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Green Chemistry in STEM Education: Light for Basic Concepts

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Abstract The principles of green chemistry can be communicated by means of didactically concise experiments and by relating them to a large variety of key terminology in chemistry. Here we report on innovative experiments in video tutorials, animations and other digital media in which light is involved as a form of energy. A tested and evaluated teaching module on the carbon cycle in animate nature applying several of these experiments and digital media is presented. All these materials enable the communication of basic concepts of chemistry didactics in Germany and contribute to the integration of green chemistry into the school curriculum.

Keywords: *video tutorial, basic concepts, photochemistry, model experiment, ground state, excited state, absorption and emission of light, molecular switch, isomerization, thermodynamic equilibrium, photosteady state, teaching module, photosynthesis, respiration, carbon cycle in animate nature.*

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1. Introduction

Being deeply convinced that light will advance to the most important form of sustainable energy within the 21st century, we put forth that processes involving light have to get a key function in science education. Actually, in order to overcome the five big challenges for the next decades regarding energy, climate, mobility, food, and water, mankind has to replace fossil energy sources step by step by so called "renewable" energy sources. Among them, light is by far the most abundant, and also the cleanest one.

The characteristics of green chemistry and its integration into the curriculum as a necessity to prepare our students for a sustainable future has recently been discussed in the prominent scientific journal *Angew. Chem. Int. Ed.* [1]. We agree with the authors of this paper who define green chemistry as "environmentally and ethically sustainable chemistry". The journal's 2021 special issue [2] was already dedicated to photoprocesses and presented a series of innovative experiments and didactic concepts. Actually, chemistry powered by light is par excellence suited to meeting the requirements of sustainable, green chemistry.

In cooperation with the European Photochemistry Association EPA [3] and the Photochemistry Division of the German Chemical Society [4] we have developed and produced video tutorials that were especially useful during the Covid-19 pandemic, but also before and afterwards. We will look at some of these in this report. The first five videos deal with the interaction between photons and molecules in general, and the next two with the matter and energy conversions in the cycle of photosynthesis and respiration. Then we present a teaching unit which was conducted with a small group of students at secondary level, and which proved suitable to introduce students to the essential features of sustainable green chemistry with light.

2. Photoluminescence and isomerization reactions in video tutorials

The **common format** of the five tutorials discussed in this section is the dialogue between the young layman *Niklas* (Figure 1) and a young scientist, a different one for each video, who introduces him to certain topics regarding photon-molecule interactions. These topics correspond to the following common **basic concepts of chemistry didactics in Germany**: the matter-particle concept, the concept of structure-property relationships, the energy concept, and the concept of chemical equilibria.

All of the five videos follow the same generic pattern: At the beginning of each movie, Niklas, who takes a keen interest in everyday phenomena and who has a comparably great urge to find out the scientific explanations behind them, presents a curious **everyday phenomenon**. In a second step, he embarks on a journey into the world of photons and molecules. He is always guided by a peer, a young scientist from the Wuppertal group of photochemistry, who takes his questions seriously and who explains the **theoretical background** of the phenomenon to him. This main part of the movie provides impressive, meaningful **experiments**, and a reasonable theoretical background explanation. This takes place as a **conversation** at eye-level. Additionally, energy models, molecular models, animations, and diagrams contribute vitally to the explanation process. Finally, Niklas rounds off the tutorial by establishing a proper frame for the entertaining, yet **scientific narrative**.

Figure 1. Screenshot from the opening scene in tutorial 1. Niklas is curious about rainbows, and raises the question how photons interact with molecules.

The five video tutorials discussed in this section, as well as further movies, videos and a **large variety of digital educational materials** are available on the platform

►https://chemiemitlicht.uni-wuppertal.de/en/movies-videos/ .

Tutorial 1: "What is a photon? Particle-wave duality." *Albert Einstein*, who was awarded the Nobel Prize in 1921 for his explanation of the photoelectric effect, confessed in 1955, the last year of his life, that fifty years of intensive thinking have not brought him any closer to answering the question "What is a photon?". The film starts as shown in Figure 1, then Niklas meets *Claudia*, who presents to him the idiosyncratic nature of a photon, that is, a quantum object which she pragmatically defines as "the smallest indivisible energy package of light". In order to present to him the complementary properties of the photon, she refers to experiments exhibiting the reflection and the grating diffraction of a laser beam (Figure 2, top left and top right).

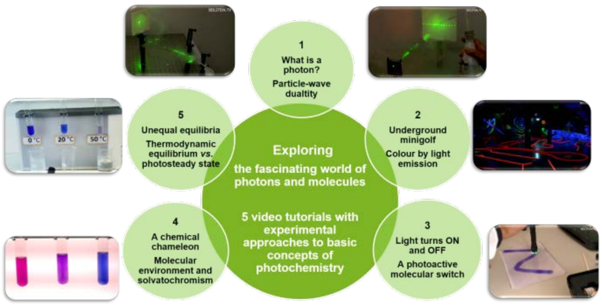

Figure 2. Overview of the titles, experimental observations, and teaching purposes of the five video tutorials in section 2

However, the special charm of this video tutorial is the metaphorical scene at the end: At *Tony Cragg's* sculpture "Photon", the two protagonists unlock their imagination and draw an allegorical analogy between this original masterpiece and the particle-wave duality of the photon. Teachers are permitted and encouraged to find such analogies and to use them for didactic purposes because according to no one less than Einstein there is no unambiguous, generally accepted answer to the question "What is a photon?".

