Photosynthesis

Chloroplasts

- A plastid containing photosynthetic pigments
- Structure:
    - Lens/Biconvex shape
    - Chloroplast envelope
        - Double membrane
    - Stroma
        - Dense fluid within the chloroplast surrounding the thylakoids
        - Contains soluble enzymes and other organic substances
        - May contain starch grains
    - Thylakoids
        - Fluid filled membranous sacs
        - Stacks of thlakoid sacs form a granum
        - Contains photosynthetic pigments such as chlorophyll a, chlorophyll b and carotenoids
            - Chlorophyll a (P700 and P680)
                - Participates directly in photosynthesis
            - Chlorophyll b and Carotenoids
                - Accessory pigments which channel the energy absorbed to chlorophyll a
                - Broadens the spectrum of wavelength over which photosynthesis can occur
    - Thylakoid membrane
        - Contains
            - Photosystems II and I
                - Consists of a reaction centre surrounded by many light harvesting complexes
                - Reaction centre contains 2 special chlorophyll a molecules (P700 in PSI and P680 in PSII) and a primary electron acceptor
                - Photosynthetic pigments are arranged in light harvesting complexes
            - ATP synthase
            - Electron transport chains
        - Function
            1. Provides a large surface area to embed many photosynthetic pigments for light absorption
            2. Maintains the sequential arrangement of the photosystems and electron carriers of the ETC for the flow of electrons
            3. Maintains the proton gradient for ATP synthesis since the hydrophobic core of the membrane is impermeable to protons which is essential for chemiosmosis
            4. Allows for many ATP synthases to be embedded so that ATP can be produced as protons flow down their gradient via chemiosmosis

from the thylakoid space to the stroma

Light Dependent Reactions

- Non-cyclic photophosphorylation
  - Location: Thylakoid membrane (PS II & I)
  - Produces:
    - NADPH
    - ATP
    - O_2
  - Steps:

    1. Photoactivation of chlorophyll
        - When a **photon of light** strikes an accessory pigment molecule such as **chlorophylls a and b** in the light harvesting complex
        - Pigment molecules in LHC pass on energy to the next pigment molecule via **resonance transfer of energy** until it reaches one of the **P680 chlorophyll a molecules** in the reaction centre of PSII
    2. Electron transport from PS II to PS I
        - When the P680 chlorophyll a molecule absorbs the energy, an electron is excited to a higher energy level, leaving an **electron hole** in **PSII**
        - The excited electron is accepted by the **PEA** in PSII and is then passed down to PSI via a series of increasingly electronegative electron carriers of the **1st ETC**
        - Energy lost during this electron flow is used to **actively pump H^+** ions across the thylakoid membrane into the thylakoid space
    3. Photolysis of water
        - The electron lost from PSII is replaced by an electron released from the **photolysis of water** in the thylakoid space which donates a pair of electrons and yields molecular oxygen as a by-product
        - The H^+ released contributes to the **high concentration of H^+** in the thylakoid space
    4. Photophosphorylation
        - H^+ accumulates in the thylakoid space, creating a **proton gradient** across the thylakoid membrane, transforming redox energy to a **proton-motive force**
        - Since the membrane is impermeable to ions, **chemiosmosis** occurs as H^+ diffuses down the proton gradient, back into the stroma via the **ATP synthase** complex
        - This drives **ATP synthesis** as ADP is phosphorylated to ATP
    5. Light harvesting at PS I
        - **Light energy** is relayed via accessory pigment molecules in PSI until it reaches one of the **P700 chlorophyll a** molecules in the reaction centre

        - When the P700 chlorophyll a molecule absorbs the energy, an electron is excited, leaving an **electron hole** in PSI
        - The electron hole left in P700 molecule is filled by an electron from PSII when it reaches the end of the 1st ETC
    6. Electron transport from PS I to $NADP^+$
        - The excited electron is captured by the **PEA** in PSI and is then passed down a series of electron carriers of a **2nd ETC**
        - Electron is finally accepted by **$NADP^+$** which form **NADPH** together with H^+ ions, catalysed by **NADP reductase**, in the stroma

