TEACHING MATERIAL ON

Botany

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LECTURE NOTE ON CARBON FIXATION PATHWAYS - C4 PATHWAY DR KAMAL KANT PATRA, ASSOCIATE PROFESSOR, DEPARTMENT OF BOTANY, SCHOOL OF SCIENCE, YBN UNIVERSITY, RANCHI

Introduction

The C4 pathway, also known as the Hatch-Slack Pathway, is an adaptation found in certain plants to efficiently fix carbon dioxide in hot, arid environments. This pathway minimizes photorespiration and enhances photosynthetic efficiency by concentrating CO_2 around the enzyme RuBisCO.

C4 plants, such as maize, sugarcane, and sorghum, have specialized leaf anatomy with distinct **Kranz anatomy**. The mesophyll and bundle sheath cells work in tandem to achieve carbon fixation and the Calvin Cycle.

Key Features of the C4 Pathway

1. **Spatial Separation of Processes**:
   - Initial carbon fixation occurs in mesophyll cells.
   - The Calvin Cycle operates in bundle sheath cells.
2. **Reduction of Photorespiration**:
   - By concentrating CO_2 around RuBisCO, oxygenation is minimized.
3. **Enzyme Specialization**:
   - PEP carboxylase fixes CO_2 into a 4-carbon compound in the mesophyll cells.
   - RuBisCO operates exclusively in bundle sheath cells where oxygen concentration is low.

Steps in the C4 Pathway

1. Carbon Fixation in Mesophyll Cells

- **Enzyme Involved**: Phosphoenolpyruvate (PEP) carboxylase.
- **Reaction**:

  PEP (3C) + CO_2 → Oxaloacetate (OAA, 4C)

  - PEP carboxylase has a high affinity for CO_2 and does not bind O_2, thus avoiding photorespiration.
- Oxaloacetate is converted to **malate** or **aspartate**, both 4-carbon compounds.

2. Transport to Bundle Sheath Cells

- Malate (or aspartate) is transported from the mesophyll cells to the bundle sheath cells via plasmodesmata.

3. Decarboxylation in Bundle Sheath Cells

- **Reaction**:

  Malate (4C) → Pyruvate (3C) + CO_2

  - Enzyme: Malic enzyme.
  - The released CO_2 is concentrated around RuBisCO, facilitating its fixation in the Calvin Cycle.

4. Calvin Cycle in Bundle Sheath Cells

- CO_2 enters the Calvin Cycle and combines with RuBP (Ribulose-1,5-bisphosphate) to form 3-phosphoglycerate (3-PGA).
- The Calvin Cycle proceeds as usual to produce glucose.

5. Regeneration of PEP in Mesophyll Cells

- Pyruvate (3C) is transported back to mesophyll cells.
- **Reaction**:

  Pyruvate + ATP → PEP + AMP

  - Enzyme: Pyruvate phosphate dikinase (PPDK).
  - ATP is consumed in this step, contributing to the energy cost of the C4 pathway.

Energetic Cost of the C4 Pathway

- The C4 pathway requires **30 ATP molecules** to synthesize one glucose molecule, compared to 18 ATP molecules in the C3 pathway.
- However, this energy investment is offset by the efficiency gained through reduced photorespiration under high-temperature, high-light conditions.

Kranz Anatomy

- C4 plants exhibit a unique leaf anatomy called **Kranz anatomy**:
  - **Mesophyll cells**:
    - Surround the bundle sheath cells and fix CO2 initially.
  - **Bundle sheath cells**:
    - Located closer to vascular tissue and contain RuBisCO for the Calvin Cycle.
  - The physical separation of these cells minimizes oxygen interference during the Calvin Cycle.

Adaptations and Advantages of C4 Pathway

1. **Minimized Photorespiration**:

- The spatial separation of CO_2 fixation and the Calvin Cycle reduces oxygenation by RuBisCO.

2. **Efficient Water Use**:
    - Stomata in C4 plants can remain partially closed, reducing water loss.
3. **High Photosynthetic Efficiency**:
    - Effective even in high temperatures and light intensity.
4. **Survival in Arid Climates**:
    - C4 plants dominate in tropical and subtropical regions.

Summary of Reactions

Mesophyll Cells:

1. **CO2 Fixation**:

    PEP + CO_2 → Oxaloacetate (OAA)

2. **Conversion**:

    OAA → Malate/Aspartate

Bundle Sheath Cells:

3. **Decarboxylation**:

    Malate → Pyruvate + CO_2

4. **Calvin Cycle**:

    CO_2 + RuBP → 3-PGA (via RuBisCO)

Regeneration:

5. **PEP Regeneration in Mesophyll**:

Pyruvate + ATP → PEP

Diagram Explanation

The diagram for the C4 pathway should illustrate the following:

1. **Kranz Anatomy**:
   - A cross-section of a C4 leaf showing mesophyll and bundle sheath cells.
2. **Pathway Flow**:
   - Highlight the movement of CO_2, PEP, OAA, malate/aspartate, pyruvate, and ATP.
   - Indicate spatial separation of processes.
3. **Enzymatic Reactions**:
   - Show PEP carboxylase activity in mesophyll cells.
   - Depict CO_2 fixation by RuBisCO in bundle sheath cells.

Conclusion

The C4 pathway represents an evolutionary adaptation to high-temperature and low-CO_2 environments. By concentrating CO_2 around RuBisCO, it minimizes photorespiration and ensures efficient carbon fixation. Understanding this pathway provides insights into plant physiology and adaptation strategies in challenging climates.