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Article

Engaging Preuniversity Students in Sustainability and Life Cycle Assessment in Upper-Secondary Chemistry Education: The Case of Polylactic Acid (PLA)

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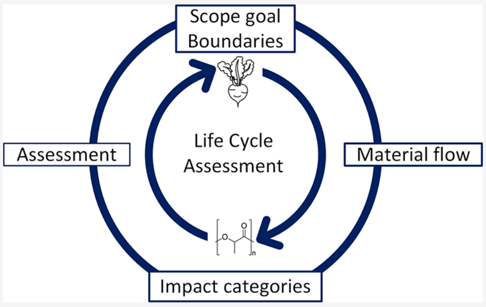
ABSTRACT: This article reports about a lesson series that focuses on engaging students in sustainability, plastics, and life cycle assessment (LCA). The purpose of the lesson series is to give students insights into sustainability in the context of plastics and to foster awareness of and insights into the benefits of the LCA method. The lesson series introduces students to sustainability by enabling them to watch a video, answer questions, read articles, conduct laboratory experiments, and experience the four stages of LCA. In general, the findings reveal that the lesson series evoked in students a more critical view of the life cycle of plastics. The students showed increasing awareness of the complexity of the sustainability issue at hand. In addition, students used their acquired knowledge about LCA and mentioned impact categories in their argumentation. The lesson series evoked predominantly life cycle thinking, and the qualitative part of an LCA, and might thus serve as a stepping stone toward the quantitative assessment. The preliminary results show that the lesson series is effective for evoking life cycle thinking among students and serves as a stepping stone towards life cycle assessment. Future research could focus on setting the goal and scope of the process to be assessed, with emphasis on the functional unit in the context of plastics, and providing students a complete and coherent understanding of the entire cycle of production, use and recycling of plastics.



KEYWORDS: *High School/Introductory Chemistry, Environmental Chemistry, Hands-On Learning/Manipulatives, Green Chemistry, Polymerization*

INTRODUCTION

Sustainability has become a prominent theme in society and is regarded as an integral part of scientific citizenship.[1−3] In the domain of chemistry, issues related to sustainability are often referred to with the term sustainable chemistry, which is intended to reduce environmental impacts while simultaneously maintaining or even improving performance.[4] Numerous educational researchers and policy makers have advocated giving sustainable chemistry a prominent place in undergraduate and secondary school chemistry curricula.[5,6] This can be seen as contributing to education for sustainable development (ESD). ESD serves as a bridge between science, industry, and society, which have an obligation to contribute to a world in which future generations will be able to live in a sustainable way. Citizens, in turn, should convert this awareness into personal choices regarding sustainability. A well-known example in which the theme of sustainability becomes tangible and visible to the general public is the production, use, and recycling of plastics. Plastics are omnipresent in daily life, and a topic that is easily introduced to young adults as being potentially problematic. Students recognize the importance of plastics in society as well as their potentially negative side effects, including the toxicity of plastics' additives and the accumulation of postconsumer plastic waste in the oceans. Most students are familiar with the recycling of plastics to reduce their environmental impact, but few are aware of the environmental impacts of the complete life cycle of plastics, from cradle to (ideally) cradle.

Life cycle assessment (LCA) is a tool to investigate the overall impact of products and processes on the environment.[11] Within the goals of ESD, LCA can be both a tool for analyzing the sustainability of a product and process and a goal in itself to teach students about the sustainability issues related to the manufacturing of products. To engage students effectively in LCA procedures, we need teaching approaches and materials that involve students in analyzing the life cycle of products and processes. By enabling students to conduct an LCA themselves, they experience how scientists view and handle sustainability issues and gain insights into the benefits and limitations of the LCA method.

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In this article, we present a lesson series and accompanying worksheets, protocols, and laboratory experiments targeting the introduction of LCA into secondary school chemistry classes. We portray and reflect on the design and report the results of the enactment in classroom practice.