- Cyclic photophosphorylation
    - Location: Thylakoid membrane (PSI only)
    - Produces:
        - ATP
    - Steps:
        1. When a **photon of light** is absorbed by an <u>accessory pigment molecule</u> such as **chlorophylls a and b** in light harvesting complex of PSI
        2. Pigment molecule passes on the energy to the next pigment molecule by resonance transfer of energy until it reaches one of the P700 **chlorophyll a** molecules in the reaction centre
        3. When the P700 chlorophyll a molecule absorbs the energy, an electron is excited and is captured by the **primary electron acceptor**, leaving an **electron hole** in PSI
        4. Excited electrons then flow down a chain of electron carriers of increasing electronegativity along the **1st ETC** that links PSII to PSI
        5. Electron hole is filled by an electron from PSI that reaches the end of the 1st ETC
        6. **Electron flow is **cyclical** passing from PSI to the 1st ETC and going back to PSI
        7. Energy lost during this electron flow is used to **actively pump H^+** ions across the thylakoid membrane to the thylakoid space
        8. H^+ accumulates in the thylakoid space, creating a proton gradient across the thylakoid membrane, transforming redox energy to a **proton-motive force**
        9. Since the membrane is impermeable to ions, **chemiosmosis** occurs as H^+ diffuses down the proton gradient, back into the stroma via the **ATP synthase complex**
        10. This drives **ATP synthesis** as ADP is phosphorylated to ATP
    - Significance:
        - The non-cyclic photophosphorylation produces ATP and NADPH in roughly equal amounts whereas the cyclic photophosphorylation produces only ATP. This is because the Calvin cycle makes use of more ATP than NADPH. Hence, the cyclic light dependent reaction makes up the difference.
    - When NADP+ concentration becomes limiting (all reduced to NADPH), no final

electron acceptor, electrons from PSI will not be passed to the 2nd ETC but will be transferred to the 1st ETC, undergoing cyclic photophosphorylation

Outline the main features of photo-phosphorylation

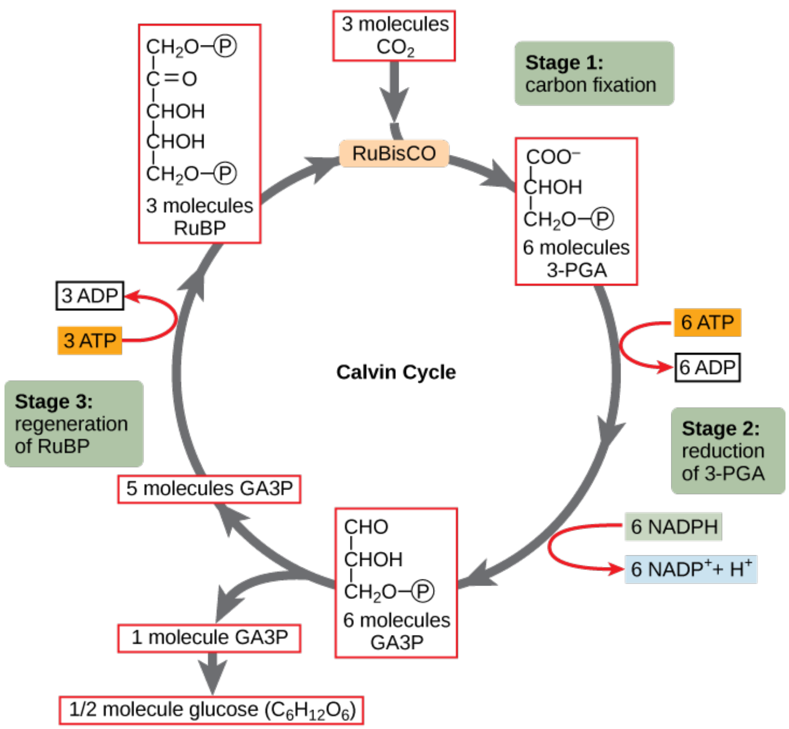
- Light energy absorbed by accessory pigment molecules such as chlorophylls a and b in the light harvesting complex of PSII and PSI
- Pigment molecules in LHC pass on energy to the next pigment molecule via **resonance transfer of energy** until it reaches one of the **special chlorophyll a molecules** in the reaction centres (P680 in PSII and P700 in PSI)
- When the special chlorophyll a molecule absorbs the energy, an electron is excited to a higher energy level, leaving an **electron hole** in **PSII**
- The displaced electron is accepted by the **PEA** in PSII and is then passed down to PSI via a series of increasingly electronegative electron carriers of the **1st ETC**
- Energy lost during this electron flow is used to **actively pump H^+** ions across the thylakoid membrane into the thylakoid space
- Electron hole in PSII is filled by the **photolysis of water** in the thylakoid space which donates a pair of electrons and yields molecular oxygen as a by-product
- H^+ accumulates in the thylakoid space, creating a **proton gradient** across the thylakoid membrane, transforming redox energy to a **proton-motive force**
- **Chemiosmosis** occurs as H^+ diffuses down the proton gradient, back into the stroma via the **ATP synthase** complex
- This drives **ATP synthesis** as ADP is phosphorylated to ATP
- Electron hole in PSI is filled by electron from PSII when it has reached the end of the 1st ETC
- The displaced electron is captured by the **PEA** in PSI and is then passed down a series of electron carriers of a **2nd ETC**
- **$NADP^+$** acts as final electron acceptor which forms **NADPH** together with H^+ ions, catalysed by **NADP reductase**
- Cyclic photophosphorylation occurs where excited electrons are recycled back to PSI via another chain of electron carriers, generating additional ATP for the Calvin cycle

