bioscience education

Descriptive Account

Problems Encountered In Teaching/Learning Integrated Photosynthesis: A Case of Ineffective Pedagogical Practice?

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Abstract

In this article we recount our experiences of teaching photosynthesis in an integrated way to secondary school students and teachers, science undergraduates and postgraduates. Conceptual questions were posed to investigate learners' fundamental understanding of simple light-dependent and light-independent processes taught to most students at secondary level and beyond. We found that students did not grasp main concepts and could not apply basic knowledge to answer simple questions about photosynthesis even after multiple exposures to the topics. We attribute these shortcomings to rote learning and master-disciple relationship generally practised in Thailand. We propose here a change of emphasis from teaching to learning, especially, self-learning, collaborative learning, self-reflection and integration of knowledge by self. Corrective suggestions are given about changing the common practices of teaching/learning with a cognizance of the present and future era of easy access to electronic information and globalization where life-long learning, problem solving skills, originality and creativity hold keys to success.

Keywords: photosynthesis, conceptual problems, secondary school, undergraduate, student-centred learning

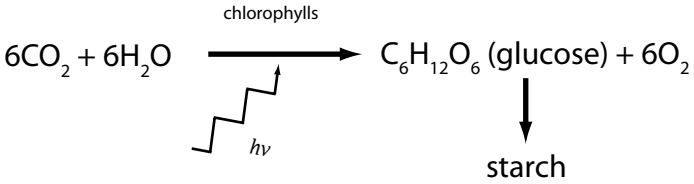
Introduction

The problems of knowledge retention, inadequate grasp of concepts and poor application of learned principles to new situations, i.e. prior knowledge and knowledge transfer, are cited in the US National Research Council Report (2005). To address these general problems the learners should be allowed and helped to achieve higher levels of learning by teachers urging them to spend more time on reflection, self-checking their level of understanding, and solving multidisciplinary problems. Given today's easy access to information by electronic means, the learners should constantly practise their skills in classifying, comparing and contrasting, analysing, synthesising and evaluating information given to them — with the teacher as a value-added guide and their friends as collaborators if need be. Naturally the curriculum has to make room for enhancing students' learning skills toward the more profound grasp of topics.

With a research background in molecular biophysics (BP) and biochemistry (BP, PR and NS), teaching green plant photosynthesis is an activity we enjoy greatly. Photosynthesis is an ideal topic to illustrate the importance of integrating different parts of science because it deals with the physics of light, chemistry and biochemistry, enzymes and membranes, as well as energy relationships. We have taught this as one of multidisciplinary topics not only to first and second-year undergraduate and beginning postgraduate students but also to secondary school students and teachers.

We would like to share our teaching experiences in Thailand with the readers around the world, and especially some of the teaching/learning problems perceived by us. We hope that having read this article at least some of the readers with similar experiences will carry out their science education research and perhaps suggest corrective measures to enable better and more integrated learning.

For simplicity we will confine ourselves to the green plant and the simplified overall equation:



From our classroom observations, secondary school students and teachers showed the lowest understanding, while first and second-year undergraduates showed equal (mis)understanding as most of the postgraduate students.

Conceptual Problems

The various levels of understanding in this field are illustrated by the questions and responses outlined below (see Appendix for some background answers).

Carbon Dioxide Fixation

Q1. When asked "what happens when CO_2 meets H_2O?", our second-year undergraduate students would ask back as to whether we were asking for a chemical or a biological answer. The chemical answer is of course H_2CO_3 and the biological one is $C_6H_{12}O_6$ and O_2. If pressed further the reply would most likely be because of the presence of chlorophyll in the latter case (even without enzymes).

Q2. What fixes CO_2?
Response: No answer or vague answers (even among university students) about what fixes the CO_2, some responded "water".

Q3. What kind of bonding is involved in the fixation of CO_2?
Response: Long pause even among those previously exposed to a detailed Calvin Cycle, only a few could come up with the covalent C—C single bond.

Q4. But fixed CO_2 can dissociate, so what makes it less likely to go back to the gaseous state (or dissolved CO_2)?
Response: Silence.

Q5. A more profound probe draws even more blank looks: if the fixation of CO_2 involves only a certain kind of bonding, why is it that light of different wavelengths (presumably with different energy quanta) can give the same product. Is it not true that the energy in a particular C—C single bond is fixed around a certain value with very little variation?
Response: Blank faces.

Q6. How is the excess energy of the short-wavelength light dissipated?
Response: A few could mention that light energy, including that of the short-wavelength light, is harvested by photocentres P680 and P700 which belong to the longer wavelength region.

Oxygen Generation

Q7. To split H_2O into O_2, one would think of using a battery connected to two electrodes dipped into water (electrolysis). So how does the green plant split H_2O at ambient temperature, even on a cloudy day, and without the help of electrodes + battery? Few students raised the possibility of a strong oxidant(s) for oxidizing H_2O into O_2 in the chloroplast. Generally they think that chlorophylls can do it all directly.

