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VCE Biology ¾
Photosynthesis & Biochemical Pathways [2.1]
Workbook

Outline:

Study Design Key Knowledge:

Study Design: Photosynthesis as an example of biochemical pathways

The general structure of biochemical pathways in photosynthesis from initial reactant to final product.

Inputs, outputs and locations of the light-dependent and light-independent stages of photosynthesis in C3 plants (details of the biochemical pathway mechanisms are not required).

The role of rubisco in photosynthesis, including adaptations of C3, C4, and CAM plants to maximise the efficiency of photosynthesis.

Potential uses and applications of CRISPR-Cas9 technologies to improve photosynthetic efficiencies and crop yields.

The factors that affect the rate of photosynthesis: light availability, water availability, temperature and carbon dioxide concentration.

https://www.vcaa.vic.edu.au/Documents/vce/biology/2022BiologySD.docx

Learning Objectives:

- [ ] **BI34 [2.1.1]** – Recall the inputs, outputs, & locations, & the relationship between both stages of photosynthesis.

- [ ] **BI34 [2.1.2]** – Explain the role of enzymes & coenzymes in the process of photosynthesis.

- [ ] **BI34 [2.1.3]** – Explain the function of Rubisco in photosynthesis, & describe the factors that increase its affinity for O_2.

- [ ] **BI34 [2.1.4]** – Describe the adaptations of $C4$ & CAM plants for reducing photorespiration, as compared to $C3$ plants, including structural & physiological differences.

- [ ] **BI34 [2.1.5]** – Use data to identify an unknown plant as $C3$, C4 or CAM with reference to conditions where they perform photosynthesis best.

- [ ] **BI34 [2.1.6]** – Identify & explain the factors - light colour, intensity, CO_2 concentration, temperature, water availability - that affect the efficiency of photosynthesis.

- [ ] **BI34 [2.1.7]** – Apply experimental principles to investigate factors affecting the rate of photosynthesis.

- [ ] **BI34 [2.1.8]** – Explain how $CRISPR-Cas9$ can be used to increase photosynthetic efficiency.

Section A: Biochemical Pathways

Sub-Section: Revision of Enzymes

What do we mean by biochemical pathway?

Do all reactions in a cell or organism happen at once?

Overview & Revision of Enzymes

- Biochemical pathways are incredibly important in the way our body functions both at a cellular level and overall.
  - Almost none of the processes or reactions in our body are "one-step processes".
- Ordinarily, you'd expect more steps to increase the time taken for a process to occur – but the usage of enzymes allows us to control the rate of these pathways!

Active Recall: What are enzymes?

____

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Active Recall: What are the models of enzyme function?

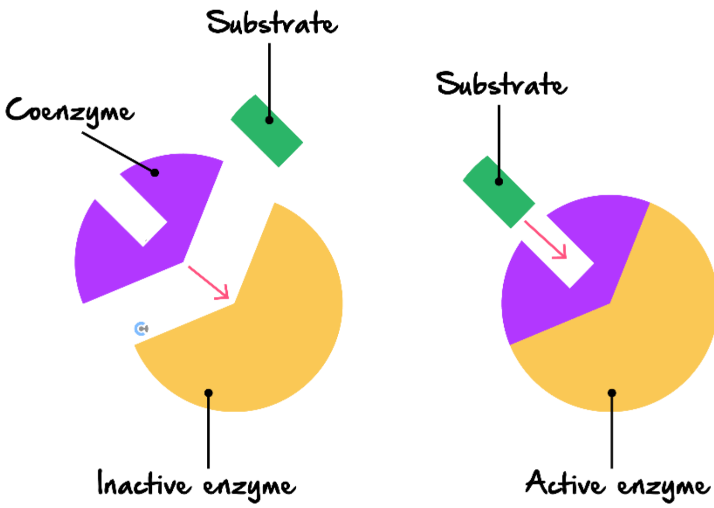
Active Recall: What are the factors of enzyme function?

Sub-Section: Coenzymes

Do enzymes need any help in performing their function?

Coenzymes

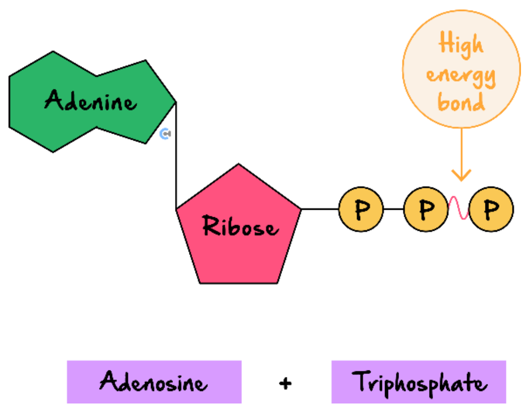
- These are molecules that are responsible for assisting in enzyme function in catalyzing the rate of reaction.
  - They can bind to the enzyme, changing the active site to allow for enzyme-substrate binding.



  - They can provide protons and electrons for reactions i.e. act as electron and proton carriers.

$$2NADP^+ + 2H^+ + 4e^- \rightleftharpoons 2NADPH$$

  - They can provide energy for cellular reactions.



Analogy

Key Takeaways

- Biochemical pathways involve multiple sequential reactions, each catalysed by specific enzymes.
- These pathways enable cellular efficiency by controlling reaction rates and ensuring metabolic balance.
- **Importance of Enzymes**:
  - Biological catalysts that reduce activation energy, allowing reactions to proceed faster.
  - They are specific to substrates, ensuring accurate reactions.
  - Models of enzyme activity: Lock-and-key and induced-fit models.
- **Role of Coenzymes**:
  - Molecules like ATP, $NADPH$, and $NADP^+$ assist enzymes by:
    - Providing energy (ATP).
    - Transferring electrons and protons ($NADPH, NADP^+$).
    - Stabilising reactions and enabling enzymatic binding.

Factors Influencing Enzyme Function:

- **Temperature**: Optimal range boosts reaction rates, but extremes denature enzymes.
- **pH**: Deviations from optimal pH can reduce enzymatic activity.
- **Concentration**: Reaction rates increase with substrate availability until saturation.

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Section B: Photosynthesis

Sub-Section: Introducing Photosynthesis

How do plants make their own food?

What are the steps of this process?

Overview

- Photosynthesis is the process by which plants convert light energy into chemical energy.
- ____
- There are many different ways that photosynthesis can occur in different species, and in VCE we look at some of the variations.
- The overall reaction is:

- CO_2 is said to be fixed to organic glucose.
- We can divide photosynthesis into 2 main stages:
  - ________________________________
  - ________________________________

Misconception

" Water reacts with CO_2 to make glucose and oxygen!"

TRUTH: Photosynthesis is a biochemical pathway, there are a lot of steps and the water and CO_2 are involved at different stages!

<u>Exploration</u>: Where in a plant does photosynthesis occur?

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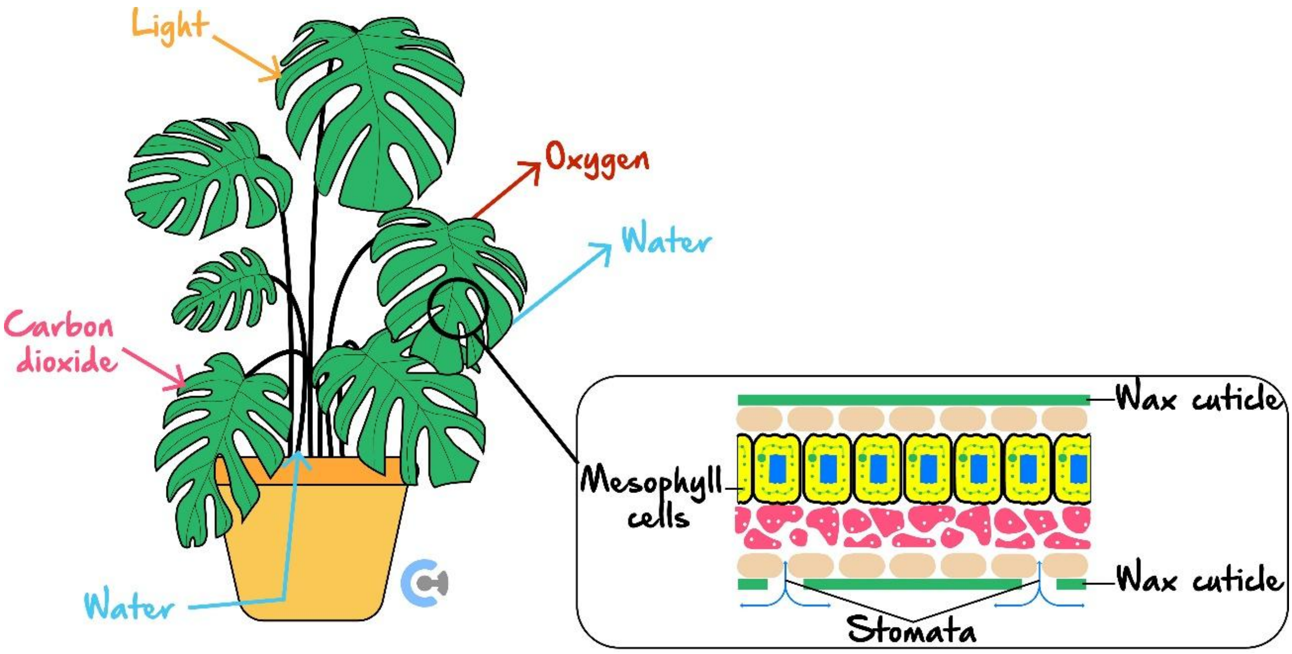
Sub-Section: Structure of Plants and Chloroplasts