Twelve Principles of Green Chemistry and Life Cycle Assessment

The 12 principles of green chemistry are a well-known lens within the movement of green chemistry.[1] These principles do primarily apply to synthesis, but for assessing environmental impacts of complete production and recycling processes a more holistic procedure like life cycle assessment (LCA) provides guidance for decision making on sustainable solutions. LCA considers the impact that products and processes have in each specific part of the life cycle and consists of a qualitative and a quantitative part. In the qualitative part, an inventory is made of all the material flows and energy consumption involved in all the steps of a product's life cycle. Next, all the resources used for production, use, and recycling are clustered into a defined set of impact categories, indicating which aspects of the product and/or process exert pressure on the environment. In the quantitative part, the magnitude of the impact is calculated using corresponding units of measurement, enabling a comparison of the impact categories and the identification of the most problematic one(s).[2] The 12 principles of green chemistry and LCA are both valuable lenses that should be integrated into ESD. Whereas the 12 principles of green chemistry have already found their way into many secondary school chemistry curricula, LCA is still in its early stages of implementation, probably due to the technical nature and complexity of the method. To make LCA accessible to students, we analyzed the authentic LCA stages in the context of plastics and transformed essential activities and chemistry (science) knowledge involved into a lesson series.

Four Stages of LCA

The International Organization for Standardization (ISO) has developed standardized methods (e.g., ISO 14040 and ISO 14044) for performing an LCA. According to the ISO, an LCA can be divided into four stages.[24] First, a goal and scope must be established. With multiple possible goals, an LCA can be performed, such as a comparison of two (or more) products or processes regarding sustainability, an examination of the production chain to determine where improvement is possible, or the identification of the best positioning in the marketplace.[7] It is also necessary to establish system boundaries to define which aspects are included in the analysis and which are not.

Second, the inventory analysis of the life cycle (LCI) is performed. In this stage, actual data and models are collected on the input (e.g., raw materials, water use, and energy) and output (e.g., emission of pollutants and waste streams) of the various steps in the process.[8] Next, all the material flows and energy use in the various steps are categorized into impact categories with suitable indicators. This part of the LCA can be considered as its qualitative part.

Third, an impact assessment (LCIA) is performed, in which the possible environmental impacts (magnitude and significance) are evaluated quantitatively in their corresponding unit of measurement (equivalents).[9,10]

Fourth, the combined results of the LCI and LCIA are evaluated.[8] From this, a conclusion, piece of advice, or answer can be obtained to achieve the goal of the investigation (first stage).

Performing an LCA is not easy, and sometimes LCAs for the same products or processes yield different results.[11] Many variables, such as the specific methodology chosen, the choice of end-of-life treatment, and the origin and collection of starting materials, play a role and can cause variations in the LCAs results. In addition, the part of the life cycle that is analyzed is important. Figure 1 depicts the three definitions of the life cycle of a product. The cradle-to-gate philosophy focuses on collecting the starting materials until the actual production of the product. The cradle-to-grave philosophy takes into account the production and use phases, from the collection of the starting material to the disposal of the product. The cradle-to-cradle philosophy is focusing on creating closed-loop recycling in which waste is considered as a starting material.

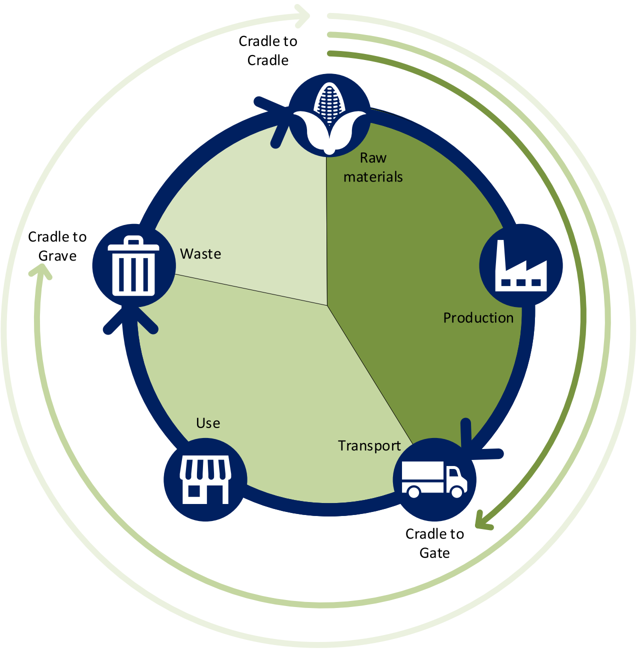

Figure 1. Schematic representation of three definitions of the life cycle of a product: cradle-to-gate (raw material to transportation), cradle-to-grave (raw material to waste), and cradle-to-cradle (raw material to raw material again).