Tutorial 2: "Underground minigolf. Colour by light emission." The context of this tutorial is an underground miniature golf course. Accordingly, this video takes its point of origin in Niklas' wondering how the light from the dark violet tubes can "create all of these bright colours" that he perceives (Figure 2, right). In this case, *Nico* helps Niklas understand the underlying concepts of fluorescence and phosphorescence by employing a model animation. In connection with a parallel luminescence experiment, the animation comprises detailed explanations concerning the *Stokes Shift* and the additional bathochromic shift by phosphorescence. It becomes evident that the emitted photons are less energetic than the absorbed ones.

However, Nico is also able to excite Niklas with an experiment he developed himself, in which the energy of the photons is up-converted while luminescence is generated (Figure 3). In a stimulating conversation, Nico even manages to explain the mechanism of this transformation to Niklas with the help of molecular models.

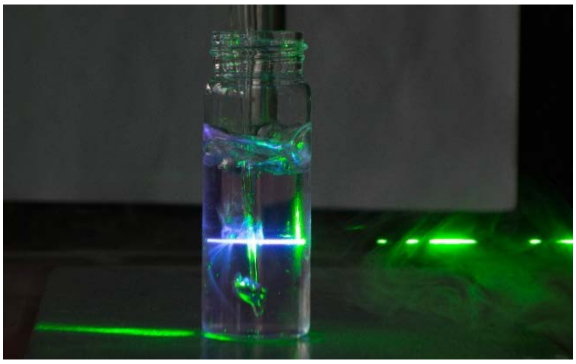

Figure 3. Photon up-conversion from green to blue - *Anti-Stokes Shift* (photograph by *Nico Meuter*)

Tutorial 3: "Light turns ON and OFF. A photoactive molecular switch." In this clip, Niklas wants to take a look behind the scenes of photochromic glasses. It is *Nuno* who guides him into the functional principle of photoactive molecular switches. He explains to Niklas that there are photosensitive molecules such as spiropyrane, which change their structure when exposed to light of a certain wavelength. In this case, the colourless spiropyrane sample switches upon irradiation with violet light into a coloured sample containing the isomer merocyanine. This process is a reversible one as thermal energy or light of a different wavelength, in this case green light, can switch the merocyanine isomer back into the spiropyrane isomer. Nuno employs an "intelligent" foil in order to visualize the process (Figure 3, right): He "draws with nothing but light", that is, by means of a LED torch.

Furthermore, Nuno uses molecular models of the aforementioned photoactive molecular switch in order to show Niklas what scientists understand by isomerism and how this gives rise to a new molecular structure with new properties. Additionally, they talk about how the new shape of molecules brings about a change in the chromophore, resulting in a different light absorption and, consequently, in a different colour of the sample. All of this lets Niklas access a higher level of understanding.

Tutorial 4: "A chemical chameleon. Molecular environment and solvatochromism." Here Niklas establishes a bridge between a living animal, a chameleon, which allegedly changes its colour based on its surroundings and a chemical "chameleon", which does so indeed. It is *Sebastian* who sheds some light on this topic by dissolving the compound spiropyrane in three different solvents. Having irradiated the three different solutions and switched the colourless spiropyrane into the coloured isomer merocyanine, the two of them now observe three different colors: red, purple, and blue (Figure 3, left). Niklas wonders: "Why's that? I thought you've only put one kind of molecule into all of these test tubes?" Sebastian explains the concept of solvatochromism to Niklas, using an absorption diagram and an energy level diagram. The same molecule generates differently coloured solutions depending on the surrounding solvent molecules. The solvent molecules' influence on the energy gaps between the respective highest occupied energy level and the lowest unoccupied energy level of the merocyanine molecule is responsible for the change in colour. Finally, Niklas has found a scientific answer to his question about the three different colours.

Tutorial 5: "Unequal equilibria. Thermodynamic equilibrium *vs.* photosteady state." In this movie, the protagonists elaborate on the idea of a specific equilibrium - the photosteady state. Before exploring the content matter, the idea of different balances (Latin: equilibra) in certain everyday situations is brought up by Niklas: "But is there also a chemical equilibrium that is linked to the presence of light?" Having raised this question, he seeks help with *Yasemin*. By means of the spiropyrane-merocyanine equilibrium from tutorials 2 and 3, the two of them carry out a sequence of experiments. First, they irradiate spiropyrane solutions at different temperatures and find out that they all turn from colourless to blue in an equally fast way. However, the hotter the solution, the faster the blue colour fades (Figure 2, left). Now Niklas wonders why the colour vanishes at all - and why at different rates. Based on the experiments, Yasemin explains the concepts of the two influences affecting the equilibrium to Niklas (Figure 4).

