Green Design: How do Leaf Structures Optimize Photosynthesis and Promote Survival?

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Abstract

One of the major learning objectives established by the American Society of Plant Biologists and the Botanical Society of America has students answer the question: *How do plant structures enable life functions?* This lesson helps students answer this question with a focus on leaf structure and function and how the anatomy and morphology of the leaf optimizes photosynthesis and promotes survival in various environments. Students are first introduced to the primary structures and cell layers of a typical angiosperm leaf, including differences between monocots and dicots, through an interactive mini-lecture. Then, students in groups are asked to design a leaf based on a provided description. These descriptions include a monocot or dicot designation and specific environmental conditions to which the leaf is adapted. After the leaves have been designed, they are collected and redistributed to new groups. These groups are then asked to analyze the leaf they've been given, determine if it is a monocot or dicot, and determine the environment where this leaf would thrive. Finally, students present and defend their findings to the class. This lesson engages students in leaf structure and function as a means to optimize photosynthesis and promote survival and prepares them for future lessons on photosynthesis and evolution.

Citation: Butler KJ. 2020. Green Design: How do leaf structures optimize photosynthesis and promote survival? *CourseSource*. https://doi.org/10.24918/cs.2020.17

Editor: Tammy Long, Michigan State University

Received: 8/12/2019; **Accepted:** 1/15/2020; **Published:** 6/17/2020

Conflict of Interest and Funding Statement: The author does not have a financial, personal, or professional conflict of interest related to this work.

Supporting Materials: Supporting Files S1. Green Design – Exam Questions; S2. Green Design – Slides; and S3. Green Design – Leaf Descriptions.

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Learning Goal(s)

Students will:

- Describe how leaf structures contribute to survival in various environments.
- Describe how leaf structures optimize photosynthesis.
- Identify the leaf anatomy of a typical angiosperm leaf.

Learning Objective(s)

Students will be able to:

- Analyze structural and anatomical features that optimize photosynthesis under various environmental conditions such as shading, water deficit, or high temperature. (ASPB-BSA Learning Objective).
- Identify & draw the cellular anatomy of a typical monocot and dicot leaf.
- Describe the internal structure of a monocot and dicot leaf and how those structures contribute to the main functions of the leaf.
- Apply the core concept of Structure & Function to plant leaves.

INTRODUCTION

Understanding how plant structures enable life functions is a core concept of plant biology outlined by the American Society for Plant Biologists (ASPB) and the Botanical Society of America (BSA) in alignment with the core concept of structure and function from the American Association for the Advancement of Science (AAAS) Vision and Change Report (1,2). Leaves are the main macrostructures of plants that perform photosynthesis, fueling all other actions the plant must perform to survive. Cellular and morphological features of the leaf work together to maximize photosynthesis which includes obtaining CO_2 while minimizing water loss (3,4). To do so, plants have evolved unique adaptations for survival in even the harshest environment (3,4).

Investigating the role of structure and function in adaptation contextualizes this core concept while giving students a tangible understanding of the adaptations required for plant survival. The ASPB-BSA learning objectives for biology students says that biology majors should be able to "analyze structural and anatomical features that optimize photosynthesis under various environmental conditions such as shading, water deficit, or high temperature" (2). The following lesson plan provides an active learning approach to accomplish this learning objective in the specific context of leaf anatomy. In addition, it sets the scene for future lessons on photosynthesis, contextualizing the process in the location where it takes place, and evolution, providing specific examples of adaptation to various environments.

Lessons about leaf anatomy will always consist of identification of the major layers, the epidermis and the mesophyll, along with the specialized cells and structures within them, the cuticle, guard cells, palisade and spongy parenchyma (3,5). Often times, this only occurs through observation and drawing of slides under a microscope without context as to how these structures contribute to adaptation and survival. However, for students to gain a framework and appreciation for these structures, conversations should expand beyond mere identification and definition of these structures towards analyzing how they work together to promote survival. Discussing these structures in a context of environmental adaptation provides students with a deeper understanding for why these structures exist in the way they do and how that contributes to plant adaptation. This includes the differences between monocots and dicots (Why don't monocots have palisade parenchyma?), similarities and differences between plants in various environments (Why do plants in dry and wet environments both have thick cuticles?), and the location of certain structures (Why are stomata on the bottom of a dicot leaf?).

