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UNIT 3

Photosynthesis and Cellular Respiration

Teaching Unit 3: Photosynthesis and Cellular Respiration

Student Textbook pages 152–199
(15% percent of the course time; approximately 15 hours)

Curriculum Fit

(see the Curriculum Correlation for full listing)
Background: This unit builds on concepts from *Science 7*, Plants for Food and Fibre, and *Science 10*, Flow of Matter in Living Systems.

General Outcomes

Student will

- relate photosynthesis to the storage of energy in organic compounds
- explain the role of cellular respiration in releasing potential energy from organic compounds

Contents

Chapter 5: Photosynthesis and Cellular Respiration

Content Summary

Three of the four themes featured in Biology 20 are included in Unit 3: energy, matter, and systems.

Both photosynthesis and cellular respiration are metabolic processes involving energy transfer. Photosynthesis uses solar energy to fix carbon dioxide and synthesize high-energy organic molecules, primarily glucose. These organic molecules may be used by the plant itself or by heterotrophs as building blocks for growth and repair or as an energy source. These compounds are oxidized to release their stored chemical energy, which is transferred to ATP and heat, a process referred to as cellular respiration. Globally, no process is more important to the welfare of life on Earth as photosynthesis. It supplies the matter and chemical energy needed to support plants and the animals dependent on them. Cellular respiration transforms the chemical energy in matter into ATP, required to do work in the cell.

In this unit, students build upon their knowledge of photosynthesis and cellular respiration. Photosynthesis consists of two separate but interacting sets of reactions—light-dependent reactions (photophosphorylation) and light-independent reactions (Calvin-Benson cycle). Photosystems II and I, via electron transport, capture light energy and convert it to a proton gradient in the chloroplast. The movement of protons through ATP synthase generates ATP. Chemiosmosis replaces previous ideas about ATP formation.

Modifications to photosynthesis are limited to C3, C4, and CAM plants. Many living things use aerobic and anaerobic cellular respiration by including plants to provide ATP for metabolic activity. Aerobic respiration includes glycolysis, transition reactions, the Krebs cycle, electron transport, and chemiosmosis. Anaerobic respiration in yeast produces ethanol and carbon dioxide, but in humans produces lactic acid. Students will explore the efficiencies of all processes.

The Unit 3 preparation feature gives students a review of animal and plant cells, passive transport, facilitated diffusion, and active transport.

Section 5.1 defines and compares photosynthesis and cellular respiration and explains the role of ATP in metabolism. The essential features of chloroplasts and mitochondria are summarized and compared in relation to storing energy (photosynthesis) and releasing energy (cellular respiration). The section includes an investigation into gases released during photosynthesis and cellular respiration.

Section 5.2 focusses exclusively on the storage of energy in organic compounds—the process of photosynthesis. Students will use chromatography to separate plant pigments in a green leaf and conduct a second investigation to look at the rate of photosynthesis. Thought labs include learning to use a model to predict and trace the source of oxygen atoms by using an isotope, as well as researching adaptations and applications of photosynthesis.

Section 5.3 takes an in-depth look at cellular respiration. Investigation 5.D tests oxygen consumption and heat production in germinating seeds, while the section's thought lab asks students to use their knowledge of cellular respiration to investigate the effects of metabolic toxins. The Connections feature looks at biogas in terms of applying knowledge of cellular respiration to solve waste management and energy problems. The Career feature continues the theme of managing waste to generate energy.

Activities and Related Skills

Activity	Target Skills
Chapter 5: Photosynthesis and Cellular Respiration	
Launch Lab: Seeing Green, p. 161	■ Observing the effect of light on chlorophyll that has been removed from a living plant
Investigation 5.A: Gases Released During Photosynthesis and Cellular Respiration, pp. 166–167	■ Collecting and interpreting experimental data to identify the gases released as a result of metabolic processes
Investigation 5.B: Using Chromatography to Separate Plant Pigments, pp. 172–173	■ Collecting and interpreting data from a chromatography experiment ■ Calculating reference flow values from data
Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions, p. 175	■ Using a model to predict and trace the source of oxygen atoms in photosynthesis
Thought Lab 5.2: Adaptations and Applications of Photosynthesis, p. 178	■ Investigating and integrating information from print and electronic sources to learn about photosynthesis and possible applications of our knowledge ■ Working cooperatively to investigate, synthesize, and present information about photosynthesis and its possible technological applications
Investigation 5.C: The Rate of Photosynthesis, pp. 180–181	■ Identifying a testable variable that would affect the rate of photosynthesis ■ Hypothesizing and predicting the effect of this variable on the rate of photosynthesis ■ Explaining how data support or refute the hypothesis
Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds, pp. 184–185	■ Demonstrating quantitatively the consumption of oxygen by germinating seeds ■ Designing an experiment to demonstrate quantitatively that cellular respiration produces heat ■ Measuring temperature changes over a period of time in germinating seeds
Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration, p. 189	■ Investigating and integrating, from print and electronic sources, the action of metabolic toxins on cellular respiration ■ Evaluating the reliability, accuracy, and validity of information sources consulted ■ Working cooperatively to investigate metabolic toxins.

Conceptual Challenges

- Students often find the biochemistry in this section difficult, particularly if they don't have any chemistry background. Even with a chemistry background, understanding what happens at a molecular level for reactions involving the synthesis and breakdown of molecules is difficult, as is differentiating between atoms and molecules. Refer students to Appendix B: A Quick Chemistry Reference for the Biology Student for help with this understanding.
- A chemistry-related topic that students may have difficulty with is oxidation-reduction reactions. Potential difficulties may include understanding what each type of reaction involves (i.e., loss and gain of electrons in oxidation and reduction, respectively), how energy-rich molecules in their reduced form have reducing power and what this means, and how some molecules can act as reducing agents to cause the reduction of another compound, and consequently, become oxidized themselves.
- In order to help students make the link between the molecular reactions/processes and the world around them, use live or model plants and animals. Ask students to identify where in the plant photosynthetic reactions take place and where in the plant and animal the reactions of cellular respiration take place. Continue refining the level of scale until students have identified the organelles involved in each reaction, in what parts of the organelles the reactions take place, and what those individual reactions are.

- The vocabulary associated with the material in this unit can be quite intimidating to students. Whenever possible read aloud the more difficult words and emphasize the pronunciation.

Using the Unit Opener and the Unit 3 Preparation Feature

The unit opener has been designed to establish a social, technical, and environmental context for the science in the unit. Use the unit opener to introduce the general unit topics within that context, and ask the Focussing Questions to guide students' thinking.

The Unit Preparation feature has been included in order to ensure that students are familiar with the science from previous courses that relates specifically to the material they are about to study. Encourage students to take the Unit Prequiz (found at **www.albertabiology.ca,** Online Learning Centre, Student Edition) to gauge their recall, noting that if they are familiar with the background science, their experience with this unit will be much easier.

The Unit 3 Preparation feature is a detailed review of plant and animal cells and passive and active transport mechanisms. An understanding of these basics is essential for mastery of the material in this unit. Use 5.0.1 (OH/HAND) Basic Structures of a Plant Cell and 5.0.1B (OH) Basic Structures of a Plant Cell (label overlay); 5.0.2 (OH/HAND) Basic Structures of an Animal Cell and 5.0.2B (OH) Basic Structures of an Animal Cell (label overlay); and 5.0.3 (OH/HAND) Review of Cell Membrane Structure and Membrane Transport Mechanisms to assist students in recalling this information.

UNIT 3: COURSE MATERIALS

Chapter, Section	Item Description	Suggested Quantity	Text Activity
Chapter 5	safety goggles	40 pairs	Investigations: 5.A, 5.B, 5.C, 5.D
Chapter 5	nonlatex disposable gloves	40 pairs x 5 investigations	Investigations: 5.A, 5.B, 5.C, 5.D; Ch 5 Launch Lab
Chapter 5	aprons	40	Investigations: 5.A, 5.B, 5.C, 5.D
Chapter 5, Section 5.1	prepared chlorophyll solution 200 mL beaker Light source (e.g., slide projector)	150 mL per student 20 5	Launch Lab: Seeing Green, p. 161
	tap or aquarium water sodium hydrogen carbonate, $NaHCO_3$(s) *Cabomba* (or other aquatic plant) 0.1 mol/L NaOH(aq) in dropper bottle bromothymol blue 600 mL beaker short-stemmed funnel test tube and stopper ring stand bright lamp (or grow light) wooden splint matches 50 mL Erlenmeyer flask and stopper drinking straw	 2 g per student 3 or 4 sprigs per student 5 mL per student 1 mL per student 1 per student 1 per student 1 per student\ 1 per student 3–5 1 per student 1 per student 1 per student 1 per student	Investigation 5.A: Gases Released During Photosynthesis and Cellular Respiration, pp. 156-157
Chapter 5, Section 5.2	coleus or spinach leaves (or pigment mixture) isopropanol (solvent) chromatography paper paper clip retort stand ruler test tube clamp cork stopper watch glass large test tube	1 per student 10 mL per student 20 1 per student 1 per student 1 per student 1 per student 1 per student 5–10 (shared by class) 1 per student	Investigation 5.B: Using Chromatography to Separate Plant Pigments, pp. 172–173
	modelling kits or other materials that can be used for building simple models of molecules (e.g., StyrofoamTM balls and paper cut-outs)		Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions, p. 175
	plant leaf liquid dish soap 0.25% sodium bicarbonate single-hole punch 10 mL plastic syringe (without the needle) medicine dropper 200 mL beaker lamp with a reflector and 150 W bulb timer materials for students to carry out Part 2 of the investigation	1 per student 100 mL per student 5 to share 1 per student 1 per student 1 per student 5–10 to share 1 per student variable	Investigation 5.C: The Rate of Photosynthesis, pp. 180–181

Chapter, Section	Item Description	Suggested Quantity	Text Activity
Chapter 5, Section 5.3	seeds of any kind (corn works well) limewater liquid detergent large test tube ruler one-hole stopper pipette wad of cotton rigid plastic tubing, 20 cm long and bent at a right angle marker balance scotch tape spatula (optional) support stand and clamp materials for students to carry out Part 2 of the investigation	1 g per student 10 mL per student 1 drop per student 1 per student 1 per student 1 per student 1 per student 1 per student 1 per student 5–10 3–5 1 per student 1 per student 	Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds, pp. 184–185

CHAPTER 5 PHOTOSYNTHESIS AND CELLULAR RESPIRATION

Curriculum Correlation

General Outcome 1: Relate photosynthesis to the storage of energy in organic compounds.

	Student Textbook	Assessment Options
Outcomes for Knowledge		
20–C1.1k explain, in general terms, how pigments absorb light and transfer that energy as reducing power in nicotinamide adenine dinucleotide phosphate (NADPH) and finally into chemical potential in adenosine triphosphate (ATP) by chemiosmosis, describing where the process occurs in the chloroplast	Launch Lab: Seeing Green, p. 161 Section 5.1 Photosynthesis: Capturing and Converting Light Energy from the Sun, p. 162 Chloroplasts: Site of Photosynthesis, p. 164 Section 5.2 The Process of Photosynthesis, pp. 169-170 The Light-Dependent Reactions of Photosynthesis, pp. 170-176	Launch Lab: Analysis 1-2, p. 161 Q question 1, p. 163; 5, 6, p. 164 Section 5.1 Review: 2, 7 Q questions 12-15, p. 170; 16, 17, p. 171; 18-24, p. 174 Thought Lab 5.1, p. 175 Section 5.2 Review: 1-12, p. 179 Unit 3 Review: 5, 6, 7, 14-21, 23, p. 198 Chapter 5 Test
20–C1.2k explain, in general terms, how the products of the light-dependent reactions, NADPH and ATP, are used to reduce carbon in the light-independent reactions for the production of glucose, describing where the process occurs in the chloroplast	Section 5.2 Biology File FYI: "Dark reactions", p. 170 The Light-Independent Reactions of Photosynthesis, pp. 176-177	Section 5.1 Review: 8, p. 168 Q questions 27, 28, p. 177 Section 5.2 Review: 13, p. 179 Unit 3 Review: 8, 22, 24, 25, p. 198; 34, p. 199 Chapter 5 Test
Outcomes for Science, Technology and Society (Emphasis on Science and Technology)		
20–C1.1sts explain how scientific knowledge may lead to the development of new technologies and new technologies may lead to scientific discovery ■ *analyze the role of photosynthesis as the biological basis of agriculture and forestry*	Biology File FYI: Replacing retinal cells, p. 176	Q questions 25, 26, p. 176 Unit 3 Review: 41, 44, p. 199 Chapter 5 Test
20–C1.2sts explain that the appropriateness, risks, and benefits of technologies need to be assessed for each potential application from a variety of perspectives, including sustainability ■ *research and analyze the effects of herbicides on the biochemistry of photosynthesis*	Thought Lab 5.2: Adaptations and Applications of Photosynthesis, p. 178 Biology File FYI: Carotenoids, p. 170	Unit 3 Review: 43, p. 199 Thought Lab 5.2: Ext. 4, p. 178 Chapter 5 Test Unit 3 Review: 45, p. 199 Chapter 5 Test
Skill Outcomes (Focus on Scientific Inquiry)		
Initiating and Planning		
20–C1.1s ask questions about observed relationships and plan investigations of questions, ideas, problems, and issues	Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions, p. 175	Thought Lab 5.1: Procedure 4, 5; Analysis 2, p. 175 Section 5.2 Review: 14, p. 179
■ *identifying a testable factor that would affect the rate of photosynthesis* ■ *predicting and hypothesizing the effect of changes in carbon dioxide and oxygen concentration on photosynthesis*	Investigation 5.C: The Rate of Photosynthesis, pp. 180-181	Investigation 5.C: Conclusion 4, p. 181 Investigation 5.C: Part 2, p. 181