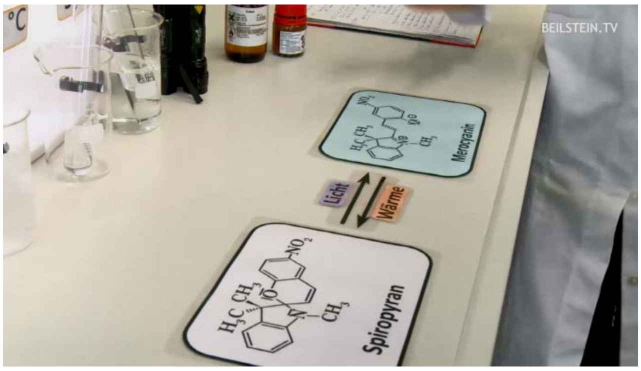

Figure 4. Reaction scheme for unequal equilibria in video tutorial No. 5

The photosteady state is reached when the light-driven reaction that promotes the formation of merocyanine and the thermal back reaction from merocyanine to spiropyrane occur simultaneously. This is emphasized by a further experiment in which a spiropyrane solution is irradiated at -16°C. This answers Niklas' question. Interactive model animations on the photosteady state can be found at

►https://chemiemitlicht.uni-wuppertal.de/fileadmin/Chemie/chemiemitlicht/files/animations/html5/photosteady_state/index.html, as well as at

►https://chemiemitlicht.uni-wuppertal.de/en/models-animations/photosteadystate-1/ .

The complete key terminology mentioned in Figure 5 can be elucidated starting from everyday phenomena, and by experiments using the isomer pair spiropyrane and merocyanine. Since merocyanine is produced in situ by irradiation of spiropyrane, this is the only starting compound for all experiments. That is the reason why we call spiropyrane a "didactical dream compound" for the exploration of photochemical basic concepts.

Technical details concerning the experiments with spiropyrane and the scientific background of the key terminology mentioned in Figure 5 have been published in the aforementioned special issue of this journal [2].

No.	Key terminology adressed in the corresponding video tutorial
1	photon, quantum object, particle-wave duality, complementary properties, reflection, diffraction, analogy, allegoric interpretation
2	colour by light emission, fluorescence, phosphorescence, UV light, visible light, model animation, ground state, electronically excited state, vibrational states, triplet triplet annihilation, photon down- and up-conversion, *Stokes Shift*, *Anti-Stokes Shift*
3	photochromic substance, photoactive molecular switch, molecular structure, molecular model, isomerism, light absorption and perceived colour, chromophore, spiropyrane, merocyanine, 'intelligent' foil.
4	solvatochromism, molecular environment, molecular switch, spiropyrane, merocyanine, highest occupied energy level (highest occupied molecular orbital HOMO), lowest unoccupied energy level (lowest unoccupied molecular orbital LUMO)
5	ground state, excited state, molecular switch, spiropyrane, merocyanine, thermodynamic equilibrium (chemical equilibrium), photo-steady state, Le Châtelier's principle, interactive model animation

Figure 5. Overview on the key terminology elucidated in the video tutorials 1-5 in section 2

3. Photoredoxreactions, photocatalysis, and photogalvanic cells in video tutorials

The video tutorial "Photosynthesis - a case for two", which is split up in two parts, applies the basic concepts and some of the key terminology mentioned in section two in the context of photosynthesis and respiration. In particular, the structure-property relationships as well as energy conversion are accentuated. They are accompanied by additional **basic concepts of chemistry didactics**, i.e. the donor-acceptor principle and deeper insights into the topic of catalysis.

The two films with a duration of approximately six minutes each were originally produced in German [5], but use in bilingual German-English settings made it necessary to re-score the films. Therefore, a new production was made in 2020, during which the English language was used. Thus, updated transcripts were created, then proofread by befriended English native speakers. After the linguistic and technical approval, the further production was coordinated with the local production company Tricast, which had already been responsible for the original versions. This resulted in two educational films suitable for both bilingual English-German students, and international, English-speaking target groups [16]. The contents of the two films are presented now. It is important to note that both videos contain an animation of a bright green maple leaf turning red, thus establishing an advanced organizer: Firstly, it prepares the viewer for the content which revolves around two colourful compounds. Secondly, it establishes a connection between the two relevant colourful compounds as they are both contained in green leaves even though only the green pigment can be visually detected whereas the existence (and potential relevance!) of the orange compound reveals itself to the human eye only when the green colour gradually vanishes.

Figure 6. Green and red maple leaves - guiding symbols in the two complementary parts of the film "Photosynthesis – a case for two"

Tutorial 6: "Photosynthesis - a case for two (part 1 of 2)" In this video tutorial, the essential aspects of the conversion of matter and energy in the photosynthesis-respiration cycle are simulated using the model experiment Photo-Blue-Bottle (PBB). Unlike natural photosynthesis and respiration, in which numerous compounds and reaction steps are involved, the PBB experiment's main compounds and energetic features are reduced to a minimum - only three chemicals and a photogalvanic cell in microscale format.

