Chapter 11: Photosynthesis in Higher Plants

Exercises — Exercises

Q1 By looking at a plant externally, can you tell whether a plant is C3 or C4? Why and how?

SOLUTION

No, it is not possible to determine whether a plant is C3 or C4 by merely looking at its external appearance.

Both C3 and C4 plants look similar from the outside — they are green, bear leaves, and show no obvious structural difference visible to the naked eye.

However, there are certain external clues that may suggest C4 status:

C4 plants are typically adapted to dry, tropical, or high-light environments. Examples include maize (corn), sorghum, and sugarcane — tall, robust grasses that grow in hot, sunny regions.

C4 plants tend to have higher biomass productivity and may appear more vigorous under high-light, high-temperature conditions compared to C3 plants in the same environment.

Despite these tendencies, these are indirect indicators, not definitive proof. The only reliable way to classify a plant as C3 or C4 requires examining its internal leaf anatomy (Kranz anatomy) or biochemical tests.

Answer: No. External appearance alone cannot distinguish C3 from C4 plants. Both look similar; classification requires examination of internal leaf anatomy (Kranz anatomy) or biochemical analysis.

Q2 By looking at which internal structure of a plant you can tell whether a plant is C3 or C4? Explain.

SOLUTION

By examining the internal anatomy of the leaf in a cross-section (vertical section), one can distinguish C3 from C4 plants.

The key distinguishing feature is the presence or absence of Kranz anatomy:

C4 plants — Kranz anatomy present:

The vascular bundles are surrounded by a ring of large, thick-walled bundle sheath cells that contain numerous chloroplasts.

The bundle sheath cells are surrounded by mesophyll cells arranged

concentrically around them.

Bundle sheath cells have chloroplasts with well-developed grana and stroma, and their walls are impervious to gaseous exchange.

'Kranz' means 'wreath' in German, referring to this wreath-like arrangement of bundle sheath cells around the vascular bundle.

C3 plants — Kranz anatomy absent:

The bundle sheath cells, if present, are small, thin-walled, and contain few or no chloroplasts.

Mesophyll cells are not arranged in a concentric pattern around the vascular bundles.

All mesophyll cells carry out Calvin cycle (C3 pathway) directly.

In summary: the presence of large, chloroplast-rich bundle sheath cells forming a wreath around vascular bundles (Kranz anatomy) is the definitive internal marker for C4 plants.

Answer: The internal leaf cross-section showing Kranz anatomy identifies a C4 plant. C4 plants have large, chloroplast-rich bundle sheath cells forming a wreath-like arrangement around vascular bundles, absent in C3 plants.

Q3 Even though a very few cells in a C4 plant carry out the biosynthetic – Calvin pathway, yet they are highly productive. Can you discuss why?

SOLUTION

In C4 plants, the Calvin cycle (C3 pathway / biosynthetic phase) is restricted to the bundle sheath cells, which constitute a relatively small proportion of the total leaf cells.

Despite this, C4 plants are highly productive for the following reasons:

1. Efficient CO_2 concentration mechanism: Mesophyll cells fix CO_2 into a 4-carbon compound (oxaloacetate/OAA) using PEP carboxylase (PEPcase). These C4 acids are transported to bundle sheath cells, where they are decarboxylated to release a high concentration of CO_2 directly at the site of RuBisCO. This CO_2 pump ensures RuBisCO in bundle sheath cells always operates in a high-CO_2 environment.

2. Absence of photorespiration: Because CO_2 concentration around RuBisCO is kept very high, the oxygenase activity of RuBisCO is suppressed. Photorespiration (which wastes fixed carbon and ATP in C3 plants) is essentially absent in C4 plants, leading to more efficient carbon fixation.

3. Efficient use of ATP and NADPH: Since no carbon is lost to photorespiration, all the ATP and NADPH produced in the light reactions is channelled productively into the Calvin cycle for sugar synthesis.
4. Adaptation to high light and temperature: C4 plants thrive under conditions (high temperature, high light intensity) where C3 plants suffer increased photorespiration, giving C4 plants a further productivity advantage.
Thus, even though the Calvin cycle is confined to few bundle sheath cells, the highly concentrated CO_2 supply to these cells and the elimination of photorespiratory losses result in very high overall productivity.

Answer: C4 plants are highly productive because the C4 pathway concentrates CO_2 in bundle sheath cells (where Calvin cycle occurs), suppressing photorespiration. RuBisCO thus operates efficiently as a carboxylase, maximising carbon fixation despite the Calvin cycle being restricted to few cells.

