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Introduction

Overview

- Green plants produce their own food by photosynthesis; called autotrophs.
- All other organisms depend on green plants for food; called heterotrophs.
- Photosynthesis uses sunlight energy to make food and releases oxygen.
- It is the primary source of food and oxygen on Earth.

Memory Aids

- Autotrophs = Self-feeders (green plants).
- Heterotrophs = Other feeders (depend on plants).
- Photosynthesis = Food + Oxygen from Sunlight.

Quick Checkpoints

- What defines autotrophs and heterotrophs?
- Why is photosynthesis vital for life on Earth?

Photosynthesis Process

Key Points

- Photosynthesis is an enzyme-controlled anabolic process in chlorophyll cells.
- It converts carbon dioxide and water into organic compounds using sunlight.
- Chemical equation: $6CO_2 + 6H_2O$ + light energy → $C_6H_{12}O_6 + 6O_2$.
- Glucose is the food made; oxygen is released as a byproduct.
- Chlorophyll, light, and CO_2 are essential for photosynthesis.
- Experiments show photosynthesis occurs only in green parts exposed to light.

$$6CO_2 + 12H_2O \xrightarrow[\text{Radiant energy}]{\text{Chlorophyll, Enzymes}} 6H_2O_6 + 6O_2\uparrow$$

Memory Aids

- Photosynthesis = Light + CO_2 + H_2O → Glucose + O_2.
- Green parts + Light = Photosynthesis site.

Quick Checkpoints

- What are the raw materials and products of photosynthesis?
- Why is chlorophyll necessary?
- How does light affect photosynthesis?

Early Experiments

Moll's Half-Leaf Experiment

- Part of leaf enclosed in KOH-soaked cotton absorbs CO2, other half exposed to air.
- Exposed half tests positive for starch; enclosed half tests negative.
- Conclusion: CO2 is essential for photosynthesis.

Priestley's Experiment

- Hypothesis: Plants restore to air what animals and burning candles remove.
- Burning candle or animal respiration produces "phlogiston" (foul air).
- Plants convert phlogiston into "dephlogiston" (pure air).

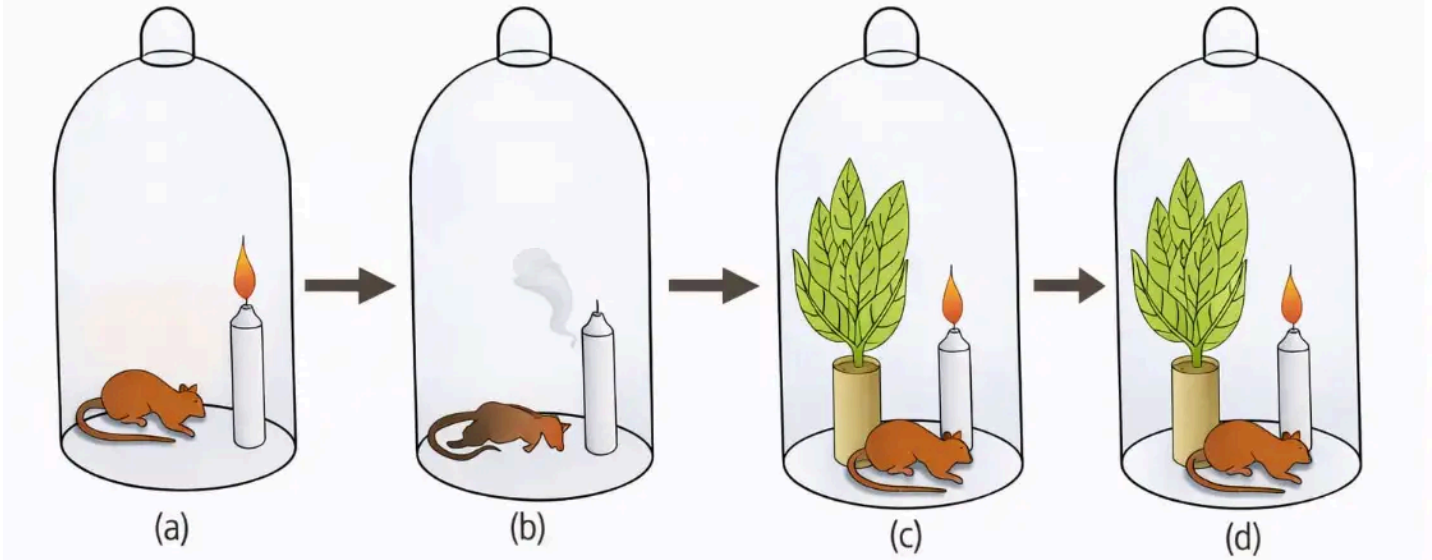


Fig.: Priestley's experiment

Explanation of Priestley's Experiment

- Mouse and burning candle in closed jar: oxygen used up, mouse dies, candle extinguishes.
- Adding a mint plant: plant produces oxygen, mouse survives, candle keeps burning.
- Shows plants release oxygen necessary for animal survival.

Memory Aids

- Moll: Half leaf + KOH = CO_2 needed.
- Priestley: Plants purify air by releasing oxygen.

Quick Checkpoints

- What does Moll's experiment prove about CO_2?
- What gas do plants release according to Priestley's experiment?
- Why did the mouse die without the plant?

Early Research Milestones

Key Discoveries

- 1727: Stephen Hales - Plants need sunlight, air, and green leaves to grow.
- 1770-1773: Joseph Priestley - Introduced "foul air" and "pure air" concepts; discovered oxygen.
- 1779: Jan Ingenhousz - Plants release oxygen bubbles only in sunlight.
- 1845: Von Mayer - Plants convert sunlight into chemical energy.
- 1854: Julius von Sachs - Plants produce glucose stored as starch, first photosynthesis product.
- 1884-1858: Engelmann - Studied light color effects on photosynthesis using algae and bacteria.
- 1905: Blackmann - Identified limiting factors and dark phase in photosynthesis.
- 1931: Cornelius van Neil - Photosynthesis depends on light; hydrogen reduces CO2 to sugar.

Table : Historical summary of early research on photosynthesis

1727	**Stephen Hales** recognised the importance of sunlight, air and green leaves for nourishment or of plants.
1770-1723	**Joseph Priestley** gave the concept of **phlogiston** (foul air) and **dephlogiston** (pure air) which led to the discovery of **oxygen**.
1779	**Jan Ingenhousz** in his experiment with an aquatic plant showed that in bright sunlight, small bubbles were formed around the green parts while in the dark, such bubbles did not form. He found these bubbles to be of oxygen. He thus, confirmed that purification of air or formation of dephlogiston is carried out by green plants only in the presence of sunlight.
1845	**Von Mayer** proved that green plants convert solar energy into chemical energy during the process of photosynthesis.
1854	**Julius von Sachs** demonstatted that green parts in plant produce glucose which is stored as starch. Starch is **first visible product** of photosynthesis.
1884-1858	**Engelmann** split light into ito components by the prism and then illuminated *Cladophora* (a green alga) placed in a suspension of aerobic bacteria, He found that bactef ia accumulated in the region of bibie and reet light ol the split spectrum, He thus, discovered the effect of different wavelengths of light on photosynthesis and ploted the first **action spectrum** of photosynthesis.
1905	**Blackmann** proposed the law or principle of limiting factors, He also proposed the occurrence of a **dark phase** in photosynthesis.
1931	**Cornelius van Neil**, on the basie of his studies with purple and green sulphur bacteria, demonstrated that photosynthesis is a light dependent reaction in which hydrogen from an oxidisable compound reduces carbon dioxide to form sugar. $2H_2A + CO_2 \xrightarrow{\text{Light}} 2A + CH_2O + H_2O$ In green sulphur bacteria, when hydrogen sulphibe instead of water was used as hydrogen donor, no oxygen was ev-evolved, the tnte evcilned oxygen evolved by green plants comes from water, but noi tro to dioxicle as earlier thought.

Memory Aids

- Hales: Sunlight + air + green leaves = growth.
- Priestley: Oxygen discovery.
- Ingenhousz: Oxygen only in light.
- Von Mayer: Sunlight to energy.
- Sachs: Glucose as starch.
- Engelmann: Light color effect.
- Blackmann: Limiting factors, dark phase.
- Van Neil: Light + hydrogen = sugar.

Quick Checkpoints

- Who discovered oxygen release in sunlight?
- What is the first product of photosynthesis?
- What did Blackmann identify in photosynthesis?
- What role does hydrogen play according to Van Neil?

Modern Discoveries

Important Findings (1937-1966)

- 1937: Hill - Oxygen released during light reaction using chloroplasts.
- 1941: Ruben and Kamen - Oxygen comes from water, not CO_2.
- 1954: Arnon et al. - Photophosphorylation and radioactive carbon for carbon fixation study.
- 1954-35: Calvin - Traced CO_2 use in Calvin cycle; Nobel Prize winner.
- 1957: Emerson - Discovered Emerson effect in photosynthesis.
- 1960: Hill and Bendall - Proposed Z-scheme with two photosystems.
- 1961: Peter Mitchell - Chemiosmotic theory explaining ATP synthesis.
- 1966: Hatch and Slack - Discovered C4 pathway for carbon fixation in tropical plants.

1937	**Hill** stated that evolution of oxygen occurs in light reaction performed by isolated illuminated chloroplasts in the presence of suitable electron acceptors and.
1941	**Ruben** and **Kamen** demonstrated that oxygen evolved during photosynthesis comes from water and not from carbon dioxide. For this, they used water, ^{18}O.
1954	**Arnon** *et al.*, discovered photophosphorylation. Also showed fixation of carbon dioxide by previously illuminated, by using radioactive carbon (^{1}C) in carbon
1954-35	**Calvin** traced the pathway of carbon fixation by using $^{14}CO_2$ and discovered C_3 cycle, now known after him as Calvin cycle. Calvin was awarded Nobel Prize for this in 1961.
1957	**Emerson** found red drop and photosynthetic enhancement or **Emerson effect.**
1960	**Hill** and **Bendall** proposed Z-scheme of two photosystems.
1961	**Peter Mitchell** proposed chemiosmotic theory of ATP synthesis.
1966	**Hatch** and **Slack** discovered supplementary mechanism of CO_2 fixation, called C_4 pathway in certain tropical plants (grasses and nongrasses).

Memory Aids

- Hill: Oxygen from light reaction.
- Ruben & Kamen: Oxygen from water.
- Arnon: Energy production and carbon tracing.
- Calvin: Carbon fixation cycle.
- Emerson: Emerson effect.
- Hill & Bendall: Z-scheme photosystems.
- Mitchell: ATP synthesis theory.
- Hatch & Slack: C4 pathway discovery.