In this video, an expert in photochemistry and chemical education introduces the substance classes of chlorophylls and carotenoids as indispensable compounds within natural photosynthesis. Then, he reduces them to the two coloured "star players" chlorophyll and beta-carotene.

Figure 7. Blue light drives the formation of a blue substance, whereas red and green light are inactive

During the following minutes, continuous reaction cycles yellow-blue-yellow are demonstrated and commented on. While the forward reaction from yellow to blue is triggered by irradiation, the reverse reaction only takes place when oxygen from the air is introduced into the solution, e.g. by shaking the vial. Irradiation with light of different colours shows that blue light drives the formation of a blue substance, while red and green light are not able to do so (Figure 7).

In order to prove whether energy is stored in the blue substance synthesized by light irradiation, a photogalvanic concentration cell is used. Actually, simultaneously with the blue colouration of the solution in the irradiated half-cell, voltage is built up between the two cells. The voltage is maintained even when the irradiation is switched off and only breaks down when the blue substance is removed by introducing air into the solution.

The film ends by establishing a frame to the expository scenes. The expert concludes that key roles in the processes sustaining life on earth are firmly occupied by coloured substances. Furthermore, the significance of energy conversion and chemical reactions within the carbon cycle in animate nature are put forth.

Tutorial 7: "Photosynthesis - a case for two (part 2 of 2)" Chlorophyll and beta-carotene complement each other in photosynthesis. It is safe to say that the first part of these two educational films deals mainly with the green compound chlorophyll. As the title "a case for two" suggests, there is another crucial compound whose function within photosynthesis needs close scrutiny. Thus, beta-carotene is put centre stage in the second part: Its light absorption qualities indeed complement those of chlorophyll. Moreover, it serves as protection against too much light exposition. Again, a selection of experiments, models and animated diagrams is provided in order to make the subject both accessible and understandable.

In an opening scene of the film, *Rebecca*, a young chemist, demonstrates the chromatographic separation of an extract from green leaves. It turns out that it is a mixture of several colourful compounds. Referring to Einstein's wisdom, "One should make everything as simple as possible - but not simpler", the professor then justifies a didactic reduction, i.e. why not all colourful compounds are being examined, but only two of them.

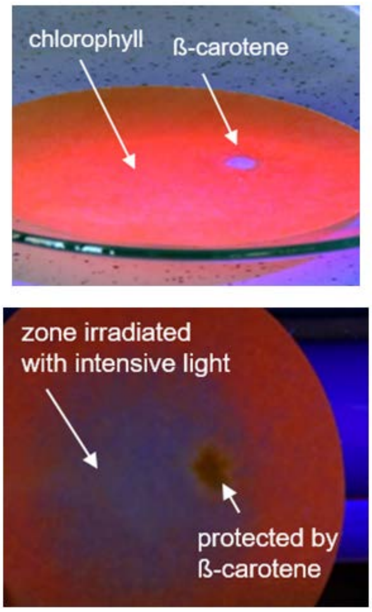

Figure 8. ß-carotene quenches the red fluorescence of chlorophyll (left), but protects it against photodegradation by intensive light (right)

Rebecca further elaborates on the role of beta-carotene. She points out the protective functions, which is again followed by laboratory experiments substantiating her claims (Figure 8). Here, the experiments take advantage of the red fluorescence of chlorophyll. It is absent when the chlorophyll molecules have been destroyed on account of too much irradiation, whereas it remains visible once the chlorophyll molecules remain unharmed. The latter is the case only on condition that the chlorophyll molecules are mixed with beta-carotene molecules – they serve as sun protectors.

What follows is a step-by-step explanation of these experimental results using model animations with chlorophyll, oxygen and beta-carotene molecules in excited singlet and triplet states as well as energy transfers between them. Finally, by forming a frame with the introductory sequences, the professor offers concluding remarks on the functions of the two colourful compounds within leaves.

No	Key terminology adressed in the corresponding video tutorial
6	photosynthesis, low-energy carbon compound, carbon dioxide molecules, high-energy carbon compound, glucose, sunlight, green pigments, chlorophylls, photocatalyst, photon, coloured compounds, light absorption, visible light, carotenoids, beta-carotene, model experiment, Photo-Blue-Bottle experiment, electronically excited state, ground state, light energy, chemical energy, reaction cycle, photogalvanic concentration cell, energy conversion, respiration, carbon cycle in animate nature.
7	photosynthesis, green leaves, colourful pigments, thin layer chromatography, chlorophylls, beta-carotene, light-harvesting complex, reactive centre, absorption light, "green gap", model experiment, protective function, fluorescence, ground state, electronically excited state,, triplet chlorophyll molecules, energy transfer, deactivation by vibrational relaxation, singulet oxygen molecules, cytotoxin.

