Biology 1002B Cycle 4: Primary Metabolism Breakdown

Introduction

Dear Student,

Thank you for opening this cycle breakdown for Bio 1002B. This resource has been created by the Education Team at WebStraw. The Education Team consists of students that have previously taken and/or students that are currently taking Bio 1002B.

Purpose

This resource focuses on key concepts that are important for students to understand to succeed within this course. This resource was created by students for other students. Our goal is to help students (1) further develop their understanding of course content and (2) achieve greater academic success. (3) Our resource is also open access meaning there are no financial or legal barriers to students who wish to access and use our resource.

Instructions

To maximize the benefits of this resource, we recommend that you read carefully through the cycle breakdown with specific focus on bolded terms and the “Think about it” paragraphs. Then, try applying your knowledge with some of our custom-made questions at the end of this document. Make sure you already have a good understanding of course content before using this resource, as it will not cover all testable content!

Disclaimer

This resource is supplementary to your course content and is not meant to (1) replace any of the resources provided to you by your instructor nor is it meant to (2) be used as a tool to learn the course material from scratch. We assume that students who use this resource will have a basic understanding of the course content. This resource does not contain everything you need to know for your evaluations. Please refer to the course material provided by your instructors if there are any discrepancies between our resource and your course content.

We wish you the best of luck on your exams!

- The WebStraw Team

Note to Instructors:
If this resource has been created for your course and you would like to collaborate with us, please email us at team@webstraw.ca

Types of Consumers

Autotrophs are organisms that can produce their own food using light, water, carbon dioxide, or other chemicals. A subtype of the autotroph is the **photoautotrophs**, which can carry out photosynthesis. **Heterotrophs** cannot make their own food by carbon fixation and instead acquire their nutrition from other sources (i.e. plants and animals).

In photosynthesis, water is oxidized, and carbon dioxide is reduced to produce glucose and oxygen. There are two stages of photosynthesis: the light-dependent reactions and the light-independent reactions (or the Calvin cycle).

The **light-dependent reactions** take place in the **thylakoid membranes** and are responsible for capturing light energy by chlorophyll and using that to synthesize NADPH and ATP (oxidizing H2O and releasing O2 in the process). The **light-independent reactions** take place in the **chloroplasts** and use the electrons and protons carried by NADPH and the energy of ATP hydrolysis to convert CO2 into a solid carbohydrate (**carbon fixation**).

Photosynthetic Thermodynamics

Photosynthesis is the light-dependent reduction of CO_2. It is a non-spontaneous, endergonic reaction driven by light energy. CO_2 has high entropy being a gas, so energy is required in the conversion of CO_2 to its reduced form (glucose). Glucose has more free energy within its bonds. This process is represented by the following chemical equation:

$$6CO_2 + 6H_2O + (\text{energy}) \rightarrow C_6H_{12}O_6 + 6O_2$$

In this reaction, CO2 is reduced (coupled to the oxidation of water) to produce glucose and oxygen.

Chloroplast Structure

The main structures within the chloroplast are the membranous stacks or the **thylakoids**. The aqueous space within the thylakoid is referred to as the **lumen**. The **thylakoid membrane** separates the lumen of the thylakoid from the stroma of the chloroplast. Photosystems I and II (as well as chlorophyll) are embedded within the thylakoid membrane. The light reactions occur along the thylakoid membrane. The aqueous compartment inside the chloroplast (analogous to cytosol within a cell) is called the **<u>stroma</u>**; it contains salts, ions, enzymes and metabolites. The stroma also contains the chloroplast's circular genome and the machinery required to transcribe and translate it.

The chloroplast genome encodes proteins fundamental to the functioning of the chloroplast. Many chloroplast proteins are encoded in the nuclear genome, however, and imported into the chloroplast. The chloroplast genome does code for a protein called **D1** that is a critical component of photosystem II. D1 is transcribed and translated in the stroma.

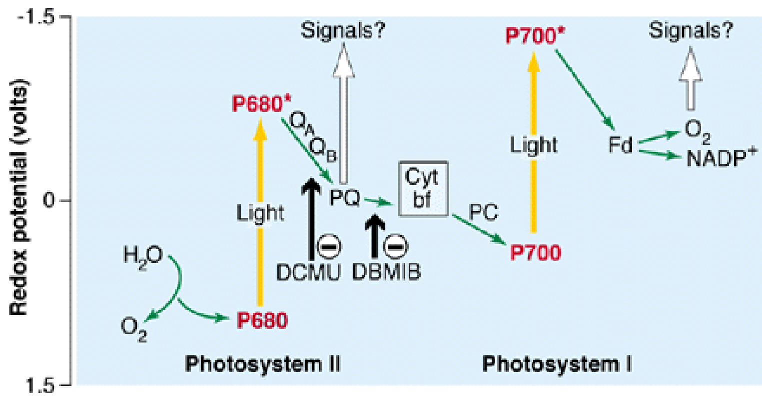
Electron Transport Chain

Photosynthetic electron transport occurs during the light-dependent reactions. Its goal is to ultimately reduce NADP+ to produce NADPH.