LCA of (Fossil-Based and Biobased) Plastics

Most of the LCA studies conducted on plastics have compared fossil-based and biobased plastics. The review by Walker and Rothman provided a comprehensive overview of the available LCA studies on this comparison.[11] After thorough analysis, they selected 25 articles reporting the LCA results of 39 fossil-based and 50 biobased polymers, enabling a comparison of seven biobased and seven fossil-based polymers across seven impact categories, namely:

1. Energy use (MJ/kg polymer)
2. Ecotoxicity (CTUe/kg polymer)
3. Acidification (kg SO_2 equiv/kg polymer)
4. Eutrophication (kg PO_4 equiv/kg polymer)
5. Climate change (kg CO_2 equiv/kg polymer)
6. Particulate matter formation (kg PM2.5−10 equiv/kg polymer)

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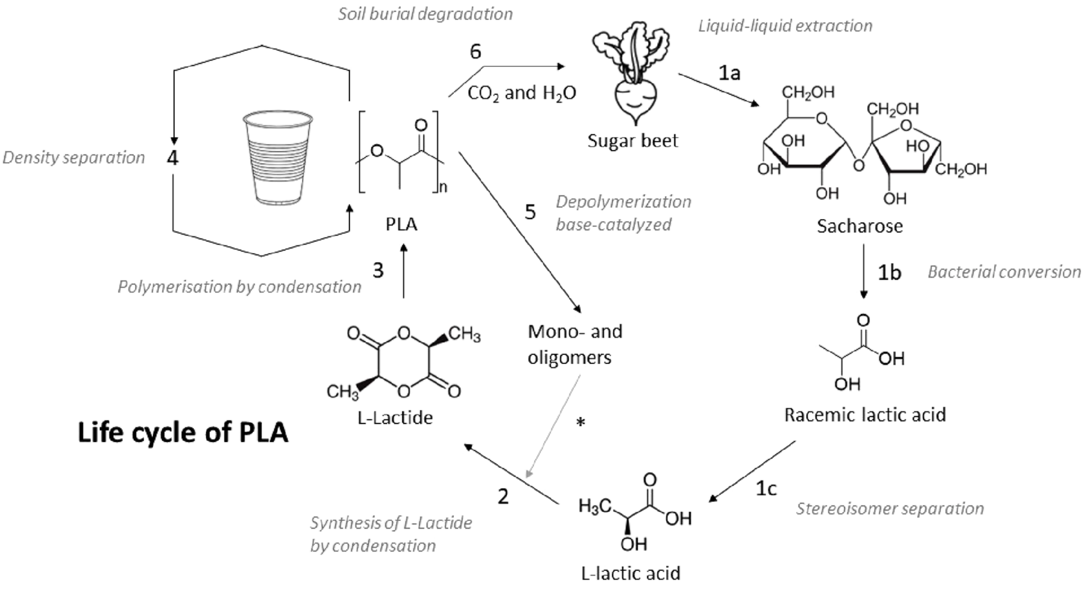

Figure 2. Life cycle of polylactic acid in six steps: (1a−c) formation of L-lactic acid, (2) formation of L,L-lactide, (3) conversion of L,L-lactide into PLA, (4) separation of plastics and recycling, (5) depolymerization of PLA, and (6) composting of PLA. The asterisk indicates an additional experiment after experiment 5.

7. Ozone depletion (kg CFC11 equiv/kg polymer)

Significant variation was found between polymer types and between fossil-based and biobased polymers, meaning that it was not possible to declare any polymer type conclusively to have the smallest environmental impact in any category. In general, it can cautiously be concluded that biobased plastics perform better in terms of energy use and climate change when only applying the cradle-to-gate philosophy and not considering the CO_2 emissions during the end-of-life treatment (recycling phase). For example, in the impact categories acidification and eutrophication (excessive richness of nutrients in a body of water), it is more often seen that fossil-based plastics outperform biobased plastics.[11]

The above findings underline that sustainability is not a one-dimensional, easy-to-capture concept. By involving students in conducting an LCA on plastics, we aim to give them more in-depth insights into sustainability aspects, that is, the different impact categories that play a role, and to enable them to grasp the nuances in the sustainability debate related to biobased and fossil-based plastics.