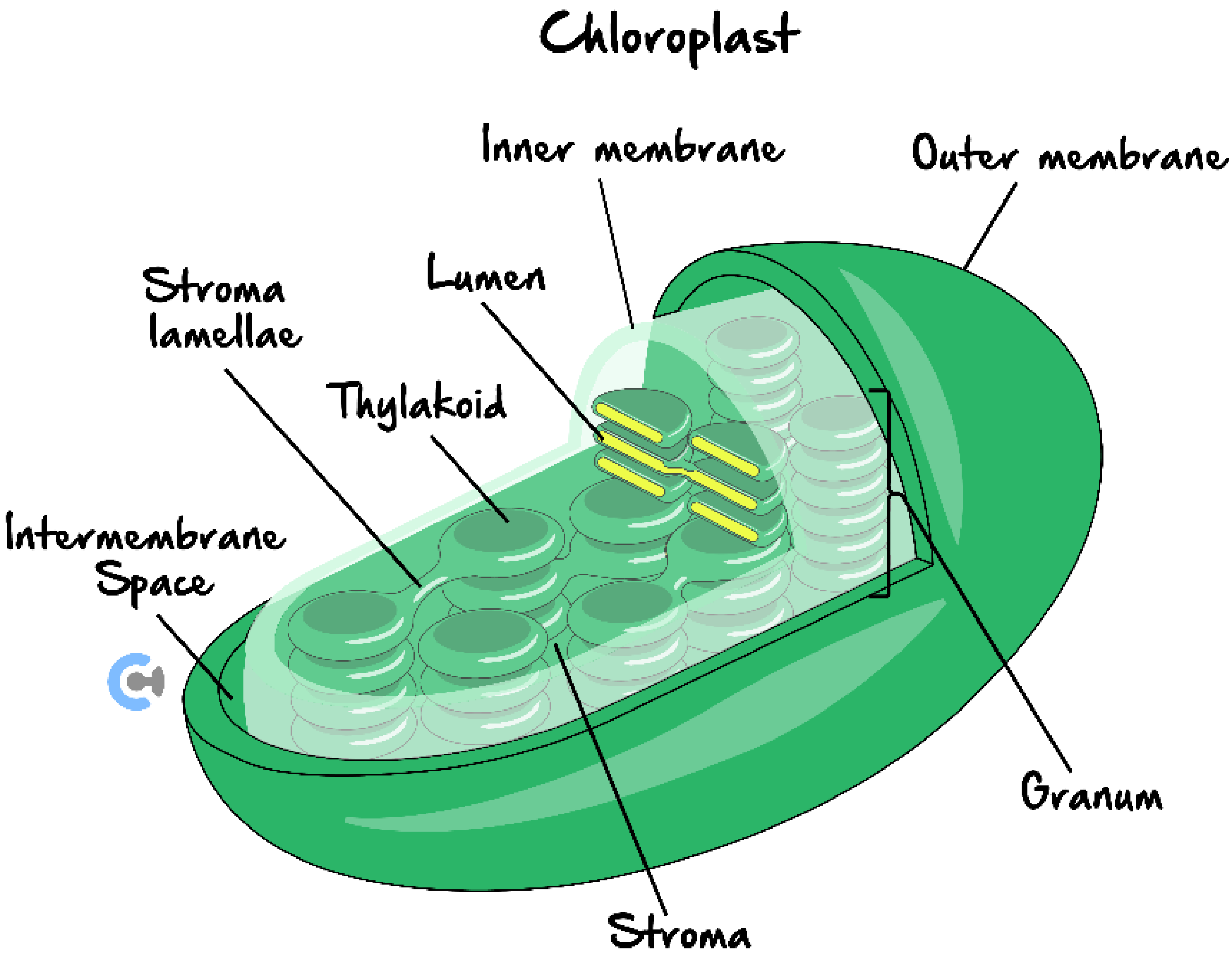
Plant Structure and Photosynthesis

- Photosynthesis, when thinking about plants, occurs in the ______________ cells of a plant.



- Leaves are sealed off by the ________________, leaving the ____________ responsible for gas transfer from inside and outside the plant.
- Specifically, photosynthesis occurs in the _____________ of the actual ______________ cells.

Chloroplasts



- This diagram shows the structure of a chloroplast in a plant cell – this is where photosynthesis occurs.

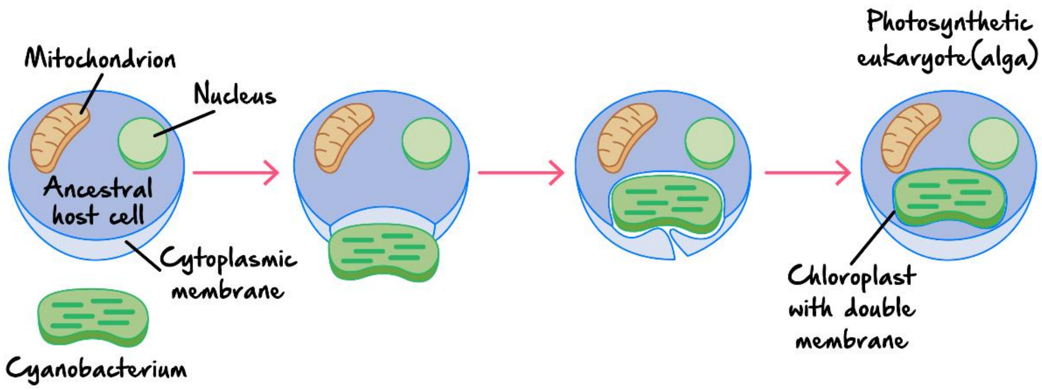
Exploration: Why is it green?

Why are plants green?

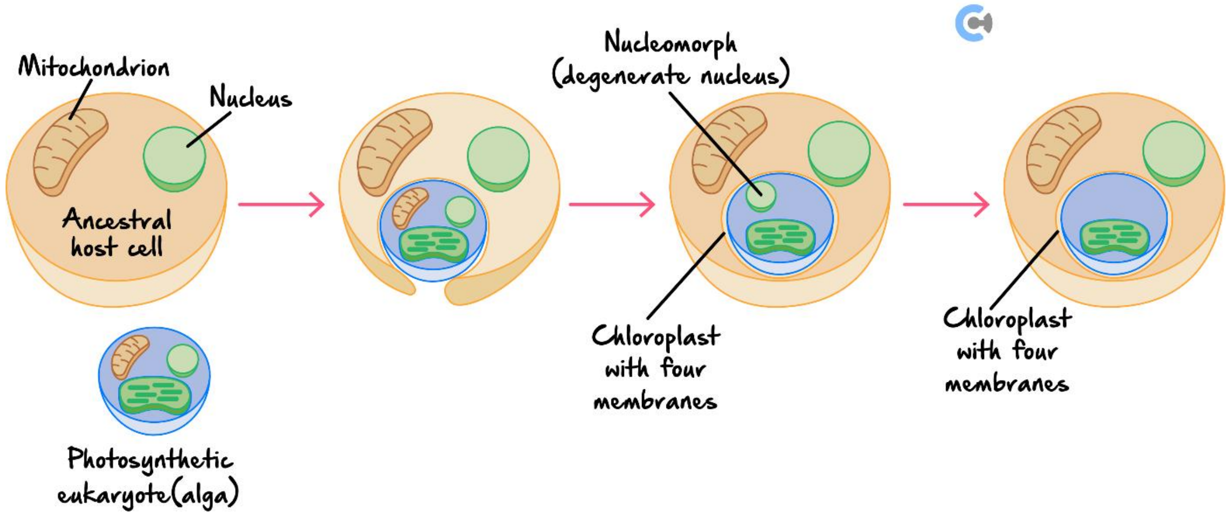
How did chloroplast evolve?

Exploration: The Origin of Chloroplasts

PRIMARY ENDOSYMBIOSIS



SECONDARY ENDOSYMBIOSIS



We can break photosynthesis into TWO key stages....

Sub-Section: Light Dependent Stage

Light-Dependent Stage

- The first set of reactions in photosynthesis - as the name suggests it requires light!
  - Occurs inside the thylakoid membranes of the chloroplasts - CHLOROPHYLL!
  - The purpose of this is to expressly convert the ______________ of the sun, to _________________ in the form of high-energy coenzymes.
- Involves 2 important coenzymes - ________ and _______________.
  - ATP is the "energy currency" of the cell - it provides energy to cellular reactions.
  - NADPH is an electron and proton carrier, it collects them and shuttles them at high energy from reaction to reaction around the cell.