Figure 9. Overview of the key terminology elucidated in the video tutorials 6-7 in section 3

4. Teaching module on the carbon cycle in animate nature

Why this topic? Much educational material in German for chemistry lessons including video tutorials 1-7 discussed in sections 2 and 3 has already been developed, disseminated and evaluated [7,8]. There is, however, still a great demand as regards material development for bilingual settings [9,10]. In a survey of 2017, we have reached out to teachers of bilingual chemistry and bilingual biology with the goal of finding out which topics from the field of photochemistry they would like to integrate into their lessons with the aim of designing bilingual material. Most prominently asked for were the topics of the carbon cycle in animate nature – the topic encompassing photosynthesis and respiration [11]. A literature review [12,13,14,15] among them the meta-study by Steigert] was carried out in order to find out whether further effort into researching this topic could be legitimate and reasonable. Besides, information about the challenges which other STEM-educators have pointed out when dealing with this subject were gathered. At its core, the review of articles predominantly from monolingual STEM backgrounds strongly supported our enterprise of bilingual material development. Additionally, we found out that the selected topic contains rather many cognitive obstacles the students will have to overcome, among them the function of light or chlorophyll during photosynthesis. These findings were then used to develop a context-based bilingual teaching module on the carbon cycle in animate nature [16].

***Elysia chlorotica* - a fascinating context.** The last part of a tripartite research and development process based on field studies [17,18,19] resulted in the creation of a module revolving around the sea slug *Elysia chlorotica* (Figure 10) [16]. While the first two modules were planned according to the principles of 5E [20,21]; for further teaching ideas in this vein see [22], this one was conceptualized following the **principles of a complex competency task** [23,24]. Two argumentative strands were used as a foundation to legitimize this profound change:

Firstly, there are **science education reasons**: We have found out in the previous modules that the students need a set of guiding questions within their learning process, in particular with view to the fact that white light can be split up into light colours. It was neither easy for the students to comprehend that different light colours contain different amounts of energy, which is why we modified [16] the basic Photo-Blue-Bottle experiment and only chose the idea that it is a selection of light colours which can trigger a photochemical reaction – i.e. only some light colours contain the necessary amount of energy.

Figure 10. The emerald sea slug *Elysia chlorotica* is an animal equipped with chlorophylls contained in chloroplasts, which can be powered directly by sunlight (photograph courtesy of Patrick J. Krug)

Second, there are general linguistic or English **language education reasons** [23,24]. By expecting the students to produce and give a poster presentation for an imagined scientific community at a conference about selected light-induced features of *Elysia chlorotica*, we provided them with a clear communicative goal they could only reach by referring to rich linguistic scaffolding. As a consequence, the students were put in the situation of a researcher who has to gather scientific knowledge about a peculiar animal, a green sea slug, which takes advantage of photoprocesses in order to sustain its life (see the lesson plan and teaching materials in supplemental information).

This is why we have offered a material package consisting of photos, background texts, video clips, hands-on experiments, vocabulary – that is, a multifaceted environment scaffolding the students' learning processes. Additionally, we offered some guiding questions and overall guidelines to help students during their learning processes [16]. In the supplement. the idea of the complex competency task as well as an overview of the steps to be taken within the module are presented. The material package itself can be accessed by the link from the supplement

Teaching practice with video tutorials No. 6-7: From the previous two module cycles, and especially from a guided interview accompanying them, we could draw the conclusion that the learners where somewhat overwhelmed with the condensed input in the video "A case for two – part 1 of 2". Typically, the feedback of students sounds like this: "*It was very difficult to understand because there were so many technical terms that you didn't necessarily hear in the film*" [16].

Therefore, we decided to implement only a short four-minute-extract from the film in the new teaching material for the module discussed here. The reception of the extract is guided by assignments asking the students to explain the key terminology transported by the video, which are then transferred to the natural counterpart, i.e. chlorophyll (cf. the worksheet "Background information 2" [supplement; 16]). We also decided to add the transcript of the film to the teaching material, thereby offering the students the opportunity of comprehending the new vocabulary used in the film more easily. They can watch the film and make sense of it by focusing on the visualizations. Furthermore, they have now the option of listening to the film and reading the transcript. They can even work with the transcript as sole source of information. The feedback we received as regards this procedure has proven us right as a bar chart reveals, which is based on closed items in an accompanying questionnaire ([16], supplement).