	Student Textbook	Assessment Options
Performing and Recording		
20–C1.2s conduct investigations into relationships between and among observable variables and use a broad range of tools and techniques to gather and record data and information	Investigation 5.A: Gases Released During Photosynthesis and Cellular Respiration, pp. 166-167 Investigation 5.B: Using Chromatography to Separate Plant Pigments, p. 172	Investigation 5.A: Procedure Part 1, 1-6, Part 2, 1-4, pp. 166-167 Investigation 5.B: Procedure 1-11, p. 173
■ *measuring rates of evapotranspiration under various environmental conditions and relate to photosynthetic activity*	Investigation 5.C: The Rate of Photosynthesis, pp. 180-181	Investigation 5.C: Procedure 9-10, p. 181
■ *investigating and integrating, from print and electronic sources, information of the C3 and C4 photosynthetic mechanisms and applications of cellular biochemistry in medicine or industry*	Thought Lab 5.2: Adaptations and Applications of Photosynthesis, p. 178	Thought Lab 5.2, Procedure 1-2; Analysis 1-3, p. 178
Analyzing and Interpreting		
20–C1.3s analyze data and apply mathematical and conceptual models to develop and assess possible solutions	Investigation 5.A: Gases Released During Photosynthesis and Cellular Respiration, pp. 166-167	Investigation 5.A: Conclusion 4-6, p. 167 Unit 3 Review: 45, p. 199
■ collecting and interpreting data and calculating Rf (reference flow) values from chromatography experiments	Investigation 5.B: Using Chromatography to Separate Plant Pigments, p. 172	Investigation 5.B: Procedure 12, Analysis 2-4; Conclusion 5, p. 173
■ drawing analogies between the storage of energy by photosynthesis and the storage of energy by active solar generating systems	Section 5.2: Mimicking Nature, pp. 175-176	Unit 3 Review: 42(b), p. 199
■ *explaining how data supports or refutes the hypothesis on how changes in carbon dioxide and oxygen concentration affect photosynthesis*	Investigation 5.C: The Rate of Photosynthesis, pp. 180-181	Investigation 5.C: Conclusion 5, p. 181
■ *collecting and interpreting experimental data that demonstrate that plant leaves produce starch in the presence of light*	Chapter 1: Investigation 1.A: Storing Solar Energy in Plants, pp. 10-11	Chapter 1: Investigation 1.A: Procedure 1-6; Analysis 1-5; Conclusion 6, pp. 10-11
Communication and Teamwork		
20–C1.4s work as members of a team in addressing problems and apply the skills and conventions of science in communicating information and ideas and in assessing results	Thought Lab 5.2: Adaptations and Applications of Photosynthesis, p. 178	Thought Lab 5.2, Procedure 1-2, p. 178
■ *working cooperatively as a group to investigate, synthesize, and present information on the effects of herbicides on the biochemistry of photosynthesis*	Biology File FYI: Carotenoids, p. 170	

General Outcome 2: Explain the role of cellular respiration in releasing potential energy from organic compounds

	Student Textbook	Assessment Options
Outcomes for Knowledge		
20–C2.1k explain, in general terms, how carbohydrates are oxidized by glycolysis and the Krebs cycle to produce reducing power in NADH and FADH and chemical potential in ATP, describing where in the cell those processes occur	Section 5.1 Cellular Respiration: Releasing Stored Energy, pp. 162-163 Mitochondria: Site of Cellular Respiration, p. 164 Section 5.3 The Process of Cellular Respiration, p. 182 Examining Aerobic Cellular Respiration, p. 183 Outside the Mitochondria: Glycolysis, pp. 183-186 Inside the Mitochondria: Krebs Cycle Preparation, p. 187 The Krebs Cycle, p. 187	Q question 2, p. 163; 7, 8, p. 164 Section 5.1 Review: 8, p. 168 Q questions 31, 32, p. 186; 33-35, p. 187 Section 5.3 Review: 3, 4, 5, p. 194 Unit 3 Review: 2, 26, 27, p. 198; 31, 36, p. 199
20–C2.2k explain, in general terms, how chemiosmosis converts the reducing power of NADH and FADH to the chemical potential of ATP, describing where in the mitochondria the process occurs	Section 5.3 Electron Transport, pp. 187-188 The Role of Oxygen in Aerobic Cellular Respiration, p. 188	Q questions 36-38, p. 190 Section 5.3 Review: 3, 6-8, p. 194 Unit 3 Review: 8, 9, p. 198; 31-33, 40, p. 199
20–C2.3k distinguish, in general terms, between aerobic and anaerobic respiration and fermentation in plants, animals, and other organisms	Section 5.3 Three Pathways for Energy Release, pp. 182-183 Examining Aerobic Cellular Respiration, p. 183 The Role of Oxygen in Aerobic Cellular Respiration, p. 188 Anaerobic Cellular Respiration Uses a Different Final Electron-Acceptor, pp. 189-190 Fermentation, pp. 190-193	Q questions 29, 30, p. 183; 39-41, p. 191 Section 5.3 Review: 2, 9-11, p. 194 Unit 3 Review: 28-30, 35, 37, 38, p. 199
20–C2.4k summarize and explain the role of ATP in cell metabolism ■ *active transport* ■ *cytoplasmic streaming* ■ *phagocytosis* ■ *biochemical synthesis* ■ *muscle contraction* ■ *heat production*	Section 5.1 ATP and Cellular Activity, p. 163	Q questions 3-4, p. 163 Web Link: ATP and implanted devices, p. 163 Section 5.1 Review: 4-6, p. 168 Unit 3 Review: 3, 4, p. 198; 42(a), p. 199
Outcomes for Science, Technology, and Society (Emphasis on Social and Environmental Contexts)		
20–C2.1sts explain that science and technology are developed to meet societal needs and expand human capability ■ *research applications of cellular biochemistry in health and industry, e.g.,* ■ *aerobic and anaerobic fitness* ■ *methane gas production from organic waste* ■ *alcohol fermentation* ■ *bread-making* ■ *yogurt*	Ethanol Fermentation and Fuel Production, pp. 191-193 Connections: Energy from Manure, p. 192 Ethanol Production, p. 193 Career Focus: Ask a Research Scientist, pp. 196-197	Web Link: Pyruvate dehydrogenase complex deficiency, p. 189 Web Link: Bacteria in your mouth, p. 190 Connections: 1-2, p. 192 Web Link: First Nation Ethanol Development Corporation, p. 194 Career Focus: 1, 2, p. 197

	Student Textbook	Assessment Options
20–C2.2sts explain that science and technology have both intended and unintended consequences for humans and the environment	Career Focus: Ask a Research Scientist, pp. 196-197	Career Focus: 3, p. 197
■ *discuss how pollutants such as cyanide and hydrogen sulfide are unintended byproducts of industrial processes and their metabolic effects on aerobic organisms*	Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration, p. 189	Thought Lab 5.3: Procedure 1-3; Analysis 1, p. 189
Skill Outcomes (Focus on Scientific Inquiry)		
Initiating and Planning		
20–C2.1s ask questions about observed relationships and plan investigations of questions, ideas, problems, and issues, e.g., by		
■ *identifying factors affecting the rate of cellular respiration*	Investigation 5.D: Oxygen Consumption and Heat	Investigation 5.D: Part 1: Analysis 1, p. 185
■ *designing an experiment to demonstrate that heat is a byproduct of respiration*	Production in Germinating Seeds, pp. 185-186	Investigation 5.D: Part 2: Exp. Plan 1-3; Data and Obs. 4-5, p. 185
■ *predicting and hypothesizing the effect of oxic and anoxic conditions on the rate of cellular respiration in a unicellular organism, i.e., yeast, bacteria*	Three Pathways for Energy Release, pp. 182-183	
Performing and Recording		
20–C2.2s conduct investigations into relationships between and among observable variables and use a broad range of tools and techniques to gather and record data and information by		
■ using experimental methods to demonstrate, quantitatively, the oxygen consumption of germinating seeds.	Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds, pp. 185-186	Investigation 5.D: Part 1: Procedure 1-8, pp. 184-185
■ measuring temperature change over time of germinating and non-germinating seeds		Investigation 5.D: Part 2: Data and Obs. 4-5, p. 185
■ investigating and integrating, from print and electronic sources, information on the action of metabolic toxins, such as hydrogen sulfide and cyanide, on cellular respiration	Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration, p. 189	Thought Lab 5.3: Procedure 1-3; Analysis 1, p. 189
Analyzing and Interpreting		
20–C2.3s analyze data and apply mathematical and conceptual models to develop and assess possible solutions by		Unit 3 Review: 45, p. 199
■ *evaluating reliability, accuracy, and validity of sources used to collect information on metabolic toxins and cellular respiration*	Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds, pp. 185-186 Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration, p. 189	Investigation 5.D: Part 1: Conclusion 3, p. 185 Thought Lab 5.3: Analysis 2, p. 189
■ *interpreting data on the oxygen consumption of an animal and relate this to metabolic rate*		
■ *interpret data that illustrate the effect of oxic and anoxic conditions on cellular respiration*	Three Pathways for Energy Release, pp. 182-183	
Communication and Teamwork		
20–C2.4s work as members of a team in addressing problems, and apply the skills and conventions of science in communicating information and ideas and in assessing results by	Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds, pp. 185-186 Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration, p. 189	Investigation 5.D: Part 2: Exp. Plan 1-3, p. 185 Thought Lab 5.3: Procedure 4, p. 189
■ *creating a concept map or flow chart to illustrate how carbon, hydrogen, and oxygen atoms in glucose are ultimately released as carbon dioxide and water*		

Chapter 5

Photosynthesis and Cellular Respiration

Student Textbook pages 152–199

Chapter Concepts

5.1 Matter and Energy Pathways in Living Systems

- Photosynthesis, the process in which certain organisms trap solar energy, occurs in chloroplasts.
- Cellular respiration, the process in which energy-rich compounds are broken down to generate ATP, occurs in mitochondria.
- ATP is the source of energy for many of the chemical reactions that occur in cells.

5.2 Photosynthesis Stores Energy in Organic Compounds

- In light-dependent reactions, chloroplasts trap solar energy and transform the energy to the reducing power of NADH and the chemical energy of ATP.
- Chemiosmosis is the mechanism by which energy stored in a concentration gradient is used to generate ATP.
- In light-independent reactions, the energy of ATP and NADPH is used to reduce carbon dioxide to synthesize glucose.

5.3 Cellular Respiration Releases Energy from Organic Compounds

- Aerobic cellular respiration involves three metabolic pathways: glycolysis, the Krebs cycle, and an electron transport system.
- Aerobic cellular respiration is the complete oxidation of glucose to release energy.
- Fermentation is the incomplete oxidation of glucose to release energy.

Common Misconceptions

- Photosynthesis is often thought of as being necessary for life to exist on Earth. However, in Chapter 1, students learned about deep ocean vent ecosystems that exist in the absence of light and that all chemosynthetic bacteria live in spite of being unable to photosynthesize. These concepts become particularly important when students learn that nitrifying and nitrogen-fixing bacteria are responsible for fixing most of the usable nitrogen for plants. Without them, plants would be exceptionally rare on Earth's surface.
- The oxygen produced in photosynthesis does not come from the carbon dioxide absorbed through the stomata—the oxygen released as O_2 is derived from water. This misconception probably arises from the idea that photosynthesis and cellular respiration are opposites, and it seems intuitive that the oxygen we breathe in and the carbon dioxide we breathe out contain the same oxygen atoms (which is untrue).
- All parts of the plant do not photosynthesize. Clearly, roots are not exposed to light, and wood surrounded by thick bark cannot photosynthesize. Photosynthesis and the presence of chloroplasts are, therefore, not characteristics of all plant cells but rather of plants as individuals.
- Often, students think that animal cells perform cellular respiration and plant cells do not. In fact, all cells carry out some form of cellular respiration. At the very least, plants must do so at night in order to remain biologically active.

Helpful Resources

Books and Journal Articles

- Alberts, B. et al., *The Molecular Biology of the Cell.* Garland Publishing Inc., New York, 1994.
- Campbell, N. et al., *Biology.* Benjamin Cummings, Menlo Park, CA, 1999.
- Raven, P. et al., *Biology of Plants.* Worth Publishers, New York, 1992.

Web Sites

Web links to information about photosynthesis and cellular respiration can be found at **www.albertabiology.ca.** Go to the Online Learning Centre, and log on to the Instructor Edition. Choose Teacher Web Links for the links to Chapter 5.

List of BLMs

Blackline masters (BLMs) have been prepared to support the material in this chapter. The BLMs are either for assessment (AST); use as overheads (OH); use as handouts (HAND), in particular to support activities; or to supply answers (ANS) for assessment or handouts. The BLMs are in digital form, stored on the CD that accompanies this Teacher Resource or on the web site at **www.albertabiology.ca,** Online Learning Centre, Instructor Edition, BLMs.