Outline of the Lesson Series

The lesson series aims to engage students in performing an LCA and consists of five parts (I−V). In part I, students are introduced to the topic. Lesson series parts II−V basically correspond to the authentic LCA stages 1−4, as described earlier. Each of the parts starts with a brief lecture by the teacher, providing a conceptualization of the LCA stage at hand, and concludes with a recap and short group discussion related to the LCA stage, guided by a worksheet. Below, each part of the lesson series is described in more detail.

Part I. Introduction to the Topic of the Sustainability of Plastics. The teacher introduces the topic to the students by discussing the sustainability issue of plastics and showing them a short film about a recycling company. Next, students' prior knowledge is activated by answering individually some questions about the production, use, and recycling phases. This is followed by the students individually reading different news articles and sharing the information with group members. At the end of this first part, students are confronted with the question "What type of plastic (biobased or fossil-based) is the most sustainable?" Based on our previous research,[12] we anticipated that the majority of the students would tend to choose biobased plastics. An argument that is commonly put forward by students is the biological origin of biobased plastics, implying that they do no harm the environment. However, it has also been found that students were open to examining their claim critically. Students are invited to zoom into the process of production, use, and recycling of bioplastics. The biobased polymer polylactic acid (PLA) serves as a case in the remainder of the lesson series.

Part II. Goal and Scope. In the second part, students are challenged to think about and make explicit the goal and scope of their LCA on PLA. In small groups, students are asked what kind of organization(s) would be interested in an LCA on PLA and for what reason. In addition, students think about the kind of information needed to perform an LCA on PLA as well as which aspects should be included in the LCA and which should not.

Part III. Inventory Analysis. The third part, the inventory analysis of LCA, entails the (empirical) data collection of all the steps in the life cycle by the students themselves. The life cycle of PLA consists of six steps. Part III of the lesson series is set up according to the jigsaw method,[23] so each member of a group of students studies a couple of steps of the total life cycle, including conducting (clusters of) the relevant laboratory experiments. Figure 2 visualizes the complete life cycle of PLA, including the experiments. All the group members together cover the complete life cycle of PLA. The starting point and main output(s) for each step, as well as their sequential order, are briefly described. The detailed protocols, worksheets, and precise activities carried out by the students are available in the Supporting Information. All of the described experiments are based on existing experimental lab protocols, adapted for use in secondary school laboratory environments and tested multiple times before use in the lesson series.

Step 1. Formation of L*-Lactic Acid.*

(1a) The PLA production starts with the isolation of glucose from sugar beets. The sugar beets are boiled, and after various filtration steps and the addition of limewater, syrup is formed. The syrup is poured onto a crystallization dish to allow sugar crystals to grow.[13]

(1b) Using lactic acid bacteria from sauerkraut, the sugar crystals in the syrup are converted into lactic acid. Bacteria are inoculated on agar−agar plates with the syrup as a breeding ground. The plates are placed in an incubator to allow the bacteria to grow. After 4 days, lactic acid colonies are formed. The presence of lactic acid is demonstrated by thin-layer chromatography (TLC), using commercially purified lactic acid as a reference.[13−15]

(1c) Information on enantiomers (L-lactic acid and D-lactic acid) is made available as well as a link to a Dutch website explaining how the separation of L- and D-enantiomers works.[16]

Step 2. Formation of L,L*-Lactide.* The end product of step 1, L-lactic acid, forms the starting point of step 2. Since the formation of lactic acid by bacteria takes about 4 days, and the separation of L- and D-lactic acid is studied by students only theoretically, step 2 starts with commercially available L-lactic acid. A reflux setup is built using a Dean−Stark trap according to the instructions. The experiment is conducted in a fume hood. Because of the safety aspects and the use of potentially hazardous chemicals, students are assisted by the teacher(s) during the setup, initiation, and termination of the reaction. Commercially purchased pure L-lactic acid is refluxed in toluene. Next, commercially purchased catalyst $SnOct_2$ is added, and the reflux is continued for 3 h.[17]