Quick Checkpoints

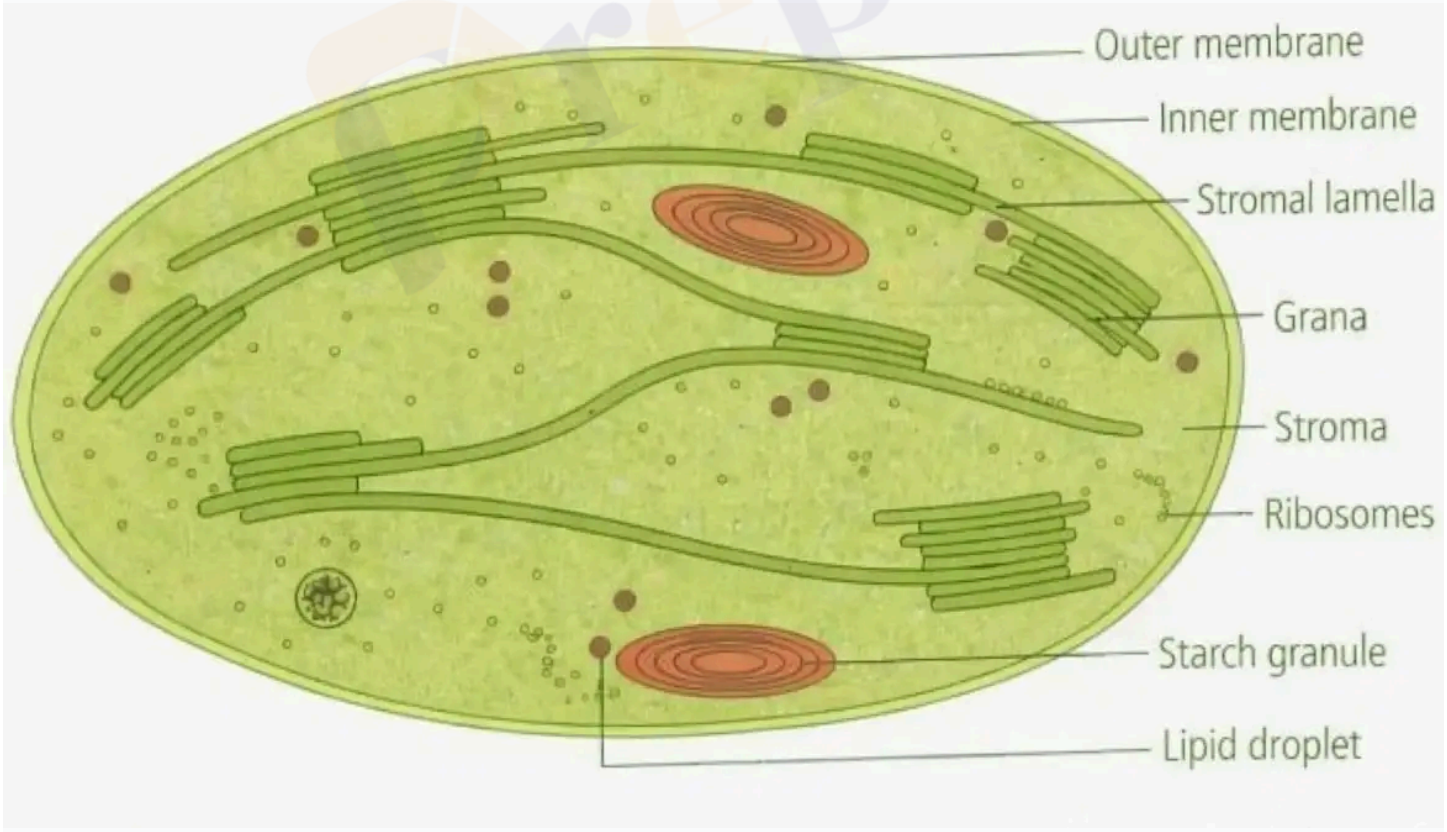
- Where does oxygen released in photosynthesis come from?
- What is photophosphorylation?
- What does the Calvin cycle do?
- What is the Emerson effect?
- What does the Z-scheme explain?
- What is the chemiosmotic theory?

- What is special about the C4 pathway?

Where Does Photosynthesis Take Place?

Sites of Photosynthesis

- Occurs mainly in green leaves and other green parts of plants.
- Mesophyll cells contain many chloroplasts, the green plastids where photosynthesis happens.
- Chloroplasts are discoid, ellipsoidal, or biconvex lens-shaped, 4–10 µm long and 1–3 µm wide.
- Each chloroplast has a double membrane envelope acting as a selective barrier.
- Inside is the stroma, a protein-rich matrix containing all enzymes needed for photosynthesis.
- Chloroplasts align along mesophyll cell walls to optimize light absorption.
- Membrane system traps light energy and synthesizes ATP and NADPH (light reactions).
- Stroma enzymes use ATP and NADPH to fix CO_2 into sugars (dark reactions).



This image shows the chloroplast structure essential for photosynthesis.

- Outer and inner membranes protect the chloroplast.
- Grana are stacks of thylakoid membranes containing chlorophyll for sunlight capture.
- Grana are connected by stromal lamellae.
- Stroma is the fluid surrounding grana where some photosynthesis steps occur.
- Ribosomes inside chloroplasts synthesize proteins.
- Starch granules and lipid droplets store energy.
- Chloroplasts convert sunlight into chemical energy.

Memory Aids

- Chloroplast = Green plastid + Double membrane + Stroma + Thylakoids (grana).
- Light reactions = ATP + NADPH synthesis in thylakoids.
- Dark reactions = CO_2 fixation in stroma using ATP and NADPH.

Quick Checkpoints

- Where are chloroplasts mainly located in leaves?
- What is the role of the double membrane in chloroplasts?
- Which part of chloroplast contains enzymes for photosynthesis?
- What are grana and their function?
- Where do light and dark reactions occur within chloroplasts?

Thylakoid and Photosystems

- Stroma contains flattened sacs called thylakoids stacked into grana.
- Grana stacks are connected by stroma lamellae (fret channels).
- Light reaction pigments and proteins cluster in thylakoid membranes forming photosystems.
- Two photosystems: Photosystem I (in stroma thylakoids and non-appressed granal thylakoids) and Photosystem II (in appressed granal thylakoids).

Memory Aids

- Thylakoids = site of light reactions and photosystems.

- Photosystem I = stroma thylakoids; Photosystem II = grana thylakoids.

Quick Checkpoints

- What structures form the grana in chloroplasts?
- How are grana connected within the chloroplast?
- Where is Photosystem I located?
- Where is Photosystem II located?

Types of Photosynthetic Pigments

Overview

- Leaf color results from four pigments, not one.
- Major pigments: **Chlorophyll a** (bright blue-green), **Chlorophyll b** (yellow-green), **Xanthophylls** (yellow), **Carotenoids** (yellow to yellow-orange).

Memory Aids

- Four pigments: a, b, xanthophylls, carotenoids.
- Chlorophyll a is the main pigment.

Quick Checkpoints

- Which pigments contribute to leaf color?
- What colors do each pigment show?

Chlorophylls

Types and Functions

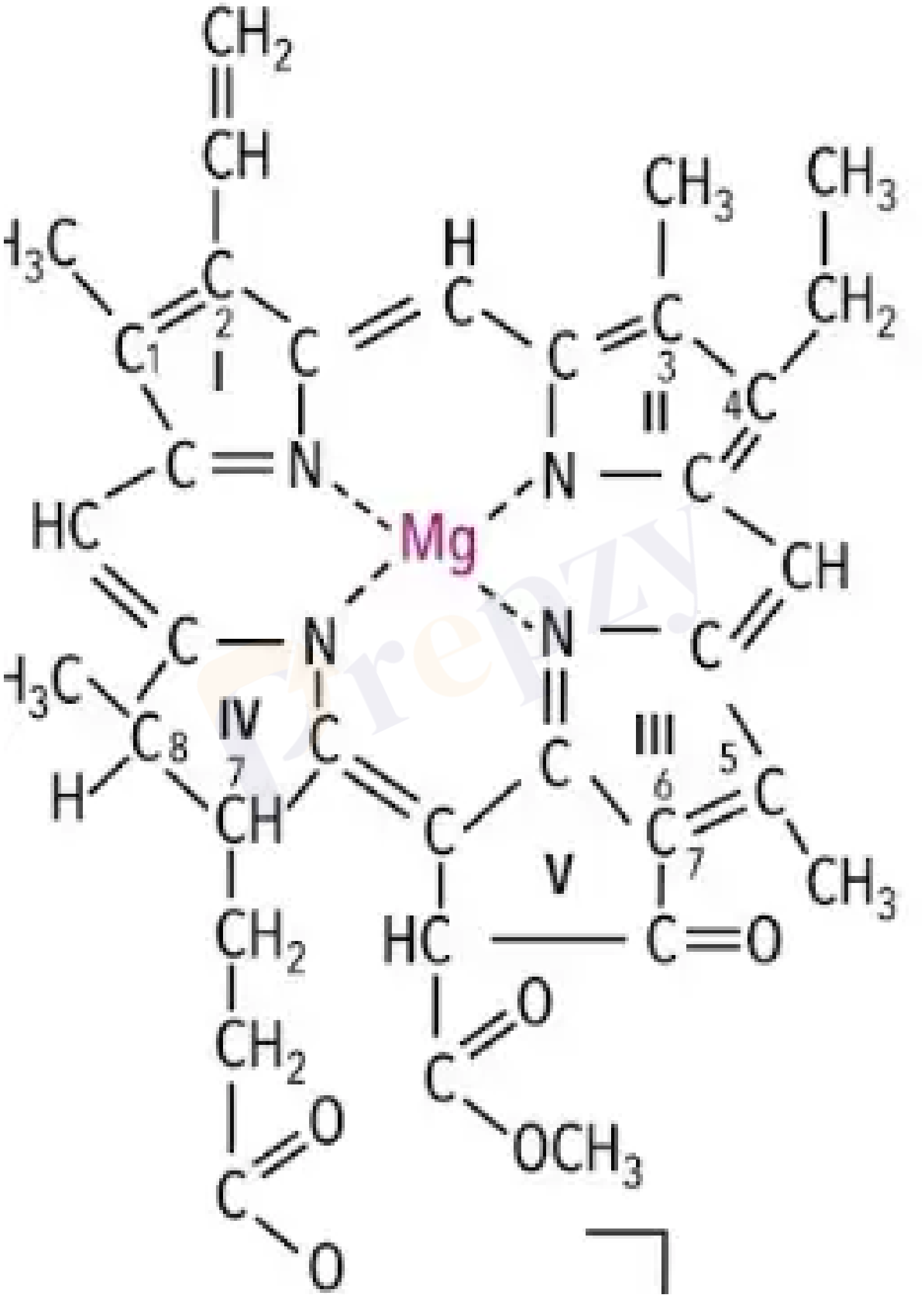
- Green photosynthetic pigments; five types exist (a, b, c, d, e).
- Only chlorophyll a and b are in higher plants; chlorophyll b is about 25% of total chlorophyll.
- Chlorophyll a is universal in photosynthetic plants except bacteria; called primary pigment.
- Chlorophyll a performs primary photosynthesis reaction converting light to chemical/electrical energy.
- Other pigments absorb different wavelengths and transfer energy to chlorophyll a; called accessory pigments.
- Some chlorophyll a molecules act as reaction centers (P700, P680) converting light energy to electrical energy.
- Structure: porphyrin head (four pyrrole rings linked by methine bridges) with central magnesium atom, and phytol tail anchoring molecule in thylakoid membrane.

Memory Aids

- Chlorophyll a = primary, universal pigment.
- Phytol tail anchors chlorophyll in membrane.
- Reaction centers: P700 and P680.

Quick Checkpoints

- Which chlorophyll types are in higher plants?
- What is the role of chlorophyll a?
- What is the structure of chlorophyll?