Light strikes the antenna complex in photosystem II and reaches the reaction centre where an electron in the chlorophyll is excited. Chlorophyll is oxidized by the primary acceptor and the electron flows through multiple protein complexes to ultimately reduce NADP+ and produce NADPH. Note that the source of electrons for the ETC is water, which is oxidized at the oxygen-evolving complex at photosystem II.

Electron transport is coupled to the proton pumping (movement of protons from the stroma into the lumen) to generate a proton concentration gradient. The proton motive force that is created by proton pumping during electron transport is used to synthesize ATP. The only way for the protons to move back into the stroma, is through ATP synthase. As the protons flow down their concentration gradient through ATP synthase, the complex acts as a molecular motor, driving the catalysis of ATP from ADP and Pi.

Redox potential is essentially the tendency of a molecule to gain electrons or lose electrons, thereby being reduced or oxidized (respectively). The more negative the redox potential is, the easier it is to oxidize an electron from that molecule. By contrast, the more positive the redox potential is, the greater that molecule's affinity for electrons (the harder it is to pull an electron away from that molecule). Electrons acceptors will always have a slightly more positive redox potential from the molecule with which it is extracting its electron. As photons of light hit the photosystem, the redox potentials of the photosystem become more negative, making them easier to be oxidized.



Science

Why does photosynthesis require light and what is it used for?
Photosynthesis needs light in order to excite the electrons in chlorophyll. Once electrons are in an excited state, they are easier to oxidize by the primary acceptor. Light also lowers the redox potential of chlorophyll, making it more negative and easier for the primary acceptor to remove an electron.

Anoxygenic vs. Oxygenic Photosynthesis

Anoxygenic photosynthesis uses hydrogen sulphide as an electron donor and, as the name suggests, oxygen is not produced. The evolution of the oxygen-evolving complex in bacteria that performed anoxygenic photosynthesis led to cyanobacteria that could perform oxygenic photosynthesis. **Oxygenic photosynthesis** uses water as the initial electron donor, and as a result, oxygen is released. The ecological significance of oxygenic photosynthesis is that it allowed the photosynthesis in other life forms to occur due to the abundance of water on earth. H2S is easier to oxidize but isn't nearly as abundant as water.

Oxygenic Photosynthesis	Anoxygenic Photosynthesis
- Both photosystems I and II are used	- Only uses 1 photosystem (Type I or II)
- H_2O is the electron donor	- H_2S are the electron donors
- Occurs in plants, algae and cyanobacteria	- Occurs in some bacteria

Photosystems

The reaction centre chlorophyll is **<u>P680</u>** in photosystem II and **<u>P700</u>** in photosystem II. When P680 (ground state) absorbs a photon of light, energy of the photon is absorbed by the electron and excites P680 to a higher energy level (**<u>P680*</u>** or excited state). The electron undergoes transport and P680* is oxidized to P680+. An electron from water reduces P680+ back to its ground state.