Step 3. Conversion of L,L*-Lactide into PLA.* As step 2 takes about 5 h in total, step 3 starts with commercially purchased L,L-lactide, which is refluxed in toluene together with the catalyst $SnOct_2$. For the conversion of L,L-lactide into PLA, a reflux setup is built in the fume hood. As in step 2, students are assisted by the teacher(s) because of the safety aspects and the use of potentially hazardous chemicals. After refluxing for 1 h, the mixture is allowed to cool down to room temperature. The reaction is terminated by adding a few drops of hydrochloric acid. The reaction mixture is further cooled in an ice−salt bath, and the product was washed with heptane and collected via vacuum filtration using a Büchner funnel and a side arm flask. The formed polymer is dried in an oven at 60 °C for half an hour.[18]

Step 4. Separation of Plastics. Step 4 focuses on separating different types of plastics based on densities, typically performed at the end of the use phase preceding recycling. Different fossil-based and biobased plastics are cut into small pieces and put into a beaker. Next, demineralized water is added. The density of the liquid in the beaker is increased through the stepwise addition of sodium chloride. To determine which plastic floats to the surface, a list of known plastics with their corresponding densities is given in the protocol.

Step 5. Depolymerization of PLA. A PLA cup is cut into small pieces, placed in a beaker with methanol, and covered with a watch glass while it is heated to 60 °C in a water bath. After 10 min of boiling time, the mixture will turn pale yellow, marking the depolymerization of PLA into oligomers and monomers. The reaction continues until all visible, solid pieces of plastic are dissolved. The beaker is cooled in an ice bath, and hydrochloric acid is added to lower the pH to 4−5. The resulting suspension is filtered, and the filtrate is analyzed through TLC.[19] A possible addition to this experiment is let students use depolymerized PLA (mixture of oligomers and monomers) and pure lactic acid (virgin material) to produce PLA.

Step 6. Composting of PLA. A piece of plastic, either a piece of PLA or a piece of a fossil-based plastic, is added to two cups of soil. A third cup of soil contains no plastic. The three cups are regularly moistened beforehand and kept in a warm place. The pH of the soil is measured regularly as well as a check to determine whether the plastic is affected and/or shows signs of degradation.[20,21]

Hazards

Appropriate protective measures should be taken such as wearing protective glasses and a lab coat at all times. In addition, because of safety aspects and the use of potentially hazardous chemicals, students are assisted by the teacher(s) or lab assistant with experiments 2 and 3. The setup should be checked before the experiment is started, and chemicals such as toluene, $Sn(Oct)_2$, and benzyl alcohol should be added by the teacher or lab assistant. The procedures of experiment 2 and 3 are completely performed in a fume hood, and in experiment 5, the addition of the hydrochloric acid should also be performed in the fume hood.

Part IV. Impact Assessment. In the fourth part, the impact assessment, the students group together and exchange all of their experiences collected in the previous part III, to create an overview of the life cycle of PLA. Next, the groups classify all of the different substances used for the production, use, and recycling of PLA into appropriate impact categories applicable to plastics (described earlier) and summarize the overall impact on the environment. Since the experiments and collected data are mainly focused on the production and recycling phases, the use phase is left out of the assessment. The students are also triggered to identify similarities and differences between the PLA production and recycling conducted in class (part III) and those in an industrial setting.

Part V. Conclusion. In the fifth and final part of the lesson series, students reflect on their gathered results related to the four stages of LCA. The students make an inventory indicating whether they would like to improve, supplement, or make changes to the LCA procedure conducted. In addition, they reflect on the environmental impact of the different steps in the life cycle of PLA. Finally, the students argue which impact category had the most influence on the sustainability of the plastic PLA.

■ EVALUATION STUDY

The lesson series has been enacted multiple times in different schools. In this article, we report findings gathered during the first enactment. A group of 16 students (12 female and 4 male), in the age group 15−18, participated voluntarily in the lesson series. All the participants gave their informed consent, following the considerations advocated by Taber.[22]

The lesson series was enacted in 2 days, separated by 1 week. The first part of the lesson series was put into practice in a 1 h class, and parts II−V were enacted in a 4.5 h class. This setup is the minimum amount of time in which the lesson series can be performed with sufficient quality, provided all preparations have been done and all equipment is there. When progressing through the four stages of the LCA, the students completed worksheets as a group. They collaborated in groups of four persons (A, B, C, and D, Table 1) and completed the worksheet of LCA stage 1 together. Next, four expert groups (1, 2, 3, and 4, Table 1) were formed, each consisting of one member of the original groups A, B, C, and D according to the jigsaw method.[23] These four expert groups studied the steps in the life cycle of PLA. Parts IV and V were performed by the original groups A, B, C, and D (stages 3 and 4 of the LCA).

