Photosynthesis
(continued lect. 3..)
Photosynthetic Apparatus

**Light Reaction**
- **Chloroplast**
  - Chloroplast lamellae (membranes)
    - Packed full of photosynthetic pigments
    - Stroma lamellae (double lamella)
    - Grana lamellae (stacked lamella)
- **Stroma**
  - A less dense fluid filled area where the reduction of CO$_2$ occurs (convert CO2 into sugar)
  - The transformation of light energy to chemical energy (photophosphorylation) occurs in the lamellae
The Chloroplast

Figure 22-2
Rate Limitation in Photosynthesis

- Rate of Pn will influence crop growth rate and finally food production.
- The three important rate-limiting factors are:
  - Level of CO$_2$,
  - Light level, and
  - Temperature
  - Water (indirectly, related to CO$_2$)
Figure 2.3  The relationship between the rate of photosynthesis and CO$_2$ concentration in _Hormidiunum_ for different light levels and temperatures.
The Biochemistry of Photosynthesis

- The central reaction of Pn takes place in Chloroplast.
- There are two distinct stages;
  - **Light Reactions**: takes place on the internal membrane of the chl. Whereby light of certain wavelength is trapped and converted to chemical energy by a series of steps
Cont.

- Dark reactions or CO$_2$ fixation
  Whereby CO$_2$ is ‘fixed’ and reduced to organic compounds (typically sugars) by a series of steps.

Takes place in stroma.
Figure 2.15  Summary of photosynthesis.
(a) The light reactions.  (b) CO₂ fixation or the dark reactions.
Light Reaction (cont.)

- Consists of the oxidation of water and production of chemical potential or reduced Nicotinamide adenine dinucleotide phosphate (NADPH) and the phosphorylation of adenosine diphosphate (ADP) to adenosine triphosphate (ATP)

1. NADPH is one of the most powerful reductants (acceptors of electrons and suppliers of hydrogen ions) known in biological systems
2. ATP is synonymous with available energy in the biological system (when a phosphate group is released from ATP, energy is also released). The released phosphate, attaching to some molecule (phosphorylation) by an energy input, raises the energy of the molecule and allowing it to undergo even more biochemical reactions

- Both NADPH and ATP are needed to convert CO₂ to organic molecules in dark reaction
The Photosystems in Photosynthesis

- Photosystem I and photosystem II.

- PS I and PS II have complementary roles which is photophosphorylation (generation of ATP).
Electron Transport System During Light Reaction

- Fairly well understood

- 2 reaction centres exist where energy from absorbed photons are used to drive the system
  - After a pigment has absorbed a photon of light, the energy lifts an electron from a ground to an excited energy state

- While in the excited state the pigment molecule can donate and accept electrons from other molecules
FIGURE 7.22 The transfer of electrons and protons in the thylakoid membrane is carried out vectorially by four protein complexes. Water is oxidized and protons are released in the lumen by PSII. PSI reduces NADP$^+$ to NADPH in the stroma, via the action of ferredoxin (Fd) and the flavoprotein ferredoxin–NADP reductase (FNR). Protons are also transported into the lumen by the action of the cytochrome $b_{6}f$ complex and contribute to the electrochemical proton...
Electron Transport System (cont.)

- Photosystem I uses more energy absorbed from photons to catalyse the removal of electrons from Q
  - This sets up the energy required for photophosphorylation (ATP formation) and the reduction of NADP$^+$ to NADPH

- **Remember**: light reactions transform light energy to the short-term chemical energy of ATP and NADPH
  - ATP and NADPH are used to reduce CO$_2$ to stable organic forms from which dry weight results.
Salient Points During Electron Transport

- Involvement of light harvesting protein complexes in thylakoid membranes
- Photosystem II catalyses the removal of electrons from water molecules and liberation of oxygen.
- Generation of ATP from ADP + P$_i$
- Generation of NADPH from NADP$^+$ + H$^+$
During light reaction, energy available to the system is utilized

- To build the chemi-osmotic or proton gradient.

- Generate ATP.

- Reduce NADP+ to NADPH.
The Biochemistry of Photosynthesis

- The Dark Reaction or CO₂ Fixation
Carbon Dioxide Fixation

- Agriculture is based on yield or weight of crop products
- Dry matter production is dependent upon the balance of CO$_2$ (Pn) uptake and CO$_2$ evolution
- During growth, respiration accounts for 25 - 30% of total photosynthesis
The pathway by which all eukaryotic organisms incorporate CO$_2$ into carbohydrate is known as carbon fixation or the photosynthetic carbon reduction (PCR) cycle.

Pathway was determined through the use of radiolabelled CO$_2$ ($^{14}$C).

CO$_2$ fixation is catalysed by the enzyme ribulose bis-phosphate (RuBP) carboxylase oxygenase (Rubisco).

Rubisco is the most abundant protein in the world accounting for 50% of protein in leaves.
Carbon Dioxide Fixation (cont.)