CH2
CH
H3C
CH3
CH3
CH2
H
C1
2
3
4
HC
Mg
CH
H3C
IV
III
V
8
7
6
5
7
H
CH
CH2
CH2
HC
O
C
O
OCH3
O
O

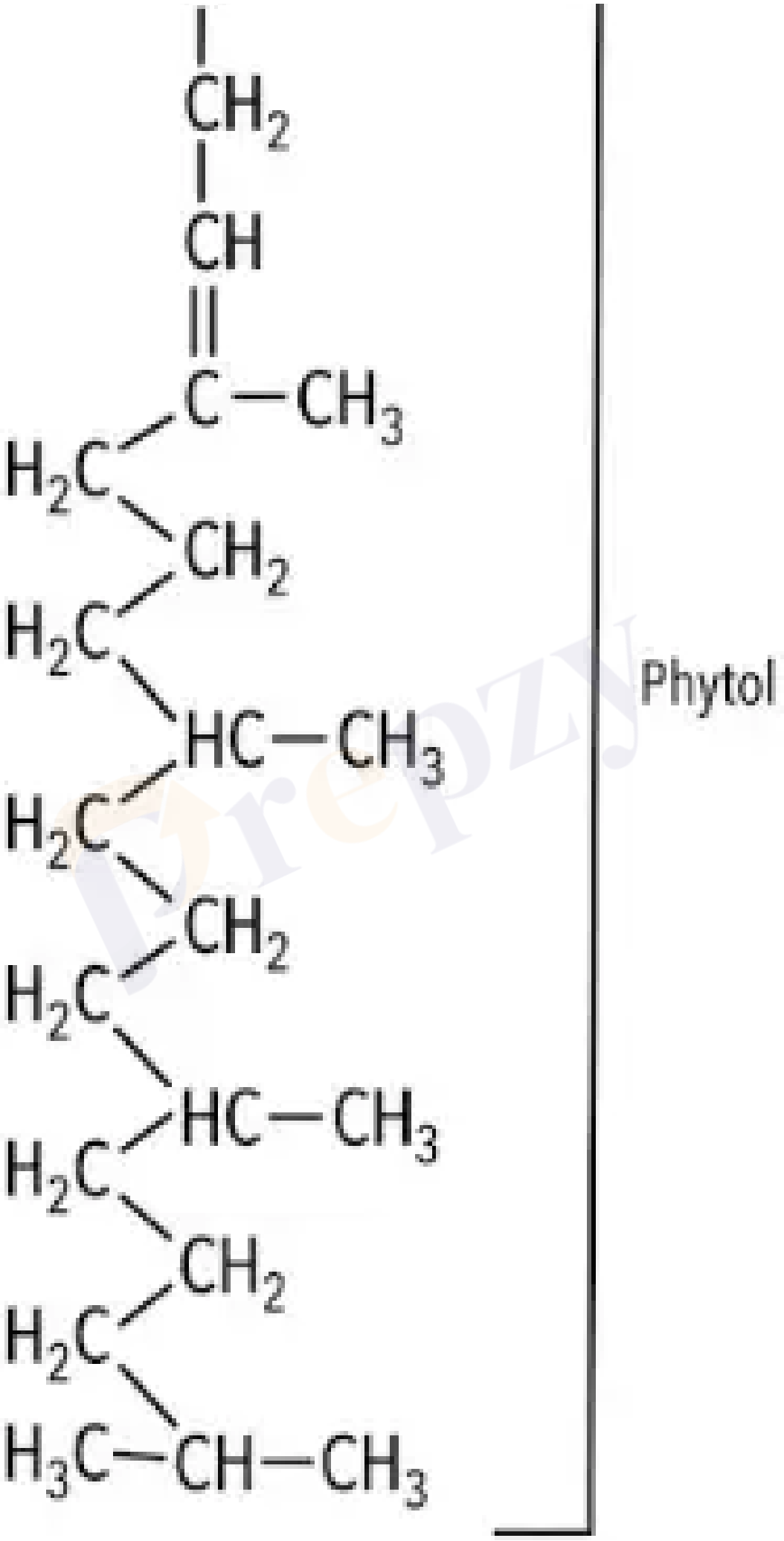

Phytol

Fig.: Structure of chlorophyll *a*

Carotenoids

Types and Roles

- Yellow, brown to reddish pigments in chloroplasts and chromoplasts.
- Accessory pigments along with chlorophyll b; transfer energy to chlorophyll a.
- Two types: carotenes (orange hydrocarbons, e.g. β-carotene, lycopene) and xanthophylls (yellow oxygen-containing derivatives, e.g. lutein, zeaxanthin).
- Carotenes are precursors to vitamin A in animals.
- Soluble in organic solvents; carotenes more soluble in carbon disulphide than xanthophylls.

Memory Aids

- Carotenes = orange, vitamin A precursors.
- Xanthophylls = yellow, oxygenated derivatives.

Quick Checkpoints

- What are the two types of carotenoids?
- Which pigment is converted to vitamin A?

Phycobilins

Characteristics

- Accessory pigments in blue-green algae, cryptomonads, and red algae.
- Protein-linked, water-soluble pigments in phycobilisomes attached to thylakoids.
- Open tetrapyrrole structure without magnesium or phytol tail.

- Two types: phycocyanin and phycoerythrin.

Memory Aids

- Phycobilins = water-soluble, protein-linked pigments.
- Found in cyanobacteria and red algae.

Quick Checkpoints

- Where are phycobilins found?
- What distinguishes phycobilins structurally?

Action and Absorption Spectrum

Key Points

- Pigments absorb light at specific wavelengths; absorption spectrum shows energy absorbed vs wavelength.
- Chlorophyll a and b absorb mostly in blue and red regions, matching high photosynthesis rates.
- Action spectrum shows photosynthesis rate vs wavelength; peaks at blue (~430 nm) and red (~680 nm).
- Carotenoids absorb mainly in blue-green range (400-500 nm).
- Accessory pigments broaden light absorption and protect chlorophyll a from photo-oxidation.
- Green-yellow light is least effective, explaining green leaf color.

Memory Aids

- Blue and red light drive photosynthesis best.
- Accessory pigments extend absorption range.
- Green light is mostly reflected, not absorbed.

Quick Checkpoints

- Which wavelengths show peak photosynthesis?
- How do accessory pigments assist chlorophyll a?
- Why are leaves green?

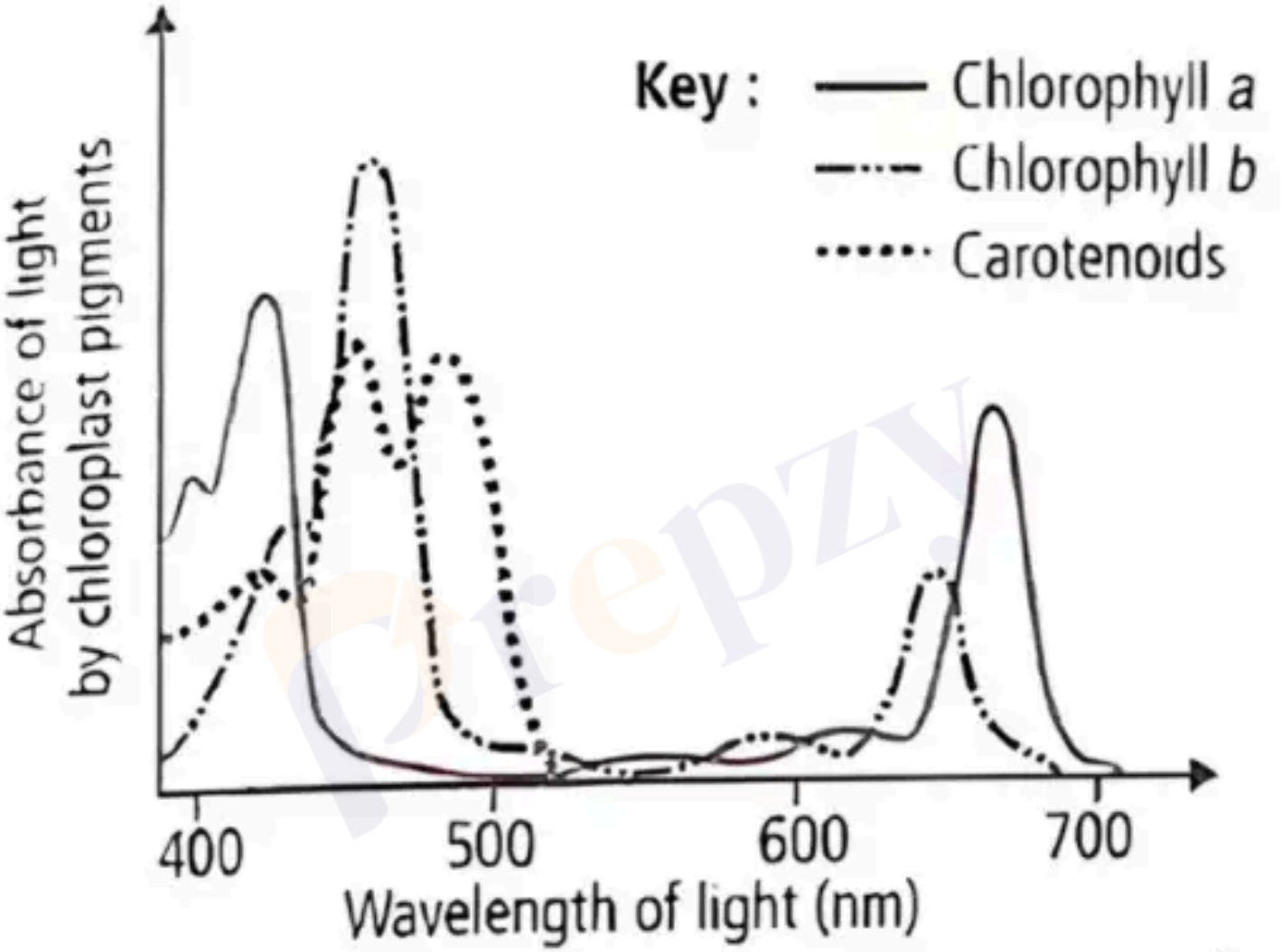


Fig.: Graph showing the absorption spectrum of chlorophyll *a*, *b* and carotenoids