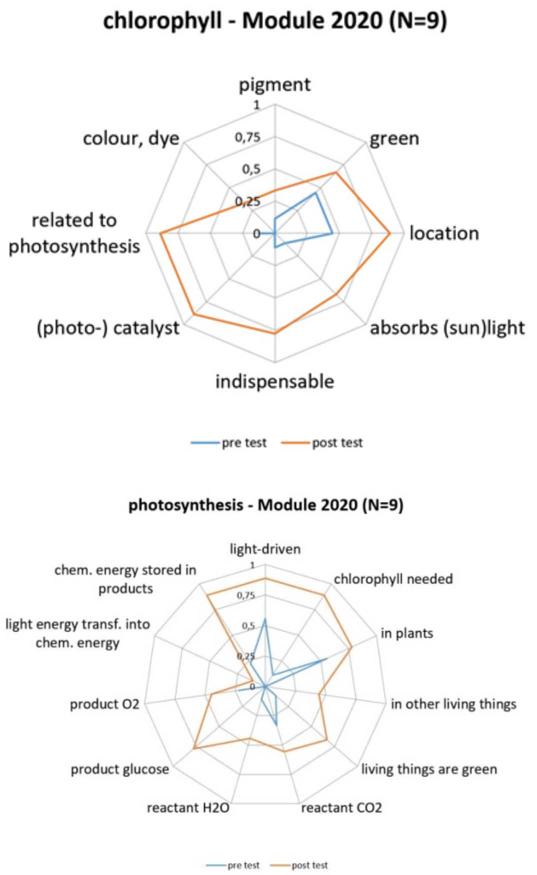

Figure 11. Spider diagrams: learning progress pre- to post-test

5. Learning outcomes

Spider diagrams. With the help of paper and pencil pre- and post-tests (N=17, but due to Covid-19 pandemic only nine could be examined), we were able to analyze the learning outcomes: Before and after the module, the students were given a double lesson of time, i.e. 90 min, to explain a set of technical terminology crucial for the module [25]. The terms photosynthesis or chlorophyll counted among them. The handwritten texts were transcribed, then thoroughly analysed several times each by means of qualitative content analysis and MAXQDA 2020 [26,27,28]. The results were graphically presented with spider diagrams inspired by [29], visually drawing attention to the knowledge before and after the topic (Figure 11).

Meeting didactical challenges. When relating the overall learning outcomes to the aspects mentioned in the didactical literature, we can say that several didactical challenges revealed by Steigert, Skribe Dimec and Strgar, Lin and Hu, or Näs [12,13,14,15] are met by the modules, in particular, by the one tested in 2020:

- the conditions, the process and the outcome (i.e. products) of photosynthesis are now being addressed by students
- the students have formed a sound understanding of the functions of chlorophylls and light
- the participants have been able to identify the processes as chemical reactions
- an understanding of different forms of energy has been established among the students

These rather roughly tuned aspects are further particularized and elaborated on in much detail in [16].

Students' mental maps. However, in order to receive further in-depth understanding of the students' mental maps of the offered concepts within the module, the written explanations [25] should in future research be accompanied by conversations with participants about the topic. At the same time, we are aware of the fact that this sole focus on verbalized knowledge limits the accessibility to the full range of the student's capabilities (for a discussion of different methods of data collection see [16]). After all, the students themselves reflect positively on their learning outcomes. Our research confirms this statement insofar as the data for each of the three parts of the tripartite research and development project underlines the overall positive student attitude towards the teaching units (between approximately 65 and 85 %). One participant of the module presented above states: "*I would tell my friends that it was exciting and interesting to deal with something like this in English. And also the topic of the module was well chosen because it was not too difficult but still interesting*" [16].

This is only one of the many aspects that we were able to gather from the participants by the accompanied qualitative research whose selection was inspired by preceding research into the field of innovative teaching settings [8,30,31,32]. Despite the positive results as regards some former problems with photosynthesis and respiration, we noted some critical aspects, quite comparable to the ones mentioned in the literature [12,13,14,15]: Firstly, the connection between photosynthesis and respiration remains hard to understand for students. This is true for energy conversion processes, too. Secondly, it seems that pre concepts have “fossilised”, i.e. some of them have remained unchanged after the teaching unit. For example, one student still believes that green chlorophylls are produced within photosynthesis. However, the formulation of the reaction scheme of photosynthesis has proven to be very useful [16].

This is in line with results and suggestions put forth by [14]. Based on interviews with Swedish secondary school students, Näs suggests the claim that “*photosynthesis is challenging and pupils do not find it interesting*” [15, p. 65] can be overcome by embedding the topic itself into a suitable and interesting context: “*A chemical formula of photosynthesis or respiration interested a few students, but the complex explanation about how a carrot, potato or an apple ‘comes out of’ photosynthesis made all 23 teenagers more interested in the difficult processes*“ ([14], p. 87).

Students’ products. After having taken stock during the first three 90-minute-sessions, the students finalized their products during a last lesson of 90 minutes. Each one of the participants was asked to create a poster to be presented at the imaginary poster session. This is the reason why they needed to plan, rehearse and record their intended presentation monologue as it was collected by the teacher at the end of the session. This pushed output resulted in several different posters of which a few are presented here (Figure 12; see further examples in supporting information).