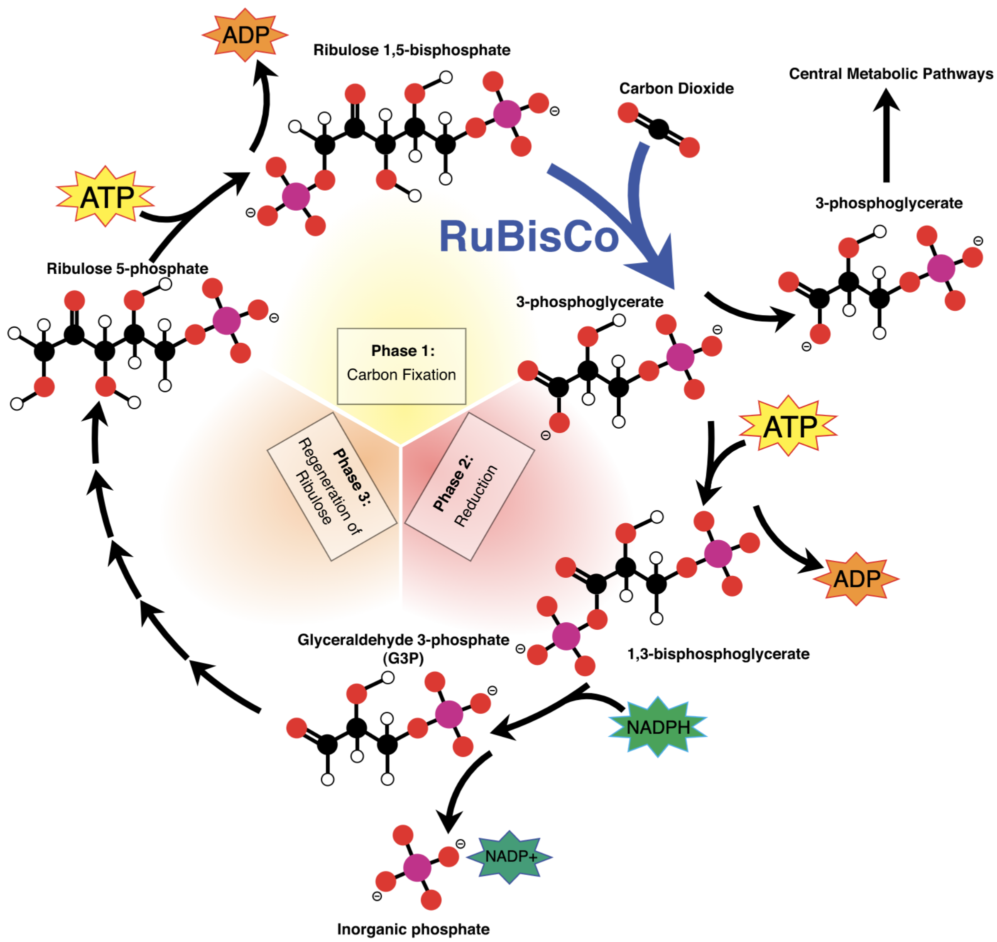
However, P680+ is a strong oxidizer. Under conditions of high light, P680 will be in its oxidized state (P680+) for a majority of the time and if water isn't replenished in time to reduce P680+, it can oxidize the protein within photosystem II that it's attached to (destroying it).

High levels of P680+ without reduction from water will usually damage the D1 protein. By harming D1, photosystem II becomes inactive and a new D1 protein will need to replace the damaged one. However, it's important to understand that photosystems need to be repaired regularly and damage is inevitable. Under normal light conditions, photosystem II lasts around 20 mins before they need to be replaced.

For repair, transcription and translation of D1 needs to be occurring constantly, which is why D1 is encoded for in the chloroplast genome. Damage is manageable as long as the rate of damage to D1 is equivalent to the rate to which it is repaired.

Consider the purpose of having negative phototaxis in *Chlamydomonas.*
Chlamy uses negative phototaxis to avoid high volumes of light. Excessive amounts of light can be harmful to photosystems within the chloroplast if they aren't repaired at a rapid rate.

Calvin Cycle



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The Calvin cycle is located in the stroma of the chloroplast and constitutes the light-independent reactions. The purpose of the Calvin cycle is to use the products of the light-dependent reactions to reduce carbon dioxide into solid carbon compounds (e.g. sugar, amino acids) that help the plant grow. There are 3 stages to the carbon cycle: carbon fixation, reduction, and regeneration. The first stage (**carbon fixation**) involves fixing carbon dioxide gas into a solid form. The **reduction stage** involves reducing the carbon compounds to give them more energy in the form of electrons. The last stage (**regeneration**) is just using what carbons are left after G3P has left to regenerate RuBP.

RuBP is the starting substrate of the Calvin cycle and is acted upon by the enzyme **rubisco**. Rubisco combines CO2 to RuBP to form **PGA**, a 3 carbon molecule that gets reduced during the second phase of the cycle. Three turns of the Calvin cycle yields

G3P, a carbohydrate precursor to glucose or other useful compounds (e.g. carbon skeleton). Once G3P is produced, the rest of the cycle focuses on regenerating RuBP.

Carboxylation vs Oxygenation of Rubisco

Recall that Rubisco can be found in the stroma of chloroplasts. Both CO_2 and O_2 can enter the active site of Rubisco, but Rubisco binds stronger to CO_2 than it does to O_2. Carboxylation occurs when a **carboxylase enzyme** catalyzes Rubisco and carbon dioxide to make two molecules of PGA. Oxygenation occurs when Rubisco and oxygen react to release a single molecule of PGA along with phospho-glycolate. Oxygenation was seen as a wasteful process because instead of promoting the fixation of carbon, it leads to a loss of carbon dioxide atoms that are already fixed. Due to the loss of the already-fixed carbon atoms, there was a decrease in sugar synthesis.

Aquatic photoautotrophs minimize photorespiration as it concentrates the carbon dioxide, leading to an increase of CO2 in the site of Rubisco.