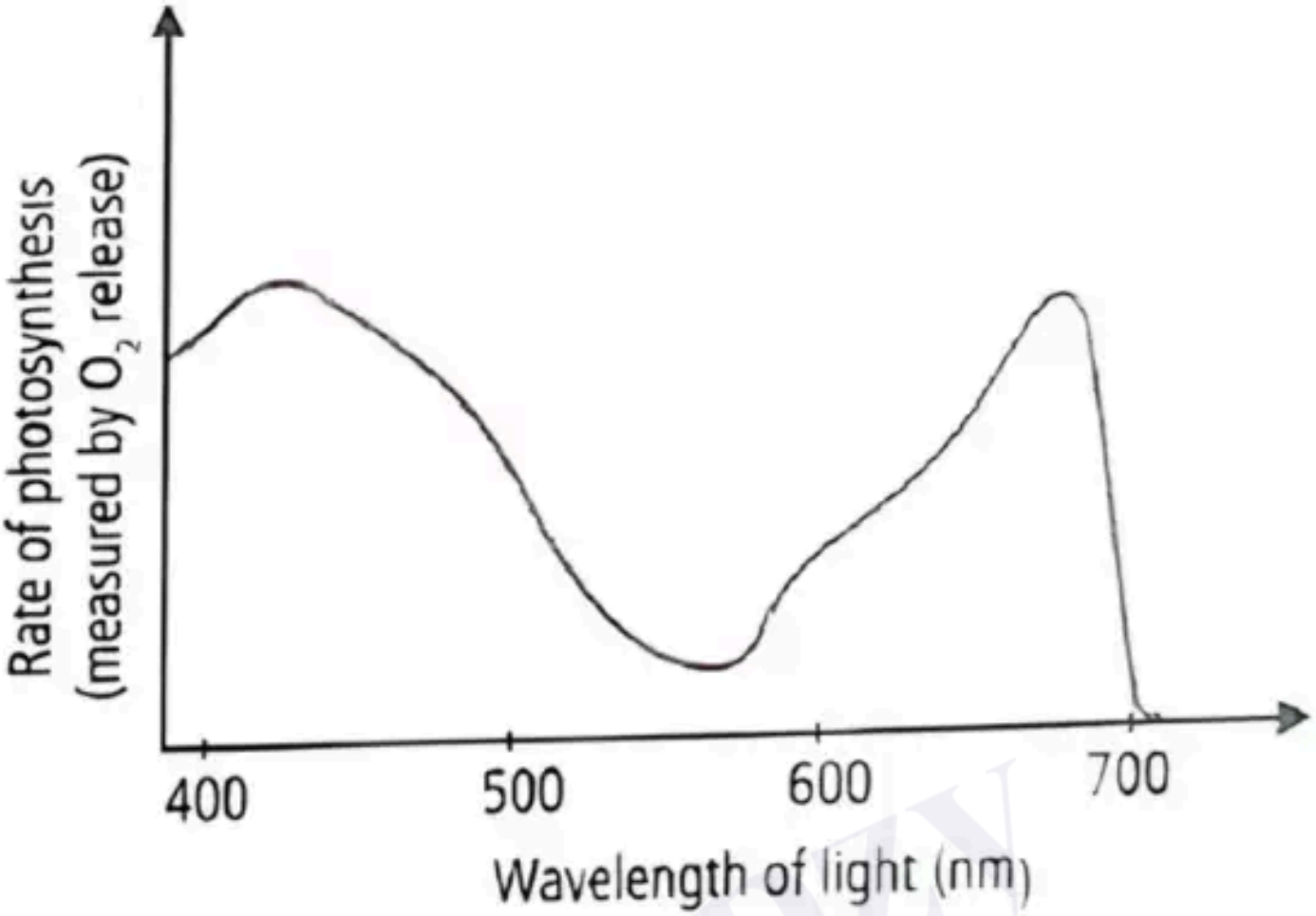


Fig.: Graph showing action spectrum of photosynthesis

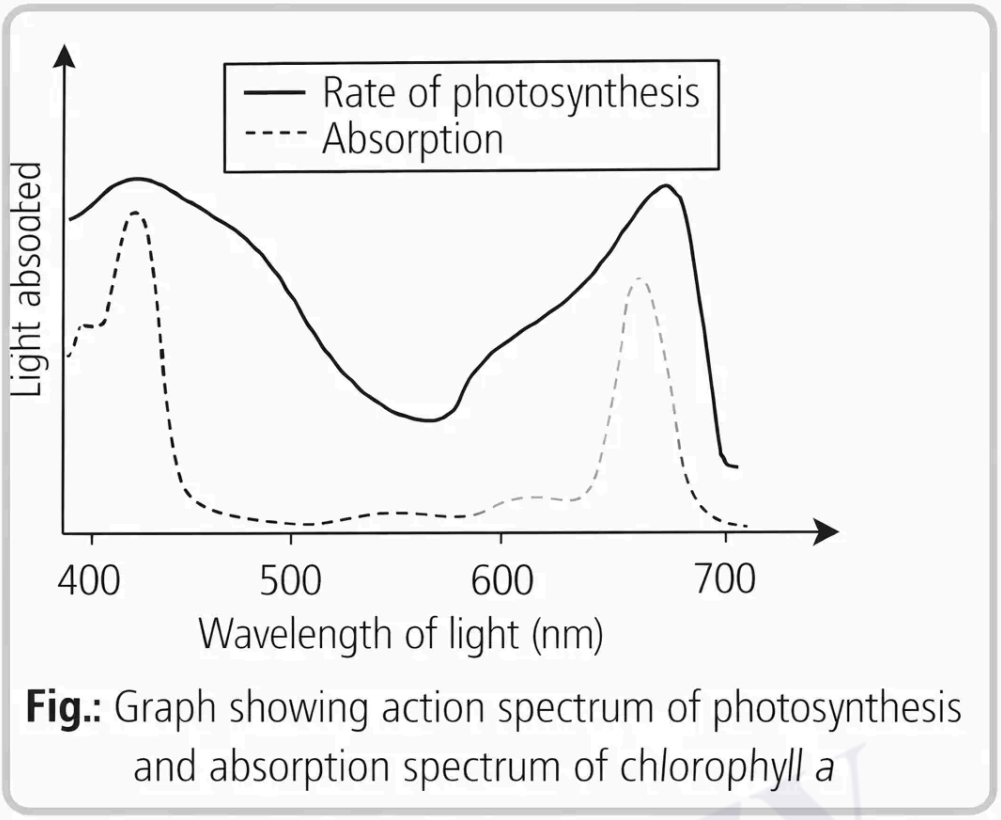


Fig.: Graph showing action spectrum of photosynthesis and absorption spectrum of *chlorophyll a*

What is Light Reaction?

Process Overview

- Light reaction (photochemical phase) involves light absorption, water splitting, oxygen release, and formation of ATP and NADPH.
- Occurs in two photosystems: Photosystem I (PS I) and Photosystem II (PS II), each with distinct light harvesting complexes (LHC).
- LHCs contain pigment molecules (chlorophyll a, b, carotenoids) that absorb light and transfer energy to the reaction center.
- Reaction center chlorophyll a absorbs light at specific wavelengths: P700 in PS I and P680 in PS II.
- Energy captured is converted into chemical energy via electron transfer to primary acceptors.

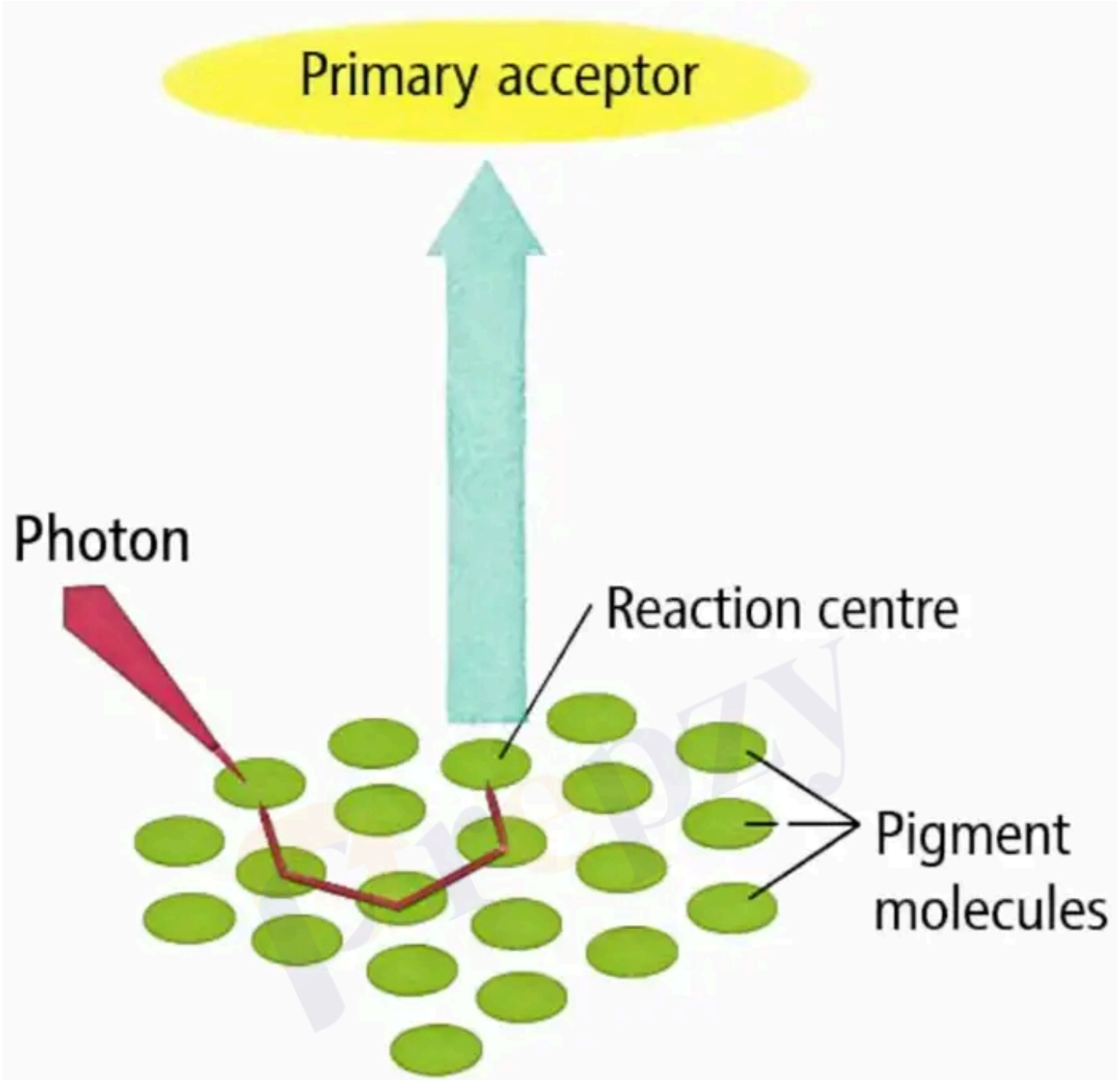


Fig.: The light harvesting complex

This image shows the light harvesting complex in photosynthesis. It illustrates how light energy (photons) is captured by pigment molecules and transferred to the reaction center, then sent to the primary acceptor.

Step-by-step explanation:

- A photon hits pigment molecules like chlorophyll.
- Energy is passed molecule to molecule to the reaction center.
- Reaction center transfers energy to the primary acceptor.
- Primary acceptor initiates conversion of light energy into chemical energy.

Memory Aids

- PS I = P700, PS II = P680 (absorption peaks).
- LHC = antennae capturing different light wavelengths.
- Light reaction = photochemical phase producing ATP and NADPH.

Quick Checkpoints

- What are the main products of light reaction?
- Difference between PS I and PS II reaction centers?
- Role of light harvesting complexes?

Photosystems

Structure and Function

- Photosystem I (PS I): More chlorophyll a, less chlorophyll b and carotenoids; involved in cyclic and non-cyclic photophosphorylation.
- PS I core antenna and P700 bound to proteins Psa A and Psa B; contains Fe-S centers (ferredoxins).
- Photosystem II (PS II): Equal chlorophyll a and b, higher carotenoids; involved only in non-cyclic photophosphorylation.
- PS II includes cytochrome b6f complex and plastocyanin; reaction center core proteins are D1 and D2.
- Primary donor chlorophyll in PS II is P680; other pigments include pheophytins and plastoquinones.

Memory Aids

- PS I = P700, cyclic and non-cyclic; PS II = P680, non-cyclic only.
- PS I has Fe-S centers; PS II has cytochrome b6f and plastocyanin.
- D1 and D2 proteins are unique to PS II reaction center.

Quick Checkpoints

- Which photosystem participates in cyclic photophosphorylation?
- What pigments are predominant in PS II?
- What proteins form the PS II reaction center?

Emerson's Enhancement Effect

Key Findings

- Photosynthesis rate drops sharply (red drop) when only light >680 nm is used.
- Shorter wavelengths alone are also ineffective.
- Simultaneous exposure to shorter and longer wavelengths increases photosynthesis rate.
- Effect explained by presence of different harvesting molecules and two interconnected pigment systems.

Memory Aids

- Red drop = low photosynthesis with >680 nm light alone.
- Enhancement effect = combined wavelengths boost photosynthesis.
- Two pigment systems work together for efficiency.

Quick Checkpoints

- What causes the red drop in photosynthesis?
- How does simultaneous light of different wavelengths affect photosynthesis?
- Why are two pigment systems important?