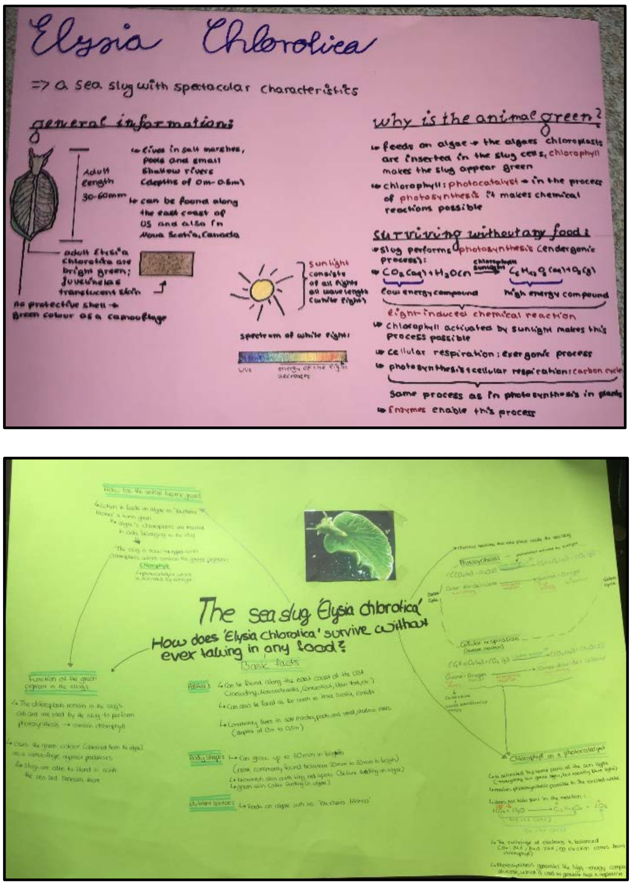

Figure 12. Posters created by two of the students

The students have created quite different posters, although the same guiding questions should be answered – a condition not all students successfully abided by. What strikes the eye is the creativity apparent in the posters, the amount of details, and the inclusion of relevant items in most of the posters. All of them have in common that they include background information on *Elysia chlorotica* and remarks on the underlying chemical reaction – even though not all reaction schemes are complete. Most of them cover the relevant aspects (i.e. light, photocatalysis, energy aspects), but to quite different degrees of in-depth examination. This can be attributed to time restriction, level of understanding, or the fact that there is an accompanying verbal presentation which might even contain aspects that are not mentioned on the posters. It needs to be emphasized that we did not use either poster or presentation for the analysis of the students’ learning process. Instead, we relied on the pen-and-pencil data collection (definitions of key terminology inspired by [25]). Moreover, some of the posters contain language errors (e.g. grammar: ‘information’ is an uncountable noun; some questions need to be formed with auxiliaries; orthography: ‘photocatalyst’ is spelt with the letter ‘c’ and ‘excited’ contains the letter ‘c’) and subject errors (e.g. it is wrong to say that all colours but green start the chemical reaction), of which we have not corrected any even though we are aware of them. We were happy that quite many of the new idioms and words were used in the posters, for example “excited state”, “photocatalyst”, “perform photosynthesis”, “generate heat”, “exergonic/endergonic process”, “convert sth. into sth.”, or “light-induced reactions”.

Most of the students used prompt cards and presented their poster eagerly to the imagined audience, whereas but a few read out their written texts. The presentations were approximately between five and eight minutes in length, with one lasting just over two minutes. Thus, it is fair to say that all of the participants were able to cover the task in the given time, with most students complying with the intended manner.

6. Conclusion

The developed educational material aims at providing relevant subject matter in a concise and entertaining way. The scientific contents are developed from a foundation which takes its origin in everyday phenomena and everyday language. Technical terminology is offered in conjunction with this procedure.

Several core scientific concepts are illuminated with the help of didactically reduced chemistry experiments which have been designed to enable clear observations [7]. These facilitate scientifically consistent interpretations on the part of the students. At the same time, the necessary chemicals are non-hazardous and used in microscale set-ups, thus ensuring that students and environment remain unharmed. Furthermore, only small amounts of chemicals are required and, in general, the experiments are low-cost. These are meaningful factors for the responsible use of resources and for application in schools – aspects which have always been principles of the didactical research and development processes within experimental-conceptual research and curricular innovation research [7,21,33,34]. Hereby, we underline that we take the idea of "green chemistry" seriously – also from the vantage point of material use and consumption [1].

The result of the cognitive test for the bilingual (English-German) module indicates that the participants have been able to acquire relevant competencies as regards content knowledge. The setting has proven to be motivational and the usage of the educational films has turned out to be viable, thereby enabling students to be successful learners. In conclusion, it is safe to say that the students were able to gain valuable experience in this setting by dealing with future-relevant applications related to green, sustainable chemistry. They have in particular been equipped with insights into the field of chemistry with light.

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Supplement

Overview of the 2020 module "Elysia chlorotica – a sea slug with spectacular characteristics"– a lesson plan

