INQUIRY & INVESTIGATION

Using Modeling to Develop a Deep Understanding of Photosynthesis & Cellular Respiration as Chemical Processes

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Abstract

Photosynthesis and cellular respiration are core concepts in high school biology, as they are at the core of all living things. However, perhaps because students can't see them happening, they very often have difficulty understanding them. Further, students often come into biology with a limited understanding of the law of conservation of matter as it relates to chemical reactions. These problems compound to create a great deal of misconceptions about these two important processes. In these lessons, I implemented the use of modeling to overcome these misconceptions and give my students a firm understanding of chemical equations, photosynthesis, and cellular respiration.

Key Words: *cellular respiration; modeling; photosynthesis.*

○ Introduction

Photosynthesis and cellular respiration are core concepts in high school biology, as they are at the core of all living things. However, perhaps because students can't see them happening, they very often have difficulty understanding them. Further, students often come into biology with a limited understanding of the law of conservation of matter as it relates to chemical reactions. These problems compound to create a great deal of misconceptions about these two important processes. In these lessons, I implemented the use of modeling to overcome these misconceptions and give my students a firm understanding of chemical equations, photosynthesis, and cellular respiration.

○ Modeling

Though scientific modeling is frequently used in the classroom, it is rarely used to its best advantage. Scientific models are often a secondary resource for providing information rather than a primary tool for developing understanding and content knowledge. Based on findings about student and teacher understanding of models, researchers suggest the inclusion of a more explicit introduction to scientific models and their uses to promote better understanding of science content (Krell et al., 2014). Specifically, they suggest that students should learn about major scientific models, the nature of models and modeling, and how to use models (Krell et al., 2014). When models are used in these ways, students will be better able to develop their own understanding of science processes and content rather than relying on teachers to simply deliver information.

When students are given the opportunity to discover content and ideas for themselves, they have a deeper, more flexible, and longer-lasting understanding. Evidence suggests that science modeling and inquiry may transfer to science content learning (Schwarz & White, 2005).

The goal of equipping students as competent science consumers is best met when they are taught to reason scientifically. A good measure of student scientific reasoning is the ability to construct and use original models (Carrejo & Reinhartz, 2014). Studies show that implementing modeling in the classroom can result in an improvement in students' ability both to reason scientifically and to construct models. One study demonstrated that through a model-based unit, students acquired several specific skills related to modeling, including constructing abstract models from specifics given, using models to make predictions, evaluating and comparing models, choosing which aspects to include in a model, and revising their models as their understanding changed (Schwarz et al., 2009). Model-based inquiry promotes student understanding of the nature and purpose of models, including abstract models, and that multiple models can be used for the same phenomenon (Schwarz et al., 2009). Overall, model-based inquiry was more effective than traditional methods at improving students' science process skills (Ogan-Bekiroğlu & Arslan, 2014).

The body of research shows that model-based learning can be an effective tool for developing both content knowledge and reasoning skills in students. When model-based inquiry was used, students showed gains in their ability to use models, which is a good measurement of their science reasoning skills. Therefore, it stands to reason that the use of models can also increase students' understanding of science content.

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○ Lessons

Balancing Equations

The first lesson in the sequence was meant to reinforce and reteach the law of conservation of matter and the important concepts involved in balancing chemical equations. Though most biology students have had experience with this material in previous courses, few demonstrate a working understanding of the ideas, especially that the same atoms of each element are present in both the reactants and the products of chemical reactions. We began with a class discussion of the basics: matter, elements, atoms, molecules, and the basics of chemical bonds.

Next, I introduced the model. Each student was given a set of pony beads, each color representing an atom of a different element. Working on a felt square to prevent rolling and bouncing, the students arranged the beads into groups to represent the different molecules that are the reactants and products of a chemical equation. With the molecules created, the students observed that there were not necessarily the same number of each atom on both sides of the equation. This allowed them to see the need to balance the equations.

The next step was using the beads to balance. I explained to the students that balancing their equations required adding entire molecules, not just individual atoms. They had time to try adding molecules to each side of the equation, making adjustments and exploring solutions until the number of atoms was equal. Students then went on to practice balancing several other equations using the beads as a model. After practice, most students were able to transfer this experience to balancing equations on paper, laying aside the models. Some were even confident enough to share the models with the class using the document camera. Most importantly, they were able to articulate an accurate understanding of the relationship between the atoms present in reactants and products in a chemical equation and of the law of conservation of matter as it applies to chemical reactions.