Cellular Respiration: A Recap

	Intracellular Location	**Metabolic Purpose**
Glycolysis: START: Glucose END: Pyruvate	- **Cytosol** in both eukaryotic and prokaryotic cells	- Modifies glucose to keep it inside the cell - Breakdown of glucose and extracts energy in the form of ATP
Citric Acid Cycle START: Acetyl CoA END: $2CO_2$, 3NADH, 1ATP, $1FADH_2$	- **Mitochondrial matrix** in eukaryotic cells - **Cytoplasm** in prokaryotic cells	- Energy production - Finishes the break-down of sugar in glycolysis and fuels production of ATP
Electron Transport START: NADH, $FADH_2$, O_2 END: ATP, NAD^+, H_2O	- Along the **inner mitochondrial membrane** in eukaryotes - Along the **cell membrane** in bacteria	- Shuttles electrons through redox reactions which generates energy that is used to create ATP

Free energy for the following is categorized from highest to lowest: glucose, pyruvate, and carbon dioxide. Glucose has the highest potential energy as it is constantly being degraded and so, the energy that is released during the process is used for other biological work. CO_2 is an inorganic molecule that lacks the bond of C-H, as such it has the lowest potential energy.

Glycolysis and the citric acid cycle can be linked through the pyruvate dehydrogenase complex. The pyruvate dehydrogenase complex is an enzyme that converts pyruvate into acetyl CoA through the pyruvate decarboxylation reaction. PDC creates two NADH molecules by simply eliminating a carboxyl group, which is later used in the electron transport chain.

ATP synthase is located in the inner membrane, where it catalyzes ADP and phosphate to produce ATP. The synthesis of ATP is steered by a flow of protons across a gradient (positive to negative) which is induced by electron transfer.

Oxidative Phosphorylation

Oxidative phosphorylation is made up of two components: the electron transport chain and chemiosmosis. The electron transport chain releases energy as electrons transfer which forms an electrochemical gradient. The energy that is stored in the electrochemical gradient is used to form ATP.

In oxidative phosphorylation, oxygen is placed at the end of the electron transport chain where it accepts electrons and receives protons to create water. If oxygen does not accept electrons, the electron transport chain will not work and chemiosmosis will not produce ATP. However, if it does receive electrons, it will pass through the enzyme, ATP synthase and ATP will be synthesized.

Would the ratio of NAD+/NADH be higher or lower if the cell were mutated such that the inner mitochondrial membrane was leaky?

If the inner mitochondrial membrane was leaky, a proton gradient would not be able to build due to proton pumping because protons would passively diffuse across the membrane down their concentration gradient. As a result, electron transport would halt, and oxidation of NADH would stop. There will be an excess of NADH over NAD+, which means that the ratio of NAD+/NADH will be lower.

Uncoupling

Electron transport and ATP synthesis coupling is the transfer of electrons through donors and acceptors which takes place in the inner membrane or the thylakoid membrane.

Uncoupling occurs when the electron transport chain pumps electrons out while ATP synthase pumps the electrons back in. Humans have three uncoupling proteins. Dinitrophenol is a very strong uncoupler and is toxic as it can alter an individual's metabolism.

Linkage between fermentation and cancer cell growth

If there is no oxygen present in the cytosol, Pyruvate will undergo a process called fermentation. The cytosol is able to sense low oxygen levels and initiate pyruvate kinase (which helps to produce energy). Cancer cells do not go by the sensation in the cytosol, instead they override it and get the pyruvate kinase to work.
Cancer cells get most of their energy from glycolysis in which glucose is turned into lactate for energy. Although oxygen is present, cancer cells favour metabolism through glycolysis rather than oxidative phosphorylation (Warburg Effect). Cancer cells uptake a large amount of glucose, resulting in the regulation of hexokinase and pyruvate kinase.

Cancer can be found and detected through scans like the PET scan. Other ways could be by using 18F which is used to detect and evaluate metastatic diseases. This can also be used to monitor an individual's response to specific therapies and see their progression.

Apply Your Knowledge

Consider the following (not multiple choice, these are designed to allow you to think more freely about the testable concepts):

1. How would the following changes affect their respective organism's metabolism?
    a. A sudden increase in the proportion of P680+ to P680 in sunflowers.
    b. Gene coding for a protein in the cytochrome c complex undergoes a mutation in which it gives the entire complex a significantly lower electron affinity.

2. Suppose you add **washed** mitochondria to an oxygenated chamber (all coenzymes are removed).
    a. What happens to the oxygen concentration overtime in the chamber?
    b. What happens when NADH is added to part a)?
    c. What happens if you then add ADP + P_i to part b)?
    d. What happens when you add an uncoupling agent to part c)?

Congratulations for making it through the entire breakdown. Remember to continually reinforce your understanding over as long a period of time as possible in order to maximize your performance. Best of luck in your studies! Here are some links that might interest you.

Want to learn more about WebStraw? Check out our website at www.webstraw.ca