Inputs	Outputs	Location

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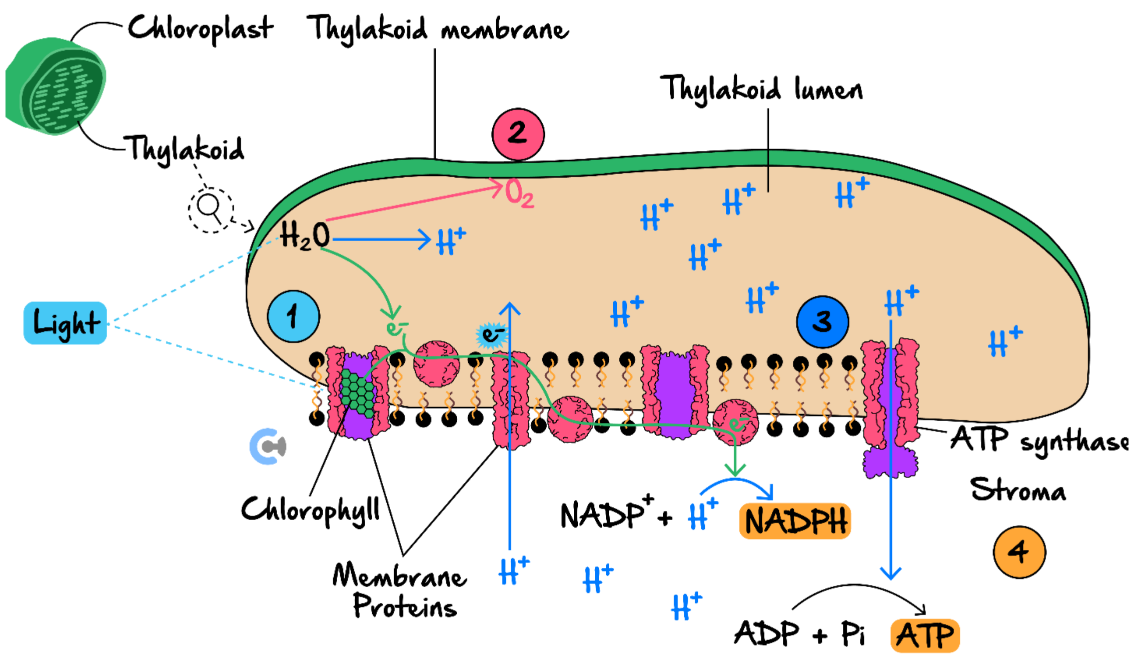
How does this work?

The Process of the Light-Dependent Reactions

- This is a complicated biochemical process but can be split into a few key steps.
  - Light energy will hit the ______________ pigment, exciting ______________ within it.
  - The ______________ of these excited electrons is used by a protein to pump H^+ ions into the lumen of the thylakoid membranes.
  - To replace the electrons used in that process, water is split to H^+, electrons and O_2 . O_2 escapes as a waste product, while the H^+ add to the increasing concentration inside the lumen.
  - H^+ ions will flow down their ___________________ from inside the lumen into the stroma, via an enzyme called ____________________.
  - ATP synthase uses its kinetic energy to make ATP.
  - $NADP^+$ collects the H^+ and the electrons to make NADPH.



1. Light energy energises chlorophyll which pumps H^+ and splits water
2. Oxygen released
3. H^+ and e^- generate NADPH and ATP
4. NADPH and ATP are inputs for the light-independent stage

NOTE: The specific details of these reactions and each step will NOT be assessed by VCAA.

ALSO NOTE: These details ARE useful in solidifying your own understanding and recognising the inputs, outputs and locations as required by VCAA.

TIP: Focus more on the inputs, outputs and locations of the process as required by VCAA, but also don't be afraid to think outside the box and think about how these steps may impact the process of photosynthesis.

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Sub-Section: Light Independent Stage

Light Independent Stage

- This is the second stage of photosynthesis, directly following the light-dependent reactions.
  - Occurs inside the ___________ of the chloroplasts.
  - The purpose of this is to fix carbon to become an organic compound which can then be used as a chemical energy source.
- Uses the direct products of the light-dependent stage.

Inputs	Outputs	Location

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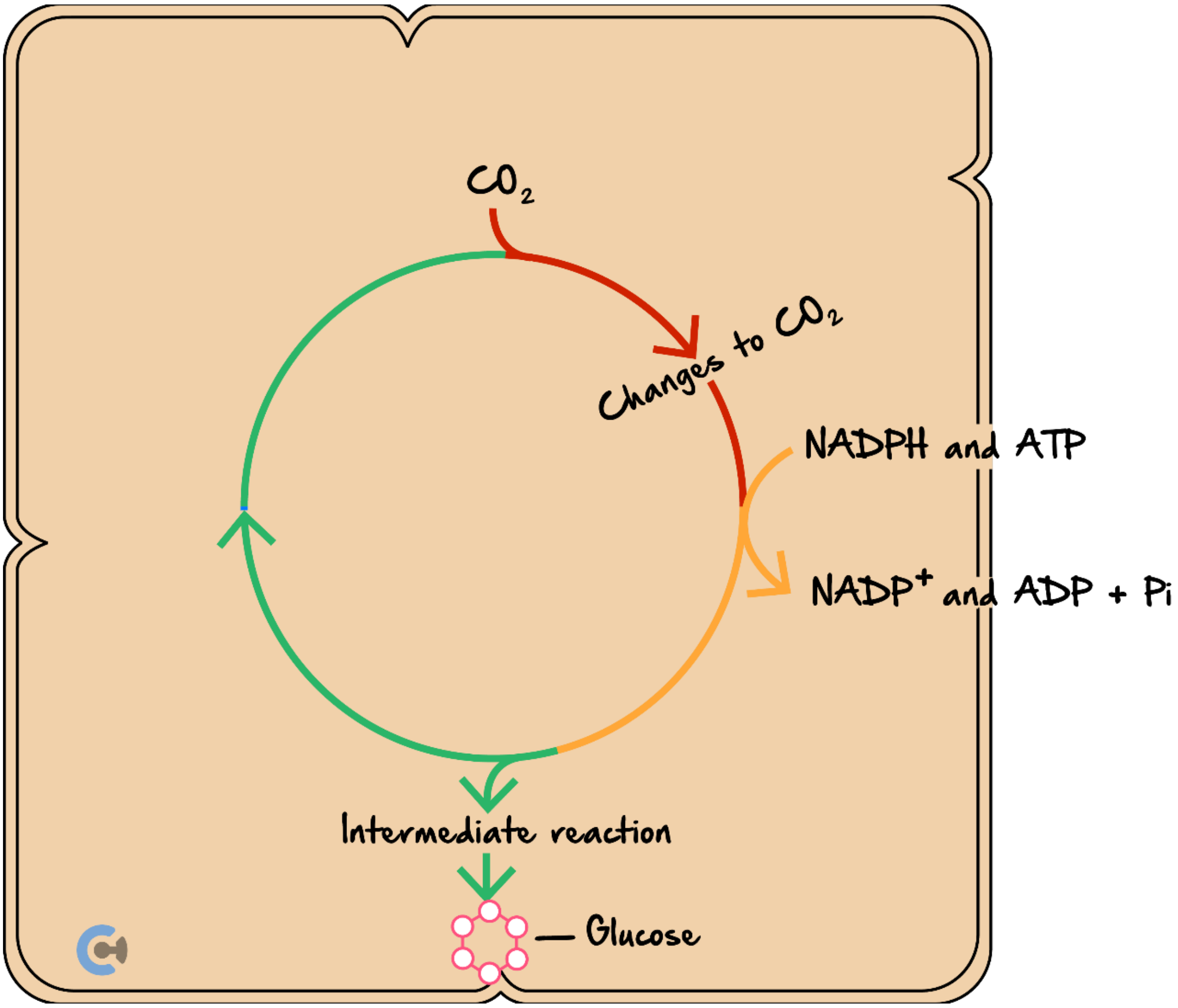
The Process of the Light-Independent Stage

- Essentially, a cycle of reactions that involves turning CO_2 into glucose.
  - CO_2 first enters the _________________________ and reacts with the enzyme _____________________ to fix it into an organic carbon compound.
  - Through a bunch of reactions, the H^+ ions, electrons and energy from them combine with the carbon compound, ultimately getting to a glucose precursor, which is the product of the Calvin cycle.
  - This is then converted to glucose via an intermediary reaction.
  - In the Calvin cycle, the oxygen remaining after the breakdown of CO_2 combines with leftover H^+ and electrons to form the output water.



TIP: Keep focusing on the inputs, outputs and location!

NOTE: Some people may use the term light-independent stage interchangeably with the "Calvin cycle" - the Calvin cycle does NOT have glucose as a final product whereas the light-independent stage DOES.

Exploration: What happens to the coenzymes in photosynthesis once they have been uploaded in the LID stage?

Key Takeaways

Overview:

- Photosynthesis converts light energy into glucose, a chemical energy source for plants.
- Balanced equation:

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

- Divided into two stages:
  1. **Light-dependent stage**: Captures light to produce energy-rich molecules ($ATP, NADPH$).
  2. **Light-independent stage**: Uses ATP and $NADPH$ to synthesise glucose from CO_2.