Number (Type)
5.0.4 (HAND) Launch Lab: Seeing Green
5.0.4A (ANS) Launch Lab: Seeing Green Answers

5.1.1 (OH) Trapping and Using the Sun's Energy
5.1.2 (OH) ATP Structure and Cycle
5.1.3 (OH) A Closer Look at Chloroplasts
5.1.4 (OH) A Closer Look at Mitochondria
5.1.5 (HAND) Investigation 5.A: Gases Released during Photosynthesis and Cellular Respiration
5.1.5A (ANS) Investigation 5.A: Gases Released during Photosynthesis and Cellular Respiration Answers
5.1.6 (HAND) Oxidation-Reduction Reactions

5.2.1 (OH) Uses of Plant Substances
5.2.2 (OH) Light-reflecting and Light-absorbing Characteristics of Pigments
5.2.3 (HAND) Investigation 5.B: Using Chromatography to Separate Plant Pigments

5.2.3A (ANS) Investigation 5.B: Using Chromatography to Separate Plant Pigments Answers
5.2.4 (OH) The Light-Dependent Reactions of Photosynthesis
5.2.5 (OH) Chemiosmosis in a Chloroplast
5.2.6 (HAND) Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions
5.2.6A (HAND) Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions Answers
5.2.7 (OH) The Calvin-Benson Cycle
5.2.8 (HAND) Thought Lab 5.2: Adaptations and Applications of Photosynthesis
5.2.8A (ANS) Thought Lab 5.2 Adaptations and Applications of Photosynthesis Answers
5.2.9 (HAND) Investigation 5.C: The Rate of Photosynthesis
5.2.9A (ANS) Investigation 5.C The Rate of Photosynthesis Answers
5.2.10 (AST) Summary of Photosynthesis

5.3.1 (HAND) Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds
5.3.1A (ANS) investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds Answers
BLM 5.3.2 Stages of Cellular Respiration
BLM 5.3.3 The Krebs Cycle
BLM 5.3.4 Aerobic Cellular Respiration
5.3.5 (HAND) Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration
5.3.5A (ANS) Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration Answers
BLM 5.3.6 (HAND) Flow of Energy between Photosynthesis and Cellular Respiration

5.4.1 (AST) Chapter 5 Test
5.4.1A (ANS) Chapter 5 Test Answer Key

Using the Chapter 5 Opener

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Teaching Strategies

- Have students read the Chapter Opener. Ask them to create a diagram of the flow of energy described. For each arrow in their diagrams, ask them to identify the processes that could transfer energy from one object to the next. Finally, have them identify which of these processes involve photosynthesis and cellular respiration. Pool their suggestions in such a way that they are visible for the duration of the unit.
- Use the Launch Lab: Seeing Green to introduce the study of chlorophyll.

Launch Lab: Seeing Green

Student Textbook page 161

Purpose

Students will work cooperatively to determine the effect of light on a solution of chlorophyll.

Outcomes

- 20–C1.1k
- 20–C1.4s

Advance Preparation

When to Begin	What to Do
1 or 2 days before	■ Photocopy **BLM 5.0.4: Launch Lab: Seeing Green** ■ Obtain a source of chlorophyll; spinach is common, but any green plant will work.
1 day before (maximum)	■ Prepare chlorophyll solution (see Helpful Tips).

Materials
■ 150 mL of chlorophyll solution ■ 200 mL beaker ■ light source

Time Required

- 45 minutes (15 minutes to teach students about the need for chlorophyll in photosynthesis and to introduce the activity. 30 minutes to perform the activity, make observations, and clean up.)

Helpful Tips

- Use **BLM 5.0.4 (HAND) Launch Lab: Seeing Green** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The function descriptions requested in Analysis questions are on **BLM 5.0.4A (ANS) Launch Lab: Seeing Green Answers.**
- The more concentrated the solution, the clearer the appearance of the colours.
- Since this is not a controlled experiment, you may wish to do this as a demonstration on the overhead projector to save time and materials. Students sitting in different parts of the classroom may then see different things.
- Chlorophyll solution may be made quickly and safely by boiling a handful of spinach leaves in 1/2 cup of water for about 5 minutes. Commercially available chlorophyll

solution, common in health-food stores, could also be used; however, the solution contains alcohol, so observe safety precautions related to combustion if it is used. Refer to Preparing Solutions in the front matter of this Teacher's Resource.

- ***Expected Results:*** If you look through a chlorophyll solution into the light, it appears green (have the chlorophyll solution between your eyes and the light). But if you place yourself at an angle so that you now see the place where the light passes through from behind, then the chlorophyll shines back with a reddish colour.

SUPPORTING DIVERSE STUDENT NEEDS

Gifted Students

- These students may benefit from the availability of a spectroscope so they can see and quantify differences between the light emitted by the source and the light transmitted and emitted by the chlorophyll.

Students Who Need Extra Help

- Some of your students may be colour-blind. These students will not necessarily see any differences in the solution's colours. A sensitive teen may become frustrated, but this can be a good moment to discuss variation in humans and diversity in society. Try to arrange student pairs so that students can help each other, and encourage colour-blind students to record other students' observations.
- Visually impaired students may benefit from a verbal description of the activity set-up and the observations.

Safety Precautions

If chlorophyll is dissolved in ethanol or acetone, the solution will become flammable. Keep away from open flames and sparks.

Answers to Analysis Questions

1. Chlorophyll absorbs red, yellow, and blue light best because green light is transmitted.
2. Fluorescence is visible at all angles, but most obvious when the chlorophyll is viewed at an angle not 180 degrees to the light source; steps 2 and 3 will show it best. The solution transmits more light from the source than it absorbs. The transmitted light will likely mask fluorescence. The chlorophyll molecules do not emit light in a single direction.

Assessment Options

- Collect and assess the students' answers to Analysis Questions.
- If students did the work as a group activity, use Assessment Checklist 4: Performance Task Group Assessment from Appendix A.

5.1 Matter and Energy Pathways in Living Systems

Student Textbook pages 162-168

Section Outcomes

Students will:

- compare and summarize the essential features of chloroplasts and mitochondria in relation to the role of photosynthesis in storing energy and the role of cellular respiration in releasing energy
- summarize and explain the role of ATP in cellular metabolism

Key Terms

photosynthesis
cellular respiration
chloroplast
thylakoids
mitochondria
metabolism
reducing power

Biology Background

- Solar energy is the ultimate source of all biological energy. Photosynthetic organisms (autotrophs) use the energy from sunlight to form ATP and NADPH, which they use as energy sources to make carbohydrates and other organic compounds from carbon dioxide and water. At the same time, they release oxygen (O_2) into the atmosphere. Heterotrophs, such as humans, use the oxygen to break down the high-energy organic products of photosynthesis to carbon dioxide and water to make ATP. The carbon dioxide formed by respiration in heterotrophs is returned to the atmosphere, to be used again by photosynthetic organisms. Thus, living organisms are interdependent, exchanging energy and matter.
- Chloroplasts have a highly permeable outer membrane and nearly impermeable inner membrane, separated by a narrow intermembrane space. The inner membrane encloses an inner aqueous compartment called the stroma, containing the enzymes required for carbohydrate synthesis. The stroma also contains the DNA, RNA, and ribosomes involved in the synthesis of several chloroplast proteins. The stroma surrounds the thylakoids, which contain stacks of interconnected sacs called grana. Embedded in the thylakoid membranes are the photosynthetic pigments, such as chlorophyll, and the enzyme complexes that carry out the light-dependent reactions and ATP synthesis. The high concentration of chlorophyll in chloroplasts produces a green appearance. However, the colour ultimately depends on the relative amounts of other pigments that are also present.
- Mitochondria, like chloroplasts, have outer and inner membranes, with an intermembrane space. The inner

membrane contains folds, called cristea, that provide a large surface area and contain enzyme complexes involved in ATP synthesis. Inside the inner membrane is the matrix, containing enzymes and intermediates involved in cellular respiration. Mitochondria contain their own DNA, RNA, and ribosomes, and are produced by the division of previously existing mitochondria.

- Both photosynthesis and cellular respiration are metabolic pathways involving sequential enzyme-catalyzed reactions, whereby the product of one reaction becomes the reactant for the next reaction. Key to the proper functioning of these metabolic pathways is a highly coordinated system for regulating the activity of the reactions. Metabolic pathways can be either catabolic, which degrade larger, energy-rich molecules (e.g., glucose, fats, and proteins) and release energy or anabolic, which are biosynthetic and produce large molecules from small simple precursors and require energy.
- Adenosine triphosphate (ATP) is the source of energy for almost all cellular activities, including biosynthetic reactions, ion transport, and cellular movement. The hydrolysis of the terminal phosphate group on ATP is highly exergonic, which can be coupled to endergonic reactions. The resulting adenosine diphosphate (ADP) can be recycled back to ATP by phosphorylation via chemical energy from the oxidation of organic molecules or by solar energy (photosynthesis).
- Almost all energy transductions in cells can be traced to the flow of electrons in oxidation-reduction reactions; some reactant is oxidized (loses electrons) and another is reduced (gains electrons). This "downhill" flow of electrons from one molecule of higher electrochemical potential to another of lower electrochemical potential is analogous to the flow of electrons in a battery-powered electric circuit.

Teaching Strategies

- **BLM 5.1.1 (OH) Trapping and Using the Sun's Energy** can be used to illustrate how photosynthesis and cellular respiration link organisms in the biosphere.
- **BLM 5.1.2 (OH) ATP Structure and Cycle** indicates the structure of ATP and what is occurring to the molecule during its turnover in the cell.
- Use **BLM 5.1.3 (OH) A Closer Look at Chloroplasts** to help illustrate how the reactions of photosynthesis are compartmentalized in the chloroplast.
- Use **BLM 5.1.4 (OH) A Closer Look at Mitochondria** to help illustrate how the reactions of cellular respiration are compartmentalized in the mitochondrion.
- The phrase and acronym provided in the FYI on page 168 of the student resource are to help students remember what happens to electrons in oxidation-reduction reactions. In order for students to be able to follow discussions of oxidation-reduction reactions, it is essential that they understand the movement of electrons in these reactions.

BLM 5.1.6 (HAND) Oxidation-Reduction Reactions will help students become more comfortable with this concept by providing them with an exercise to perform.

SUPPORTING DIVERSE STUDENT NEEDS

Gifted Students

- These students may ask questions, which are related to information that is at a higher level than what this introductory section covers. Guide them to resources that will assist them with their curiosity. Bonus work is often a big incentive, which can be used to increase either the depth or the breadth of their learning.

Students Who Need Extra Help

- Some students may have difficulty associating molecular processes with the "bigger picture" of the organisms involved and environment or biosphere. Whenever possible, remind students of how they are linked.
- For Investigation 5.A, visually impaired students may have difficulty seeing the changes in colour of the indicator solution. Ensure that someone in their group describes each step of the procedure for them.

ESL Students

- These students may find some of the vocabulary in this section difficult. Contact your resource personnel well ahead of time with a list of terms that may prove problematic so the students can be properly prepared. Alternately, read the text with the students, helping with pronunciation and explaining the terms as they come up.

Answers to Questions for Comprehension

Student Textbook page 163

Q1. Photosynthesis traps energy from the Sun and converts it to chemical energy, in the form of high-energy molecules such as carbohydrates.

Q2. Cellular respiration involves the process of breaking down high-energy compounds, such as glucose, in order to generate ATP, which is required as an energy source for numerous cellular activities.

Q3. Adenosine triphosphate (ATP) acts as an energy source for almost all cellular activities, which includes ion transport, synthesis of complex molecules, muscle contraction, and cilia and flagella movement. It supplies energy through the breaking of the bond to the third phosphate group.

Q4. When ATP is used as an energy source (i.e., to release energy), the third phosphate group is cleaved off to produce ADP (adenosine diphosphate). ATP can be regenerated by the addition of a free phosphate group to ADP and an input of energy (i.e., energy is consumed).

Biology File: Web Link

Student Textbook page 163

As of 2006, scientists and engineers have succeeded in developing prototypes for "molecular motors," some of which are designed to function using ATP as a fuel/power source. A useful article from the BBC archives, summarizing the state of research in 2004 ("Scientists make molecular motor," by Dr. David Whitehouse), may be accessed at http://news.bbc.co.uk/2/hi/science/nature/441670.stm. Although geared to a graduate-level audience, a general sense of current research may be found through the Biomolecular Nanotechnology program, part of the Photosynthesis Center at Arizona State University. (See, for example, http://photoscience.la.asu.edu/bionano/research2.htm.) Students may also consult research databases such as those administered by the NCBI (National Center for Biotechnology Information) and the NRC (National Research Council), as well as articles from print and/or electronic science sources such as Science/AAAS, PhysOrg, and Scientific American.

Answers to Questions for Comprehension

Student Textbook page 164

Q5. Chlorophyll is a photosynthetic pigment that causes the green colour in plants and most species of algae and acts to trap the Sun's energy for photosynthesis.

Q6. Chlorophyll, which causes the green colour in plants, is present in the thylakoid membranes of chloroplasts.

Q7. In mitochondria, reactions involving the breakdown of carbohydrates and other high-energy molecules are carried out, in order for required energy to be produced (ATP).

Q8. Eukaryotic organisms (plants, animals, fungi, and protists) contain mitochondria.

Investigation 5.A: Gases Released During Photosynthesis and Cellular Respiration

Student Textbook pages 166-167

Purpose

Students will perform a variety of tests in order to identify the gases released by plants and animals.

Outcomes

- 20-C1.2s
- 20-C1.3s

Advance Preparation

When to Begin	What to Do
1 or 2 days before	■ Photocopy **BLM 5.1.5 Investigation 5.A** ■ Obtain Cabomba or other aquatic plant.* ■ Prepare the 0.1 mol/L NaOH(aq) solution.

*Refer to Preparing Solutions in the front matter of this Teacher's Resource.