Non-cyclic Photophosphorylation

Process Overview

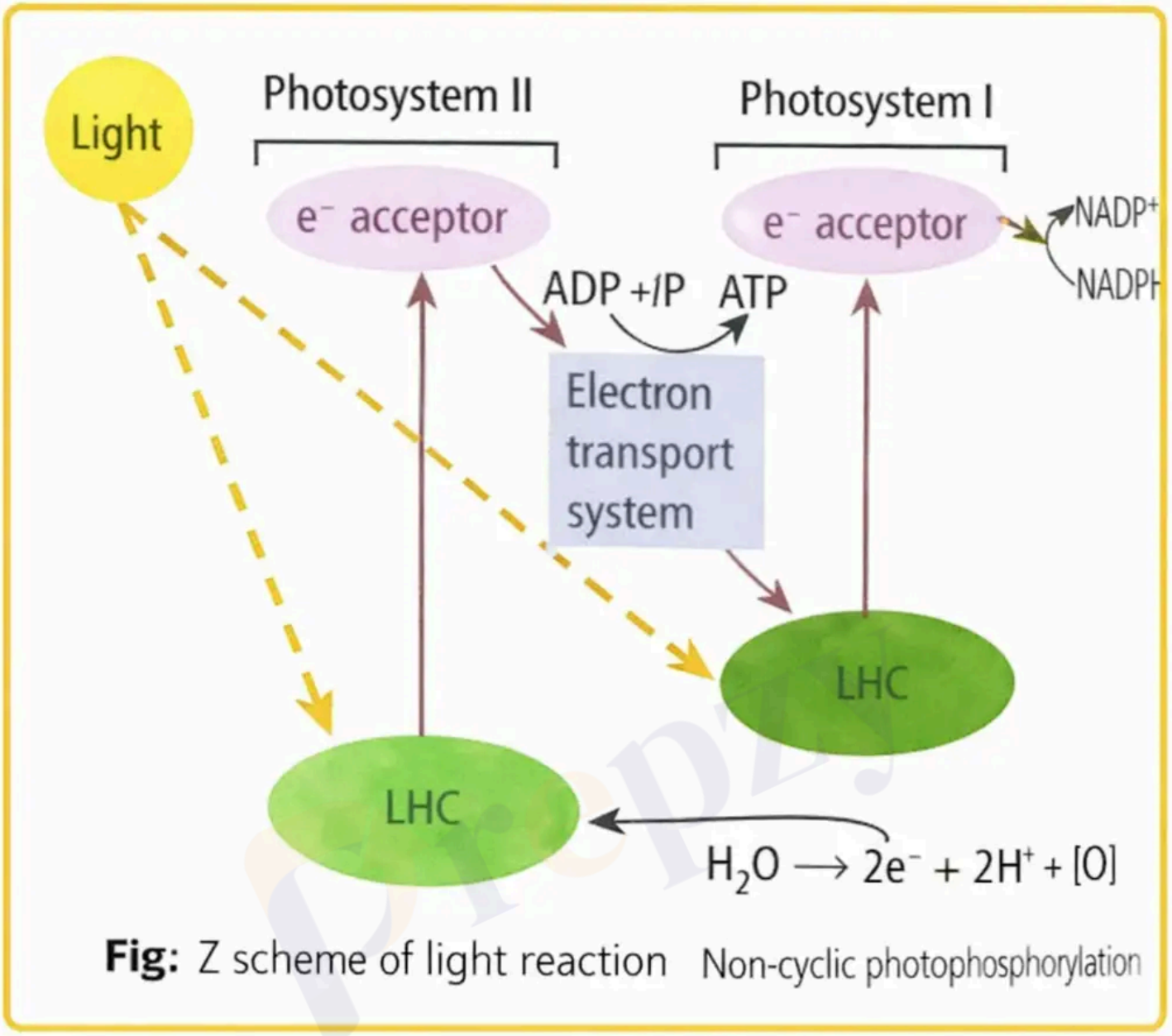
- ATP synthesis by cells is called phosphorylation.
- Non-cyclic photophosphorylation involves both photosystems: PS II followed by PS I.
- Electrons flow through an electron transport chain connecting PS II and PS I.
- Both ATP and NADPH + H^+ are produced.
- PS II absorbs 680 nm red light, exciting electrons to higher energy states.
- Electrons pass downhill through cytochromes to PS I pigments.
- PS I absorbs 700 nm red light, re-exciting electrons to reduce $NADP^+$ to NADPH + H^+.
- This electron flow pattern is called the Z scheme due to its shape on the redox potential scale.

Memory Aids

- Z scheme: Electron flow forms a 'Z' shape on redox scale.
- PS II absorbs 680 nm, PS I absorbs 700 nm light.
- Non-cyclic means electrons do not return to the original photosystem.

Quick Checkpoints

- What are the products of non-cyclic photophosphorylation?
- Which photosystem absorbs 680 nm light?
- Why is it called the Z scheme?



Splitting of Water

Process Details

- Electrons lost from PS II are replaced by electrons from water splitting.
- Water splits into protons (H^+), oxygen (O), and electrons.
- Oxygen is released as a net product of photosynthesis.
- Electrons from PS II replace those lost from PS I.
- Chemical reaction: $2H_2O \rightarrow 4H^+ + O_2 + 4e^-$.

- Water splitting complex is on the inner side of the thylakoid membrane near PS II.

Memory Aids

- Water splitting produces oxygen and electrons for photosynthesis.
- Reaction: $2H_2O$ yields $4H^+$, O_2, and 4 electrons.

Quick Checkpoints

- What replaces electrons lost from PS II?
- Where is the water splitting complex located?
- What is the net product of water splitting?

Cyclic Photophosphorylation

Process Overview

- Electron expelled by PS I photocentre returns after passing electron carriers.
- Occurs under low light, wavelength > 680 nm, or inhibited CO_2 fixation.
- Only photosystem I is involved.
- Photocentre P_{700} loses electron gaining 23 kcal/mole energy after light absorption.
- Electron passes through P_{700} chlorophyll, plastoquinone, FeS complex, ferredoxin, cyt b_6 f, plastocyanin, then returns to P_{700}.
- ATP is produced without NADPH or oxygen.

Memory Aids

- Cyclic means electrons cycle back to PS I.
- Only ATP is produced, no NADPH or oxygen.
- Photocentre involved: P_{700}.

Quick Checkpoints

- Which photosystem is involved in cyclic photophosphorylation?
- What is the fate of electrons in cyclic photophosphorylation?
- What energy molecule is produced?

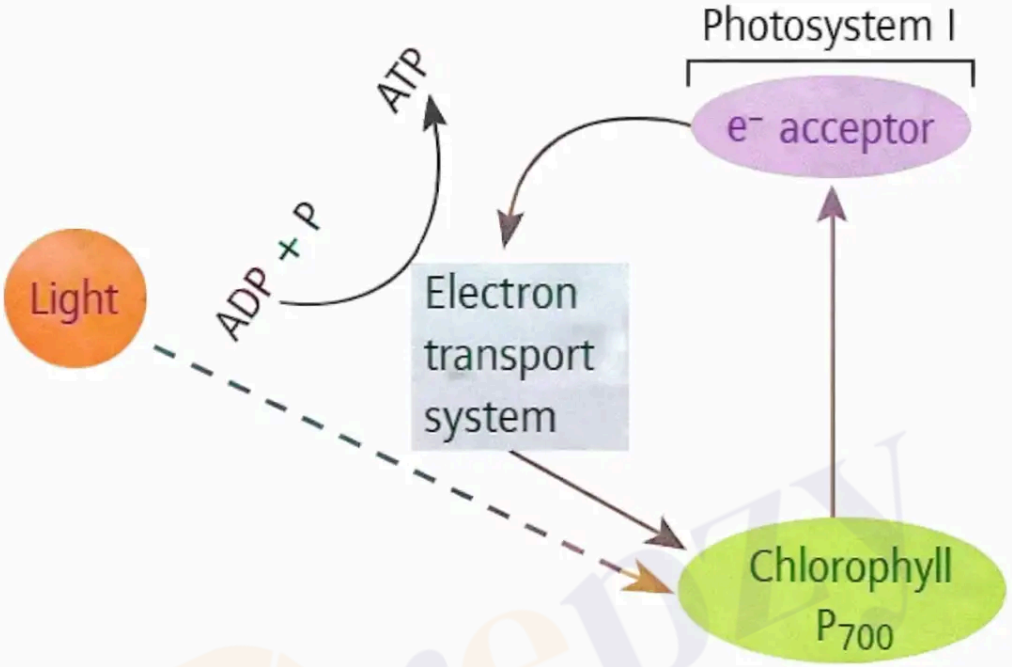


Fig.: Cyclic photophosphorylation

Chemiosmotic Hypothesis

Mechanism of ATP Synthesis

- Proposed by Peter Mitchell in 1961.
- ATP synthesis linked to proton gradient across thylakoid membrane.
- Protons accumulate inside thylakoid lumen due to water splitting.
- Electron transport moves protons from stroma to lumen, creating gradient.
- Proton gradient lowers pH inside lumen.
- Protons flow back to stroma via CF_0 channel of ATPase enzyme.
- ATPase has two parts: CF_0 (membrane channel) and CF_1 (enzyme protruding into stroma).
- Proton flow causes conformational change in CF_1, synthesizing ATP from ADP + Pi.

- ATP and NADPH produced are used for CO_2 fixation and sugar synthesis in stroma.
- Requirements: membrane, proton pump, proton gradient, ATPase enzyme.

Memory Aids

- ATP synthesis driven by proton gradient (chemiosmosis).
- CF_0 forms proton channel; CF_1 synthesizes ATP.
- Protons pumped into lumen, flow back to stroma to generate ATP.

Quick Checkpoints

- Who proposed the chemiosmotic hypothesis?
- Where do protons accumulate during photosynthesis?
- What drives ATP synthesis in chloroplasts?

Prepzy

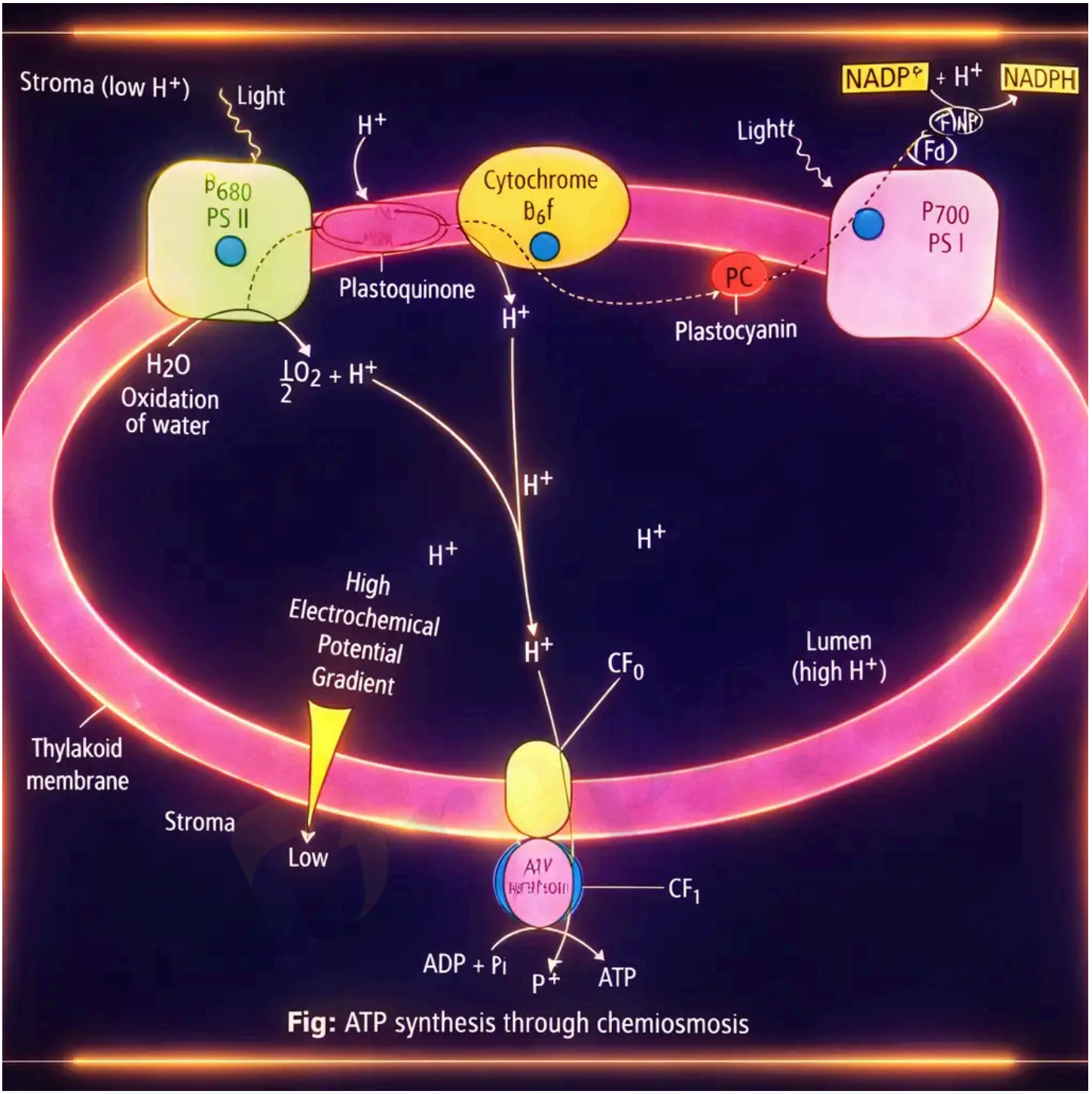


Fig: ATP synthesis through chemiosmosis

Where are the ATP and NADPH Used?