- 5 carbon sugar: ribulose 1,5 bisphosphate (RuBP) is the acceptor molecule for which a 3 carbon molecule is made.
- ATP produced in photophosphorylation is used to convert ribulose-5-phosphate to RuBP which is extremely unstable and is quickly hydrolysed into 2 molecules of 3-PGA.
- After CO$_2$ fixation, ATP along with the reduced nucleotides from the light process, change the 3-phosphoglyceric acid (3-PGA) to 3-phosphoglyceraldehyde (3-PGald).
Fig. 1.13. The Calvin cycle, a model of CO₂ fixation as it occurs in a C₃ photosynthesizing chloroplast.
Light energy

(a) Energy-transduction reactions (thylakoid membrane)

Outer membrane of chloroplast

Inner membrane of chloroplast

(b) Carbon-fixation reactions (stroma)

CO₂

Calvin cycle

Sugars

P₅ + ADP → ATP

H⁺ + NADP⁺ → NADPH

2e⁻ → H₂O

2H⁺ + 1/2 O₂
The Reactions of the Calvin cycle

- 3 cycles involve:
  - Carboxylation
  - Reduction
  - Regeneration
Light reactions

Cycle begins here:
- 3 molecules of carbon dioxide (CO₂) (3 × 1 carbon)
- 3 molecules of unstable intermediate (3 × 6 carbons)

(a) Stage 1: Fixation
- 3 molecules of ribulose 1,5-bisphosphate (RuBP) (3 × 5 carbons)
- 6 molecules of 3-phosphoglycerate (PGA) (6 × 3 carbons)

(b) Stage 2: Reduction
- 5 molecules of glyceraldehyde 3-phosphate (PGAL) (5 × 3 carbons)
- 6 molecules of 1,3-bisphosphoglycerate (6 × 3 carbons)

(c) Stage 3: Regeneration of acceptor
- 1 molecule of glyceraldehyde 3-phosphate (PGAL) (1 × 3 carbons)

Synthesis of sugars, starch, amino acids, and fatty acids

Calvin cycle (3 turns)
The Calvin cycle

- **Carboxylation**

  Carbon dioxide \((C_1)\) combines with RuBP \((C_5, \text{ acceptor})\) to give 2 molecules of 3-carbon acid (PGA).

  Enzyme involves is Rubisco (ribulose biphosphosphate carboxylase/oxygenase).

  ATPs from light reactions are used.
1. Carboxilation

Ribulose 1,5-bisphosphate (RuBP) + CO$_2$ + H$_2$O → 2 Molecules of 3-phosphoglycerate (PGA)
The Calvin cycle

- **Reduction**
  PGA is reduced to form glyceraldehyde 3-phosphate (also known as triose phosphate).
  NADPH from light reactions are used.
  Only one molecule of triose phosphate is used to produce end products.
2. Reduction

\[
\begin{align*}
&\text{3-Phosphoglycerate (PGA)} \\
&\quad \text{ATP} \quad \text{ADP} \\
&\quad \text{3-Phosphoglycerate kinase} \\
&\quad \text{1,3-Bisphosphoglycerate} \\
&\quad \text{H}^+ \quad \text{NADPH} \quad \text{NADP}^+ \\
&\quad \text{Glyceraldehyde 3-phosphate dehydrogenase} \\
&\quad \text{Glyceraldehyde 3-phosphate (PGAL)}
\end{align*}
\]
The Calvin cycle

- **Regeneration**

  5 molecules of triose phosphate is used to produced more RuBP for the next cycle.

  ATP from light reactions.
Photorespiration

- Involves uptake of oxygen and release of carbon dioxide in green leaves.
- Most pronounced in high light and high temperature
- Why we concerned? A process of loss of carbon during Calvin cycle.
(a) Rubisco carboxylase activity

\[ \text{RuBP} \rightarrow \text{3-Phosphoglycerate (PGA)} \]

(b) Rubisco oxygenase activity

\[ \text{O}_2 \rightarrow \text{3-Phosphoglycerate (PGA)} \]

\[ \text{RuBP carboxylase/oxygenase (Rubisco)} \]

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{HCOH} \]

\[ \text{CH}_2 - \text{O} - \text{P} \]

\[ \text{CH}_2 - \text{O} - \text{P} \]

\[ \text{COO}^- \]

\[ \text{CH}_2 - \text{OH} \rightarrow \text{Glycolate} \]

\[ \text{P}_i \]

\[ \text{O}_2 \rightarrow \text{CO}_2 \]

\[ \text{HCOH} \]

\[ \text{CH}_2 - \text{O} - \text{P} \]

\[ \text{to Calvin cycle} \]

\[ \text{to Calvin cycle} \]
The process of photorespiration

- Starts with enzyme Rubisco which acts as oxygenase.