Materials
■ tap or aquarium water ■ sodium hydrogen carbonate, $NaHCO_3(s)$ ■ *Cabomba* (or other aquatic plant) ■ 0.1 mol/L NaOH (aq) in dropping bottle ■ bromothymol blue ■ 600 mL beaker ■ short-stemmed funnel ■ test tube ■ bright lamp (or grow light) ■ clamp and ring stand ■ wooden splint ■ matches ■ 50 mL Erlenmeyer flask ■ drinking straw

Time Required

- Day 1: 1 hour (Part 1: Steps 1 to 5: 30 minutes; Part 2: Steps 1 to 5: 30 minutes)
- Day 2: 70 minutes (Part 1: Testing for Oxygen: 15 minutes (actual time may be longer if the teacher supervises each group separately); Part 2: Observations: 10 minutes; Clean-Up 15 minutes; Analysis and Conclusion questions: 30 minutes)

Helpful Tips

- Use **BLM 5.1.5 (HAND) Investigation 5.A: Gases Released during Photosynthesis and Cellular Respiration** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.1.5A (ANS) Investigation 5.A: Gases Released during Photosynthesis and Cellular Respiration Answers.**
- Use several sprigs of plant (at least 3 or 4) so that enough gas is produced to be observable. A number of vine-type house plants can be used instead of *Cabomba*. For example, *Tradescantia zebrina* (the plant commonly referred to as "Wandering Jew") has been demonstrated to work well as a substitute.
- For safety purposes, you may choose to conduct the tests for identifying gases released from plants in Part 1. It is advised that, when the test tube is removed from the funnel to test for gases, your thumb be placed over the mouth of the test

tube to trap the water and gas. Have a lit splint ready. Holding the test tube horizontal and the splint at the mouth of the tube, remove your thumb and immediately place the lit splint into the tube mouth, being careful not to get it wet with water. A flame should be observed. If the test tube is simply removed and kept inverted, any oxygen or carbon dioxide will escape downwards and won't be present to be tested (only hydrogen is lighter than air and would remain in the inverted tube).

- For Part 2 (steps 1 and 2), placing the Erlenmeyer on a sheet of white paper will help to better observe the colours. Note that, depending on the water source, mixing the bromothymol blue in water might result in a yellow to greenish colour. Adding sodium hydroxide will produce the basic conditions for production of a blue solution. Specify to students that no more than one dropperful of 0.1 mol/L NaOH should be added, otherwise more blowing (i.e., air) will be required in step 3 to turn the solution yellow.
- For Part 2 (steps 3 and 4), students are to blow until the solution turns yellow, indicating that it has become acidic (i.e., carbon dioxide has reacted with the water to produce carbonic acid).
- For Part 2 (step 5), it is important that the flask be stoppered since the carbon dioxide in the air will naturally make the water acidic, which will counteract the activity of the plant and desired observation of the solution turning from yellow back to blue. You could prepare a stoppered flask with yellow solution and an unstoppered flask with yellow solution as controls for the class.
- ***Expected Results:*** In Part 1, the sprigs of the plant should produce observable amounts of gas. The trapped gas should flare when the lit splint is inserted into the tube, indicating the presence of oxygen gas.

  In Part 2, the bromothymol blue solution will be yellow when the pH is below 6.0, it will be blue at a pH above 7.6, and green in a neutral pH (pH 7.) When the students bubble carbon dioxide into the solution, it will turn light yellow (indicating that the pH is slightly acidic). After the Cabomba has been added, the solution should turn blue (indicating that the pH of the solution is now slightly basic).

Safety Precautions

- Sodium hydroxide is caustic and may cause burns if students spill any on their skin. Caution them regarding handling this solution and to immediately wash any spills from their skin using cold running water for at least 10 minutes.
- Caution students that for Part 2, when they are to blow into a flask using a straw, they are to blow gently and never suck on the straw.

Answers to Analysis Questions

1. Students should indicate that they saw a flame or the splint burn faster, indicating the presence of oxygen.

2. Students should indicate that they saw the colour change to pale yellow, indicating an acidic solution.

3. Students should identify the gas in their exhaled breath as carbon dioxide. The presence of carbonic acid, due to carbon dioxide in exhaled breath, will cause the solution to become acidic.

Answers to Conclusion Questions

4. The oxygen collected in the test tube over the *Cabomba* plant is from photosynthesis.

5. The carbon dioxide exhaled in breath is from cellular respiration.

6. Students may notice that the colour of the solution is no longer pale yellow and returns to a greenish-blue colour. This is due to the *Cabomba* carrying out photosynthesis and using the carbon dioxide in solution, which will cause the solution to decrease in acidity. (See note under Helpful Tips to counteract the possibility of this not being observed due to carbon dioxide in the air.)

Assessment Options

- Collect and evaluate students' answers to Analysis and Conclusion questions.
- Use Assessment Checklist 2: Laboratory Report (if applicable) and Assessment Checklist 3: Performance Task Self-Assessment from Appendix A.

Answers to Questions for Comprehension

Student Textbook page 167

Q9. Metabolic pathways that break down larger molecules into smaller ones release energy.

Student Textbook page 168

Q10. The electrons are transferred to another compound, which as a result, becomes reduced.

Q11. A compound in its reduced form contains more energy.

Section 5.1 Review Answers

Student Textbook page 168

1. A green plant converts light energy from the Sun into chemical energy to sustain its life processes. Herbivores such as a rabbit or deer eat the plant to obtain its stored chemical energy for their own use. When the herbivore is eaten by a mountain lion, the chemical energy that is transferred to the cat is delivered to the mitochondria of the muscle cells where it is converted to ATP and heat energy through the process of cellular respiration. The ATP produced is used in the contraction of the muscles of the mountain lion.

2. Photosynthetic organisms can use the energy from the Sun to synthesize energy-rich compounds that it can then use as "food." Thus, they do not need to rely on other organisms for those high-energy compounds.
3. Student answers should include points that are summarized in the following table. Note, a * indicates that the process listed occurs in that cellular activity.

Statement	Photosynthesis	Cellular Respiration
Converts light energy to chemical energy	*	
Converts the chemical energy in glucose to ATP		*
Occurs as a series of reactions	*	*
Involves the use of catalysts (enzymes)	*	*
ATP is produced	*	*
Oxygen is a waste product	*	
Oxygen is used		*
Occurs in the mitochondria		*
Carbon dioxide is produced		*
Carbon dioxide is consumed	*	
Water is a by-product		*
Occurs in the chloroplasts	*	
Glucose is synthesized	*	
Is a pathway that synthesizes larger molecules from smaller ones, and it requires energy		*
Is a process that breaks down large molecules to smaller ones, and it releases energy	*	

4. ATP is considered the "energy currency" of the cell because it is "spent" when the cell requires energy.
5. Student diagrams should include labels for the sugar group (ribose), nitrogenous base, and phosphate groups.
6. Student diagrams or descriptions should be similar to what is depicted in Figure 5.3 on page 163 of the student textbook. The energy that is released upon cleavage of the third phosphate group is used for numerous cellular activities. By phosphorylation of the ADP, ATP can be regenerated for further energy requirements by the cell.
7. A: Stroma

   B: Chloroplast membranes (outer and innner)

   C: Thylakoid

   D: Grana
8. The matrix is the part of a mitochondrion that performs a function related to the processes that occur in the stroma. Like the stroma, the matrix is a fluid-filled space that contains proteins and other chemicals used in reactions involving carbohydrates. (The difference between the two fluids is that the matrix supports the breakdown of carbohydrates, while the stroma supports their synthesis.)
9. Metabolism refers to all the chemical reactions that occur in a cell in order for it to survive. Metabolic pathways are discreet series of reactions that carry out specific functions. The two general categories of metabolic pathways that occur are: (1) those that synthesize large compounds from small precursor molecules and require energy, and (2) those that break down large compounds to produce smaller ones and release energy.
10. "Reducing power" refers to the amount of energy that a molecule has to reduce another compound. Molecules in their reduced state that have a large amount of available energy are considered to have "reducing power."

5.2 Photosynthesis Stores Energy in Organic Compounds

Student Textbook pages 169-181

Section Outcomes

Students will:
- describe how pigments absorb light energy and transfer it as reducing power in NADPH
- explain how absorbed light energy is transferred to the chemical potential energy of ATP by chemiosmosis
- describe where the energy transfer processes take place in chloroplasts
- explain how scientific knowledge may lead to the development of new technologies
- collect and interpret data and calculate R_f values from chromatography experiments
- conduct investigations in print and electronic resources on C3 and C4 photosynthetic mechanisms

Key Terms

light-dependent reactions
light-independent reactions
photosystems
chemiosmosis
Calvin-Benson cycle

Biology Background

- Pigments such as chlorophylls, beta-carotenoids, xanthophylls, and phycobilins each absorb different colours of light (also called wavelengths or photons). The colours we see in leaves represent the light not absorbed or transmitted. The pigments are assembled into antennae complexes and reaction centres (photosystems I and II), which are protein systems mounted in the membrane of the thylakoids in chloroplasts.
- In the light-dependent reactions, energy absorbed by pigments is transferred directly to electrons in chlorophylls. These electrons are replaced by electrons from water molecules. Photosystem II is the first protein complex to absorb light. In order to produce an oxygen molecule, 4 photons are absorbed and 2 water molecules are hydrolyzed. The result is 4 hydrogen ions, 4 electrons, and 1 oxygen molecule. The high-energy electrons are passed through a series of proteins, collectively called the electron transport system, losing energy along the way. Electrons eventually end up in photosystem I, where each electron absorbs another photon of light. This gives the electrons sufficient energy to reduce NADP+ to NADPH. Two photons are required to form every NADPH. Contrary to models presented in many older textbooks, ATP is not produced directly by this system. Rather, hydrogen ions are pumped into the thylakoid space.
- The energy lost by electrons as they pass along the electron transport system is used to pump hydrogen ions (protons) into the thylakoid disks from the stroma. The hydrogen ion concentration in the thylakoid space is augmented by the production of hydrogen ions during the hydrolysis of water, and the concentration gradient is further increased by the uptake of hydrogen ions in the stroma through the formation of NADPH. The result is a significant hydrogen ion gradient across the thylakoid membrane.
- The hydrogen ion concentration created by pumping protons into the thylakoids is used for production of ATP through the action of ATP synthase. As hydrogen ions move out of the thylakoid, the shape of ATP synthase is altered in such a way as to create a covalent bond between inorganic phosphate and ADP to produce ATP. This process is called chemiosmosis.
- Light-independent reactions are localized in the stroma of the chloroplast. In the stroma, ATP and NADPH from the light-dependent reactions accumulate and provide the energy and hydrogen required to fix carbon dioxide via the Calvin-Benson cycle, for eventual synthesis of carbohydrates and other high-energy compounds. Carbon dioxide is supplied through the stoma, common on the undersides of leaves.
- The Calvin-Benson cycle is driven by the presence of carbon dioxide, ATP, and NADPH in the stroma. Each carbon dioxide molecule entering this cycle is fixed by chemically bonding to ribulose bisphosphate (RuBP), a reaction catalyzed by the enzyme rubisco (short for ribulose bisphosphate carboxylase). The resulting six-carbon compound ultimately yields two three-carbon compounds that undergo activation by ATP and reduction by NADPH (both from the light-dependent reactions) to produce a metabolically important compound called glyceraldehyde-3-phosphate or PGAL. Some of the PGAL is a precursor for glucose synthesis and is shunted from the Calvin-Benson cycle to other metabolic pathways. The remainder continues on in the cycle to regenerate RuBP, in an ATP-dependent manner, allowing continuation of the Calvin-Benson cycle. For every molecule of glucose synthesized, 2 PGALs are required. Therefore, the Calvin-Benson cycle must be completed six times, which produces 2 PGALs (for glucose synthesis) and 10 PGALs (for RuBP regeneration).
- Photorespiration is responsible, in part, for the low efficiency of photosynthesis. Rubisco has a high affinity for oxygen and will fix oxygen instead of carbon dioxide when carbon dioxide concentrations are low. This occurs when stoma are closed, for example, at times of high evapotranspiration. Up to one third of fixed carbon dioxide is lost due to photorespiration, and no useful energy is stored.
- C3 plants use a 3-carbon compound (PGAL) to capture carbon dioxide. They generally have chloroplasts distributed about the mesophyll of the leaves and suffer most from photorespiration.

Teaching Strategies

- Use **BLM 5.2.1 (OH) Uses of Plant Substances** to illustrate the importance of photosynthesis for both plants and animals. You can also use it to ask students if they can come up with any other ideas that could be added.
- Students will likely need an introduction to the spectrum of light either through a demonstration using a prism or the use of diffraction gratings. This is a good opportunity to take them outside to examine sunlight. Caution them not to look at the Sun directly, but to use the prism or diffraction grating to project the light onto a piece of white paper. This experience will help them to understand the absorption spectra they will see in this unit.
- Take the students for a walk about the school grounds and collect as many different leaves as possible. You can use these to illustrate both the similarities and differences in pigments, since the leaves will be different shades of green. Even in winter, leaves can be found under the snow and on evergreen trees.
- Use **BLM 5.2.2 (OH) Light-reflecting and Light-absorbing Characteristics of Pigments** to illustrate an absorbance spectrum for photosynthetic pigments and how it relates to an action spectrum for photosynthesis. This should help students make the link from solar energy, the capturing of it by pigments, and the conversion to a biological process (photosynthesis).
- **BLM 5.1.3 (OH) A Closer Look at Chloroplasts** can be re-used to point out where the light-dependent reactions are occurring.

- Use **BLM 5.2.4 The Light-Dependent Reactions of Photosynthesis** to provide students with a visual image to follow as you discuss the steps in the light-dependent reactions.
- The process of chemiosmosis is often a difficult one for students to conceptualize. To help clarify this process, use an analogy of a situation with which students may be familiar. For example, a ball rolling down a ramp hits the trigger of a mousetrap. When the trap shuts, it grabs onto something like a clothes peg. The rolling ball represents the flow of protons down the proton gradient. The mousetrap is ADP and the clothes peg is inorganic phosphate. The ramp is ATP synthase. Ask students if they can think of any other analogies.
- **BLM 5.2.5: Chemiosmosis in a Chloroplast** can be used to show the development of the hydrogen ion gradient across the thylakoid membrane and the generation of ATP.
- Caution students that older high school textbooks and web sites will likely not discuss chemiosmosis, so when they do research they will have to pay close attention to the date and quality of the information.
- Use **BLM 5.2.7: The Calvin-Benson Cycle** to introduce the light-independent reactions. Start by asking students to identify the molecules they recognize and where they have seen them before. Then, use it as a visual for students to follow as you discuss the steps in the cycle.
- Some students may find it easier to begin with concentrating on the carbon backbone of molecules in the different stages of the Calvin-Benson cycle, as a way of following and learning the steps. Once they understand what is happening to the carbon backbone of the molecules, names can be added. In addition, have students initially just focus on the molecules involved and not the number and required turns of the cycle to produce glucose.
- Point out to students the FYI on page 177 of the student resource, which discusses the enzyme that catalyzes the reaction between carbon dioxide and RuBP, rubisco. Use this to make the point that, although not mentioned in their text, each metabolic reaction that they will look at is catalyzed by its own particular enzyme.
- Have students complete **BLM 5.2.10 Summary of Photosynthesis** to assess their retention and understanding of the information presented in this section. Once students have completed this handout, go over the answers with them and clarify any points that may be problematic or confusing to students.