Usage in Photosynthesis

- The light reaction produces ATP, NADPH, and O□; O□ diffuses out of chloroplast.
- ATP and NADPH drive the biosynthetic or dark phase of photosynthesis.
- Dark phase depends on ATP, NADPH, CO□, and H□O, not directly on light.
- Occurs in chloroplast stroma (matrix) where enzymes are present.

- Discovered by F.F. Blackman; detailed by Calvin, Benson, and J. Bassham (Nobel Prize 1961).

Memory Aids

- ATP & NADPH = energy carriers for sugar synthesis.
- Dark phase = light-independent but needs light reaction products.
- Stroma = site of dark phase enzymes.

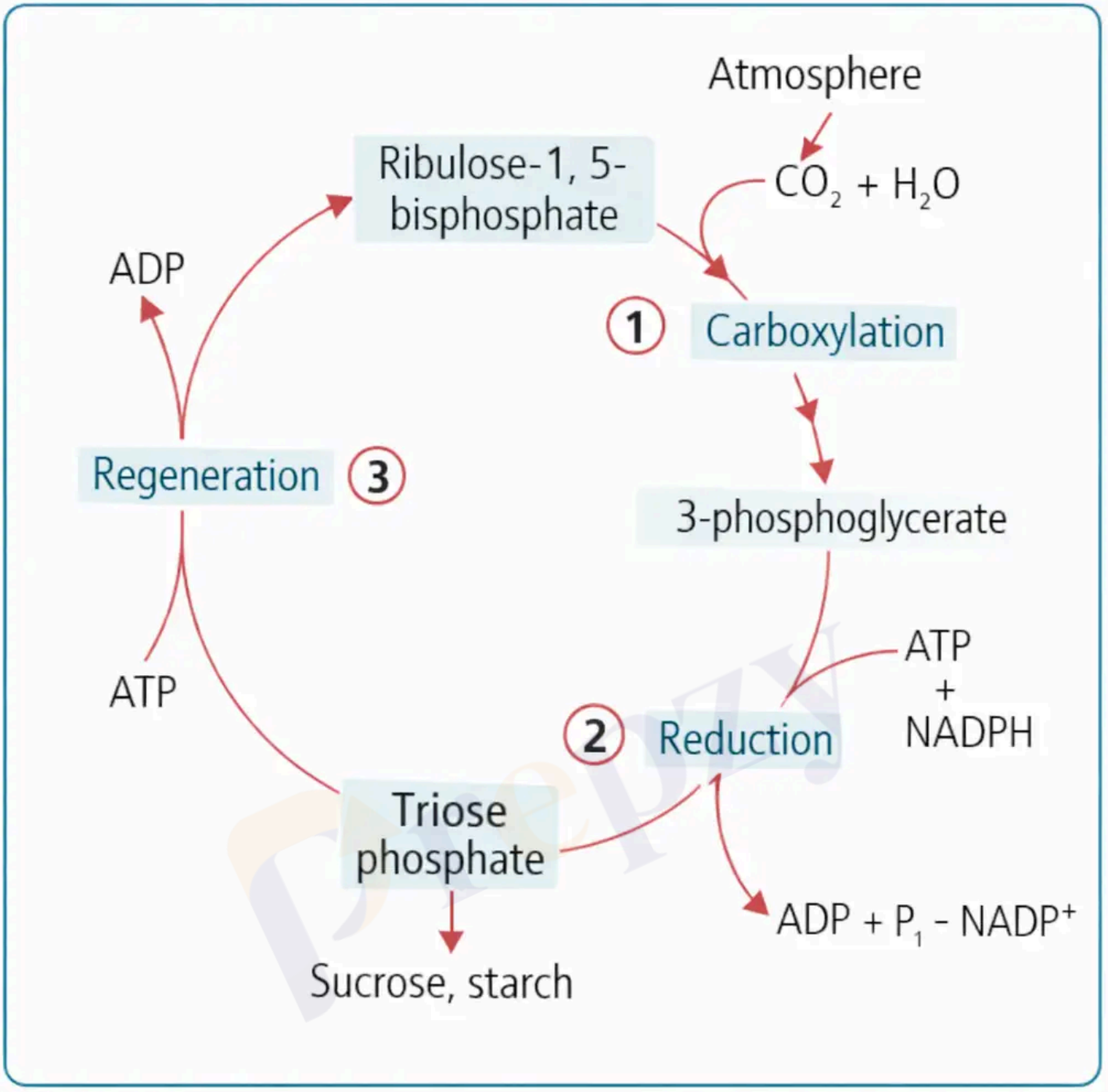
Quick Checkpoints

- What are the products of the light reaction?
- Where does the dark phase occur?
- Who discovered the dark reaction?

The Calvin cycle

Phases and Process

- Fixes CO_2 using ATP and NADPH to form glucose.
- Primary CO_2 acceptor: Ribulose-1, 5-bisphosphate (RuBP), a 5-carbon sugar.
- First stable product: 3-Phosphoglyceric acid (3C).
- Three phases: Carboxylation, Reduction, Regeneration of RuBP.
- Carboxylation: CO_2 + RuBP catalyzed by RuBisCO enzyme.
- RuBisCO: most abundant protein globally.
- Intermediate: 2-carboxy 3-keto 1,5-bisphophoribotol splits into two 3-phosphoglyceric acid molecules.
- Reduction: Uses 2 ATP and 2 NADPH per CO_2 to form glucose precursors.
- Six CO_2 molecules and six cycles produce one glucose molecule.
- Regeneration: RuBP regenerated using 1 ATP to continue the cycle.
- Each CO_2 fixed requires 3 ATP and 2 NADPH molecules.



Memory Aids

- RuBisCO = key enzyme for CO□ fixation.
- 3 phases: Carboxylation, Reduction, Regeneration.
- 3 ATP + 2 NADPH per CO□ fixed.
- 6 turns = 1 glucose molecule.

Quick Checkpoints

- What is the first stable product of the Calvin cycle?
- Which enzyme catalyzes CO□ fixation?
- How many ATP and NADPH molecules are used per CO□?
- What is regenerated to continue the cycle?

Net Reaction of C□3 Dark Fixation

Summary

- Overall reaction: 6 RuBP + 6 CO□ + 18 ATP + 12 NADPH □126; 6 RuBP + C□H□2□0O□ + 18 ADP + 18 Pi + 12 NADP□ + 6 H□O.
- Shows ATP and NADPH consumption and glucose formation.

Memory Aids

- 6 CO□ fixed per glucose formed.
- High ATP and NADPH demand for sugar synthesis.

Quick Checkpoints

- What are the reactants and products of the net reaction?
- How many ATP molecules are used per glucose?
- How many NADPH molecules are used per glucose?

The C□4 Pathway

Overview

- Also called Hatch-Slack Pathway.

- Found in tropical monocots and dicots like maize, sugarcane, *Sorghum*, *Atriplex*, *Amaranthus*.
- Called C□4 plants as first stable product is a 4-carbon compound.

Anatomy and Cell Types

- C□4 plants have Kranz anatomy: vascular bundles surrounded by large bundle sheath cells in wreath-like layers.
- Mesophyll cells lack starch and RuBisCO but have PEP carboxylase (PEPcase) for initial CO□2 fixation.
- Bundle sheath cells have agranal chloroplasts, possess RuBisCO, and are protected from O□2.
- Mesophyll cells perform light reactions, produce ATP and NADPH, and evolve O□2.

Biochemical Steps

- Primary CO□2 acceptor: phosphoenol pyruvate (PEP).
- PEP + CO□2 (via PEPcase) □14 oxalo-acetic acid (OAA).
- OAA reduced to malic acid or transaminated to aspartic acid.
- Malic/aspartic acid transported to bundle sheath cells.
- Decarboxylation releases CO□2 and pyruvate in bundle sheath cells.
- CO□2 enters Calvin cycle; pyruvate returns to mesophyll.

Overall Reaction

- 6 PEP + 6 RuBP + 6 CO□2 + 30 ATP + 12 NADPH □14 6 PEP + 6 RuBP + C□6H□12O□6 + 30 ADP + 30 H□3PO□4 + 12 NADP□b + 6 H□2O

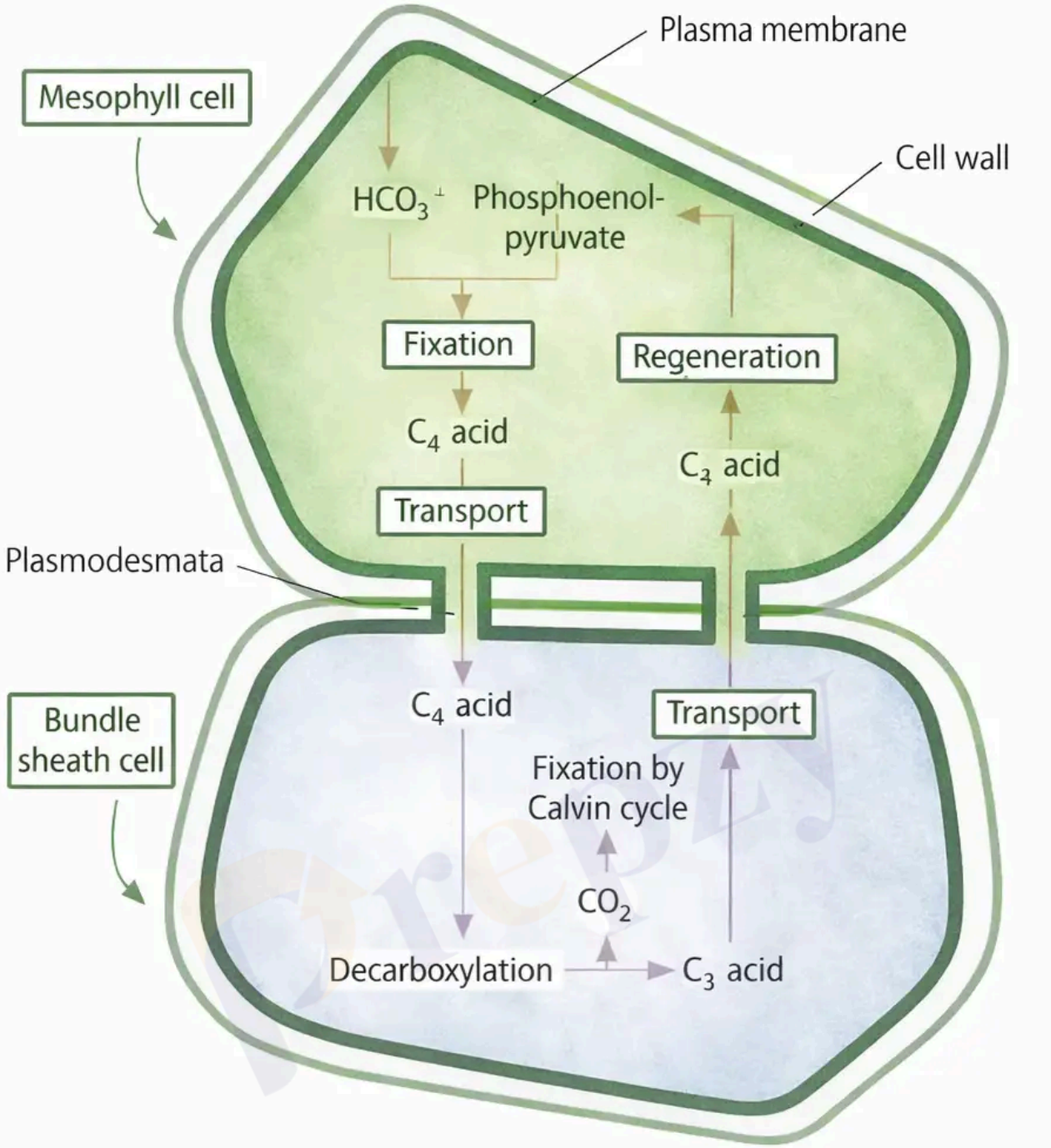


Fig.: Diagrammatic representation of the Hatch and Slack pathway

Memory Aids

- "PEP first" - PEP is initial CO□2 acceptor.
- Kranz = wreath, bundle sheath cells surround vascular bundles.
- Mesophyll = light reactions; bundle sheath = Calvin cycle.