Table 1. Distribution of Students During the Activities[a]

Main Group	Expert Group: 1 (Expt 1a−c)	2 (Expt 2, 3, 4)	3 (Expt 5, 4)	4 (Expt 4, 6)
A	Student 1	Student 2	Student 3	Student 4
B	Student 5	Student 6	Student 7	Student 8
C	Student 9	Student 10	Student 11	Student 12
D	Student 13	Student 14	Student 15	Student 16

[a] The students were grouped and are indicated by A, B, C, and D. The expert groups are indicated by 1, 2, 3, and 4. Stages 1, 3, and 4 of the LCA were performed in the original groups A, B, C, and D. Stage 2 of the LCA was performed in the expert groups 1, 2, 3, and 4. The experiments that each expert group carried out are indicated in brackets.

Assessment of the Lesson Series

At the end of part I, a written pretest was administered to all the students individually. At the end of the lesson series (part V), the students were probed to answer the same questions. The questions of the pre- and post-tests are available in the Supporting Information. For each question, the first and second authors of this paper agreed beforehand on the expected students' notions as a result of attending the lesson series. These expected notions (I−XI) served as a frame of reference to determine the students' level of performance (summarized below and further elaborated in the Supporting Information).

(I) Awareness of three steps in the life cycle
(II) Awareness of leaving out the use phase
(III) Critical view of the data
(IV) Awareness of the complexity of the sustainability issue
(V) Awareness of the four stages of an LCA
(VI) Use of impact categories
(VII) Awareness of experiments as a primary source for data collection
(VIII) Mentioning findings related to the conducted experiments
(IX) Awareness of the need for normalization of the data
(X) Awareness of the purposes of LCA
(XI) Peripheral matters of LCA
(F) From a scientifically point of view incorrect notions

Table 2. Results Data Analysis[a]

Student	Notion																							
	I		II		III		IV		V		VI		VII		VIII		IX		X		XI		F	
	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post
1						■					■	■	■	■		◧			■	◧	■	■		
2	■	■									■	■		■					■	■				
3		■						◧			■	■		■				■		◧	■	◧		
4	■	■										◧				■				■	■	◧	■	
5	■	■				■					■	◧		◧						◧	■	□	■	
6	■	■				■		◧				◧		◧						◧		◧	■	
7		■		□				■				◧		■				◧		◧			■	
8	■	■			■	■		□				■		◧		■			■	◧		◧	■	
9		■						□			■	◧		■					■	◧	■	■		
10		■				■		◧				◧	■			◧			■	◧	■	◧	■	
11	■	■				■		■				■		■		□						◧		
12		■						□				■				◧			■	◧		■		
13						◧		◧				■				■			■	□		■		
14	■										■	■		□					■			□		
15								■				■	■			□				◧	■	◧	■	
16	■	■				◧		■				■	■	◧		□				◧				
■: pre/post	8	12	0	0	1	6	0	4	0	0	6	10	4	6	0	3	0	1	8	2	7	4	7	0
◧: post/interview	0	0	0	0	0	2	0	4	0	0	0	6	0	4	0	3	0	1	0	11	0	7	0	0
□: interview	0	0	0	1	0	0	0	3	0	0	0	0	0	1	0	3	0	0	0	1	0	2	0	0
Total	**8**	**12**	**0**	**1**	**1**	**8**	**0**	**11**	**0**	**0**	**6**	**16**	**4**	**11**	**0**	**9**	**0**	**2**	**8**	**14**	**7**	**13**	**7**	**0**
Δ (pre-post)		4		1		7		11		0		10		7		9		2		6		6		-7

[a] Filled square: notion is expressed in the written answers (pre- and/or post-test). Half-filled square: notion is expressed in both the post-test and the interview. Open square: notion is expressed in the interview.