SUPPORTING DIVERSE STUDENT NEEDS

Gifted Students

- Artistically gifted students may enjoy cartooning the processes described in the light-dependent and light-independent reactions.
- Let these students assist in organizing the class in modelling the Calvin-Benson cycle.
- These students may be frustrated with the simplified version of the Calvin-Benson cycle that is presented in their student resource. They might benefit from a series of questions that will assist them in finding and understanding more detail. Questions might include "How are the different structures of the metabolic intermediates altered by ATP and NADPH?" or "What functional group does carbon dioxide become incorporated into as when it enters the cycle?" In addition, they can carry out similar exercises to what is done in Thought Lab 5.1—using tracers to follow different atoms through the different reactions of the Calvin-Benson cycle.
- For Investigation 5.B, you can have these students redesign and carry out a modified experiment including a different species of plant and a manipulated (independent) variable. Alternatively, provide them with different solvents to determine the effect of solvent on the separation process.
- For Investigation 5.C, these students may go way overboard in designing their experiment. Remind them that a single manipulated variable and a single responding variable is all that can be incorporated into experiments at this level.

Students Who Need Extra Help

- To assist students in visualizing the processes of photosynthesis, you can have students dramatize the reactions. Assign students to roles such as light, hydrogen atom, electron, oxygen, photosystems I and II, NADP/NADPH, carbon dioxide, RuBP, etc. Then have them act out the process. Students with ADHD or similar issues may be given the more active roles. This also allows the stronger students and weaker students to practice working together cooperatively to carry out a task.
- In presenting the Calvin-Benson cycle, some steps are missed, and this discontinuity can interfere with weak (as well as gifted) students' comprehension. It might help to use a standard set of objects (like poker chips) to model the process with those who need extra help. Poker chips would represent the carbon atoms, with tape representing the bonds between the carbon atoms.
- To assist these students, you can model the light-dependent and light-independent reactions and movement of hydrogen, electrons, and oxygen using coloured paper shapes, which can be manipulated with the student to illustrate the process.

ESL Students

- These students may find the vocabulary in this section difficult. Contact your resource personnel well ahead of time with a list of terms that may prove problematic so the students can be properly prepared. Alternately, read the text with the students, helping with pronunciation and explaining the terms as they come up.
- These students may find it difficult to move from the complicated names of the chemicals to their acronyms. Showing the relationship between the word and the acronym and talking them through the pronunciation may help.

Answers to Questions for Comprehension

Student Textbook page 170

Q12. The two sets of reactions in photosynthesis are the light-dependent reactions and the light-independent reactions.

Q13. A pigment is a molecule capable of absorbing certain wavelengths of light and has a particular colour.

Q14. Chlorophyll is green because it absorbs other colours of light (red and blue) better than green. Therefore, green light is reflected back, providing the appearance of its green colour.

Q15. Since different pigments absorb different wavelengths of light, a plant can use a greater percentage of the Sun's light for photosynthesis by having more than one pigment.

Student Textbook page 171

Q16. A photosystem is a group of proteins that are embedded in the membrane of the thylakoid. The photosystems absorb light energy and transfer it to the electrons.

Q17. Each photosystem is made up of various pigments molecules, including chlorophyll and careotenoids, and a specialized electron-accepting chlorophyll *a* molecule called the reaction centre.

Investigation 5.B: Using Chromatography to Separate Plant Pigments

Student Textbook pages 172-173

Purpose

Students will learn to use paper chromatography to separate pigments found in a green leaf and to identify the pigments.

Outcomes

- 20–C1.3s
- 20–C1.4s

Advance Preparation

Photocopy **BLM 5.2.3: Investigation 5.B**

Materials
■ coleus or spinach leaves (or pigment mixture) ■ isopropanol (solvent) ■ chromatography paper ■ paper clip ■ retort stand ■ test-tube clamp ■ cork stopper ■ watch glass ■ large test tube

Time Required

- 55 minutes (15 minutes to introduce the process of chromatography; 40 minutes to conduct the activity, make and record measurements, and clean up.)

Helpful Tips

- Use **BLM 5.2.3 (HAND) Investigation 5.B: Using Chromatography to Separate Plant Pigments** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.2.3A (ANS) Investigation 5.B: Using Chromatography to Separate Plant Pigments Answers.**
- A demonstration of a paper towel or cloth soaking up some food colouring will set the stage for this activity.
- Caution the students not to let the activity run for too long. Once the solvent front stops moving, the experiment should be terminated, regardless of how far the front has actually moved.
- Caution the students that allowing the paper to touch the side of the test tube can invalidate the outcome of the experiment.
- ***Expected Results:*** Here is some sample data for this investigation:

Band (using diagram in textbook)	Pigment	Colour	Migration Distance (mm)	rF value
D (farthest from original position)	Carotene	Orange	59	0.94
C	Xanthophyll	Yellow	56	0.89
B	Chlorophyll *a*	Light green	29	0.46
A (closest to original position)	Chlorophyll *b*	Dark green	14	0.22
Solvent Front			63	

Safety Precautions

Isopropanol is flammable and should be kept away from open flames or sparks. Exposing mucus membranes to isopropanol can cause irritation. Isopropanol should be disposed of following appropriate procedures. The activity should be carried out in a fume hood. Students have been known to try to steal alcohols for later experimentation.

Answers to Analysis Questions

1. The sketch should show the solvent front, the original spot, and 3 to 4 pigment circles.
2. The most soluble is the carotenes, which travel the farthest. The least soluble is chlorophyll *b*, which travels the shortest distance. The most soluble is either the

smallest or the most polar. The least soluble is either the largest or the least polar.

3. Students should provide evidence of comparison in the form of a table. Sources of error may include moving the test tube after set-up, allowing the paper to touch the edge of the test tube, not allotting enough time for the experiment, working too slowly, or having too much or too little pigment on the paper.
4. Answers will depend upon the pigment mixture used. Students should be able to provide the majority of the names of the pigments using the table provided.

Answers to Conclusion Questions

5. **(a)** Pigments in the coleus: if green and cream leaf, the same as in the green leaf; if the leaf includes red, add anthocyanins. Pigments in the green leaf: carotenes, xanthophylls, chlorophyll *a* and *b*.
   (b) Students may answer yes or no. The hypothesis should include a prediction linking a manipulated variable to a responding variable and an explanation as to why they think the link is valid.

Assessment Options

- Collect and evaluate students' answers to Analysis and Conclusion Questions.
- Use Assessment Checklist 2: Laboratory Report (if applicable) and Assessment Checklist 3: Performance Task Self-Assessment from Appendix A.

Answers to Questions for Comprehension

Student Textbook page 174

Q18. In the electron transport system, electrons are passed along a series of electron-carrying molecules. With each transfer or "step" through the electron-carrying molecules, electrons give off a small amount of energy. Therefore, high-energy electrons will enter the electron transport system, lose energy with each transfer through the electron transport system, and enter photosystem I as low-energy electrons.

Q19. NADPH is formed from the reduction of $NADP^+$, using electrons from photosystem I.

Q20. In photosystem I, an electron is replaced by one that has reached the end of the electron transport system from photosystem II.

Q21. The effect is the establishment of a hydrogen ion concentration gradient across the membrane. There is potential energy associated with the establishment of this gradient.

Q22. Hydrogen ions cannot diffuse out of the thylakoid space because the membrane is impermeable to these charged particles.

Q23. ATP synthase is an enzyme complex embedded in the thylakoid membrane that provides a pathway for hydrogen ions to move down their concentration gradient, from the thylakoid space to the stroma. This enzyme catalyzes the formation of ATP from inorganic phosphate and ADP.

Q24. The movement of hydrogen ions down the concentration gradient and the bonding of a free phosphate group to ADP to form ATP are linked in the process known as chemiosmosis.

Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions

Student Textbook page 175

Purpose

Students will use modelling to understand the use of isotopes to trace atoms in chemical reactions and to predict the source of oxygen in photosynthesis.

Outcomes

- 20-C1.2s

Advance Preparation

When to Begin	What to Do
1 or 2 days before	■ Collect materials that can be used for model building. ■ Photocopy **BLM 5.2.6: Thought Lab 5.1**

Materials
■ modelling kit or other materials that can be used for building simple models of molecules

Time Required

- 30 minutes (15 minutes to make models; 15 minutes to answer Analysis Questions)

Helpful Tips

- Use **BLM 5.2.6 (HAND) Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.2.6A (HAND) Thought Lab 5.1: Modelling the Source of Oxygen in the Light-Dependent Reactions Answers.**
- If modelling kits are not available, you can use other materials such as Styrofoam™ balls and paper cut-outs.

Answers to Analysis Questions

1. The radioactive isotope form of an atom can be differentiated from its non-radioactive form. This allows the tracing or "following" of that atom through a chemical reaction, from reactant to product. Products can be analyzed for the isotope in order to identify the source of a particular atom in it.
2. **(a)** Based on their models and the chemical equation given, students should predict that oxygen atoms that originate from carbon dioxide end up in $CH_2O(s)$ and $H_2O(l)$.
   (b) Based on their models and the chemical equation given, students should predict that all carbon atoms from carbon dioxide end up in $CH_2O(s)$.
   (c) Based on their models and the chemical equation given, students should predict that all hydrogen molecules from water end up in $CH_2O(s)$ and $H_2O(l)$.

Assessment Options

- Collect and evaluate students' answers to Analysis Questions.
- Use Assessment Checklist 3: Performance Task Self-Assessment from Appendix A.

Answers to Questions for Comprehension

Student Textbook page 176

Q25. Reasons that hydrogen is not easily used as a fuel include its lack of availability as a gas in nature, the high input of energy required to obtain it from water, and the generation of carbon dioxide when obtaining it from sources other than water.

Q26. Scientists are investigating using an artificial system similar to photosystem II because the system is designed to use solar energy to split water and convert the released ions and electrons into hydrogen gas. This would avoid the problems currently associated with hydrogen production.

Student Textbook page 177

Q27. The Calvin-Benson cycle is a pathway in plants that uses the ATP and NADPH produced from the light-dependent reactions and carbon dioxide to synthesize glucose and other high-energy molecules that are needed by plants. This cycle involves the incorporation of carbon from carbon dioxide into ribulose bisphosphate for the synthesis of glyceraldehyde-3-phosphate (PGAL), which is used to synthesize glucose.

Q28. In the case of the Calvin-Benson cycle, carbon fixation refers to the carbon from carbon dioxide becoming chemically bonded to a pre-existing organic molecule (ribulose bisphosphate). It is a way that the carbon from carbon dioxide can become incorporated into a compound and can contribute to carbohydrate synthesis.

Thought Lab 5.2: Adaptations and Applications of Photosynthesis

Student Textbook page 178

Purpose

Students will expand their understanding of photosynthesis and apply that understanding to new situations.

Outcomes

- 20-C1.2s
- 20-C1.4s
- 20–C2.1sts

Advance Preparation

When to Begin	What to Do
7 days ahead, or as appropriate for your school's library and computer room use	■ Book space in the library and computer resource room.

Time Required

- 4 hours (2 hours for research and 2 hours for developing answer material.)

Helpful Tips

- Use **BLM 5.2.8 (HAND) Thought Lab 5.2: Adaptations and Applications of Photosynthesis** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.2.8A (ANS) Thought Lab 5.2 Adaptations and Applications of Photosynthesis Answers.**
- Students are likely to need assistance with search terms. Go to **www.albertabiology.ca**, Online Learning Centre, Instructor Edition. Teacher Web Links for suggested search terms and sites.
- If you are in a town with a university or college, suggest that students visit that institute for more complete resources. For example, the Alberta Library Card will allow them to take books home from all university and college libraries in the province.

Answers to Analysis Questions

1. **(a)** C_3 plants: most common trees, flowers, and herbs. C_4 plants: crabgrass (*Digitaria sanguinalis*), corn (*Zea mays*), sorghum (*Sorghum vulgare*), and sugarcane (*Saccharum officinale*) are most commonly encountered. CAM plants: cacti and stonecrops (*Sedum* species).

(b) Each group will select a plant. The problem is an environmental one relating to the plant; for example, cacti live in places with high temperatures and evapotranspiration rates, so their stomata are closed during the day. Groups should describe the solution appropriate for the plant. Cacti fix carbon at night, forming malic acid. During the day, malic acid is decomposed into carbon dioxide and a 3-carbon molecule, which supplies carbon dioxide when light is available.

2. Similarities include the use of ATP, NADPH, and the Calvin-Benson cycle. Differences are localized as to how carbon dioxide is provided to the cycle. In C_3 plants, carbon dioxide is provided directly through diffusion. In C_4 plants, diffusion is augmented by the formation of 4- carbon compounds during the day, which are transported into the bundle sheaths where they are decomposed to release carbon dioxide. In CAM plants, stomata are opened at night and carbon dioxide is fixed to malic acid, which is stored in vacuoles. During the day, malic acid decomposes to release carbon dioxide.

3. Accept any answer that links our understanding of photosynthesis to each topic. The more specific the link and the example used for each topic, the better.