	phase	contents	materials	format
The sea slug	**introduction and overview**	Discussion of the conference invitation	conference invidation sheet, smart board	individual work & team work
	working phase	Working out the background of the sea slug on the basis of a photograph and an information text	worksheet (ws) "Background information 1" and associated "Assignments", smart board	individual work & team work
	consolidation and evaluation	Pooling and consolidation of the work done so far, discussion of difficulties, clarification of questions		plenary work
Chlorophyll	**introduction**	Recap, joint view on the further work		individual work, plenary work
	working phase 1 & interim consolidation	Acqusition of background information about the pigment chlorophyll by means of experiments and information texts; main focus: role of chlorophyll, step 1 and 2; subsequent interim consolidation similar to the one above	ws "Background information 2"; material: prisms, torches with white light, white sheets of paper (DIN A4), ws "White light - an experiment"	individual work, student experiment, plenary work
	working phase 2	Further development of background information on chlorophyll; second main focus: role of chlorphyll, step 3	ws "Background information 2"; material: torches with different light colours (blue, red, green, UV, white), Photo-Blue-Bottle solution in vials	individual work, student experiment, plenary work
	consolidation and evaluation	Pooling and consolidation of the work done so far, discussion of difficulties, clarification of questions; outlook on next lessons		individual work, plenary work
Photocatalysis & Poster Production	**introduction**	Recap, joint view on the further work		plenary work
	working phase 1 & interim consolidation	Working on the topic of photocatalysis, focus on proflavine in a model experiment with an educational film; then interim consolidation similiar to the one above	ws "Background information 3", iPads, Video als Download, Filmtranskript	individual work & team work, plenary work
	working phase 2 & interim consolidation	Elaborations on the photocatalyst chlorophyll on the basis of the findings on proflavin; then intermediate consolidation in accordance with the phases above.	ws "Background information 3", iPads, Video als Download, Filmtranskript	individual work & team work, plenary work
	transition	Meething phase: poster production		plenary work
	poster production	Poster- und Vortragsvorbereitung (je ein Lernprodukt je Schüler*in), Dokumentation des Lernprodukts durch Videographie	poster, felt tips, tablet pc	individual work/partner work

Overview of the 2020 module "Elysia chlorotica – a sea slug with spectacular characteristics" – competency task grid based on [23]

competence goals	Learners can give a presentation on the sea slug E. Chlorotica from the information provided in the materials, answering the guiding questions (becoming green; meeting energy needs via light-induced processes; locating selected aspects of the carbon cycle in the animal).
topics, contents	Studying the carbon cycle in animate nature using a curious animal; working out the chemical processes involved in photosynthesis and cellular respiration; exploring light colours and their specific effects; the importance of chlorophyll as a photocatalyst.
input: texts, visuals	Material package consisting of: invitation, background text 1 "Sea slug", background text 2 and experiment "Chlorophyll", experiment "Prism/White light as a product of additive colour mixing", background info 3.
genres	Productive: presentation; Receptive: non-fiction texts, visuals, experiments; scientific video "A Case for two" on the Photo-Blue-Bottle-Experiment (incl. transcript)
linguistic means	Topic-specific vocabulary on above-mentioned content; coherent speaking in a structured technical presentation; active participation in class discussions on (photo-) chemical technical content.
subtasks, exercises	Selection of relevant content from videos, visuals, and texts (reading, listening); construction of a concept map with new components, preparation of a structured presentation to answer the provided key questions; speaking (monologue) in front of an imaginary audience of experts in the field of chemistry.
scaffolding	annotated texts; glossary; flashcards with task solutions; concept map to build up a topic-specific vocabulary; dictionaries; word banks: oxidation, reduction; for the negotiation processes: comparing and contrasting, giving examples, (dis)proving, hypothesizing.
task instruction	The central task is provided in conjunction with the conference invitation letter; further tasks for text reception and production are handed out in conjunction with the material.

cognitive processes
Assuming the role of a person in science; compiling the information relevant to the presentation from the package of materials and collecting it in a concept map; identifying relevant technical vocabulary and integrating it into text production; exploring photochemical experiments (light colour and effect; splitting white light) and integrating the findings from them.
linguistic-discursive functions
Compiling technical vocabulary from glossary, factual text(s) and video clip (cf. material package) in order to answer the guiding questions and to use it for the poster as well as for the presentation (on prompts cards, applied in oral language
interactional processes
Negotiating the findings from the experiments or from the video in plenary or partner work phases; creating presentations.

outcome, students' products
Poster presentation at a fictional scientific conference on the sea slug Elysia Chlorotica.

Teaching materials

The material for the 2020 module as described above can be found here:

The QR-Code redirects to this source:

https://doi.org/10.25926/BUW/0-31 | DOI: 10.25926/BUW/0-31

There are two downloads available.

PDF-download:

If you download the PDF (17.3 MB), you will find the material on pp. 334 ff.

It comprises the following parts:

- Intro: A conference invitation
- Hints for the students
- Background information 1: The sea slug Elysia chlorotica and assignments
- Background information 2: 'Which role does the pigment chlorophyll play?' and assignments
- Material: Experiment on light colours and energy
- Background information 3: A deeper understanding of photosynthesis
- Transcript of the educational film 'A case for two: part 1 of 2'
- Glossary

ZIP-download:

If you download the ZIP-file (107.2 MB), you will find the aforementioned material in the ZIP-folder "Digitaler Anhang_Modul 2020 Typ A", all of which available as Portable Network Graphics (*.png-files).

Bar chart: Evaluation of the 2020 module by participants (N=9; only 8 fully filled-in questionnaires received)

This diagram comprises a selection of closed items of the provided questionnaire. The selected items deal predominantly with the general attitude towards the whole 2020 module, and particularly with the used video clip extract.