Q8. Can an H_2O molecule with an atom of an oxygen isotope exchange it with the oxygens of dissolved CO_2 and H_2CO_3/ HCO_3^-? If this is possible what does one have to do to prove that gaseous oxygen produced comes directly from H_2O only and not CO_2, which H_2O can react with to give H_2CO_3? Most had forgotten their first year chemistry about the oxygen of H_2O giving rise to one oxygen of H_2CO_3/ HCO_3^- and vice versa, and the resonance structures which chemical 'equate' all oxygen atoms in the molecule of CO_2 and H_2CO_3/ HCO_3^-.

Sugar Formation

Q9. Do you know that turning CO_2, a gas into a solid like starch involves quite a bit of energy (Hint: Just imagine compressing CO_2 gas into dry ice.) ?
Response: Never thought along these lines before!

Q10. Do plants really convert CO_2 or HCO_3^- and H_2O directly into carbohydrate?
Response: Long pause, not sure.

Q11. If CO_2 does not meet with H_2O to give $C_6H_{12}O_6$ then what does the simple equation imply about the reactions of the Calvin Cycle? Hint: think of members of a track relay team passing the baton: you will see that, when summed up, it is as though the first runner handed the baton to the last runner even though the two did not come into contact.
Response: Expression of enlightenment!

The Chloroplast

Despite all the facts they had learned (some by heart) from secondary school and first-year biology relating to: chloroplast, granum, lumen, thylakoid membrane, electron transport components, proton pumps and ATP synthase on the CF complex, most higher level students could not answer the following convincingly.

Q12. If one were to put all the Calvin Cycle enzymes and chlorophyll molecules together in a test tube, would this system sustain the Calvin Cycle reactions and CO_2 fixation if light of appropriate wavelength were shone on it?
Response: Quite a few would nod their heads, "Yes".

Q13. If the chloroplast membranes are broken up will the light-dependent reactions be affected? And will the light-independent reactions be affected?
Response – Very few understand this well enough to give good answers. There seemed to be poor understanding that the light powered generation of ATP was a membrane-dependent process.

Starch to sugar and sugar to starch

Q14. Although starch is formed in the leaf cells it may be stored on a larger scale in other parts of a green plant, e.g. fruit and root. Have you ever thought about the energy involved in the conversion of dissolved sugar into a solid like starch?
Response: Generally "No"!

Q15. How does the starch in the leaf move around the plant to form the starch in the fruit and root? Think of the concentration gradient in moving the sugar from leaf starch into the relatively solid (highly concentrated) starch immediate environment of the fruit and root?
Response: Generally no answer offered!

Discussion: Learning versus Teaching

Here we have shown that some students have problems retaining their knowledge, mastering basic concepts, and applying them in different situations. Our intentions are to point out that things could be taught in a more integrated way for better understanding, although we hasten to add that some students are better than others in grasping concepts and applying them. First-year students that still retain their knowledge of basic biology, physics and chemistry are more amenable to applying basic knowledge when prompted than older students and teachers who have forgotten or otherwise committed (differentiated) to working or learning in narrow fields. But even older science students can be brought around to think more holistically once various aspects have been addressed more provocatively and clarified by similes and metaphors.

We are sure that our Thai students are not unique in lacking the skills mentioned above, but because of the general practice of spoon-feeding by the teacher who usually acts like a classical master training his/her disciples, the students become obedient absorbers and regurgitators of knowledge. Students take lecture notes (some almost verbatim), reread them at some later date and seemingly put different subjects in different spaces in their brains (each space is a pigeonhole for a different lecture). Usually they do not interconnect what they have learned. One wag was heard to say that our students registered their learning at the meninges level where there was a delete button acting immediately after the exam. Moreover assessments by teachers are usually summative without any genuine formative ones being provided. In Thailand, tutorials as an aid to profound learning are not generally carried out especially in the biosciences. In our opinion tutorials should be implemented.

Even current teachers may have to be retrained to understand the importance of aligning learning objectives with implementation of the lesson plan and assessment. They should know the subject well and have enough experience and training in student-centered, inquiry-based pedagogy to make students learn more effectively, i.e. pedagogical content knowledge. In the Thai language the word for school (Rong-Rien) means 'place to learn': however, the actual practice makes this rather a misnomer because of the overemphasis on teaching. It should renamed Rong-Sonn, meaning 'place to teach'. This must be true in some other countries as well. We would like particularly to urge readers to make the topic of photosynthesis less requiring of memory work, but rather use it as a 'multidisciplinary' example, perhaps with help from a team of teachers with backgrounds in biology, chemistry or biochemistry, and physics or biophysics, who are prepared to teach collaboratively.