This activity, inspired by a previously published cell biology lesson, provides students with a background in leaf structures, their function, and cultivates a deeper understanding of the role of these structures in survival across environments (6). In this lesson, students are introduced to key leaf structures through an interactive mini-lecture. They are then asked to design a leaf to survive in a specific environment which is then analyzed by another team of students. As such, it moves beyond traditional plant anatomy activities that ask students to identify structures towards a deeper understanding of the functional relationship between the individual component parts. In addition, it takes microscopic cellular and morphological anatomy and connects it to the survival of the whole plant in its environment. Students will still leave being able to identify cell layers and differentiate monocot and dicot leaves while also gaining a deeper appreciation of what these structures mean for the survival of the plant.

Intended Audience

This lesson was taught to a class of 20-25 biology majors in a second semester introductory biology course focused on plant biology. It was taught at a four-year liberal arts university.

Required Learning Time

This lesson is designed to take 40-50 minutes. Time will depend on length of discussions and time provided to work. It can be shortened to accommodate other class business that might take place. Originally, this lesson took 40 minutes with the other 10 minutes devoted to review of a previous quiz and a review of last class.

Prerequisite Student Knowledge

This lesson is designed for introductory biology undergraduates. Any students with at least high school biology would be prepared for this lesson as long as some basic plant biology has been covered or reviewed. Students should understand the biology of a plant cell, in particular what chloroplasts are and what they do. Also, it would be an advantage for students to have a familiarity with ground tissue cell types (parenchyma, sclerenchyma, and collenchyma), as these terms are used in the introductory lesson. A basic understanding that plants perform photosynthesis, including the requirements for photosynthesis, is also necessary, although detailed understanding of the mechanism is not required. Previous knowledge of water transport through the plant is also an advantage so that students know that water is transported from roots through stems to leaves through xylem. This lesson was taught within the first two weeks of a second semester freshman level biology class. Basic biology knowledge is assumed, but plant specific knowledge is not. Students can read section 30.4 from *Biology 2e* for additional knowledge on leaf anatomy. Other sections of this open source textbook can provide background on cells (section 4.3), ground tissue cell types (section 30.2), or an intro to photosynthesis (section 8.1). Chapter 30 provides a general overview of plant structure and function used to guide the unit of which this lesson was a part (3).

Prerequisite Teacher Knowledge

Instructors should familiarize themselves with the anatomy of the leaf to the level that is presented in this lesson. The open source textbook, *Biology 2e*, provides an introduction to this material in section 30.4 which includes both descriptions of the structures and how they vary depending on environment (3). This video (https://www.youtube.com/watch?v=co0JdqUlycg) provides a basic introduction to leaf anatomy but, but does not provide a comparison between monocot and dicot leaves. For a brief comparison between monocot and dicot leaves, instructors can watch this video (https://www.youtube.com/watch?v=3P4Z5WUTd80).

SCIENTIFIC TEACHING THEMES

Active Learning

The introductory mini-lecture is broken up by three scheduled think-pair-share activities, including one to engage students from the beginning of the class. These discussions get students thinking individually about the information, encourage immediate recall, and utilize discussion with peers to enrich learning (7). The questions are designed to engage students in higher-order application of the newly learned materials. Instructor feedback keeps students on the right track. In this lesson, students are asked to draw a leaf cross section with their notebooks closed. By closing their notebooks, students must retrieve and apply the information they just learned. Retrieval improves long-term learning (8). In addition, drawing the leaf cross sections has students engage the material in a new way and can improve learning (9). As they are drawing something new that we had not yet seen in class, they are also applying the information to a new context rather than regurgitating something they've seen. By working in groups to design and analyze the leaves, students share their thoughts while also hearing other student's ideas providing depth and breadth to their understanding (7). This also occurs as students are asked to present and defend their classifications.

Assessment

The leaf drawing activity is a mode of informal, real-time assessment that the instructor can observe during class. This provides an opportunity for immediate elaborative feedback. Students were formally assessed on the material learned during this class on a unit exam with questions that matching the learning objectives (Supporting File S1. Green Design – Exam Questions).

Inclusive Teaching

The use of think-pair-share establishes an inclusive environment for students across the introversion-extroversion spectrum. Quieter students are provided a solitary moment to think individually while students who prefer verbal processing are able to do so with peers and the class. The artistic nature of this lesson provides opportunities for creative students to use their artistic skills, which can sometimes be overlooked in the science classroom. Finally, the fact that these drawings can be designed and analyzed in multiple different ways celebrates the diversity of thought that is important in science. The fact that there is no 100% right answer helps students understand that science indeed requires creativity.