- **Light-Dependent Stage**:
  - **Inputs**: Light, H_2O, $ADP + Pi$, $NADP^+$.
  - **Outputs**: Oxygen, ATP, NADPH.
  - **Location**: Thylakoid membranes in chloroplasts.
  - **Process**:
    1. Light excites electrons in chlorophyll, passing them to the electron transport chain.
    2. Water undergoes photolysis, producing oxygen, electrons, and protons.
    3. ATP synthase generates ATP as protons flow down their gradient.
    4. $NADP^+$ captures high-energy electrons to form NADPH.
- **Light-Independent Stage**:
  - **Inputs**: CO_2, ATP, NADPH.
  - **Outputs**: Glucose, $ADP + Pi$, $NADP^+$.
  - **Location**: Stroma of the chloroplast.
  - **Process**:
    1. The Calvin cycle begins with CO_2 fixation by Rubisco.
    2. Energy from ATP and NADPH converts CO_2 into 3-carbon molecules.
    3. The final steps produce glucose and regenerate RuBP to continue the cycle.
  - Note: This stage depends on ATP and NADPH from the light-dependent stage.

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Section C: Photorespiration

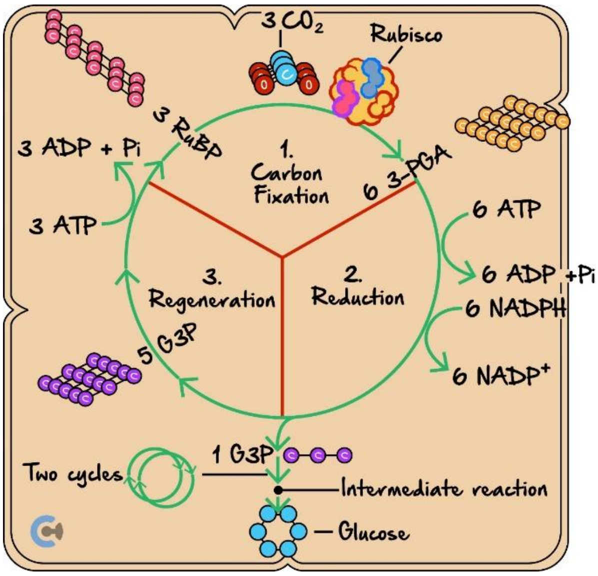
Sub-Section: Rubisco

What is Rubisco?

What does it do?

Role of Rubisco in Photosynthesis

- Rubisco is a very important enzyme that is involved with the very first step of the Calvin cycle.
  - This reaction is the ________________________ step (______________________________________).
  - Initiates the ___________________________.
- Calvin Cycle Overview:
  - Carbon Fixation - CO_2 and RuBP are converted into 3-PGA, by Rubisco.
  - Reduction - NADPH gives electrons to an intermediate, to form G3P.
  - Regeneration - G3P molecules are also converted to regenerate the RuBP required for step 1.



Active Recall: What is carbon fixation?

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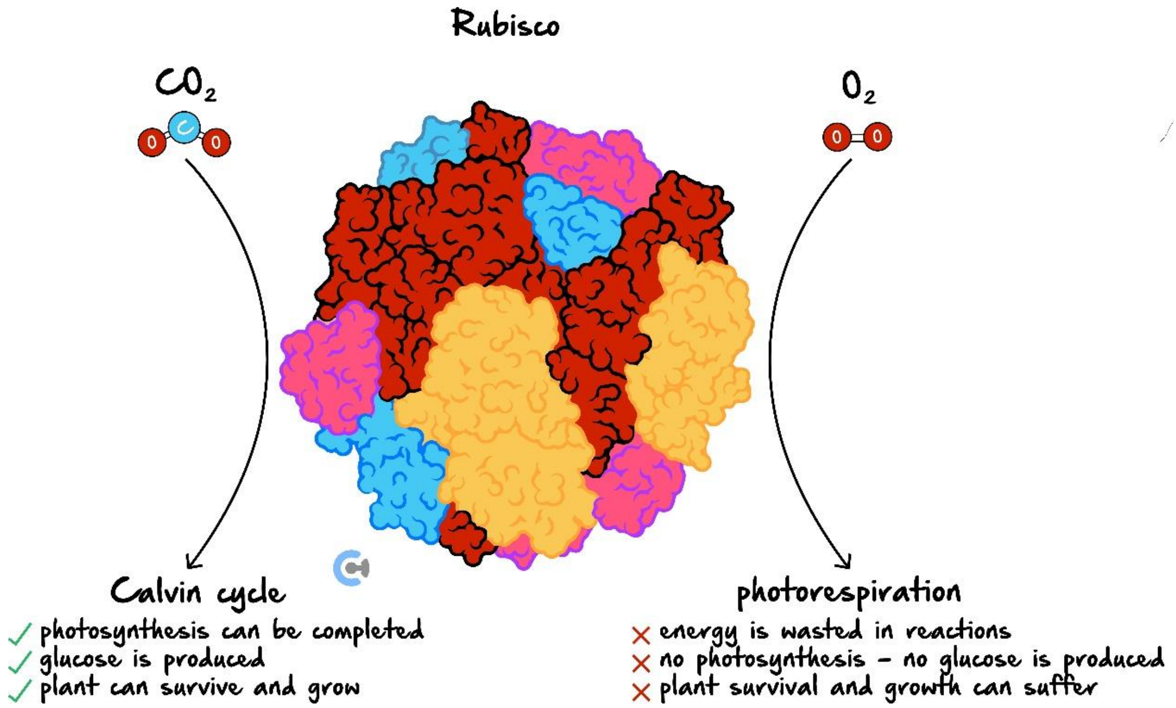
Sub-Section: Photorespiration

What else can Rubisco bind to?

- Rubisco can bind to ____________!
- Leads to something called ________________________, which does ________ produce glucose.



Discussion: Why can Rubisco bind to oxygen?

NOTE: The specifics of Rubisco's function are not necessary to remember fully but can be useful in understanding its shortcomings.

<u>Exploration</u>: **Why is it a flaw for Rubisco to be able to bind to O_2 as well?**

What factors affect photorespiration?

<u>Exploration</u>: **In what condition would a plant most likely undergo photorespiration?**

- **Factors Impacting Photorespiration!**
- Relative Concentrations
  - Higher concentration of O_2 leads to a higher affinity of Rubisco to O_2.
- Temperature
  - Higher temperatures increase the affinity of Rubisco to O_2.
- Knowing this then – photorespiration will be increased in ____
  -

Context

- Plants, over time, to adapt to certain environmental conditions have seen changes result in their processes of photosynthesis to overcome the Rubisco problem.
- Generally, this is seen through the changes in the Light Independent Stage – there are two types we talk about in VCE, $C4$ plants and CAM plants.

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Key Takeaways

- **Role in Photosynthesis**:
  - Catalyses CO_2 fixation in the Calvin cycle, initiating the synthesis of organic molecules.
  - Can also bind oxygen, resulting in **photorespiration**.
- **Photorespiration**:
  - An inefficient process where oxygen binds to Rubisco, wasting energy and reducing glucose production.
  - Triggered by:
    - High temperatures, which increase Rubisco's affinity for oxygen.
    - Low CO_2 levels, often due to stomatal closure in hot, dry conditions.
  - Hence normal ($C3$ plants) perform worse in hotter and drier environments.

What can plants do to overcome this problem?

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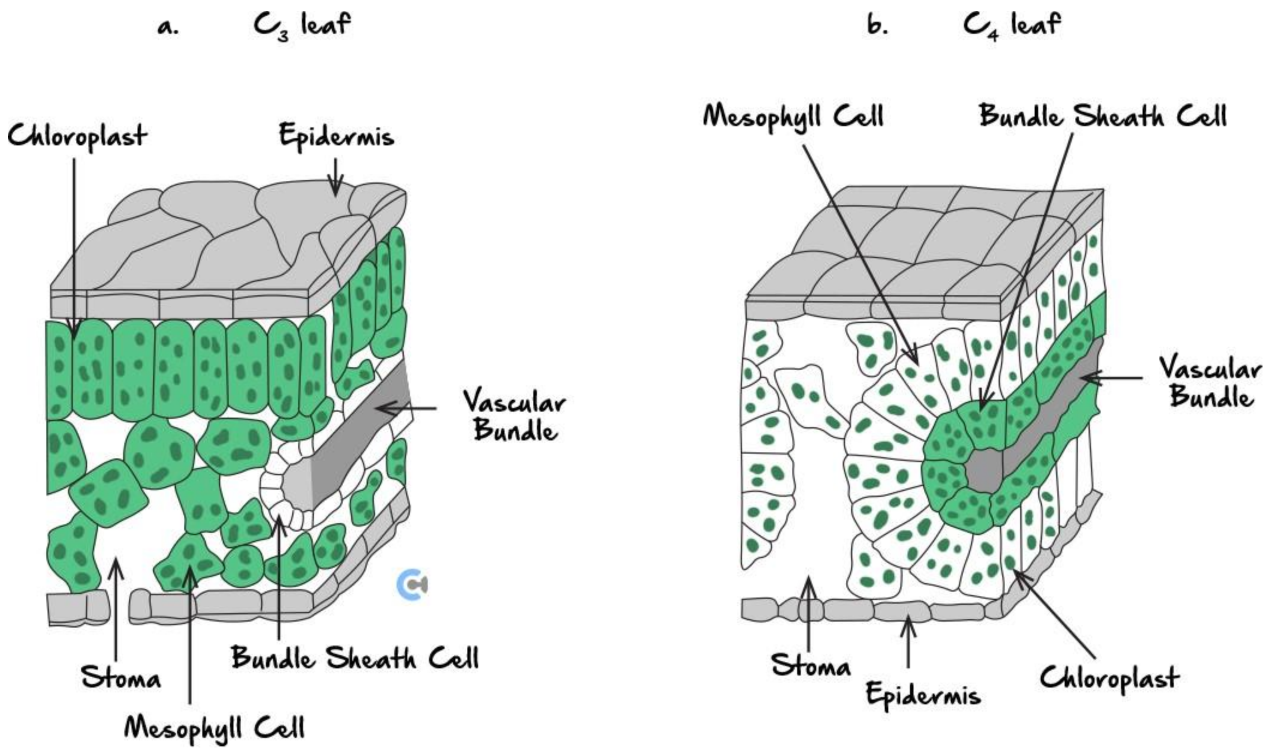
Section D: Adaptations of Photosynthesis

