Non-cyclic photophosphorylation involves both PS I and PS II. Here electrons are not cycled back and are used in the reduction of NADP to $NADPH_2$. The electrons generated by PS II are passed over a series of electron carriers in a downhill journey and handed over to reaction centre of PS I. PS I again passes the electrons to $NADP^+$ which combines with H^+ ions to form NADPH.