Q4 RuBisCO is an enzyme that acts both as a carboxylase and oxygenase. Why do you think RuBisCO carries out more carboxylation in C4 plants?

SOLUTION

RuBisCO (Ribulose bisphosphate carboxylase-oxygenase) has an active site that can bind to both CO_2 and O_2. The reaction it catalyses depends on the relative concentrations of these two gases at its active site.
In C4 plants, RuBisCO carries out more carboxylation (and less oxygenation) because of the CO_2 concentrating mechanism:
Step 1 — Initial CO_2 fixation in mesophyll cells: CO_2 from the atmosphere is first fixed by PEP carboxylase (PEPcase) in mesophyll cells to form the 4-carbon acid oxaloacetate (OAA). PEPcase has a very high affinity for CO_2 and does not bind O_2, so it efficiently scavenges even low atmospheric CO_2.
Step 2 — Transport of C4 acids to bundle sheath cells: The C4 acids (OAA, malate or aspartate) are transported from mesophyll cells to bundle sheath cells.
Step 3 — Decarboxylation in bundle sheath cells: In bundle sheath cells, these C4 acids are broken down to release CO_2 (and a 3-carbon molecule). This releases a large burst of CO_2 directly inside the bundle sheath cells.
Step 4 — High CO_2 around RuBisCO: The CO_2 concentration around RuBisCO in the bundle sheath cells becomes very high. Since the binding of CO_2 and O_2 to RuBisCO is competitive, the high CO_2:O_2 ratio strongly favours the carboxylase reaction over the oxygenase reaction.

As a result, RuBisCO in C4 plants functions almost exclusively as a carboxylase, and photorespiration (caused by its oxygenase activity) is negligible.

Answer: In C4 plants, the C4-acid shuttle (PEPcase in mesophyll cells) concentrates CO_2 in bundle sheath cells where RuBisCO is located. The elevated CO_2:O_2 ratio at the active site favours carboxylation over oxygenation, so RuBisCO acts predominantly as a carboxylase with negligible photorespiration.

Q5 Suppose there were plants that had a high concentration of Chlorophyll b, but lacked chlorophyll a, would it carry out photosynthesis? Then why do plants have chlorophyll b and other accessory pigments?

SOLUTION

No, a plant with only chlorophyll b (and no chlorophyll a) would NOT be able to carry out photosynthesis.

Reason: Chlorophyll a is the primary photosynthetic pigment and is indispensable for photosynthesis. It forms the reaction centre of both photosystem I (as P700) and photosystem II (as P680). The reaction centre chlorophyll a is the molecule that actually undergoes photoexcitation and transfers electrons to initiate the light reactions. No other pigment can substitute for this function.

Chlorophyll b, xanthophylls, and carotenoids are accessory pigments. They can absorb light energy but they cannot directly drive the photochemical reactions — they must transfer their absorbed energy to chlorophyll a.

Why do plants have chlorophyll b and other accessory pigments?

1. Broadening the absorption spectrum: Chlorophyll a absorbs mainly red (~680-700 nm) and blue (~430 nm) wavelengths. Accessory pigments absorb different wavelengths (e.g., chlorophyll b absorbs blue-violet; carotenoids and xanthophylls absorb blue-green, yellow). This allows the plant to harvest a wider range of wavelengths from the solar spectrum, increasing overall efficiency of light capture.
2. Protection against photo-oxidation: Accessory pigments (especially carotenoids) protect chlorophyll a from destruction by excess light energy. They dissipate or quench excess light energy, preventing photooxidative damage.
3. Energy transfer to reaction centre: They form the light-harvesting complexes (LHC) or antenna, funnelling absorbed energy to the reaction centre chlorophyll a, thus amplifying the light energy available for photosynthesis.

Answer: No. Without chlorophyll a, photosynthesis cannot occur because only chlorophyll a forms the reaction centres (P700, P680) that drive electron excitation. Chlorophyll b and other accessory pigments widen the absorption spectrum and protect chlorophyll a from photo-oxidation, but must transfer energy to chlorophyll a — they cannot replace it.

Q6 Why is the colour of a leaf kept in the dark frequently becomes yellow, or pale green? Which pigment do you think is more stable?

SOLUTION

When a leaf is kept in the dark for a prolonged period, it loses its green colour and becomes yellow or pale green.