Modeling & Manipulating Photosynthesis

The next set of lessons in the progression introduced photosynthesis. We began with a group discussion of the question "Where does a tree get its mass?" As expected, many students responded that it must come from nutrients in the soil, water, and even sunlight. I then introduced von Helmot's famous experiment, using a short video, followed by another class discussion, which led into a discussion of the equation for photosynthesis. Students were able to identify the reactants and products of the equation and identify that the atoms of each element in the products were the same as in the reactants. Many students referred back to the balancing equations activity in their explanations of the phenomena.

Once students established an understanding of photosynthesis as a chemical reaction, I presented them with the opportunity to create a physical model of the reaction using the leaf disk flotation method (Appendix A). In this method, the air is removed from leaf disks so that they no longer float in a liquid. The rate of photosynthesis can be seen as the leaves produce oxygen and begin to float.

As a class, we discussed whether changing some of the reactants in the equation would have an impact on the products and which reactants might feasibly be manipulated. In groups, students had time to brainstorm possible changes they could make to the reactants (independent variables) to measure a change in the products (dependent variables). At this stage, most students wanted to change either the measure of carbon dioxide or the type of water. I provided students two different methods for altering the amount of carbon dioxide present in the water: blowing bubbles with a soda straw (to create carbonic acid, which can be measured with universal indicator) and adding baking soda. For the first round of tests, all students measured the impact of a changed carbon dioxide level.

After completing the first test, students completed their lab reports (Appendix B) and began planning their next investigation. This time, we widened the options to include not only changes to the reactants, but also the energy input (light). Students could now choose to alter several aspects of light. Some chose color, others duration, and others intensity. Students set up their new models, carried out the test again, recorded data, and completed lab reports. Students were asked to share their lab results with the class. This led to a class discussion of how the changes they made impacted the rate of photosynthesis, as demonstrated by the rate at which the leaves floated. Ultimately, we tied the results back to the equation for photosynthesis and even the law of conservation of matter. Though this model of photosynthesis does not demonstrate glucose production, students' increased understanding of photosynthesis helped to overcome their previous misconceptions surrounding the ways in which plants gain mass; they now correctly attribute growth to photosynthesis rather than soil, water, or sunlight alone.

Modeling & Manipulating Cellular Respiration & Fermentation

The final group of lessons introduced students to cellular respiration and fermentation. Again, we began with a question for which many students have deeply ingrained misconceptions: "What types of organisms perform cellular respiration?" As expected, the majority of my students responded, "Animals." I then introduced the equation for cellular respiration and led a class discussion of the reactants and products. Students recognized the inputs glucose and oxygen and the outputs water and carbon dioxide; many of them again referred back to the initial bead activity in their explanations. I went on to introduce them to ATP as chemical energy produced by the cells of all living things.

Again, after the initial discussion, I provided my students an opportunity to model this process, this time using a fungus, yeast (Appendix C). As with photosynthesis, the class discussed what changes could be made to the reactants to effect a change in the products. Students quickly jumped on the idea of changing the amount or type of sugar present. Groups worked together to test their ideas and then completed lab reports. On subsequent days, groups had the opportunity to test new variables. Some chose to test water temperature, while others chose to test new amounts or types of sugar.

Again, students shared their lab results with the class. Group discussion focused on differences and similarities in results. Finally, we discussed how this chemical process relates to what students understood about chemical reactions and how the reactions of photosynthesis and cellular respiration are related.

To further reinforce that all organisms carry out cellular respiration, an additional lab can be added. In this lab, students will observe changes in water pH as a result of carbon dioxide created by cellular respiration in a plant and in a human (Appendix D). After the initial lab, students may have the opportunity to test different variables like the size or type of plant used, the amount of light available, increased activity by the human subject, and so on.

○ NGSS Alignment

Though my main focus in these lessons was the impact using models had on my students, these lessons incorporate several *Next Generation Science Standards* (NGSS) science and engineering practices, including the following:

- Developing and using models
  - Every lesson focused on a model.
- Planning and carrying out investigations
  - In both the photosynthesis and cellular respiration lessons, the models students used were tested through investigation. They manipulated the variables of the model to investigate their ideas.
- Analyzing and interpreting data
  - In the second and third lessons, students collected data from their investigations. They represented these data in tables and graphs and then used the data as evidence in their explanations.
- Using mathematics and computational thinking
  - Students used mathematics to compare data between experimental and control groups.
- Engaging in argument from evidence
  - Each lab report culminated with a CER (claim, evidence, reasoning). Students used the data from their investigations as evidence to argue in support of their claims.