- $\text{RuBP} + \text{O}_2 \rightarrow \text{PGA} + \text{phosphoglycololate}$

This phosphoglycololate cannot enter Calvin cycle. Converted to glycolate in chloroplast. It is a complex process which involves Chloroplast, Peroxisome and Mitochondria.
Fig. 1.15. Pathway of photorespiration in a leaf mesophyll cell of a $C_3$ photosynthesizing plant.
In 1966, Hatch and Slack presented evidence that another pathway for CO$_2$ fixation exists.

1st product from the mesophyll is a 4C compound

Pathway incorporates CO$_2$ using phosphoenolpyruvate (PEP) carboxylase enzyme

ATP produced in photophosphorylation is used to convert pyruvate to PEP
The PEP (3C) is carboxylated to three four-carbon acids (oxaloacetate, malate, and aspartate).

These acids are converted to the vascular sheath cells where they are converted to pyruvate.

In the change to pyruvate, a carbon is released that is converted, either by addition to RuBP or by addition to a two-carbon molecule to 3-PGA by RUBP carboxylase.

After 3-PGA is produced, the Calvin cycle is operative.
The C4 Pathway of Tropical Plants

Figure 22-34
Schematic diagram of the essential features of the C4 pathway. CO2 is concentrated in bundle-sheath cells by the expenditure of ATP.
Phosphoenolpyruvate (PEP) \[\xrightarrow{\text{PEP carboxylase}}\] Oxaloacetate

\[\xrightarrow{\text{Aspartate}}\] Malate
Fig. 1.14. CO₂ movement and fixation in a C₃ photosynthesizing plant.
Comparing C3 and C4 Species

- Anatomical differences

- C4 species have chloroplasts in the vascular sheath cells, C3 species do not.

- Chloroplasts in mesophyll of C3 and C4 are structurally similar but no starch is produced in C4 plants (just 4C compounds).

- Chloroplasts in vascular sheath cells of C4 species are larger and have less developed grana than in mesophyll cell chloroplasts (since Calvin cycle is operative, they store starch).
Differences between C3 and C4

- **Physiological differences**
  
  C4 able to maintain high concentration of CO$_2$ in bundle–sheath cell thus, avoid wasteful photorespiration.
**TABLE 10.1** A comparison of significant features of C3 and C4 plants.

<table>
<thead>
<tr>
<th>Feature</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photorespiration</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>CO₂ compensation (μl CO₂ l⁻¹)</td>
<td>20–100</td>
<td>0–5</td>
</tr>
<tr>
<td>Temperature optimum (°C)</td>
<td>20–25</td>
<td>30–45</td>
</tr>
<tr>
<td>photosynthesis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubisco</td>
<td>20–25</td>
<td></td>
</tr>
<tr>
<td>PEPcase</td>
<td></td>
<td>30–35</td>
</tr>
<tr>
<td>Quantum yield as a function of temperature</td>
<td>declining</td>
<td>steady</td>
</tr>
<tr>
<td>Transpiration Ratio</td>
<td>500–1000</td>
<td>200–350</td>
</tr>
<tr>
<td>Light saturation (μmole photons)</td>
<td>400–500</td>
<td>does not saturate</td>
</tr>
</tbody>
</table>
Crassulation Acid Metabolism (CAM) Plants

- Occurs predominately in succulent plants
- Adapted to arid conditions where low transpiration is a survival necessity
- Stomata are closed during the day and open at night to absorb CO$_2$.
- Domestic examples of CAM plants:
  - Pineapple, cactus
- Fix CO$_2$ into 4-C acids with PEP carboxylase only at night when stomata are open and energy required comes from glycolysis
Stage 1: Initial fixation of CO₂ to form 4-carbon acids

Stage 2: Release of CO₂ to Calvin cycle

(a) C₄ photosynthesis

(b) CAM photosynthesis
Comparison Between C4 and CAM

- The first product when CO2 is fixed is the same (the C-4 carbon).
- Low photorespiration occurs in C4 and CAM pathways, although the exact mechanisms are different.
Comparison Between C4 and CAM (cont.)

- Different time of the day to fix CO2. CAM at night, C4 during daytime.
- Fixation of CO2 and Calvin cycle occur in different cells in C4. However, in CAM both processes occur in the same cell (single cell).
(a) Night: stomata open
(b) Day: stomata closed
Summary of Pn

- Pn in green plant is mediated by two photosystems located in thylokoïd membranes of chloroplast.
- Electrons from PS II flow to PSI through the cytochrome $bf$ complex.
- ATP and NADPH form in the light rxn of Pn are used to convert CO2 into hexoses and other organic cpds.
Summary of Pn

- The dark phase of photosynthesis, called the Calvin cycle, starts with the reaction of CO2 with RuBP.
- Three ATP and two NADPH molecules are consumed for each CO2 converted into a hexose.
- The recycling of phosphoglycolate leads to CO2 production and further consumption of O2 is called photorespiration.
Photorespiration is a wasteful reaction, but is minimized in tropical plants by concentrating CO2 at the site of Calvin cycle.

The C4 pathway enable tropical plants to take advantage of high light level and minimized the oxygenation of ribulose 1,5-bisphosphate (RuBP).
End

STOP