Sub-Section: C4 Photosynthesis

Context

- C4 photosynthesis is essentially a process of photosynthesis that has been adapted slightly to suit hotter and humid conditions better.
  - The key difference can be described as the actual fixation of CO_2 by Rubisco occurring in a separate cell to the initial light-dependent interactions.
- C4 photosynthesis is used by plants such as corn, sugarcane, switchgrass and some weeds.



TIP: You don't need to remember the full biochemical pathway as I will explain it, but understand that it will help you describe the differences between C3, C4 and CAM photosynthesis.

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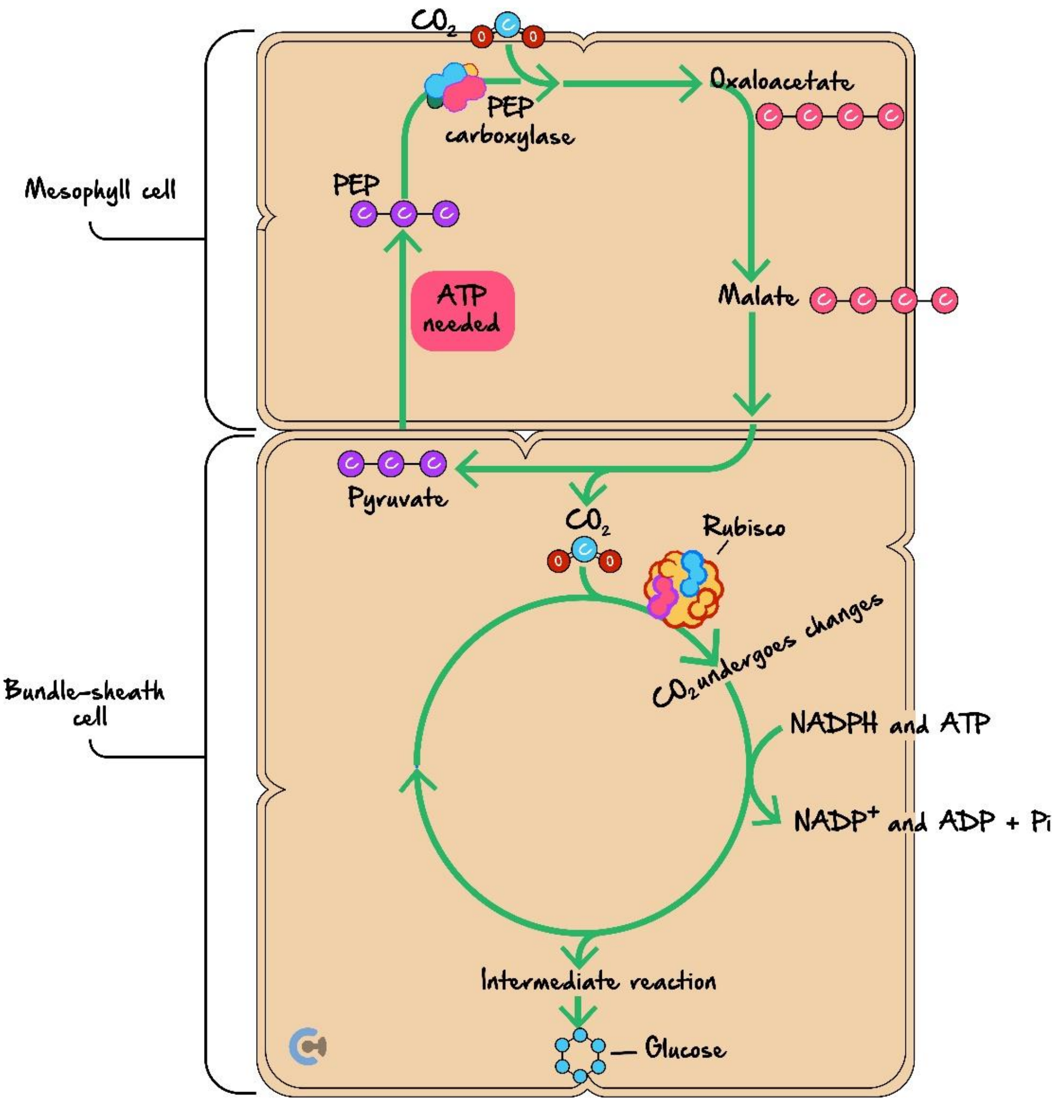
The Process

- Light-Dependent Stage remains the same and occurs in a chloroplast of a mesophyll cell.
- However, the light-independent stage is split across 2 cells.
  - CO_2 enters the mesophyll cell, and instead of first interacting with Rubisco, it reacts with PEP and is fixed by the enzyme PEP carboxylase, creating oxaloacetate. PEP Carboxylase does NOT interact with O_2!
  - Oxaloacetate is converted into malate – which can be transported to bundle and sheath cells.
  - Malate is released to CO_2 in the bundle and sheath cell – which then reacts with Rubisco to trigger the Calvin cycle, resulting in the production of glucose.
  - The pyruvate that is formed from the breakdown of malate, is taken back to the mesophyll cell with the use of some ATP to regenerate PEP.



Exploration: Will the stomata be open or closed here?

Discussion: Why is this important that the PEP carboxylase has no affinity for O_2?

Discussion: How does this process overcome the problem of photorespiration in hot and dry conditions?

Discussion: Why don't all plants use C4 if it overcomes photorespiration issues so efficiently?

Key Takeaways

- ☑ $C4$ photosynthesis avoids the issue of Rubisco binding to O_2 resulting in photorespiration by separating the light-dependent stage and Rubisco in different cells.
- ☑ Achieves this by fixing CO_2 to a different carbon compound and transferring that to a bundle and sheath cell.
- ☑ This means that Rubisco can operate in an environment that has high temperatures and is humid, improving photosynthetic efficiency.

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Sub-Section: CAM Photosynthesis

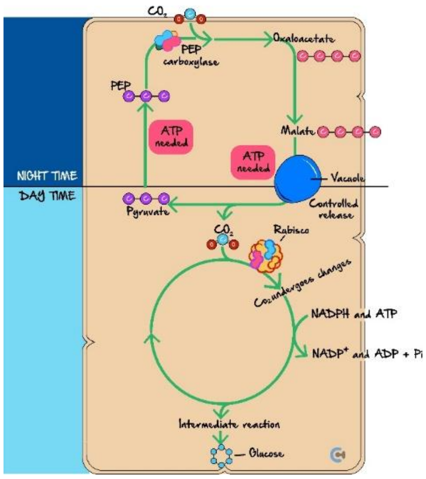
Overview

- Primarily suited to hot and dry conditions where they become more forgiving at night.
  - Light-dependent stage and initial carbon fixation are separated by time.
- Found in plants such as cacti, pineapples etc.

Will the stomata remain open or closed?

The Process

- Light-Dependent Stage will occur during the day as normal.
- As the stomata are closed during the day, the only time CO_2 enters during the night, when there aren't enough products of the light-dependent stage.
  - To overcome this, CAM plants fix CO_2 to malate and store it in vacuoles. This process is similar to C4 plants, where CO_2 is converted into oxaloacetate and then malate.
  - During the day, there is a controlled release of the malate into CO_2, which allows the concentrations to be maintained to minimise the impact of photorespiration.
  - There is ATP required to convert pyruvate into PEP and to release and store it in the vacuoles.



<u>Discussion:</u> How does this process overcome the problem of photorespiration in hot and dry conditions?

<u>Discussion:</u> Why doesn't every plant do CAM photosynthesis?