Reason: Chlorophylls (both chlorophyll a and chlorophyll b) are relatively unstable pigments — they degrade and are broken down in the absence of light. Light is required for the continuous synthesis/replenishment of chlorophyll in leaves. Without light, the chlorophyll molecules are not regenerated as they break down.

Carotenoids and xanthophylls, on the other hand, are more chemically stable pigments. They do not break down as rapidly in the dark. Once chlorophyll degrades, the yellow-orange colours of carotenoids and xanthophylls are unmasked, giving the leaf its yellow or pale-yellow appearance.

This is the same process responsible for the yellowing of leaves in autumn — as chlorophyll breaks down faster than the carotenoids, the underlying yellow-orange pigments become visible.

The more stable pigment is the carotenoid (and xanthophyll group). These persist longer even when chlorophyll has broken down, revealing the yellow colour.

Answer: In the dark, chlorophyll degrades faster (no light-driven synthesis to replenish it). The more stable carotenoids and xanthophylls (yellow-orange) remain, making the leaf appear yellow or pale green. Carotenoids are the more stable pigments.

Q7 Look at leaves of the same plant on the shady side and compare it with the leaves on the sunny side. Or, compare the potted plants kept in the sunlight with those in the shade. Which of them has leaves that are darker green? Why?

SOLUTION

Leaves on the shady side (or plants kept in shade) are darker green compared to leaves on the sunny side (or plants in full sunlight).

Reason:

Plants in shade receive less light. As an adaptive response to low light availability, shade leaves develop a higher concentration of chlorophyll (and particularly chlorophyll b and accessory pigments) per unit area of leaf. This increases the leaf's light-harvesting capacity to capture as much of the available limited light as possible.

Shade leaves are also typically thinner and broader, with fewer but larger chloroplasts, maximising surface area for light absorption.

In contrast, sun leaves receive abundant light. They do not need to maximise chlorophyll content for light capture. Sun leaves tend to be smaller and thicker with more protective mechanisms (higher carotenoid content to protect against photooxidation), which dilutes the green colour.

The greater chlorophyll concentration in shade leaves gives them their characteristically darker green colour.

Answer: Shade leaves are darker green. Leaves in low-light conditions adapt by producing more chlorophyll per unit area to maximise light capture. Sun leaves have relatively less chlorophyll (higher carotenoid protection) and appear lighter green.

Q8 Figure 11.10 shows the effect of light on the rate of photosynthesis. Based on the graph, answer the following questions:

(a) At which point/s (A, B or C) in the curve light is a limiting factor?

(b) What could be the limiting factor/s in region A?

(c) What do C and D represent on the curve?

SOLUTION

(a) At which point/s (A, B or C) is light the limiting factor?

Light is a limiting factor at points A and B.

In the region from A to B, the rate of photosynthesis increases linearly as light intensity increases. This means light is directly limiting the rate — the more light provided, the more photosynthesis occurs. Beyond B the curve flattens, indicating

another factor becomes limiting.

(b) What could be the limiting factor/s in region A?
In region A (low light intensity), light itself is the primary limiting factor — the rate of photosynthesis is directly proportional to light intensity.
However, other factors can also limit the rate in region A, such as:
- CO_2 concentration (very low atmospheric CO_2 limits carbon fixation)
- Temperature (low temperature reduces enzyme activity in the dark reactions)
- Water availability
These factors interact, but at low light intensities, light is the principal limiting factor.

(c) What do C and D represent on the curve?
C (light saturation point): The plateau region where the rate of photosynthesis no longer increases despite increasing light intensity. At this point, some other factor (CO_2 concentration, temperature, or enzyme capacity) has become the new limiting factor. Adding more light does not increase the rate.
D (the x-axis intercept / compensation point context): D represents the point on the x-axis (high light intensity end) where, if light intensity increases further beyond the saturation point, excess light can cause photoinhibition — breakdown of chlorophyll and a decline in the rate of photosynthesis. D indicates the light intensity level at or beyond which further increase causes damage.

Answer: (a) Light is a limiting factor at points A and B. (b) In region A, limiting factors include light intensity, CO_2 concentration, and temperature. (c) C is the light saturation point (plateau where rate stops increasing); D indicates the light intensity beyond which excess light causes photoinhibition and rate declines.