Answer to Extension Question

4. Students should provide a clear outline of their opinion and a few key points that support their opinion. Make it clear to students that there is no right or wrong answer, but that they are stating their opinion and are to provide support for that opinion based on their readings.

Assessment Options

- Collect and evaluate students' answers to Analysis and Extension questions.
- Use Assessment Checklist 4: Performance Task Group Assessment or Assessment Checklist 7: Independent Research Skills from Appendix A.

Section 5.2 Review Answers

Student Textbook page 179

1. A plant uses glucose for cellulose and other structural tissues, for the synthesis of other carbohydrates, for storage as starch, and in the synthesis of other essential compounds such as amino acids.

2. The light-dependent reactions require the absorption of light from the Sun via photosynthetic pigments, to produce ATP and NADPH in the stroma of the chloroplast. When there are sufficient amounts of ATP and NADPH, these molecules are used for the synthesis of glucose. The synthesis of glucose occurs in the light-independent reactions, which as the name implies, can be carried out in the presence or absence of light.

3. Students' sketches should resemble Figure 5.9B.

4. The shape of the action spectrum will parallel that of the absorbance spectrum for the photosynthetic pigments together. However, an action spectrum describes how the rate of photosynthesis varies with the wavelength of light absorbed, and an absorbance spectrum describes how individual pigments absorb light.

5. Most green plants contain more than one photosynthetic pigment because each absorbs light of different colours (wavelengths). Having more than one type of pigment allows plants to use as much solar energy as possible.

6. Photosystems are complexes located on the thylakoid membrane that contain light-absorbing pigments.

7.
- Pigment molecules that are assembled in photosystems absorb light energy, which is concentrated in a chlorophyll *a* molecule.
- Excited electrons are raised to a higher energy level.
- The electrons pass through an electron transport system where the energy released is used to produce ATP.
- A water molecule is split into its elements. The hydrogen atoms reduce $NADP^+$ to NADPH, which participates in the Calvin-Benson Cycle.
- The oxygen atoms combine and leave the cell as oxygen molecules.

8. The electron transport system can be described as a staircase. On each step is a carrier molecule that accepts high-energy electrons from above and passes them down to a carrier below. High-energy electrons lose energy as they are passed from carrier to carrier. This energy can be used to produce ATP molecules.

9. NADPH is a reduced molecule. The oxidized version (i.e., the version containing one less electron) is $NADP^+$.

10. Electrons that are lost from chlorophyll molecules in photosystem II are replaced by the splitting of water.

11. The process of chemiosmosis involves the use of a proton gradient across a membrane to synthesize ATP.

12. The ATP and NADPH required for the synthesis of glucose is obtained from the light-dependent reactions.

13. Carbon dioxide enters the Calvin-Benson cycle by combining with a molecule of ribulose bisphosphate to form an unstable six-carbon compound that immediately breaks down to two three-carbon compounds. ATP and NADPH produced in the light-dependent reactions act in converting these compounds to PGAL molecules. Some PGAL molecules combine to form glucose. Others are converted back to ribulose bisphosphate, which is needed to continue the cycle.

14. (a) Since aerobic bacteria need oxygen to survive, greater concentrations of bacteria reflect greater concentrations of oxygen, and thus imply greater rates of photosynthesis. Photosynthesis is greatest in violet and blue light and red light. Photosynthesis is least in green and yellow light.

(b) Each hypothesis should have a manipulated variable, a responding variable, and an explanation of why the effect might be expected. For example, light of differing colours will have different rates of photosynthesis because each photosynthetic pigment will absorb light differently. Support (or lack of support) must be provided based on Englemann's experiment. For the hypothesis provided, support is provided by the differing concentrations of bacteria around blue light as compared to green light.

Investigation 5.C: The Rate of Photosynthesis

Student Textbook pages 180-181

Purpose

Students will investigate how different variables, such as light, affect the rate of photosynthesis.

Outcomes

- 20-C1.1s
- 20-C1.3s
- 20-C1.4s

Advance Preparation

When to Begin	What to Do
1 or 2 days before	■ Photocopy **BLM 5.2.9: Investigation 5.C** ■ Prepare sodium bicarbonate solution.* ■ Obtain sufficient plant leaves.

*Refer to Preparing Solutions in the front matter of this Teacher's Resource.

Materials
■ plant leaf ■ liquid dish soap ■ 0.25% sodium carbonate ■ single-hole punch ■ 10 mL plastic syringe (without the needle) ■ medicine dropper ■ 200 mL beaker ■ lamp with a reflector and 150 W bulb ■ timer ■ materials for students to carry out Part 2 of the investigation

Time Required

- Part 1: 60 minutes (15 minutes set up; 20 minutes to do investigation; 10 minutes clean up; 15 minutes to do analysis and conclusion questions)
- Part 2: 60 minutes (20 minutes to plan investigation; 20 minutes to carry out the investigation; 20 minutes to write up results;
  Note: times will depend on the ability and experience of students

Helpful Tips

- Use **BLM 5.2.9 (HAND) Investigation 5.C: The Rate of Photosynthesis** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.2.9A (ANS) Investigation 5.C The Rate of Photosynthesis Answers.**
- In order to reduce concerns about reliability in this lab, have the students pool data for the class to increase the number of replicates.
- Students will have to design a system to reduce ambient light; turning off the classroom lights might work if everyone coordinates their timing.
- ***Expected Results:***
  Part 1:
  Here are some sample results – your results will vary depending on the intensity of light, the concentration of the sodium bicarbonate solution, or the leaves used in this investigation.

Time (minutes)	Number of Leaf Desks Floating
1	0
2	0
3	0
4	0
5	0
6	0
7	1
8	2
9	2
10	3
11	5
12	7
13	8
14	10

The point at which 50% of the disks are floating is between 10 and 12 minutes.
Part 2: Results will depend on the variable selected.

Safety Precautions

For Part 2 of this investigation, ensure that you have checked the students' experimental designs for potential safety hazards.

Answers to Analysis Questions

1. Students' graphs should illustrate a curve that starts gradually and then rises sharply as photosynthesis proceeds more rapidly due to light exposure.
2. Some students may need a hint to look at the y-axis and use the mid-point (5 leaf disks) to make their estimates.
3. The air was removed by infiltrating the spaces with sodium bicarbonate solution. The result is that air is removed from the spaces, which allows the leaves to sink to the bottom of the beaker.

Answers to Conclusions Questions

4. The variable tested was the effect of white light on oxygen production.
5. The leaf disks should start to float after being exposed to white light due to the production of oxygen gas, a product of the light-dependent reactions, which collects in chambers within the plant leaf.

Assessment Options

- Collect and evaluate students' answers to Analysis and Conclusion Questions.
- Use Assessment Checklist 2: Laboratory Report from Appendix A.
- Use Assessment Checklist 1: Designing an Experiment from Appendix A for Part 2.

5.3 Cellular Respiration Releases Energy from Organic Compounds

Student Textbook pages 182-194

Section Outcomes

Students will:

- distinguish, in general terms, among aerobic respiration, anaerobic respiration, and fermentation
- explain how carbohydrates are oxidized by glycolysis and the Krebs cycle to produce reducing power in NADH and $FADH_2$ and chemical potential in ATP
- explain how chemiosmosis converts the reducing power of NADH and $FADH_2$ to the chemical potential of ATP
- design an experiment to demonstrate that oxygen is consumed during aerobic cellular respiration and that heat is produced
- explain that science and technology are developed to meet societal needs such as the production of foods and fuels
- investigate and integrate, from print and electronic sources, information on the action of metabolic toxins such as hydrogen sulfide and cyanide

Key Terms

aerobic cellular respiration
anaerobic cellular respiration
glycolysis
Krebs cycle
electron transport system
chemiosmosis
fermentation

Biology Background

- Cellular respiration is linked to the cytoplasm and mitochondria. It is divided into four processes: glycolysis (in the cytoplasm), transition reactions (in the cytoplasm and the intermembrane space of the mitochondria), the Krebs cycle (in the inner matrix of the mitochondria), and electron transport (on the inner membrane, or cristae, of the mitochondria). Electron transport creates a hydrogen ion (proton) gradient with high concentrations of hydrogen ions in the intermembrane space of the mitochondrion. This gradient is used by ATP synthase (as in photosynthesis) to produce ATP as hydrogen ions move back into the inner matrix of the mitochondrion.
- Glycolysis is an anaerobic pathway that begins with glucose and results in the production of G3P (glyceraldehyde-3-phosphate) and dihydroxyacetone phosphate. These molecules are isomers of each other, and as G3P is used in transition reactions, dihydroxyacetone phosphate converts to G3P. (In the student resource, these two molecules are indicated as "intermediate three-carbon molecules".) The G3P is converted to pyruvate, also a three-carbon compound. Glycolysis produces a small amount of ATP and NADH. Pyruvate is transported into the mitochondrial matrix for the transition reaction, which converts pyruvate to acetyl CoA and results in production of 2 NADH per pyruvate conversion.
- Aspects of the Krebs cycle that this unit focusses on are the production of ATP, $FADH_2$, NADH, and CO_2. In the Krebs cycle, acetyl CoA is incorporated into a four-carbon compound to produce a six-carbon compound. During one turn of the cycle, that six-carbon compound breaks down. The four-carbon compound required for further acetyl CoA incorporation is regenerated and 2 carbon atoms are oxidized and released as 2 CO_2 molecules. Note, however, that while each turn of the cycle removes two carbons, research has revealed that these are not the same two carbons that enter as acetyl CoA. Ultimately, the Kreb's cycle converts the energy originally stored in glucose to reducing power in $FADH_2$ and NADH.
- NADH and $FADH_2$ transport hydrogen ions and their accompanying electrons to the electron transport chain. As the electrons are passed, energy is released and is used for pumping hydrogen ions out of the inner matrix into the

intermembrane space. The last receptor of the hydrogen ions and electrons is oxygen, and the product is water. This reduces the concentration of hydrogen ions in the inner matrix, further increasing the concentration gradient. Hydrogen ions re-enter the inner matrix through ATP synthase, and as they do, the change in shape of the enzyme results in the binding of a phosphate to ADP to form ATP. Thus, ATP synthesis occurs via chemiosmosis, as it does in the chloroplast.

- In the absence of sufficient oxygen, fermentation will occur in many species. In humans, fermentation produces lactic acid (or lactate) and results in re-oxidation of NADH (from glycolysis) to NAD^+. However, no extra energy is produced from what is generated in glycolysis. In yeast, similar reactions can produce carbon dioxide and ethanol, likewise with no further generation of energy. Fermentation has been used for the production of a variety of substances, depending upon the sugar and organisms that are used.
- Fermentation for the production of ethanol on an industrial scale has been of particular interest given ethanol's use as an additive in gasoline and as a fuel.

Teaching Strategies

- Begin by pointing out that animals, fungi, protists, and, during the night, plants, cannot photosynthesize; yet they still carry on metabolic functions. For example, humans still pump blood, breathe, and dream at night. Ask where the chemical energy comes from to accomplish these tasks. In other words, lead the students to recognize that there has to be another chemical energy-producing system besides photosynthesis in order for living things to survive.
- **BLM 5.1.4 (OH) A Closer Look at Mitochondria** can be re-used to point out where the reactions associated with cellular respiration occur.
- Use **BLM 5.3.2 (OH) Stages of Cellular Respiration** to introduce the names of the 4 stages and where they occur in the mitochondrion. Do not go into detail at this point, but tell students that once you have gone through each stage you will return to this figure as a way of summarizing all the stages in cellular respiration.
- Introduce glycolysis by reminding students where in the mitochondrion it takes place and explaining that glucose begins to be broken down in this pathway. The majority of the glycolytic reactions have not been included in the student resource, so use Figure 5.19 as a guideline, emphasizing the net production of 2 ATP, why it is referred to as a net production, and that two pyruvates are synthesized per glucose molecule broken down. Remind students that they have seen ATP before in photosynthesis.
- Use **BLM 5.3.3 (OH) The Krebs Cycle** to outline the important aspects of the Krebs cycle. There may be some confusion between NADH and NADPH, so you may need to point out very basic similarities in structure and function, as well as the differences in structure.
- Re-use **BLM 5.3.2 Stages of Cellular Respiration** to summarize the stages of cellular respiration.
- Explaining the process of chemiosmosis and relating it to the structure of the mitochondria will be beneficial. Re-use **BLM 5.1.4 (OH) A Closer Look at Mitochondria** to highlight the intermembrane space and where the proton gradient is occurring. Prompt students to recall the analogy that was discussed for photosynthesis. Ask students if they can think of their own analogies, which will increase the likelihood of them remembering the basic steps in the process.
- **BLM 5.3.4 Aerobic Cellular Respiration** provides a good summary of the key molecules that are generated and released during cellular respiration.
- Most textbooks and web sites provide more information than students require. This can be confusing for students, since they may not know what level of detail you expect. Identifying the compounds with which you expect them to be familiar and the processes they are expected to master can go a long way to reducing the stress and confusion they will experience otherwise.
- Have students complete **BLM 5.3.6 (OH) Flow of Energy between Photosynthesis and Cellular Respiration** to assess their retention and understanding of the information presented in this section and Section 5.2. Once students have completed this handout, go over the answers with them and clarify any points that may be problematic or confusing to students.

SUPPORTING DIVERSE STUDENT NEEDS

Gifted Students

- Some of these students will be frustrated by the simplified version of cellular respiration presented. These students might benefit from a series of questions that will assist them in finding and understanding more detail. Questions might include "How does the cell create carboxylic acids in the Krebs cycle?" or "What functional group does carbon dioxide come from?" In addition, they can carry out similar exercises to what was done in Thought Lab 5.1—using tracers to follow different atoms throughout the different reactions of cellular respiration.