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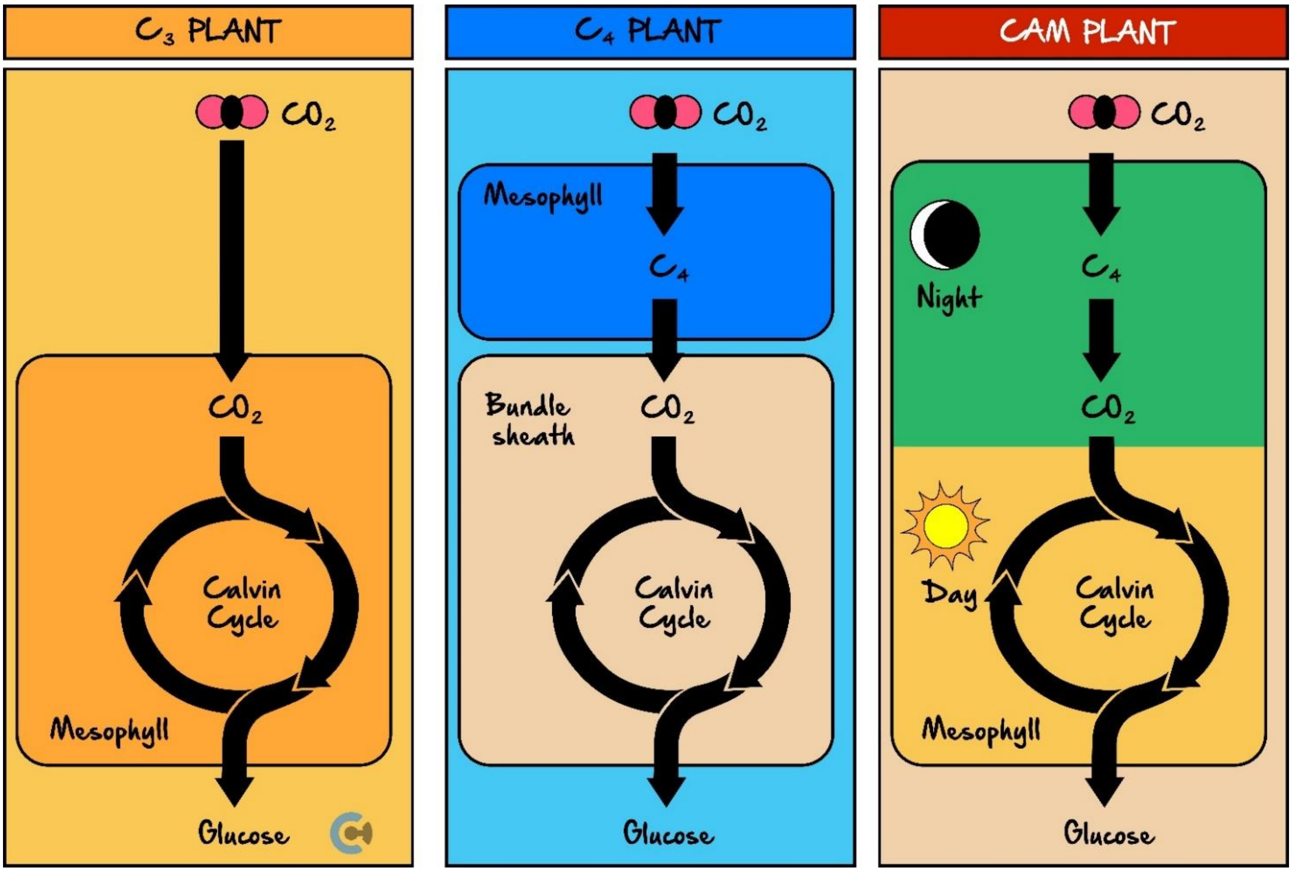
Sub-Section: Comparing Photosynthetic Pathways

Type	C3	C4	CAM
Separation of CO_2 fixation and Rubisco			
Stomata Open			
Advantages			
Disadvantages			
Adapted to			
Examples			

Plant Characteristic	C3 Plant	C4 Plant	CAM Plant
Ideal temperature for photosynthesis	15-25°C	30-40°C	> 40°C
Pathway to fix CO_2	Only Calvin cycle	C4 pathway and Calvin cycle	C4 pathway and Calvin cycle
Stomata during the day	Yes	Yes	No
Photorespiration occurring	High	Low	Only observed in the middle of the day.
Water loss during the day	High	Moderate	Low
Plant growth rate	Moderate	Fast	Very slow



Key Takeaways

- C4 Photosynthesis:
  - **Adapted for**: Hot, humid environments where high temperatures and high oxygen concentrations would otherwise promote photorespiration.
  - **Key Features**:
    - **Spatial Separation of Processes**:
      - **Mesophyll Cells**:
        - CO_2 enters the leaf and is initially fixed into a 4-carbon compound (usually oxaloacetate) by **PEP carboxylase**, an enzyme with no affinity for oxygen.
        - Oxaloacetate is then converted into malate, a stable intermediate, which is transported to bundle sheath cells.

- **Bundle Sheath Cells**:
  - Malate releases CO_2, creating a high local concentration around Rubisco, ensuring that Rubisco binds CO_2 rather than oxygen.
  - The Calvin Cycle operates in these cells to produce glucose.
- **Key Enzymes**:
  - PEP carboxylase for the initial fixation of CO_2.
  - Rubisco operates only in CO_2-enriched bundle sheath cells, minimising photorespiration.
- **Energy Costs**:
  - Additional ATP is required to transport malate and regenerate PEP (phosphoenolpyruvate), but this is compensated by the reduction in photorespiration.
- **Advantages**:
  - Reduces water loss since stomata can remain partially closed without affecting CO_2 intake.
  - Operates efficiently in environments with high light intensity and high temperatures.
- **Examples**: Corn, sugarcane, millet, sorghum.

- **CAM Photosynthesis:**
  - **Adapted for**: Arid conditions where water conservation is critical, such as deserts and dry environments.
  - **Key Features**:
    - **Temporal Separation of Processes**:
      - **Night**:
        - Stomata open during cooler, more humid nighttime conditions to minimise water loss.
        - CO_2 is fixed into oxaloacetate by **PEP carboxylase** and stored as malate in vacuoles.
        - This allows the plant to stockpile CO_2 without excessive water loss.

- **Day**:
  - Stomata remains closed to conserve water.
  - Malate is transported from vacuoles to the chloroplast, where it releases CO_2 for the Calvin Cycle.
  - The high internal CO_2 concentration reduces the risk of photorespiration even in high temperatures.
- **Energy Costs**:
  - CAM is energy-intensive due to the storage and controlled release of malate.
  - ATP is required to regenerate PEP for repeated CO_2 fixation.
- **Advantages**:
  - Extremely water-efficient, making CAM plants well-suited to survive in desert ecosystems.
  - Adaptable to prolonged periods of water scarcity.

- **Examples**: Cacti, pineapples, agave, jade plants.

Characteristic	C3 Plants	C4 Plants	CAM Plants
Temperature Optimum	**15–25°C**	**30–40°C**	**> 40°C**
Pathway	Calvin Cycle	C4 + Calvin Cycle	C4 + Calvin Cycle
Stomata Open	During the day	During the day	At night
Photorespiration	High	Low	Minimal
Water Loss	High	Moderate	Very low
Growth Rate	Moderate	Fast	Very slow