LESSON PLAN

Class Context

This activity is planned for a single, 50-minute class session for an introductory botany class of 20-25 students. It can be taught in 40 minutes if there is other "course business" to take care of at the start or end. Originally this lesson fell on the third day of a unit focusing on the structure and function of plants in alignment with the American Society for Plant Biologists learning goal, "How do the structures of plants enable life's functions?" (1). Students had already been introduced to the plant cell and root and stem anatomy, including transport of water and nutrients and specialized plant tissues and cells. They have also been briefly introduced to monocot and dicots as a way to classify angiosperms including some features that differentiate them. In addition, students have been introduced to the Vision and Change five core concepts of biology and therefore are familiar with the associated language.

Pre-Class Preparation

Instructors should preview the slides and review the material to be covered in class (Supporting File S2. Green Design – Slides). In addition, the leaf description sheets (Supporting File S3. Green Design – Leaf Descriptions) will need to be printed and cut into strips. Enough blank paper and green markers or colored pencils for each group should be acquired. The number of groups will depend on the size of the class, but groups should be no larger than four students.

Introduce Leaf Anatomy

The instructor introduces students to angiosperm leaf anatomy through a brief 15-minute interactive lecture. Class is started by asking students "What does a leaf do?" (Supporting File S2. Green Design – Slides, Slide 3) as a think-pair-share activity. Students will immediately come up with photosynthesis. As students have not been formally introduced to the process of photosynthesis yet, it will usually take some prompting for students to come up with gas exchange and water regulation. However, most students are aware of the need for carbon dioxide and the release of oxygen. By reminding students of xylem and water transport from previous class, they will come up with water regulation. This brief discussion is concluded with a statement such as, "The main purpose of leaves is to perform photosynthesis without losing too much water, so how is that accomplished?" This sets up the driving question for the day's lesson.

The instructor then introduces students to general macroscopic features of a leaf (Supporting File S2. Green Design – Slides, Slides 4-5). This provides the first differentiating feature between monocots and dicots. If students have been introduced to more distinctions between monocot and dicot plants, this is a good time to ask students what other differences between the two groups exist.

The discussion of the cellular anatomy first focuses on a dicot leaf cross-section. It begins with a discussion of the epidermal layer, starting with the cuticle. After an introduction to the cuticle, the concept that leaf structures contribute to adaptations in different environments is introduced through another think-pair-share activity (Supporting File S2. Green Design – Slides, Slide 9). Students are asked why a jade plant, native to a dry environment, and an Alocasia plant, native to a wet environment, both have a thick cuticle. After soliciting student responses, the instructor then summarizes the correct reasoning, emphasizing the importance of water regulation in both wet and dry environments.

The lesson continues to the epidermal cells. The instructor presents a cross-section of a dicot leaf with chloroplasts absent from the epidermal cells (Supporting File S2. Green Design – Slides, Slide 10) The instructor prompts students to think about why that might be, eventually pointing out that the cells underneath seemed to have an abundance of chloroplasts. Textbooks often teach that the epidermal cells do not contain chloroplasts. However, recent studies have demonstrated that there are underdeveloped chloroplasts in these cells. They are not the primary source of photosynthesis, however (10). This could be a great time to mention how science changes and can rewrite textbooks! Guard cells, meanwhile, have robust chloroplasts which are important for guard cell function.

In the discussion of the epidermal layer, the instructor also teaches about guard cells and trichomes. After a discussion of the basic function of the stomata, the instructor asks students why stomata are usually found on the bottom of dicot leaves but on both sides of a monocot leaf. While there are additional differences between stomata of monocot and dicot plants (such as the shape of guard cells), these were not discussed but can be added if the additional depth is desired. The instructor then teaches about the role of trichomes in water conservation and herbivore defense.

The lesson then moves to discuss the mesophyll. The instructor makes clear distinctions between the palisade and spongy parenchyma. The discussion focuses on the role of parenchyma cells in the mesophyll and how the two types of parenchyma differ and why (Supporting File S2. Green Design – Slides, Slide 15). Here is also where the main differences are highlighted between monocot and dicot leaves. It is important to lead them through a discussion of why monocots lack palisade parenchyma (due to their vertical leaf orientation). This is a good opportunity to emphasize that the morphology of the leaf is arranged to optimize photosynthesis. Leaf vascular anatomy was not discussed in this lesson but it could be added if such discussion is desired. The fact that the vascular tissue is present in the leaf is mentioned, just so students don't forget that it would also be present in the leaf.

The instructor then speaks to a few specific adaptations that leaves can have to survive extreme environments. First, the adaptations of xerophytes are introduced. These are plants that can survive in water-limiting conditions. This can include both hot and cold environments and to emphasize this the example of the pine needle is discussed. Then the adaptations of plants that are shade-tolerant or shade-adapted are discussed.