Note

At our Institute we have been running our postgraduate programme in science education for the last 5 years in which students with different scientific backgrounds have to work on their own most of the time with teachers (professors) giving advice and suggestions. At the beginning of each academic year the students feel lost for 2–3 months. Then they work collaboratively after obtaining their information online, e.g. journal articles, Wikipedia and Google. The general improvements we have noticed are their self-confidence in tackling new problems and evaluating information thus obtained because they exchange ideas and help one another to conceptualize. They still need to be spurred to work harder, be more inquisitive, ask better questions and conceptualise more effectively. Several of our Ph.D. graduates have produced publications in peer-review international journals with relatively high-impact factors and we look forward to seeing them perform in their careers as teachers.

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Appendix

Hints and Answers (see: Voet and Voet, 2004; Metzler, 2003; McDonald, 2003, and Heldt, 2005)

Q1,2. When the question about what fixes CO_2 in a C-3 plant was posed more directly such as "what compound does CO_2 react with in the Calvin Cycle?" their answer was typically better, i.e. not water, but still most likely not R-1,5-BP (ribulose-1,5-bisphosphate). In posing the original question we were not looking for a specific answer but a more general one such as a 'fixed' gas, be it CO_2 or N_2, should be converted to a form that is less volatile and/or better retained in the cell.

Q3–5. A carbon-carbon single bond is formed between the fixed CO_2 and R-1,5-BP in the stroma at the first step of fixation. The chemical energy of formation should be around a certain value (allowing for energy variations due to non-electronic modes). The physical energy of exited electrons due to light is not directly involved here.

Q 6. A blue quantum of light (wavelength 450 nm, energy 266 kJmol-1) has about twice the energy of a red quantum of light (wavelength 650 nm, energy 184 kJmol-1). Since chlorophylls can capture the red light and blue light 'equally' well and get the process of photosynthesis going is supported by the fact the action spectrum follows the absorption spectrum closely. Blue light energy must be dissipated even more than red before being exploited for the Calvin Cycle through the chloroplast electron transport chain, hence NADPH and ATP formation due to protons flowing back through the CP-Complex. The photosystems I and II absorb maximally around 700 nm and 680 nm, respectively. Eventually the first chemical step of bond formation between CO_2 and R-1,5-BP involves fixed chemical energy.

Q7. A strong oxidant which turns out to be high oxidation state manganese atoms in a protein ('oxygen evolving complex') is used to oxidize water to give O_2 in the lumen of the chloroplast.

Q8. The proof that O_2 comes from H_2O and not CO_2 came from Hill's experiment (1937) showing that H_2O with labeled oxygen atoms in the presence of unlabeled CO_2 gave rise to labeled oxygen molecules with the expected isotope proportion as oxygen in water

Q9. Conversion of gas into solid involves entropy change (among other things) and needs inputs of free energy.

Q12. The Calvin Cycle has steps that involve inputs of energy from reactions involving ATP hydrolysis and reduction by NADPH leading the reactions away from dissociation of the fixed CO_2 at the first step. The breakdown of one molecule of R1,5-BP-CO_2 to two molecules of 3-PG (3-phosphoglycerate) also helps.

Light energies of short and long wavelengths are harvested by the chlorophylls and other pigments and percolate through the latter to reach the photosystems (P680 and P700) and are further used up in the electron transport chains during electron flow. ATP and NADPH are generated by the energy-utilizing processes of the electron transport system.

Q13. An intact chloroplast is vital for sustaining photosynthesis. Intact outer and inner membranes of the chloroplast are essential for electron flow in the electron transport chain, maintenance of the proton gradient and therefore the sustenance of the Calvin Cycle reactions. An understanding of this part of cell biology usually eludes students.

Q14,15. Entropy is involved in the conversion of dissolved sugar molecules to a virtual solid like starch. To go against the concentration gradient near the solid surface of starch involves energy as well (Chang, 2000).

Additional miscellaneous background information

When asked from what kind of materials plants derive their bulk, students need more time to think before getting the correct answers. If it is pointed out to them that there are plants that grow in clear water (hydroponic cultivation) and some virtually have most of their body parts hanging in the air and not touching the ground and do not necessarily feed on the above-ground structure (biological or nonbiological) they are attached to, e.g. plants growing in humid and shady zones, the Spanish moss found in southeastern states of USA and orchids, both are photosynthetic. The students might reach the conclusion that for plants to grow they do not principally consume soil as originally thought by quite a few of them. Plants acquire their bulk from CO_2 and H_2O as shown in the overall textbook equation with assistance from a small amount of minerals. Some plants gain bulk more from gaseous CO_2 and water vapour than others. Growing pot plants do not reduce the amount of soil in the pot detectably.

When students were shown the absorption spectra of chlorophylls a and b and asked if they could say what kind of transparent plastic sheet one could use to cover a greenhouse still allowing photosynthesis to proceed, most would answer green! This in spite of the 'obvious' lack of absorption in the green region and much higher absorption in the blue and red regions in the chlorophyll-plus-carotenoid absorption spectrum. A better answer would of course be either red or blue sheet.