Students Who Need Extra Help

- To assist students in visualizing the processes of cellular respiration, you can have students dramatize the reactions. Assign students to roles such as glucose, pyruvate, acetyl CoA, oxygen, carbon dioxide, electrons, ATP, etc. Then have them act out the process. Students with ADHD or similar issues may be given the more active roles. This also promotes cooperation between the stronger students and weaker students.
- You can help students conceptualize the processes in cellular respiration by using models. Modelling clay can be easily manipulated to illustrate each of the four stages of cellular respiration.
- In presenting the Krebs cycle, a great deal of detail is left out, and this discontinuity can interfere with weak (as well as gifted) students' comprehension. It might help to use a standard set of

objects (like poker chips) to model the process. For example, poker chips could represent the carbon atoms, with tape representing the bonds between the carbon atoms.

ESL Students

- This section is vocabulary intense. Contact your resource teacher the week before you begin this section for suggestions and assistance in designing ways to help ESL Students learn the vocabulary.

Answers to Questions for Comprehension

Student Textbook page 183

Q29. Oxic conditions are those containing oxygen, while anoxic conditions lack oxygen.

Q30. Aerobic cellular respiration requires oxygen to produce ATP, while anaerobic respiration does not require oxygen to produce ATP.

Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds

Student Textbook pages 184-185

Purpose

Students will measure the consumption of oxygen and production of heat in germinating seeds.

Outcomes

- 20-C2.1s
- 20-C2.2s

Advance Preparation

When to Begin	What to Do
3 or 4 days before	■ Obtain sufficient seeds for your class. (It may be difficult in winter to obtain seeds. You may wish to ensure sufficient seeds are available at the beginning of the school year.)
2 or 3 days before (depending on the kind of seeds you obtained)	■ Soak sufficient seeds in room temperature water to initiate germination. ■ Photocopy **BLM 5.3: Investigation 5.D**

Materials
■ 1 g of seeds of any kind ■ limewater ■ liquid detergent

Materials
■ large test tube ■ ruler ■ one-hole stopper ■ pipette ■ wad of cotton ■ 18 mm test tube ■ rigid plastic tubing, 20 cm long and bent at a right angle ■ marker ■ balance ■ spatula ■ Scotch™ tape ■ support stand and clamp ■ materials for students to carry out Part 2 of the investigation

Time Required

- Part 1: 60 minutes (15 minutes to set up; 30 minutes to conduct investigation; 15 minutes for clean up)
- Part 2: 30 minutes (15 minutes for set up; students check temperature at 5 minute intervals)

Helpful Tips

- Use **BLM 5.3.1 (HAND) Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.3.1A (ANS) Investigation 5.D: Oxygen Consumption and Heat Production in Germinating Seeds Answers.**
- Students will typically count the seeds they use. They may need assistance in realizing that it is not the number of seeds that is important, but their mass.
- Tests using radish, pea, bean and corn seeds indicated that corn seeds give the best results. Also, it is advisable to pre-soak the seeds overnight.
- Flexible 6-inch transparent rulers can be cut from rulers printed on overhead transparencies.
- A card with a horizontal line (meniscus reader) can be used to extrapolate the level of the detergent plug to the shorter markings of the ruler to assist in reading the distance.
- You may wish to approve the procedures of the students for Part 2 before they begin the experiment in order to ensure that they have carefully considered their experimental plan. In a large class, a wide variety of apparatus will be chosen. Indicate that students will have to provide their own apparatus. Alternatively, you may show students what apparatus you will provide before they begin designing their own procedure.
- ***Expected Results:*** The results of this investigation will depend on the seeds used, the amount of time that the seeds have had to germinate, and the size of the tubing (bore) used in the respirometer. In tests of this investigation, corn seeds used significantly more oxygen than pea or bean seeds.

Investigation 6.A Testing for Macromolecules pp. 212-213
Part 1

Test tube	Contents	Colour change	Conclusions
1	distilled water	turns blue when Biuret added	no protein present
2	albumin	turns violet when Biuret added	proteins are present
3	pepsin	turns violet when Biuret added	enzymes are proteins
4	starch	turns a creamy-blue colour	no protein present; colour resulting of mixing reactants

Part 2

Test tube	Contents	Colour change	Conclusions
1	starch	turns blue-black	starch is present
2	distilled water	turns orange (colour of the iodine)	starch not present

Part 3

Test tube	Contents	Colour change	Conclusions
1	distilled water	stayed blue	no sugar present
2	glucose solution	orange-red	very high
3	onion juice	yellow-orange	moderate amount
4	potato juice	green	very low
5	starch suspension	stayed blue	no sugar present

Part 4

Sample	Results
distilled water	no translucent spot after drying: no fat present
oil	translucent spot remained; fat present
solid fat	translucent spot remained; fat present

Safety Precautions

- If glass tubing is used, advise students to handle it very carefully in order to avoid breakage.
- For Part 2 of this investigation, ensure that you have checked the students' experimental designs and set-ups for potential safety hazards. Students may design a system that builds up pressure from the gases evolved. This increases the possibility of an explosion.

Part 1

Answer to Analysis Question

1. Students should provide some type of summary statement comparing the results from different groups in the class.

Answers to Conclusions Questions

2. Students should identify that carbon dioxide production was the indication that cellular respiration was occurring.
3. Sources of error could include carbon dioxide lost to the environment, mass of the seeds used, accuracy of the respirometer apparatus, age and health of the seeds used, human judgment in reading the respirometer.

Part 2

Answers to Analysis Questions

1. Students should identify one manipulated variable and at least three controlled (fixed) variables. One of these fixed variables will likely be the type of seed used.
2. Sources of error could include heat lost to the environment, mass of the seeds used, accuracy of the measuring devices used, age of the seeds used, human judgment in reading the measuring devices, and health of the seeds used.

Answers to Conclusions Questions

3. Students should state if their results supported their hypothesis or not. Their explanation should be based on a comparison of their data or their classmates' pooled data and the hypothesis they wrote.
4. Net total heat given off by the germinating seeds will increase if the experiment is run for a longer time, but the temperature will not continue to go up indefinitely. Two things will stop the increase in temperature: heat

loss to the environment and, if the temperature gets too high, denaturation of metabolic enzymes in the seeds.

Assessment Options

- Collect and evaluate students' answers to Analysis and Conclusion questions.
- Use Assessment Checklist 2: Laboratory Report if applicable.
- Use Assessment Checklist 3: Performance Task Self-Assessment from Appendix A.
- Use Assessment Checklist 1: Designing an Experiment from Appendix A for Part 2.

Answers to Questions for Comprehension

Student Textbook page 186

Q31. Glycolysis occurs in the cytoplasm of the cell and does not require oxygen.

Q32. Products of glycolysis include intermediate 3-carbon molecules, pyruvate, ATP, and NADH.

Student Textbook page 187

Q33. The reactions of the Krebs cycle take place in the mitochondrial matrix.

Q34. The glucose-derived acetyl CoA is the compound that enters the Krebs cycle.

Q35. During the Krebs cycle, NAD^+ is reduced to NADH and FAD is reduced to $FADH_2$.

Biology File: Web Link

Student Textbook page 189

Symptoms of pyruvate dehydrogenase complex deficiency (PDCD) include loss of coordination, developmental delay, reduced muscle tone, seizures. Treatments include diet modification (low in carbohydrates and high in fats), measures to correct lactate acidosis (buildup of lactate in the body), anti-convulsant and/or muscle-relaxant medications, and thiamine as well as carnitine and lipoic acid supplementation. Success of treatment depends on severity of the disease.

Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration

Student Textbook page 189

Purpose

Students will expand their knowledge of metabolic toxins and how these compounds affect cellular respiration.

Outcomes

- 20-C2.2s
- 20-C2.3s
- 20-C2.4s

Advance Preparation

When to Begin	What to Do
Several days ahead	■ Book time in the library and computer resource room. ■ Photocopy **BLM 5.3.5: Thought Lab 5.3**

Time Required

- 120 minutes: 60 minutes to do the research; 60 minutes to share their profiles and do the Analysis questions

Helpful Tips

- Use **BLM 5.3.5 (HAND) Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration** to support this activity. Remove sections as appropriate to meet the needs of the students in your class. The answers can be found on **BLM 5.3.5A (ANS) Thought Lab 5.3: The Effects of Metabolic Toxins on Cellular Respiration Answers.**
- Students are likely to need assistance with search terms. Go to **www.albertabiology.ca**, Online Learning Centre, Instructor Edition. Teacher Web Links for suggested search terms and sites.
- If you are in a town with a university or college, suggest that students visit that institute for more complete resources. For example, the Alberta Library Card will allow them to take books home from all university and college libraries in the province.
- You may wish to discuss topics such as validity of information, validity of sources of information, bias, and accuracy of information from various sources with students before they begin their searches for resources.

Answers to Analysis Questions

1. Antimycin, cyanide, hydrogen sulfide, malonate, and rotenone are electron transport system inhibitors. Oligomycin is a phosphorylation inhibitor. Arsenic is a Krebs cycle inhibitor.
2. Students' answers to these questions will provide an indicator of their researching skills and their patience and/or perseverance in consulting information resources. Students may benefit from first deciding among themselves what the terms accuracy, validity, and reliability mean. They should appreciate that consulting many resources (e.g., medical journals, encyclopedias, government health publications) adds to greater confidence in the information that they discover. While four such resources might often be sufficient for providing accurate and reliable information, students should also realize that discrepancies among these resources require

further additional research, either to verify a given fact or to more fully represent the nature of a given discrepancy.

Assessment Options

- Collect and evaluate students' answers to Analysis Questions.
- Use Assessment Checklist 4: Performance Task Group Assessment and Assessment Checklist 7: Independent Research Skills from Appendix A.

Biology File: Web Link

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Streptococcus salivarius is the first bacterium to colonize the mouth, and it remains dominant until the appearance of teeth. The non-epithelial surfaces of teeth support the growth of species such as *Streptococcus mutans* and *Streptococcus salnguis*. At least 200 different bacterial species have been identified as common inhabitants of the human mouth. Common bacterial-related diseases of the teeth and gums include plaque, caries (cavities), and periodontal disease (such as gingivitis and periodontitis).

Answers to Questions for Comprehension

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Q36. Electron carriers of the electron transport system are attached to the inner membrane of the mitochondrion.

Q37. The source of high-energy electrons is the NADH and $FADH_2$ from the Krebs cycle.

Q38. Oxygen functions as the final electron acceptor at the end of the electron transport chain. The oxygen accepts the electrons and some hydrogen ions, with water ultimately being produced.

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Q39. Glycolysis is considered an anaerobic process because it can proceed without oxygen.

Q40. Fermentation occurs under anaerobic conditions (i.e., oxygen-lacking conditions).

Q41. Similarities between lactate and ethanol fermentation include: both occur under anaerobic conditions, both involve the production of pyruvate from glucose via glycolysis, and both result in the oxidation of NADH to NAD^+. The major difference between these two pathways is the final product that is formed. In lactate fermentation, pyruvate is converted to lactate, while in ethanol fermentation the pyruvate is converted to carbon dioxide and a 2-carbon molecule that is converted to ethanol.

Connections (Science and Technology) Energy from Manure

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Teaching Strategies

- Students may not be familiar with the tainted water crisis in Walkerton, Ontario in 2000, when 7 people died and hundreds more became ill when the local water supply became contaminated by e-coli bacteria in cattle manure after heavy rains. In addition to giving off greenhouse gases, manure can be a source of toxic pollutants if it is not disposed of carefully.
- An investment in biogas production can turn a cost—of animal waste disposal—into something positive to solve a different social problem.
- This can be a case where developed countries can learn from and transfer technology from developing countries.

Answers to Questions

1. In contrast to the anaerobic respiration processes that produce ethanol and lactic acid, which are well treated in many high school resources, the anaerobic production of methane is generally ignored. Researching integrated manure utilization systems (IMUS) is intended to extend students' understanding of anaerobic respiration processes, alternative fuel sources, and societal issues surrounding waste management and atmospheric degradation. Although anaerobic production of methane and carbon dioxide is complex, students can be shown that acetic acid can be decomposed into methane and carbon dioxide, and acetic acid can be linked to acetyl-CoA to tie biogas production to students' knowledge of cellular respiration. Detailed reactions can be found at **http://www.fao.org/docrep/w7241E/w7241e0f.htm**.
2. This Connections item can be used after studying ethanol and lactic acid production to illustrate how students can build on their basic biology knowledge to expand their understanding of cellular processes. It can also provide an example of how understanding basic biological reactions can lead to the development of new technologies and partial solutions of global issues. This underscores the value of basic scientific research.

Biology File: Web Link

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Other products planned include carbon dioxide, drying distillers' dried grains and solubles (DDGS), distillers wet grain (DWG), steam, and electricity. Corn is an appropriate choice because it is a traditional food of First Nations.

Section 5.3 Review Answers

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1. In cellular respiration, glucose is oxidized in the mitochondria to produce carbon dioxide, water, and ATP molecules. In photosynthesis, carbon dioxide molecules are reduced, resulting in the formation of glucose and oxygen.
2. Aerobic respiration occurs in the mitochondria of eukaryotic organisms. It is the complete oxidation of glucose in the presence of oxygen resulting in the production of carbon dioxide, water and ATP.

   Anaerobic cellular respiration is used by some organisms (prokaryotes) in anoxic environments to obtain energy. Like aerobic respiration it includes an electron transport chain and a concentration gradient to produce ATP. However, this process is not as efficient in ATP production as aerobic respiration is. In addition, since oxygen is not available to act as the final electron acceptor, other molecules (sulfate, nitrate, carbon dioxide) serve as the electron acceptor.