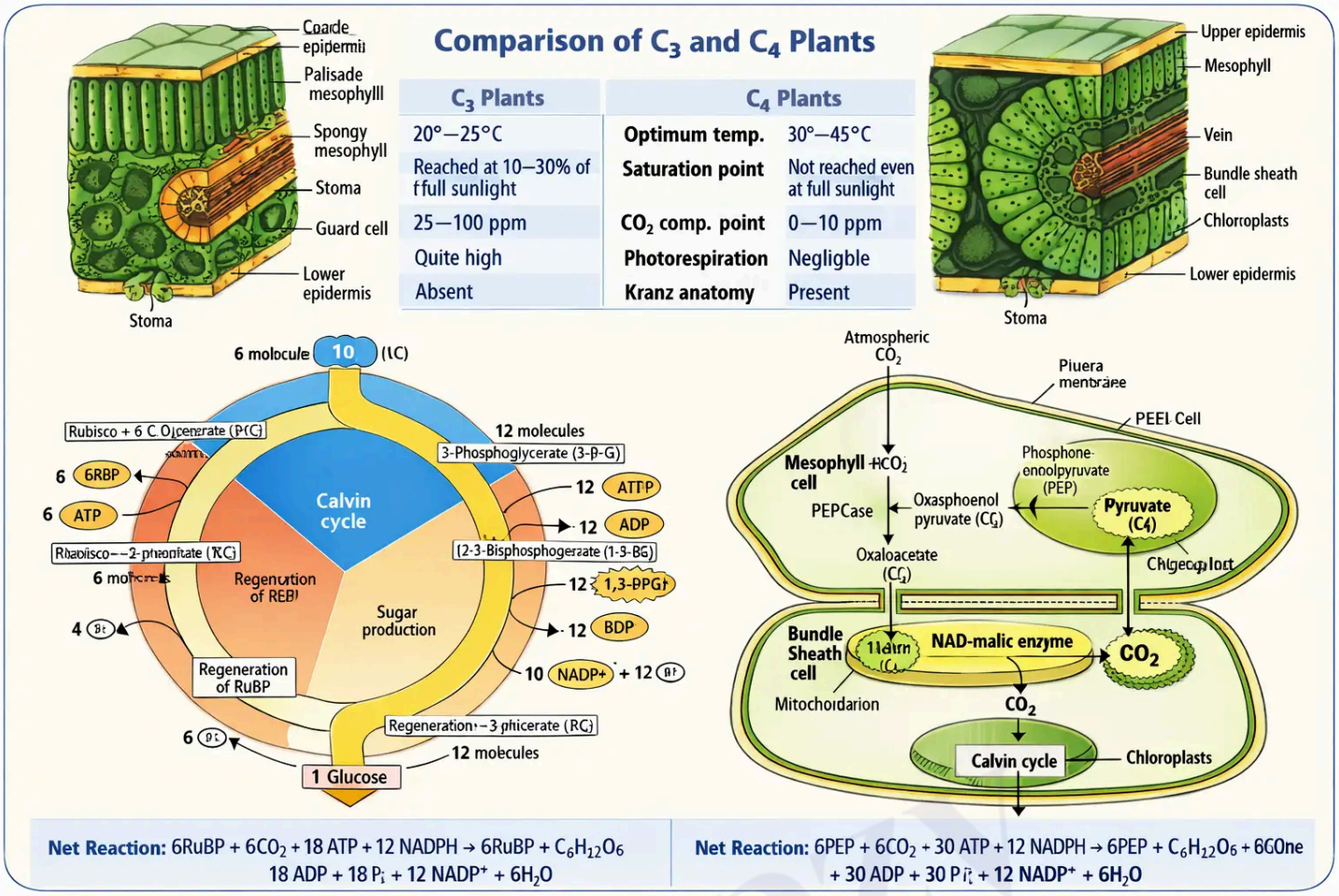
Quick Checkpoints

- What is the primary CO□2 acceptor in C□4 plants?
- Describe Kranz anatomy.
- Where does the Calvin cycle occur in C□4 plants?
- What enzyme fixes CO□2 initially in mesophyll cells?
- What compounds transport CO□2 to bundle sheath cells?

Comparison between C□3 and C□4 Plants

Key Differences

- **Leaf Structure:** C□3 plants have palisade and spongy mesophyll; C□4 plants have Kranz anatomy with bundle sheath cells.
- **Temperature:** C□3 plants prefer 20□0□5□dc; C□4 plants prefer 30□0□5□dc.
- **CO□2 Compensation Point:** Higher in C□3 (25□100 ppm), lower in C□4 (0□10 ppm).
- **Photorespiration:** High in C□3, negligible in C□4.
- **Photosynthesis:** C□3 uses Calvin cycle directly in mesophyll; C□4 fixes CO□2 first into 4C acid in mesophyll, then Calvin cycle in bundle sheath.
- **Efficiency:** C□4 plants better adapted to hot, dry, low CO□2 environments.



Memory Aids

- C□3 = "Cool, Calm, Calvin" (direct Calvin cycle).
- C□4 = "Hot, High, Hatch" (Hatch-Slack pathway).
- Kranz = wreath, key to C□4 efficiency.

Quick Checkpoints

- What is Kranz anatomy?
- Which plants have higher photorespiration?
- At what temperature do C□3 plants grow best?
- How does CO□2 fixation differ in C□3 and C□4 plants?
- Why are C□4 plants more efficient in hot climates?

Crassulacean Acid Metabolism (CAM) Cycle

Process Overview

- Occurs in succulent plants of Crassulaceae family.
- Stomata open at night; CO□2 absorbed and fixed by PEP carboxylase into malic acid.
- Malic acid stored in vacuoles overnight.
- Daytime stomata closed; malic acid decarboxylated releasing CO□2 for Calvin cycle.
- Photosynthesis separated by time: initial fixation at night, Calvin cycle during day.
- Minimizes water loss while fixing CO□2 efficiently.

Memory Aids

- CAM = "Crassulacean Acid Metabolism" with night fixation.
- Night = CO□2 uptake; Day = Calvin cycle.
- PEP carboxylase active at night.

Quick Checkpoints

- When are stomata open in CAM plants?
- What is the initial CO□2 acceptor in CAM?
- Where is malic acid stored overnight?
- How does CAM reduce water loss?
- How is CAM different from C□4 photosynthesis?

Photorespiration

Process and Site

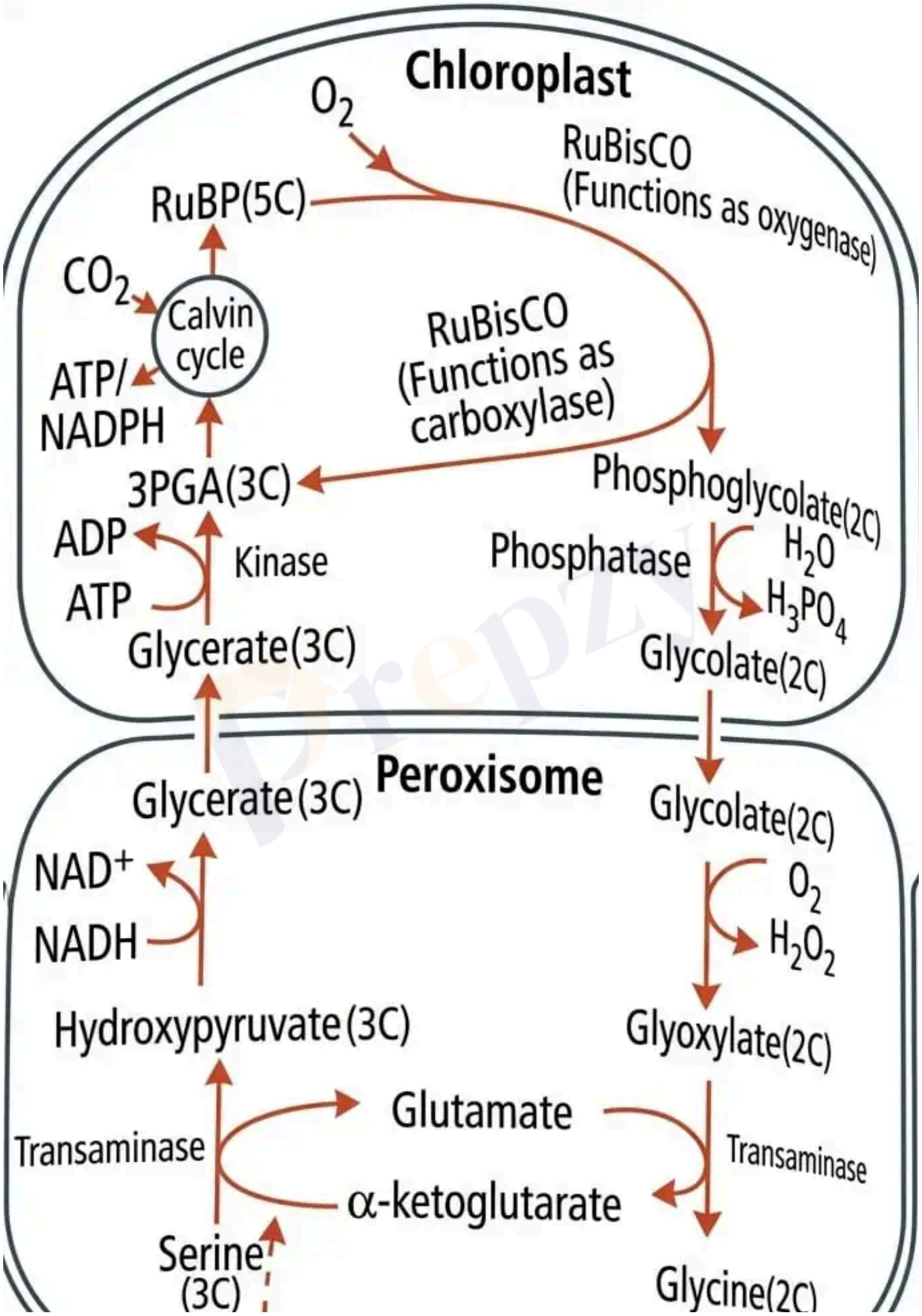
- Occurs in chloroplast, peroxisome, and mitochondrion.
- Enzyme involved: RuBP carboxylase-oxygenase (RuBisCO).
- RuBisCO acts as oxygenase at high temperatures, producing phosphoglyceric acid (3-carbon) and phosphoglycolate (2-carbon).
- Photorespiration is cyclic and does not produce ATP, NADPH, or sugars.

Photorespiration in C4 Plants

- Photorespiration is absent in C4 plants.
- C4 plants increase CO_2 concentration in bundle sheath cells by breaking down C4 acids.
- High CO_2 ensures RuBisCO acts as carboxylase, reducing oxygenase activity.
- Results in higher productivity, yield, and heat tolerance.

Photorespiratory Pathway

- Starts in chloroplast: RuBisCO oxygenase produces phosphoglycolate.
- Phosphoglycolate converted to glycolate, moves to peroxisome.
- In peroxisome, glycolate → glyoxylate → glycine.
- Glycine moves to mitochondrion, breaks down into CO_2, NH_3, serine, releasing NADH.
- Serine returns to peroxisome, then chloroplast.
- In chloroplast, serine regenerates 3-phosphoglycerate (3PGA) for Calvin cycle.
- Process salvages carbon but releases CO_2 and consumes energy.