Q9 Give comparison between the following:
(a) C3 and C4 pathways
(b) Cyclic and non-cyclic photophosphorylation
(c) Anatomy of leaf in C3 and C4 plants

SOLUTION

(a) Comparison of C3 and C4 Pathways:
C3 Pathway (Calvin Cycle):
- First CO_2 fixation product is a 3-carbon compound — 3-phosphoglyceric acid (3-PGA)
- Primary CO_2 acceptor is a 5-carbon compound — ribulose bisphosphate

(RuBP)
- CO_2 fixation enzyme is RuBisCO (present in mesophyll cells)
- Calvin cycle occurs in mesophyll cells
- Susceptible to photorespiration (RuBisCO acts as oxygenase at normal O_2:CO_2 ratios)
- Lower productivity under high light, high temperature, and low CO_2
- Temperature optimum: 20-25°C
- Examples: wheat, rice, pea, sunflower

C4 Pathway (Hatch-Slack Pathway):
- First CO_2 fixation product is a 4-carbon compound — oxaloacetic acid (OAA)
- Primary CO_2 acceptor in mesophyll is a 3-carbon compound — phosphoenol pyruvate (PEP)
- Initial CO_2 fixation enzyme is PEP carboxylase (PEPcase) in mesophyll cells; RuBisCO present in bundle sheath cells
- Initial carboxylation in mesophyll; Calvin cycle in bundle sheath cells
- No photorespiration (high CO_2 concentration in bundle sheath cells suppresses oxygenase activity of RuBisCO)
- Higher productivity and biomass yield under high light, high temperature
- Temperature optimum: 30-40°C
- Examples: maize, sorghum, sugarcane

(b) Comparison of Cyclic and Non-cyclic Photophosphorylation:
Cyclic Photophosphorylation:
- Only Photosystem I (PS I) is involved
- Electrons from P700 are excited and transferred to an acceptor, then cycled back through the electron transport chain to PS I
- Electrons do not leave the cycle — they return to the same chlorophyll molecule
- Products: Only ATP is produced; no NADPH is formed; no O_2 is evolved
- Water is not split
- Occurs in stroma lamellae (which lack PS II)
- Occurs when only light beyond 680 nm is available or when $NADP^+$ is not available

Non-cyclic Photophosphorylation:
- Both Photosystem I (PS I) and Photosystem II (PS II) are involved
- Electrons flow in a non-cyclic (linear) path — Z-scheme: PS II to electron transport chain to PS I to $NADP^+$

- Electrons do not return to the original chlorophyll; they are used to reduce NADP+ to NADPH
- Products: Both ATP and NADPH are produced; O2 is evolved from splitting of water
- Water is split at PS II to replenish electrons
- Occurs in thylakoid membranes of grana (which have both PS I and PS II)

(c) Comparison of Leaf Anatomy in C3 and C4 Plants:
C3 Leaf Anatomy:
- Kranz anatomy absent
- Bundle sheath cells are small, thin-walled, and contain few or no chloroplasts
- Mesophyll cells are loosely arranged, not in a concentric pattern around vascular bundles
- All mesophyll cells perform the Calvin cycle directly
- Only one type of photosynthetically active cell (mesophyll) for CO2 fixation
- Intercellular spaces present between mesophyll cells

C4 Leaf Anatomy (Kranz Anatomy):
- Kranz anatomy present — 'Kranz' means 'wreath' in German
- Bundle sheath cells are large, thick-walled, and contain numerous chloroplasts
- Bundle sheath cell walls are impervious to gaseous exchange (no intercellular spaces within bundle sheath)
- Mesophyll cells are arranged concentrically around bundle sheath cells
- Two types of photosynthetically active cells: mesophyll (initial C4 fixation) and bundle sheath (Calvin cycle)
- PEPcase present in mesophyll; RuBisCO present only in bundle sheath cells

Answer: (a) C3: first product PGA (3C), acceptor RuBP (5C), has photorespiration, lower productivity. C4: first product OAA (4C), acceptor PEP (3C), no photorespiration, higher productivity. (b) Cyclic: only PS I, only ATP produced, no O2 evolution; electrons return to PS I. Non-cyclic: both PS I and PS II, produces ATP + NADPH + O2; electrons flow linearly (Z-scheme). (c) C3: no Kranz anatomy, small bundle sheath, Calvin cycle in mesophyll. C4: Kranz anatomy present, large chloroplast-rich bundle sheath, initial fixation in mesophyll, Calvin cycle in bundle sheath.