After the lesson series, 2 weeks after the enactment, a closing group interview was conducted with each of the groups A, B, C and D. The interview protocol is available in the Supporting Information. The interviews lasted for approximately 25 min. The groups were asked to revisit their (individual) answers in the post-test and decide whether they, in retrospect, would like to add or change anything. Next, the students in a group were asked to reflect on the benefits, limitations, and added value of LCA in sustainability issues and feedback on the lesson series. The students also provided feedback on the overall setup of the entire lesson series.

■ OUTCOMES AND FINDINGS

Both the written answers to the pre- and post-test and the statements of the students in the closing interview were scored on the presence of the expected notions. Table 2 reports the individual students' notions in either in the pre- or the post-test. The sources of the notions are represented by different types of squares.

In general, the findings reveal that the lesson series evoked the intended and relevant learning outcomes in students, given the rise in the number of notions from the pre- to the post-test. All the notions, except for V, were mentioned more often in the post-test than in the pretest. In particular, notions III, IV, and VI−VIII were mentioned considerably more frequently. Below, we reflect on a number of trends that are visible in the data and substantiate the trends with students' notions.

The results show the emergence of a critical inquisitive view among the students (notions III and IV). For example, students indicated that they had only looked at the LCA of a biobased plastic and that they would also like to zoom in on an LCA of a fossil-based plastic to make a comparison.

In addition, students indicated that they lacked relevant information, such as the amount of energy needed or pollution created in particular steps. Moreover, the students used the learning outcomes related to the lesson series to substantiate their opinion (which plastic is the most sustainable). Students, among other things, used details from the experiments, indicated which kind of data can be collected to test the overall sustainability of PLA, and/or noted that empirical experiments can be used to collect data (notion codes: VI−VIII).

Notions X and XI were often expressed, meaning that students had gained a view on the purpose(s) of an LCA (notion X) and were aware of peripheral matters that are *not* taken into account (notion XI). As for notion X, in the pretest, students mentioned (1) the harmfulness of the product, (2) what kind of material and how much is used, (3) how bad or good the product is, (4) how it can be improved, and (5) what kind of emissions are produced. In the post-test, the same points were mentioned; however, they were much more elaborated upon and mentioned more often.

As for the peripheral matters (notion XI), the students stated that the making of machines to manufacture PLA has influence on the environment and needs to be taken into account. Also, it was mentioned that energy is necessary to obtain the starting materials and transporting materials.

In the post-test answers, the same arguments reappeared with more emphasis on (1) the number of plastics that are available that have an influence on the recovery of plastics and (2) the difference between the lab scale experiments and the processes in the factories.

However, notions regarding the absence of the use phase in the assessment (notion II), the awareness of the four stages of LCA (notion V), and the normalization of data to enable the comparison (notion IX) were much less often expressed than other notions. No students expressed doubts regarding the lack of information on the use phase. Students showed awareness that the use phase also has an impact, but it was not mentioned that empirical data on the use phase were missing.

The lack of reflection of the content of the four stages of the LCA was remarkable. The second part of the lesson series was designed according to those stages. However, no student felt the need to reflect on or describe these stages in response to questions. We expected that student would mention the broader applicability of LCA in assessing the level of sustainability of other processes and products and show awareness of the number of decision points in performing an LCA. Regarding the normalization of the data (notion IX), although the students worked with normalized data sets of experts, the majority of the students did not express insights into why normalized data sets are needed.

Finally, the results of the pretest showed that a number of students did not fully understand the meaning of concepts such as biodegradable, renewable, and/or energy costs (notion F). For example, it was mentioned that all biological products can always be degraded by nature and therefore be environmentally friendly. In the post-test, these incorrect understandings (from a scientific viewpoint) were not mentioned.

■ LIMITATIONS AND REFLECTIONS

We reported preliminary results of a lesson series tested in a small setting. In general, the lesson series functioned well and according to the expectations. It was observed that the students were able to conduct the experiments. Apart from minor uncertainties and errors, the majority of the students were able to set up and carry out the experiments as intended.