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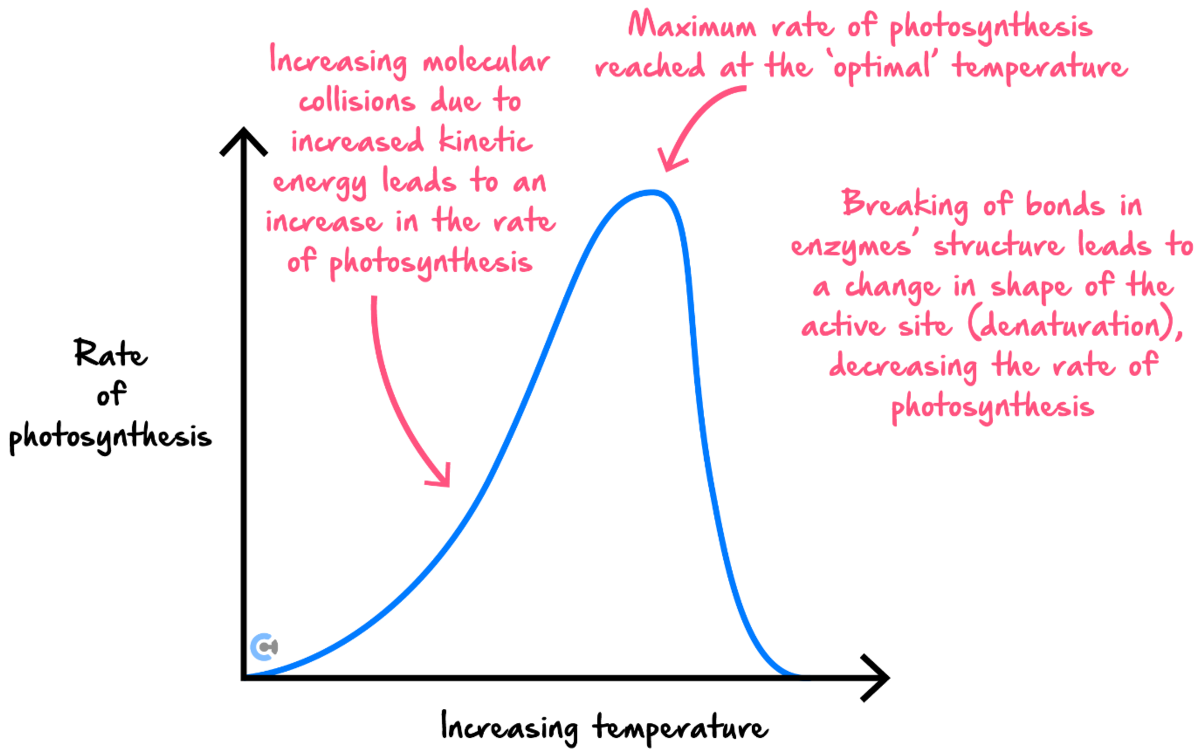
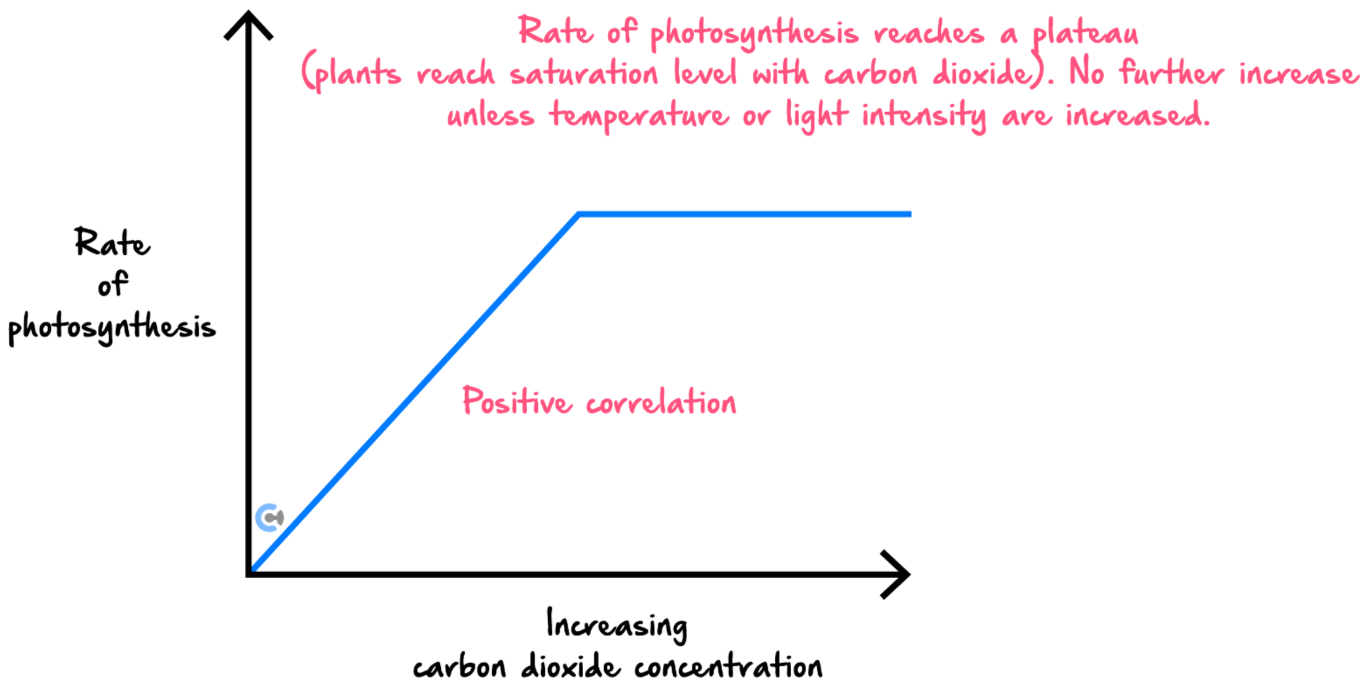
Section E: Factors Affecting Photosynthesis (7 Marks)

Exploration: Factors

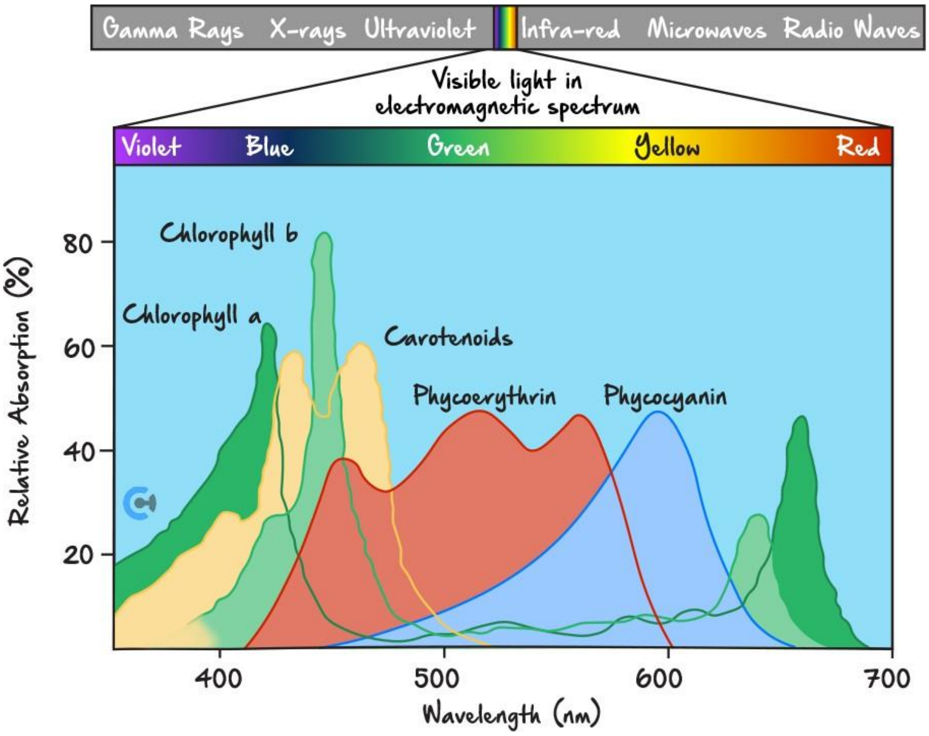
- There are a number of factors that impact the rate of photosynthesis in plants.
- These factors do not act in isolation, it is important to realise that it is all of them working in combination to determine the rate of photosynthesis.
- Light:
  - Generally speaking, the more light, the ___________ the rate of photosynthesis will occur.
  - Happens to a certain extent until limited by other factors.
- Temperature:
  - Increasing the temperature will ___________ the rate until _________________________________.



- Water:
  - More water available will generally ___________ the rate of photosynthesis. However, plants maintain water the best out of all other factors!
- CO_2 availability:
  - More CO_2 available will generally ____________ the rate of photosynthesis, until __________________________________.



- Colour:
  - Different wavelengths of light are absorbed to different extents!



Exploration: How else might temperature and water influence the rate of photosynthesis?

Exploration: How will these factors affect C3, CAM and C4 plants differently?

Question 1 (7 marks)

A student found an unusual plant species growing in the local park. Without knowing what type of plants they were, the student undertook experiments to identify the photosynthetic output of the plants as measured by the rate of starch formed per day. Plants of the same size were exposed to different environmental conditions, and the rate of starch formed per day was measured. The results are shown in the table below.

Temperature (°C)	**Light Source**	**CO_2 (%)**	**Relative Humidity (%)**	**Rate of starch formed (mg/day)**
20	White	5	70	1.7
20	White	1	70	1.3
20	White	5	30	1.9
20	Green	5	30	0.6
20	Blue	5	30	1.6
40	White	5	70	3.2
40	White	1	70	2.6
40	White	5	30	3.4
40	Green	5	30	0.8
** 40	Blue	5	30	2.9

**VCAA inspired from 2023!

a. To which plant group (C3, C4 or CAM) would this unusual plant species most likely belong? Justify. (3 marks)

b. Why does exposing the plants to green or blue light as opposed to white light affect the formation of starch? Justify your answer. (4 marks)

____

____

____

____

____

____

____

____

TIP: Make sure you know which environment works for each plant type.

- Try and compare "like" measurements, i.e. where only one variable is changing.
- Look for overall trends in the data as well as individual measurements referenced in your answers.

Key Takeaways

- Factors Affecting Photosynthesis:
  - **Light Intensity**:
    - Increased light boosts the rate of photosynthesis until other factors become limiting.
    - Saturation occurs when enzymes and substrates are fully utilised.
  - **Temperature**:
    - Optimal temperature allows enzymes to function efficiently.
    - Beyond the optimal range, enzymes denature, and photorespiration increases.