This lesson is targeted to teach the basic trends of leaf anatomy and there are exceptions to the themes introduced in this lesson. However, this lesson provides the framework for an introductory student to understand how plant structures enable and optimize life functions.

Leaf Designer

After the mini-lecture, the instructor launches the "Leaf Designer" activity. The instructor provides a brief explanation of the activity following the outline on the slides (Supporting File S2. Green Design – Slides, Slide 25). The instructor breaks the class into groups of three to four students. It's easiest to break students into groups based on location, but any system the instructor has in place in their classroom is fine. Students are then instructed to close their notes. By doing the activity without notes, it boosts retrieval of the material and deepens learning (8). The instructor provides the students with a blank sheet of paper, a green marker or colored pencil, and a leaf description (Supporting File S3. Green Design – Leaf Descriptions). This description includes whether the leaf they are to design is a monocot or dicot and the environmental conditions to which the leaf is adapted. Students are given approximately 10 minutes to draw a cross-section of a leaf that fits the description provided. The instructor circles around the room, asking questions and clarifying any misconceptions they observe. It's good practice to check in with each group during the 10 minutes, if possible. The green marker is used to draw chloroplasts to make them obvious. Students should not label their diagram. Encourage students to draw in as much detail as possible and include all the structures that are relevant. As students are often self-conscious about their drawings, it helps to encourage them to exaggerate leaf features to make them obvious for the group that will be analyzing their drawings. For example, they can draw their palisade parenchyma extremely tall and skinny compared to their spongy parenchyma, even if it might not be biologically accurate. Some students like to draw the sun to help the next group orient the leaf appropriately.

After students have drawn their leaf, they label their drawing with the assigned numbers from the description slips. The instructor collects the leaf drawings and redistributes them to other groups. These groups are asked to analyze the drawing they received and determine: 1) if the leaf belongs to a monocot or dicot and 2) the native environment of this plant. Students can now label their drawing while they analyze, if they so choose. This should take three to four minutes. After each group has come to a consensus, they elect one member of the group to share their analysis. This student informs the class of what type of leaf they believe they have and the associated environment. Students must provide the rationale for all of their decisions. For example, a student should not just say "this is a dicot leaf," but instead "this is a dicot leaf because there is palisade parenchyma and the stomata are located on the bottom of the leaf." The instructor elaborates on each presentation. If students are incorrect, it is important to point out why they may have been misled. Many times it is because adaptations for different environments can be similar (as was seen with the jade and *Alocasia* example). This is a great place to have a discussion of how structural features may serve many purposes depending on the environment. This discussion may last 10-15 minutes depending on the amount of feedback and student questions.

If time allows, lead students through a brain dump exercise by asking students to close all their notes and write down everything they can remember from today's class. This can last as long as time permits and students can partner up to share and compile their lists. This provides time for students to reflect individually on the material, which is particularly valuable for those students who are more reserved during class activities. This type of strategy is also demonstrated to improve long-term retention (8).

TEACHING DISCUSSION

Reflection on Efficacy

This lesson proved engaging for students and it led to good discussions about leaf structure and function related to adaptation. As I circulated the room, I could hear students having on-topic and relevant discussions and did not have to correct many erroneous drawings or analyses. While some students were hesitant to draw ("But I'm such a bad artist!"), my more creative students appreciated the opportunity to use their skills that tend to be overlooked in the science classroom. Students were a bit confused about the fact that their leaf drawn for cold environment could have also been analyzed as living in a hot environment. However, this led to good conversations about the reason why adaptations can be similar between environments. Though I did not do the proposed retrieval practice brain dump, where students are asked to write down everything they remember from class, it would provide an excellent opportunity for students to retrieve individually. This allows students who may have slipped through the cracks in group work to engage the material.

An exam at the end of the plant structure and function unit included four exam questions derived from this lesson (Supporting File S2 Green Design – Exam Questions). Of these four questions, students were best able to identify what adaptation two plants from different environments would share. This is likely because we emphasized how a structure like a thick cuticle prevents water loss across environments and three of the five provided descriptions could have had this structure. As I have had conversations with students in future classes, they were able to recall structures of the leaf. It is really exciting to see students a year later and have them remember something from your class!