Light Independent Reaction

- Calvin cycle
    - Location: Stroma
    - Produces:
        - G3P
    - Steps:
        1. Carbon Fixation
            - During the **carbon fixation** stage, **CO_2** is combined with ribulose bisphosphate (**RuBP**) to form an unstable 6 carbon molecule
            - This is catalysed by the enzyme RuBP carboxylase (**RuBisCo**)

- Unstable 6 carbon molecule splits up immediately into 2 molecules of glycerate phosphate (**GP**)

2. Reduction by NADPH
    - **NADPH** provides the reducing power
    - while **ATP** provides the energy required to reduce GP to glyceraldehyde-3-phosphate (G3P)
    - **G3P** is the first sugar formed in photosynthesis and the end product of the Calvin cycle
    - 2 molecules of G3P may be used to form 1 molecule of glucose
3. Regeneration of RuBP
    - 5 molecules of **G3P** are used to regenerate 3 **RuBP** so that the cycle of carbon fixation can continue. This requires 3 **ATP**.
    - The net synthesis of 1 molecule of G3P requires 3 CO_2 to be fixed



Role of NADP+

1. NADP+ is a **coenzyme**
2. which carries high energy protons and electrons
3. It is the **final electron acceptor** in the **non-cyclic light dependent reaction** in the thylakoid membrane
4. Electrons carried in NADPH are used in the Calvin cycle in the stroma of the chloroplast
5. where NADPH provides the reducing power used to reduce GP to G3P
6. When GP is reduced to G3P, NADP is regenerated to carry out its role as an electron

carrier from the light dependent reactions

Factors affecting rate of photosynthesis

- Light intensity
  - Rate of photosynthesis increases as light intensity increases
  - Light is needed for the photoactivation of chlorophyll molecules in the light dependent stage of photosynthesis where ATP and NADPH are produced
- CO_2 concentration
  - Rate of photosynthesis increases as CO_2 concentration increases
  - CO_2 is needed for carbon fixation in the light independent stage (Calvin cycle) of photosynthesis
- Temperature
  - Light-dependent and light-independent reactions are enzyme-controlled
  - Rate of reaction doubles for every 10 degree rise up to 35 degrees
  - Beyond 40 degrees, rate of photosynthesis falls as enzymes start to denature
- O_2 concentration
  - Competitive inhibitor of RuBisCo when CO_2:O_2 ratio is low
  - Oxygenase function of RuBisCo causes RuBP to be split into a 3C and 2C compound

Data response questions:

<u>Why does rate of photosynthesis level off at higher light intensity?</u>

1. At higher light intensity, chloroplasts are saturated with light (**light saturation point**)
2. and hence, photosynthesis is occuring at the maximum rate
3. Light is no longer a limiting factor and other factors are now the limiting factors

<u>Why is the CO_2 assimilation rate negative at the lowest light intensity?</u>

1. At the lowest light intensity, there is no photosynthesis occuring
2. because there is less photons of light for photoactivation of chlorophyll molcules in the light dependent stage of photosynthesis
3. Hence, respiration occurs at a higher rate than photosynthesis

<u>Describe the significance of the point where CO_2 assimilation rate is equals to 0 to the plant</u>

1. That is the **<u>light compensation point</u>** where the rate of photosynthesis equals to the rate of respiration
2. Hence, the amount of CO_2 given out during respiration is equal to the amount of CO_2 fixed during the light independent stage of photosynthesis
3. Thus, there is <u>no net gain in dry mass and no growth</u> as the products of photosynthesis

are used up in respiration

Photophosphorylation vs Oxidative phosphorylation

Similarities

- Energy lost from the flow of electrons along an electron transport chain is used to actively pump protons across a membrane to generate a protein gradient
- ADP is phosphorylated to form ATP via ATP synthase using energy directly from chemiosmosis which is the flow of protons down its gradient
- Both processes take place on membranes