- **Water Availability**:
  - Essential for photolysis in the light-dependent stage.
  - Limited water leads to stomatal closure, reducing CO_2 intake.
- **CO_2 Concentration**:
  - Higher CO_2 levels increase the rate of photosynthesis until Rubisco is saturated.
- **Light Wavelength**:
  - Blue and red light are most effective; green light is reflected, giving plants their colour.

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Section F: Applications of CRISPR-Cas9 in Photosynthesis

Overview

- CRISPR-Cas9 is a gene editing technology which allows us to make precise edits.
- If we can determine greater control over this technology, we can use it to alter the DNA of crops to make them more suited to our needs – increasing their efficiency and crop yields.

Exploration: Why would it be important to try and increase crop yields and efficiency?

- ____.
- ____.
- ____.

Potential uses of CRISPR-Cas9

- CRISPR-Cas9 can alter and intervene at a variety of stages in the plant's cycle which could improve the efficiency of photosynthetic processes.
  - Improve the Calvin Cycle. How?
  - Plant Tolerance?
  - Diseases?

- Product Enhancement?

- Chemical Efficiency?

Exploration: What would be the steps in applying this gene editing tool to determine and improve crop yields?

- ____.
- ____.
- ____.
- ____.

Key Takeaways

- Applications of CRISPR in Photosynthesis:
  - **Potential Improvements**:
    - **Rubisco Efficiency**: Modify Rubisco to reduce oxygen binding, minimising photorespiration.
    - **C4 and CAM Pathways**: Introduce these adaptations into C3 crops for broader resilience.
    - **Environmental Tolerance**: Engineer plants to tolerate drought, heat, or frost.
    - **Yield Enhancement**: Optimise photosynthesis for greater crop production.
  - **Steps in CRISPR Application**:
    1. Identify inefficiencies in photosynthesis using computational models.
    2. Target genes responsible for inefficiencies.
    3. Design CRISPR systems to edit these genes precisely.
    4. Test and refine plants for improved photosynthetic performance.

Contour Check

Learning Objective: [2.1.1] – Recall the inputs, outputs, & locations, & the relationship between both stages of photosynthesis

Study Design

Inputs, outputs and locations of the light-dependent and light-independent stages of photosynthesis in C3 plants (details of the biochemical pathway mechanisms are not required).

Key Takeaways

- Light-Dependent Stage:
  - Inputs: ______________________________.
  - Outputs: ______________________.
  - Location: __________________________________.
  - Process:
    1. Light excites electrons in chlorophyll, passing them to the electron transport chain.
    2. Water undergoes photolysis, producing oxygen, electrons, and protons.
    3. ATP synthase generates ATP as protons flow down their gradient.
    4. $NADP^+$ captures high-energy electrons to form NADPH.

- **Light-Independent Stage**:
  - **Inputs**: ________________________.
  - **Outputs**: _____________________________.
  - **Location**: _____________________________.
  - **Process**:
    1. The Calvin Cycle begins with CO_2 fixation by Rubisco.
    2. Energy from ATP and $NADPH$ converts CO_2 into 3-carbon molecules.
    3. Final steps produce glucose and regenerate $RuBP$ to continue the cycle.
  - Note: This stage depends on ATP and $NADPH$ from the light-dependent stage.

Learning Objective: [2.1.2] – Explain the role of enzymes & coenzymes in the process of photosynthesis

Study Design

The general structure of biochemical pathways in photosynthesis from initial reactant to final product.

Key Takeaways

- **Role of Coenzymes**:
  - Molecules like ATP, NADPH, and $NADP^+$ assist enzymes by:
    - Providing energy (_______).
    - Transferring electrons and protons (__________________________).
    - Stabilising reactions and enabling enzymatic binding.
- **Importance of Enzymes**:
  - Biological catalysts that reduce activation energy, allowing reactions to proceed faster.
  - They are specific to substrates, ensuring accurate reactions.
  - Models of enzyme activity: _________________ and ________________ models.

Learning Objective: [2.1.3] - Explain the function of Rubisco in photosynthesis, & describe the factors that increase its affinity for O_2

Study Design

The role of rubisco in photosynthesis, including adaptations of $C3$, $C4$, and CAM plants to maximise the efficiency of photosynthesis.

Key Takeaways

- **Role in Photosynthesis**:
  - Rubisco fixes CO_2 into organic molecules in the Calvin Cycle, initiating the synthesis of organic molecules.
  - Can also bind oxygen, resulting ________________________.
- **Photorespiration**:
  - An inefficient process where oxygen binds to Rubisco, wasting energy and reducing glucose production.
  - Triggered by:
    - ____.
    - ____.

Learning Objective: [2.1.4] - Describe the adaptations of C4 & CAM plants for reducing photorespiration, as compared to C3 plants, including structural & physiological differences

Study Design

The role of rubisco in photosynthesis, including adaptations of C3, C4, and CAM plants to maximise the efficiency of photosynthesis.

Key Takeaways

- C_4 **Photosynthesis**:
  - **Adapted for**: Hot, humid environments where high temperatures and high oxygen concentrations would otherwise promote photorespiration.
  - **Key Features**:
    - **Spatial Separation of Processes**:
      - **Mesophyll Cells**:
        - CO_2 enters the leaf and is initially fixed into a 4-carbon compound (usually oxaloacetate) by ________________, an enzyme with no affinity for oxygen.
        - Oxaloacetate is then converted into malate, a stable intermediate, which is transported to bundle sheath cells.
      - **Bundle Sheath Cells**:
        - Malate releases CO_2, creating a ______________________ around Rubisco, ensuring that Rubisco binds with ____ rather than oxygen.
        - The Calvin Cycle operates in these cells to produce glucose.
      - **Key Enzymes**:
        - PEP carboxylase for the initial fixation of CO_2.
        - Rubisco operates only in CO_2-enriched bundle sheath cells, minimising photorespiration.

- **Energy Costs**:
  - Additional ATP is required to transport malate and regenerate PEP (phosphoenolpyruvate), but this is compensated by the reduction in photorespiration.
- **Examples**: Corn, sugarcane, millet, sorghum.

- CAM **Photosynthesis**:
  - **Adapted for**: ____.
  - **Key Features**:
    - **Temporal Separation of Processes**:
      - **Night**:
        - Stomata opens during cooler, more humid nighttime conditions to minimise water loss.
        - CO_2 is fixed into oxaloacetate by ________________ and stored as malate in vacuoles.
      - **Day**:
        - Stomata remains closed to conserve water.
        - Malate is transported from __________ to the chloroplast, where it releases CO_2 for the Calvin Cycle.
        - The ___________________________ reduces the risk of photorespiration even in high temperatures.
    - **Energy Costs**:
      - CAM is energy-intensive due to the storage and controlled release of malate.
      - ATP is required to regenerate PEP for repeated CO_2 fixation.
  - **Examples**: ______________________________.

Learning Objective: [2.1.5] - Use data to identify an unknown plant as $C3$, $C4$, or CAM with reference to conditions where they perform photosynthesis best

Key Takeaways

- **Key Indicators in Data:**
  - $C3$ **Plants**: Moderate temperatures ($15–25°C$), high photorespiration under high oxygen conditions, and significant water loss during the day.
  - $C4$ **Plants**: High temperatures ($30–40°C$), low photorespiration due to CO_2 concentration mechanisms, and moderate water efficiency.
  - CAM **Plants**: Extreme heat ($> 40°C$), minimal photorespiration, stomata open at night to conserve water, very slow growth.

Learning Objective: [2.1.6] – Identify & explain the factors - light colour, intensity, CO_2 concentration, temperature, water availability - that affect the efficiency of photosynthesis

Study Design

The role of rubisco in photosynthesis, including adaptations of $C3$, $C4$, and CAM plants to maximise the efficiency of photosynthesis.

Key Takeaways

- **Light Intensity:**
  - ____.
  - Saturation occurs when enzymes and substrates are fully utilised.
- **Temperature:**
  - ____.
  - Beyond the optimal range, enzymes denature, and photorespiration increases.

- **Water Availability**:
  - ____.
  - ____.
- CO_2 **Concentration**:
  - Higher levels increase the rate of photosynthesis until Rubisco is saturated.
- **Light Wavelength**:
  - ____.

Learning Objective: [2.1.7] - Apply experimental principles to investigate factors affecting the rate of photosynthesis

Key Takeaways

- This objective can be achieved by applying the information in **[2.1.6]** to design experiments that test the impact of individual or combined factors such as light intensity, CO_2 concentration, or temperature on photosynthesis. By controlling variables and measuring outputs (e.g., oxygen release, and starch production), the specific role of each factor can be analysed.

Learning Objective: [2.1.8] - Explain how CRISPR-Cas9 can be used to increase photosynthetic efficiency

Study Design

Potential uses and applications of CRISPR-Cas9 technologies to improve photosynthetic efficiencies and crop yields.

Key Takeaways

- **Potential Improvements**:
  - **Rubisco Efficiency**: ____.
  - C4 **and** CAM **Pathways**: ____.
  - **Environmental Tolerance**: ____.
  - **Yield Enhancement**: ____.
- **Steps in** CRISPR **Application**:
  1. ____.
  2. ____________________________.
  3. __________________________________.
  4. ______________________________________.

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