   Fermentation is an anaerobic process. In some organisms and in animal cells temporarily without oxygen, lactate fermentation occurs, resulting in the formation of lactic acid and considerably less energy than aerobic respiration. Yeast can undergo ethanol fermentation, whereby glucose is converted to carbon dioxide, ethanol, and ATP.
3. The three energy-releasing metabolic pathways associated with aerobic cellular respiration are glycolysis, the Krebs cycle, and the electron transport chain.
4. Students may choose to generate a graphic indicating the reactants and products; if so, it should be similar to Figure 5.19. Also indicated should be that glycolysis takes place outside of the mitochondria in the cytoplasm, that oxygen is not required, and that the product, pyruvate, is then converted to acetyl CoA in the mitochondrial matrix.
5. Students may choose to generate a graphic indicating the reactants and products; if so, it should be similar to Figure 5.20. Also indicated should be that the Krebs cycle takes place in the mitochondrial matrix, the $FADH_2$ and NADH produced contribute electrons to the electron transport chain, and that oxygen is required for these reactions to occur—although not used directly in the reactions. (If oxygen is not present, pyruvate from glycolysis is reduced by fermentation.)
6. The electron transport system involves the passing along of high-energy electrons from NADH and $FADH_2$ using electron-carrying molecules that are attached to the inner membrane of the mitochondria. As electrons are passed along, energy is released in discreet amounts. The energy released is used to pump hydrogen ions across the mitochondrial intermembrane space to produce a hydrogen ion concentration gradient for ATP synthesis via chemiosmosis. Oxygen is the final acceptor of the electrons and combines with hydrogen to form water.
7. Chemiosmosis refers to use of the potential energy associated with a hydrogen ion concentration gradient across a membrane to synthesize ATP by binding a phosphate group to ADP.
8. The final electron acceptor in aerobic respiration is oxygen. If this molecule is not present, then the pyruvate that is generated from glycolysis begins to build up. When this occurs, the cell starts to break down pyruvate by fermentation, which also involves the oxidation of NADH to NAD^+.
9. Anaerobic cellular respiration is not as efficient as aerobic respiration, so fewer ATP are synthesized.

   Note: If you want to ask a more challenging question, change the term "anaerobic cellular respiration" to "fermentation." The answer would then be:

   Aerobic cellular respiration produces much more ATP than fermentation does because fermentation relies solely on glycolysis to generate ATP, whereas aerobic respiration also generates ATP via the Krebs cycle and the electron transport system.
10. Fermentation is a metabolic pathway that uses glycolysis to break down glucose to pyruvate, and then, in association with the oxidation of NADH to NAD^+, reduces pyruvate to various compounds. Compounds that are synthesized by fermentation include ethanol and lactate. This metabolic pathway is considered to be anaerobic because it does not require the presence of oxygen. In fact, in many cases, it occurs as a result of the lack of oxygen.
11. Both lactate and ethanol fermentations involve the reduction of pyruvate (from glycolysis) with associated oxidation of NADH to NAD^+ and result in the synthesis of the same amount of ATP (from gylcolysis). However, the products of these two pathways differ. Lactate fermentation results in the production of lactate, while ethanol fermentation results in the production of carbon dioxide and ethanol.

Career Focus: Ask a Research Scientist

Student Textbook pages 196-197

Teaching Strategies

This feature is intended to introduce another STS connection to the study of cellular respiration. There are links to ecology and human nutrition and waste production as well. After reading the feature, students may simply be directed to accomplish the tasks in the "Go Further" section.

Answers to Go Further Questions

1. This feature can be tied to a field trip to a local solid waste management site, to an analysis of students'

household solid waste production, or to an analysis of what your school contributes to solid waste and how it is handled. Classes located in larger cities will have a wide variety of waste management facilities to potentially visit, while teachers in smaller cities may have to direct students to do some on-line research.

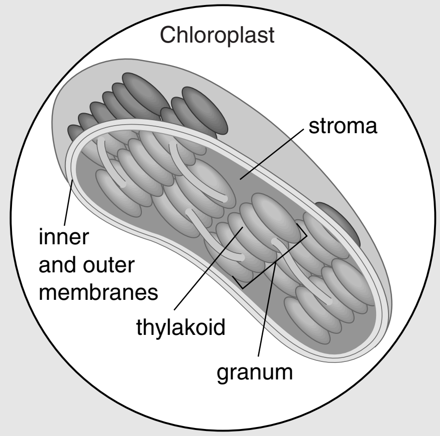
2. With the understanding gained in the previous question, students can make suggestions about how to improve the handling of local solid waste, and perhaps take a hand in implementing improvements to the waste handling system. Questions may arise about how different types of materials (metals, plastics, organic solids) are separated for proper treatment, the cost effectiveness of composting, or the NIMBY (not in my backyard) attitude toward waste management.
3. Students should be able to identify VOCs as being molecules that may be derived from living things and evaporate easily. Some examples might be methanol, ethanol, or chlorofluorocarbons (CFCs). Students should also research laws and/or guidelines concerning the proper disposal of hazardous wastes.

Unit 3 Review Answers

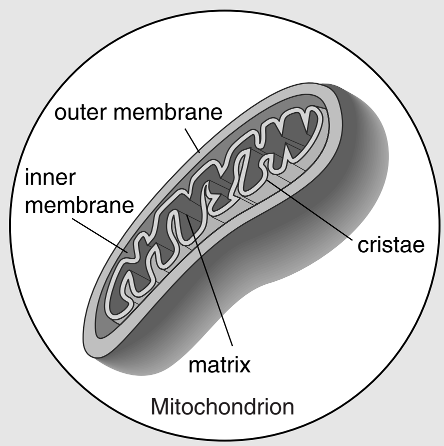
Student Textbook pages 198-199

Answers to Understanding Concepts Questions

1. Autotrophic organisms are those that carry out photosynthesis. They contribute to an ecosystem by using solar energy to produce energy-rich compounds (carbohydrates). They also produce oxygen, which is released into the ecosystem.
2. Both autotrophs and heterotrophs release the energy stored in glucose by carrying out cellular respiration.
3. Cellular activities that require ATP include: ion transport across cell membranes; movement of chromosomes during cell division; movement of cilia and flagella; muscle contraction; and synthesis of carbohydrates, fats, proteins, and nucleic acids.
4. The breakdown and regeneration of ATP is a continuous cycle, which involves the cleavage of a terminal phosphate group in ATP to produce ADP (breakdown) and subsequent addition of a phosphate group to ADP to reform ATP.
5. The chloroplast is the organelle where photosynthesis takes place.
6. Students' sketches should resemble the structure depicted in Figure 5.4 of the student resource, including appropriately labelled structures.



7. In chloroplasts, grana are made of thylakoid disks.
8. In photosynthesis, NADPH is produced in the light-dependent reactions and is a source of reducing power (i.e., electrons) that is used in the light-independent reactions to synthesize carbohydrates. In cellular respiration, NADH, which is generated in glycolysis and the Krebs cycle, provides electrons that enter the electron transport chain for the synthesis of ATP.
9. Students' sketches should resemble the structure depicted in Figure 5.5 of the student resource, including appropriately labelled structures.



10. **(a)** Oxygen gas can be tested for by using a slow-burning, glowing splint of wood. The splint will burn faster and a flame will appear if oxygen is present.
    (b) Carbon dioxide in water will result in the production of carbonic acid. This will cause the pH of the solution to decrease, which can be detected using a pH indicator such as bromothymol blue.
11. Metabolic pathways that synthesize large molecules from smaller ones require energy, while those that break down large molecules to smaller ones produce energy. Both types of pathways are catalyzed by enzymes.

12. Oxidation-reduction reactions are a central type of reaction in photosynthesis and cellular respiration. Products from these processes, such as ATP and carbohydrates, are required for numerous processes in organisms.

13. In the chloroplast, light energy is stored as chemical energy in glucose (matter). In the mitochondria, the glucose molecule is decomposed, releasing the energy which eventually is returned to the environment as heat.

14. Photosynthetic pigments are organic molecules capable of absorbing specific wavelengths of visible light. They act in photosynthesis by trapping energy from the Sun.

15. The light splits into its constituent colours, producing a spectrum. This spectrum could be used to study photosynthesis by controlling the colour a leaf is exposed to and measuring the rate of photosynthesis for each independent colour.

16. An action spectrum differs from an absorption spectrum in that an action spectrum describes how the rate of photosynthesis varies with wavelength of light absorbed, and an absorbance spectrum describes how individual pigments absorb light.

17. Photosystems are protein complexes that contain light-absorbing pigments. They are located on the thylakoid membrane.

18. The energy that is released at each step is stored temporarily in a hydrogen ion concentration gradient across the thylakoid membrane.

19. The electron for photosystem II is replaced through the splitting of water.

20. Water is the source for the oxygen released from chloroplasts during photosynthesis. Water is split, which releases hydrogen ions, oxygen, and electrons.

21. NADPH is formed from the reduction of $NADP^+$, using electrons from photosystem I.

22. Reducing power means that the molecule has a strong tendency to donate electrons to other molecules. NADPH has a strong tendency to donate electrons (and thus hydrogen ions) to other molecules.

23. **(a)** Protons can only move through the ATP synthase enzyme complex.

(b) Chemiosmosis is the process associated with movement of hydrogen ions through ATP synthase, and results in the phosphorylation of ADP to produce ATP.

24. The reactions take place in the stroma of chloroplasts.

25. The Calvin-Benson cycle begins with carbon dioxide fixation, whereby carbon dioxide is incorporated into carbohydrates via reaction with ribulose bisphosphate (RuBP). In order for a central compound called glyceraldehyde-3-phosphate (PGAL) to be synthesized the three-carbon compounds produced after carbon dioxide fixation must be activated by ATP and reduced by NADPH. While some of the PGAL molecules are used for glucose synthesis, the majority are used to regenerate the RuBP that is required for carbon dioxide fixation and the continuation of the cycle.

26. The reactions of glycolysis take place in the cytosol of the cell (i.e., outside of the mitochondrion).

27. The products of glycolysis that contain useful energy are ATP, NADH, and pyruvate.

28. The burning sensation is caused by the build-up of lactic acid (lactate), produced by fermentation.

29. If fermentation begins with pyruvate, the products are $NADP^+$, arcon dioxide, and ethanol.

30. Lactic acid is converted back to pyruvate, and it is metabolized as usual.

31. **(a)** From glycolysis pyruvate, ATP and NADH are produced.

(b) From the Krebs cycle carbon dioxide, NADH, $FADH_2$, and ATP are produced.

(c) From electron transport, the energy generated is used to produce ATP in chemiosmosis.

32. The greatest numbers of ATPs are generated during electron transport.

Answers to Applying Concepts Questions

33. Student answers should include a proton concentration gradient, movement of the ions down the gradient through the ATP synthase complex, and phosphorylation of ADP to form ATP.

34. The set of reactions is called a cycle because one of the initial reactants (ribulose bisphosphate) is regenerated through the set of reactions.

35. Glycolysis does not directly require oxygen for it to occur.

36. Yes it is correct because 2 ATP are required in the initial reactions converting glucose three-carbon intermediates. Thus, net result is a gain of 2 ATP.

37. Under those conditions fermentation occurs, whereby the pyruvate is converted to lactic acid.

38. Lack of oxygen prevents the last organic electron acceptor from getting rid of its electrons. This blocks the entire electron transport chain. With the chain blocked, NAD^+ cannot be regenerated. This stops those steps in the Krebs cycle that need NAD^+ in order to occur, and the cycle stops.

39. "Oxygen debt" describes the state where glycolysis is increased to such a point due to high energy demands (like intense exercise) that it exceeds the oxygen supply. It is "repaid" by blood transporting oxygen from the lungs.

40. **(a)** The stroma (chloroplast) fixes carbon while the matrix (mitochondrion) oxidizes acetyl CoA.

(b) Outer membrane: in plants, glucose moves out of the chloroplast, but in mitochondria, pyruvate moves into the mitochondria.

(c) Either inner membrane or thylakoid membrane: If thylakoid membrane, the difference in function lies in the fact that ATP synthase is oriented in opposite directions. In chloroplasts, protons moving into the thylakoid can be used to create ATP. In mitochondria, protons moving out of the inner membrane can be used to make ATP.

(d) Thylakoid membrane (see above).

Answers to Making Connections Questions

41. In addition to glucose, plants produce many chemicals that they use to kill or discourage herbivores. These chemicals have been extracted from the plants and converted into medications, some of which are used in treating heart disease and cancer. As these species of plants disappear, so do the beneficial chemicals that they produce.

42. (a) A charged battery could represent ATP and a drained battery ADP; a controlled quantity of energy is delivered, and energy delivered does useful work.

(b) An active solar system may be represented by solar panels, wind generation, or heat pumps. In the analogy, the original sources of energy must be identified, transfers described, and the tasks accomplished also described. The analogy must be reasonable. For example, the Sun is the source in both systems. The solar panel catches the light and converts it to electrical energy just like the chloroplast catches light and turns it into chemical energy. The energy in a solar system is transferred through wires. This is analogous to the ATP produced in photosynthesis. The electrical energy from the solar panel can be used to do many mechanical tasks just as the ATP can be used to accomplish many metabolic tasks.

43. Pyruvate is transferred from the cytosol to the inner matrix of the mitochondria during transition reactions in cellular respiration. Extra pyruvate would mean more could be sent into the mitochondria for formation of acetyl CoA, which may cause more oxidation in the Krebs cycle, and ultimately more ATP production. There is no logical way to explain weight loss from ingesting pyruvate. In fact, without dietary alterations or increased exercise, weight gain would be predicted.

44. Student answers should reflect the principal functions of photosynthesis that have been discussed in this unit. For example they may include: an ability to conduct photosynthesis outside of plant cells would increase glucose production; food could be produced anywhere, even in places where plants do not normally grow well; glucose production could be automated.

45. (a) The data indicating volume of $O_2(g)$ released is for the chloroplast.

(b) The most active organelle would be considered to be the one generating the largest volume of gaseous product, which is the chloroplast.

(c) Since the chloroplast suspension had a more significant drop in activity with a change from 5% to 15% DNP, the chloroplast is at more risk to changing DNP concentrations.