These lessons also addressed a variety of cross-cutting concepts, including the following:

- Cause and effect
  - Students looked for the impact of changes to variables on outcomes and drew conclusions about the cause and effect relationships demonstrated.
- Energy and matter
  - All of the lessons ultimately focused on the law of conservation of matter as students tracked the flow of elements into and out of chemical processes.
- Systems and system models
  - Each lesson focused on a system model. The chemical equation lesson used modeling to demonstrate the relationships in the system. The other lessons demonstrated the effects of changes to the system.

Finally, these lessons addressed specific NGSS disciplinary core ideas, including the following:

- Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy (HS-LS1-5).
  - Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed, resulting in a net transfer of energy (HS-LS1-7).

○ Conclusion

For most students, these lessons marked a shift in their understanding of biology. To measure students' gains in understanding, I administered pretests and posttests for the units. The mean pretest score was 47.8%, and the mean posttest score was 63.9% (n = 169). Using a paired-samples t-test, I determined that there was a significant difference between the scores ($p = 0.000$). From the first lesson, when they manipulated beads, to their final cellular respiration investigations, they were engaged and interested. Listening to their group conversations and answering their questions, I observed an ever-deepening understanding of the content. Even more, their ability to carry out a wide variety of scientific practices grew. The students gained confidence in planning their investigations and understanding their results. They were able to share their findings with confidence. Truly, they grew as scientists, not just students.

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Appendix A: Leaf Disk Flotation Method for Modeling Photosynthesis

Materials (per group):

- Three or four clear plastic punch cups
- Spinach leaves

- Drinking straws
- Water
- Baking soda
- Universal indicator
- Desk lamp
- Food coloring, colored transparency paper, or colored light bulbs
- One 20 mL syringe
- Dish soap
- Small paint brush

Methods:

1. Use the drinking straw (or a hole punch) to cut 30–40 disks from the spinach leaves.
2. Fill each cup about two-thirds full of water (these could be the varying solutions of CO_2, plain water, or perhaps another student-chosen variable) and a drop of dish soap. Mix the soap in well.
3. Place 10 leaf disks in the syringe with about 20 mL of solution drawn from the cup. Push the plunger to remove any air. Covering the end of the syringe with a finger, pull back on the plunger as far as possible, then let go. You should see air bubbles come out of the leaf disks. Push the released air out. Repeat the process until the leaf disks no longer float.
4. Holding the syringe, plunger down, over your cup, remove the syringe to allow the water and leaves to fall into the cup. You may need to use the paint brush to remove any remaining leaves.
5. Repeat steps 2 and 3 for each water sample.
6. Place the cups under the lamp. In 10-second intervals, record the number of leaves floating to the top.

Appendix B: Lab Report Template

Lab Title:

Group Members:

Study Question:

State your expectations:

What is your. . .

- Independent variable
- Dependent variable
- Constant
- Control group
- Experimental group

Null hypothesis:

Alternate hypothesis:

How will you conduct your experiment and record your data? (This should be detailed enough that you could hand this to someone outside of the class to do the lab.)

Write a one paragraph explanation of your findings, using the CRE format--Claim, Evidence, Reasoning.

Include table(s) and appropriate graph(s) of your data. Be sure that each table and graph is labeled and scaled appropriately and that each has a complete and accurate caption.

Appendix C: Yeast Method for Modeling Cellular Respiration

Materials:

- Three 80 mL test tubes in a test tube rack
- Masking tape

- Ruler
- Water
- Dry active yeast
- Sugar
- Warm water

Methods:

1. To each test tube add 20 mL warm water and one teaspoon yeast. Invert the tube several times to dissolve the yeast.
2. In one test tube add no sugar. In the other two, add the amounts or types of sugar the students previously decided on.
3. Use masking tape to mark the top line of the solution in the tube.
4. In one-minute intervals, measure the distance the solution has risen above the starting point.

Appendix D: pH Method for Modeling Cellular Respiration

Materials:

- Sealable clear test tube or other clear glass container
- Small aquatic plant
- Clear disposable cups
- Drinking straws
- Universal pH indicator

Methods:

1. Place the aquatic plant in the glass container and cover with water. Add enough of the universal indicator to see the color well. Seal and place in a dark location (or cover tightly with foil) and leave overnight. The next day, students will check the water, looking for a change in color to indicate lower pH caused by released carbon dioxide mixing with water to create carbonic acid.
2. Fill a clear cup about half full of water and add enough of the universal indicator to see the color well. Ask one student in each group to blow bubbles in the water until it changes colors. Students will watch the water, looking for a change in color to indicate lower pH caused by released carbon dioxide mixing with water to create carbonic acid.