As for the design, at least two aspects need to be reconsidered. First, although the general setup using the jigsaw method functioned well, students expressed the feeling that they had not mastered the complete life cycle of PLA yet. It should be mentioned that the students are not used to working in a setup like Jigsaw. The students reported having limited time or support to share their outcomes with each other. The experiments in the jigsaw method should be followed by enough time for students to share their findings and experiences. Adding a plenary activity with attention to all steps of the life cycle can help students better understand the life cycle. For instance, students could give a short presentation, or if time is limited, the teacher could take on this task. In this way, students might gain a better overview of and insights into the steps of the life cycle that they do not study themselves. Second, in the lesson series, the students were told that the life cycle of a product consists of production, use, and recycling. However, the experiments were focused on production and recycling. These two parts of the life cycle are also mostly considered in the literature. As for the production phase, it might be considered to further emphasize the material extraction, production, and processing, as well as the impact of the agriculture. This may help students develop a more complete picture of the product supply chain. Concept mapping might be a suitable activity to help student pull together all of the aspects of an LCA into a visual display of stages in a plastic's lifetime.

However, the use phase is the part of the life cycle on which students have an influence in their daily life. This part could be emphasized with an additional activity, such as letting students explicitly think about the functional unit in the context of plastics. In this lesson series, students could compare the properties of PLA and high-density polyethylene and focus on their purposes of use. Additionally, we suggest that the students are triggered to think about separation of PLA and HDPE after their use from a consumer perspective.

This lesson series has been designed with the constraints of the secondary school environment in mind. More in-depth chemical explanations of the processes that are done in the experiments could provide opportunities to even better illustrate green chemistry in addition to sustainability. For example, students could focus on liquid−liquid extraction, which often requires high volumes of solvent and requires high temperatures for increased solubility resulting in an increased energy cost and harder disposal of generated solvent waste. Similarly, the filtration/extrusion of polymer following polymerization can lead to hard isolation procedures industrially. The additional processing of the raw PLA polymer into a product is also not assessed within this lesson series. By putting more depth into the chemical explanation, it would be possible to make the lesson series suitable for introductory laboratory classes at the university level. We hope and expect this work will provide a starting point for redesigning the lesson series for use in undergraduate chemistry courses.

CONCLUSIONS AND IMPLICATIONS

The lesson series proved to evoke in students a critical view on the life cycle of plastics. We noticed progress in students' critical view of the data based on the pre- and post-test answers. The students showed that they were aware of the complexity of the issue at hand. They also showed an increasing awareness of lacking information and knowledge, especially regarding missing the LCA data of fossil-based plastics, to compare the two types. Students showed that they were able to describe a number of peripheral matters of LCA. Furthermore, the number of statements moving from the pre- to the post-test was increased. In the post-test, new peripheral matters, which had not been mentioned in the pretest, were also put forward, such as the length of time for which the product had been used. These statements underline the students' deepened insight.

As for the benefits and limitations of the LCA methodology, the students tended to stick to the level of "sustainability of plastics", whereas the lesson series also strived to enrich students' knowledge of the LCA method itself. In essence, the lesson series should give students more opportunities to reflect on the LCA method and/or to apply the method to other processes and products. In addition, more emphasis on the use of normalized data sets and the seven impact categories are expected to support students' notions regarding LCA's benefits further. In addition, the students' answers revealed that the difference between life cycle thinking and assessment could also feature more prominently. In retrospect, in the enactment of the lesson series, more time was spent on life cycle thinking than on assessment. At this stage, the students showed that they were able to engage in life cycle *thinking*, but performing a life cycle *assessment* demands more time and proper instruction. In our opinion, in an educational setting, stages 2 and 3 of the LCA mark the transition from life cycle thinking to assessment. To facilitate the assessment part for this target group of learners, there are tools available, e.g., Sustainable Minds web-based LCA and Idemat, and these can be implemented in an educational setting. Authentic LCA, consisting of four stages, functioned as a source of inspiration and provided a basic backbone for the design of the lesson series. However, more research is needed to integrate LCA further into preuniversity chemistry education, both within the context of plastics and outside it. It would be interesting to see if students are able to look at different LCAs of, for example, different plastics. A good alignment is necessary to ensure that the students get the appropriate information from the then more complex data. It is also interesting to see whether students can also make a translation to other plastics after completing the life cycle from PLA. Can they obtain the same insight from paper?

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00374.

LCA data PLA (XLSX)
Worksheets for students (PDF, DOCX)
Written pre- and posttest (PDF, DOCX)
Teacher manual (PDF, DOCX)
Interview protocol (PDF, DOCX)
Laboratory experiments (PDF, DOCX)

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Notes

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