Options for Modification

Including a wider variety of leaf descriptions would provide greater diversity, allow for students to work in smaller groups, and deepen discussion. While the descriptions provided are general and not associated with a specific plant species, finding real-life examples of each of the descriptions (or generating descriptions based on known plant species) could enrich the discussion as students present their analysis. This would require extra time and forethought, but would be an excellent addition to the lesson. It might be fun for students to see "how close they got" to the real thing. However, care should be taken to emphasize that just because the student drawing does not match the natural example does not mean they are "wrong," just that they took a different approach. For students that have learned more about the vascular anatomy and the arrangement of vascular bundles in the leaf, this would provide a great opportunity to review that material again by asking them to appropriately draw the vascular bundles.

For larger class sizes, multiple groups could be provided the same description in order to maintain the group size of three to four students. However, it would be important to ensure students analyze a drawing that is different from their own description. Having multiple groups draw the same description could present an interesting opportunity to compare and contrast how the different groups approached their leaf design. In fact, after many groups presented their drawings I would ask them how else this leaf could have been designed. For example, to reduce water loss many students drew a thick cuticle. I would subsequently ask them how else they could accomplish this, for example through reducing stomatal density. In addition, for extremely high enrollment classes this activity could be incorporated into the start of a leaf anatomy lab. If desired, additional complexity and adaptations could be added to support a more advanced plant anatomy course or unit.

Integration into Future Lessons

This lesson sets students up for future lessons on plant evolution and photosynthesis. I referred back to this lesson multiple times during the remainder of the semester. For example, when we began our photosynthesis lesson, I began by asking my students to recall the concepts from this lesson. I ask them to describe what stomata are, where they are, and how they function. I also had them recall what cells would be performing the bulk of photosynthesis. This provided an opportunity for retrieval and the spacing from the first lesson to the photosynthesis unit encourages long-term memory and continuity. Most of my students were able to answer these questions later in the semester, supporting the efficacy of this lesson. In addition, during evolution when adaptation is taught, these adaptions can be discussed as a familiar example to how plants adapt to various environments.

SUPPORTING MATERIALS

- S1. Green Design – Exam Questions
- S2. Green Design – Slides
- S3. Green Design – Leaf Descriptions

ACKNOWLEDGMENTS

I would like to acknowledge the *CourseSource* Writing Studio for the helpful guidance and focused writing time to get this manuscript off the ground.

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Table 1. Green Design Teaching Timeline

Activity	Description	Time	Notes
Preparation for Class			
Print and cut leaf assignments	1. Print enough copies of the leaf assignments to divide your class into groups of three to four students. 2. Cut the assignments into slips to hand to groups individually	Depends on class size	Leaf assignment slips are found in Supporting Information S3. Green Design – Leaf Descriptions.
Gather materials	Gather enough sheets of blank paper and green markers/colored pencils/pens for each group.	5 minutes	
Class Session			
Mini-lecture on leaf anatomy	Lesson with three Think-Pair-Share or class discussion activities	~15 minutes	• Lesson slides with notes are found in Supporting File S2. Green Design – Slides. • When doing Think-Pair-Share, encourage students to physically write down their answer in their notes.
Leaf Design	1. Instructor briefly explains the activity. 2. In groups of 3-4, students draw a leaf cross section based on the leaf assignment sheet.	~10 minutes	• Leaf assignment slips, found in Supporting File S3. Green Design – Leaf Descriptions are handed out to each group. • Students should draw their leaves with their notes closed. They may ask the instructor for help if they can't remember something. • Instruct students to exaggerate leaf features to make them more obvious for the next group. Draw chloroplasts in green. • The instructor circulates the room as students draw, checking in. It's beneficial to ask student groups questions like "Why don't you have palisade parenchyma?" so they defend their design. It is best to direct these questions to the more timid group members.
Leaf Analysis	1. Instructor collects drawn leaves and redistributes to new groups. 2. Groups analyze the leaves to determine if 1) it is a monocot or dicot and 2) the environment in which this leaf would grow. 3. Student groups share with the rest of the class their findings and justify them with rationale from the leaf drawing.	10-15 minutes	• If possible, try to provide groups with leaves very different from the one they drew. • Students may label the drawing they receive if they would like. • As students analyze, the instructor should circulate and check in with as many groups as possible to make sure students are on the right track. • After each group shares, the instructor should facilitate a discussion about other interpretations of the drawings and relate it to how plants in very different environments might share similar structural adaptations.
Specific Examples & Review	Instructor provides two specific examples of unique leaf adaptations (needles and cactus spines).	~5 minutes	These slides provide a few more specific examples of leaf modifications in extremely cold and hot environments.
Brain Dump (if time)	Have students write down everything they remember from today's class with their notebooks closed		If extra remaining time, students can pair up to compare their brain dumps.