Chloroplast
O_2
RuBisCO
(Functions as oxygenase)
RuBP(5C)
CO_2
Calvin cycle
ATP/
NADPH
RuBisCO
(Functions as carboxylase)
3PGA(3C)
Phosphoglycolate(2C)
ADP
ATP
Kinase
Phosphatase
H_2O
H_3PO_4
Glycerate(3C)
Glycolate(2C)
Peroxisome
Glycerate(3C)
Glycolate(2C)
NAD^+
NADH
O_2
H_2O_2
Hydroxypyruvate(3C)
Glyoxylate(2C)
Glutamate
Transaminase
Transaminase
α-ketoglutarate
Serine
(3C)
Glycine(2C)

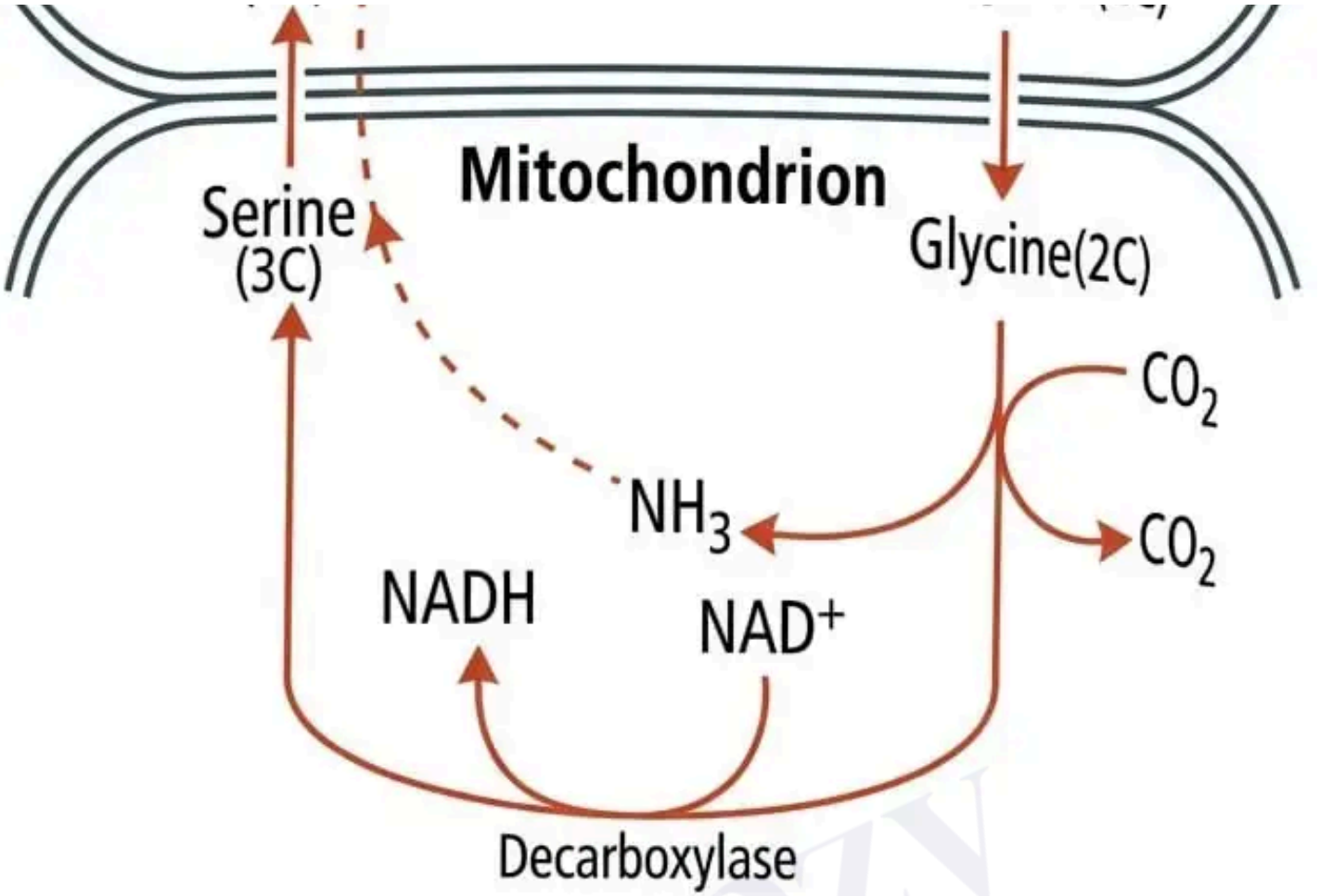


Fig.: Diagrammatic representation of photorespiratory pathway

Memory Aids

- RuBisCO = RuBP carboxylase-oxygenase (dual function enzyme).
- C4 plants avoid photorespiration by CO2 concentration mechanism.
- Photorespiration wastes energy and releases CO2.

Quick Checkpoints

- Where does photorespiration occur?
- What enzyme catalyzes photorespiration?
- Why does RuBisCO act as oxygenase at high temperatures?
- How do C4 plants prevent photorespiration?
- What are the products of RuBisCO oxygenase activity?
- What organelles are involved in the photorespiratory pathway?
- Does photorespiration produce ATP or sugars?

CO□9 Concentration

Subtopics

- Increase in CO□9 concentration up to 0.05% raises photosynthesis rate in most *C□3* plants.
- **CO□9 compensation point**: CO□9 fixed in photosynthesis equals CO□9 released in respiration and photorespiration.
- Compensation point values: 25-100 ppm in *C□3* plants, 0-10 ppm in *C□4* plants.
- *C□4* plants saturate at ~360 □bcL Lb9b9; *C□3* plants saturate beyond 450 □bcL Lb9b9.

Memory Aids

- CO□9 compensation point = balance of CO□9 uptake and release.
- *C□4* plants saturate earlier than *C□3* plants.

Quick Checkpoints

- What is the CO□9 compensation point?
- How do *C□3* and *C□4* plants differ in CO□9 saturation?

Light

Subtopics

- **Light compensation point**: Light intensity where photosynthesis gas exchange stops.
- Photosynthesis rate increases with light intensity.
- **Light saturation point**: Maximum photosynthesis rate achieved.
- Light saturation occurs at 10% full sunlight.
- Excess light breaks down chlorophyll, reducing photosynthesis.

Memory Aids

- Light compensation point = no net gas exchange.
- Light saturation point = max photosynthesis at 10% sunlight.

Quick Checkpoints

- Define light compensation point.
- What happens beyond light saturation point?

Temperature

Subtopics

- Photosynthesis rate doubles for every 10b0C rise from minimum to optimum.
- Above optimum, rate rises briefly then declines (**time factor**).
- Tropical plants have higher temperature optimum than temperate plants.

Memory Aids

- Rate doubles every 10b0C till optimum.
- Time factor causes decline after optimum.

Quick Checkpoints

- What is the time factor in photosynthesis?
- How does temperature optimum vary among plants?

Oxygen

Subtopics

- High oxygen levels reduce photosynthesis rate.
- This reduction is called the **Warburg effect**.

Memory Aids

- Warburg effect = oxygen inhibits photosynthesis at high levels.

Quick Checkpoints

- What is the Warburg effect?
- How does oxygen concentration affect photosynthesis?

Water

Subtopics

- Water used in photosynthesis is minimal.
- Photosynthesis is highly sensitive to dehydration.

Memory Aids

- Small water use but critical for photosynthesis.
- Dehydration quickly reduces photosynthesis.

Quick Checkpoints

- How much water is used in photosynthesis?

- Why is photosynthesis sensitive to dehydration?

Limiting Factor

Subtopics

- A limiting factor is deficient enough to restrict process rate.
- Increasing limiting factor increases photosynthesis rate.
- F.F. Blackman (1905) proposed this law based on Liebig's law of minimum.
- Liebig's law: process rate limited by slowest factor.

Memory Aids

- Limiting factor controls process speed.
- Blackman's law = Liebig's law applied to photosynthesis.

Quick Checkpoints

- Define limiting factor in photosynthesis.
- What does Liebig's law state?

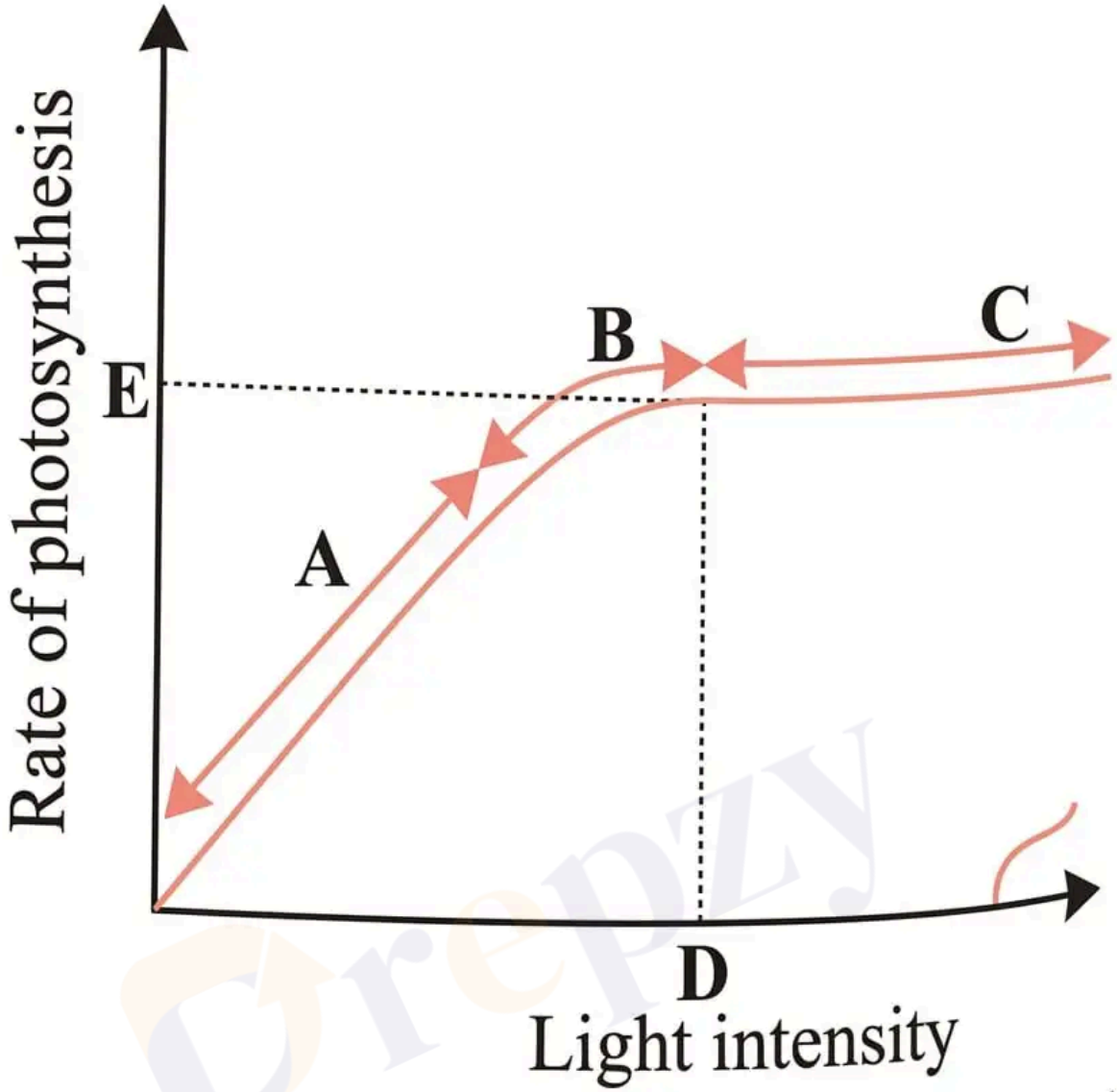


Fig.: Graph for effect of light intensity on the rate of photosynthesis

Light Intensity Graph

Subtopics

- Region A: Low light, photosynthesis rate rises quickly; light is limiting.
- Region B: Medium light, rate rises slower; other factors limit photosynthesis.
- Region C: High light, rate plateaus; other factors limit further increase.
- Point E: Maximum photosynthesis rate.
- Point D: Light intensity where photosynthesis stops increasing.

- Photosynthesis depends on light intensity only up to a point.

Memory Aids

- Photosynthesis rate limited by light until saturation.
- Beyond saturation, other factors control rate.

Quick Checkpoints

- What happens at light saturation point?
- Which factors limit photosynthesis beyond light saturation?