Differences

	Photophosphorylation	Oxidative phosphorylation
Location	Thylakoid membrane of chloroplasts	Inner membrane of mitochondria
Source of energy	Light energy	Oxidation of glucose which stores chemical energy
Electron donors	Water in the non-cyclic pathway and PSI in the cyclic pathway	NADH and FADH2
Electron acceptors	NADP+ in the non-cyclic pathway and PSI in the cyclic pathway	Oxygen
By-product	Oxygen during non-cyclic pathway	Water
Energy conversion	Light energy is converted to chemical energy	Chemical energy from glucose is converted to chemical energy in the form of ATP
Location of proton reservoir	Thylakoid space	Intermembrane space
Establishing proton gradient for ATP synthesis	Protons are pumped inwards from the stroma into the thylakoid space, across the thylakoid membrane	Protons are pumped outwards from the matrix into the intermembrane space, across the inner membrane

Electron flow	Non-cyclic and cyclic	Non-cyclic

Chloroplast vs Mitochondria
Similarities

- Both are membrane bound
- Inner membrane encloses a fluid filled cavity
- Both contain 70s ribosomes
- Both contain circular DNA strands and enzymes
- Both contain stalked particles/ATP synthase

Differences

	Chloroplast	Mitochondria
Size	Larger	Smaller
Shape	Lens shaped	Generally rod or spherical shaped
Inner membrane	Not folded, not arranged into folds and do not contain stalked particles	Extensive folded into folds known as cristae and inner portion of membrane contains stalked particles
Granules/grains present	Starch grains are present	Numerous phosphate granules present
Internal membrane system	Present in the form of stacks of thylakoids and intergranal lamella	Internal membrane system absent
Location of stalked particles (ATP synthase)	Found on thylakoid membranes	Found on inner membrane
Coloured pigments	Presence of photosynthetic pigments on thylakoid membranes	Absence of coloured pigments

Cyclic Photophosphorylation vs Non-cyclic Photophosphorylation

	Cyclic Photophosphorylation	Non-cyclic photophosphorylation
End products	ATP	ATP, NADPH and Oxygen
Conditions under which the process occurs	When plants require ATP only	When plants require ATP and NADPH
Photosystem involved	PSI	PSII and I
Source of electrons	P700 in PSI Does not involve splitting of water by an enzyme	Water Invovles splitting of water by an enzyme
Pathway of electrons	Electron flow is cyclical, passing from PSI to the 1st ETC and back to PSI	Electron flow is in one direction (non-cyclical) from water, through 2 ETCs to NADP via 2 photosystems
Final electron acceptor	P700 in PSI	NADP+
Maintenance of high H+ concentration in the thylakoid space	Active transport of H+ ions by electron carriers of ETC	Active transport of H+ ions by electron carriers of ETC and lysis of water molecules

Photosynthesis vs Aerobic Respiration

	Photosynthesis	Aerobic Respiration
Anabolic/Catabolic process	An anabolic process which results in the synthesis of carbohydrate molecules from simple inorganic molecules and light energy	A catabolic process which results in the breakdown of carbohydrate molecules to simple inorganic molecules
Storage of energy	Energy from light is stored in carbohydrates	Energy from food is incorporated into ATP
Oxygen	Oxygen is released	Oxygen is used

Carbon Dioxide and Water	Carbon dioxide and water are used	Carbon dioxide and water are produced
Change in dry mass	Process results in an increase in dry mass	Process results in a decrease in dry mass
Organelle involved	Chloroplast	Mitochodrion
Occurence	Process only occurs in cells possessing chloroplasts and in the presence of light	Process occurs in all living cells throughout their lifetime
Electron carrier	$NADP^+$	NAD^+ and FAD
Major reactions	Ligh dependent and light independent reactions	Glycolysis, link reaction, Krebs cycle and oxidative phosphorylation
Location of proton reservoir	Thylakoid space	Intermembrane space

Calvin Cycle vs Krebs Cycle

	Calvin Cycle	Krebs Cycle
Location	Stroma of chloroplast	Matrix of mitochondria
Role of coenzymes involved	NADPH as electron and proton donor	NAD^+ and FAD as electron and proton acceptors
Role of carbon dioxide	1 CO_2 fixed by RuBisCo to RuBP	2 CO_2 released during oxidative decarboxylation steps
Role of ATP	Used in reduction of GP to G3P and in regeneration of RuBP	Synthesised by substrate level phosphorylation
	Anabolic process involving formation of G3P and	Catabolic process involving the breakdown of acetyl

Nature of the process	involves a reduction reaction	CoA and intermediates and involves an oxidation by dehydrogenation reaction
Substance regenerated	RuBP	Oxaloacetate