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Pre-university students' perceptions about the life cycle of bioplastics and fossil-based plastics

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Sustainability has become a prominent theme in society and can be considered as an integral part of scientific citizenship. This study investigates to what extent the production, use and re-use of (bio)plastics initiates students' reasoning and to identify the kind of content knowledge students put forward. The structure of students' arguments was mapped according to Toulmin's model of argumentation, *i.e.*, claim, data, warrant & backing and qualifier & rebuttals. Students (N = 27, grade 10 & 11) participated in groups of three. The students were introduced to the topic of the production, use and re-use of plastics by watching a video, answering questions, reading articles and having interviews and group discussions. Students were prompted to argue on the sustainability of bioplastics and fossil-based plastics. The results show that students frequently used arguments related to preventing pollution, designing to recycle and designing to degrade. However, themes such as avoiding waste, origin of energy and materials, energy efficiency and costs were rarely used or even absent in students' reasoning. Overall, the students' reasoning contained all of Toulmin's categories, and especially the increase in the number of qualifier & rebuttals is interpreted as an indication of awareness of the complexity of the issue at hand. This study underlines that students are able to bring in relevant scientific knowledge when confronted with a suitable sustainability issue, but also more societally oriented arguments enriched their perspective. Implications for the design of interventions aiming to engage students in life cycle analysis (on plastics) are discussed.

Introduction

To achieve a more sustainable future, it is important that the current generations live in such a way that they do not jeopardize opportunities for future generations (United Nations, 1987). Education about and for sustainability is one way to address sustainability issues among students. In the last decades, numerous initiatives for design and incorporation of Education for Sustainable Development (ESD) have been taken. Central concepts in ESD are skills related to validation and justification of claims, argumentation, morality, decision making and the ability to discuss (Sadler and Zeidler, 2005; Juntunen and Aksela, 2013) Future citizens need to develop these skills to help them to make well-considered choices in social debates on sustainable issues (Eilks and Rauch, 2012). Chemistry education takes a central role in teaching future generations on sustainability and to motivate them to act sustainably (Eilks and Rauch, 2012). Therefore, it has been advocated that ESD should be integrated in chemistry curricula (Burmeister *et al.*, 2012). ESD can provide a context for engaging students in (informal) reasoning and argumentation, which are basic skills for scientifically literate future citizens (Burmeister *et al.*, 2012).

In higher education, a relatively large amount of attention goes to ESD, and some well-documented examples are available (Galgano *et al.*, 2012; Ribeiro and MacHado, 2013; Mälkki and Alanne, 2017). The examples show the intention to incorporate sustainability, with relevant scientific knowledge and skills, into curricula. However, in contrast to higher education, current secondary chemistry curricula and chemistry textbooks do not provide sufficient opportunities for students to become engaged in sustainability issues and dilemmas (Eilks, 2015; de Goes *et al.*, 2018). This might be partly due to the fact that (most) sustainability issues are ill defined, with no single, straightforward solution(s) that works always and everywhere, and involves various stakeholders with (sometimes) conflicting ideas. Sustainability issues might be regarded as so-called socio-scientific issues (SSI), which are (also) defined as rather open-ended problems that do not have an one-dimensional (*i.e.*, politics, economics or ethics), clear solution (Sadler, 2011). Several studies have reported that using SSIs as contexts increases students' interest in science learning, creates ethical awareness and prepares students for participation in society (Juntunen and Aksela, 2014), in line with the goals of ESD. However, which sustainability issues are suitable for ESD in

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chemistry education? It is not trivial to develop high quality teaching materials, incorporating innovative pedagogies, that enable students to study complex sustainability issues in which multiple dimensions must be dealt with at the same time (Hofman, 2015). Burmeister and Eilks (2012) have shown that plastics are a suitable topic for ESD in chemistry education. In this study, we investigate to what extent the production, use and re-use of (bio)plastics forms a suitable context to initiate students' life cycle reasoning and to engage them in arguing on a well-known sustainability issue in the domain of chemistry.

Principles of green chemistry and life cycle analysis

For a few decades now, sustainability has been a widely debated concept in multiple levels within society, *i.e.*, politics, industry and science. In 1987, the concept of sustainability was introduced by the Brundtland committee (United Nations, 1987) resulting in an increased demand for guidelines for industry on how to behave in a more sustainable manner. Some example of those guidelines are the well-known twelve principles of green chemistry (Anastas and Warner, 1998) and the twelve principles of green engineering (Anastas and Zimmerman, 2003). Those sets of guidelines strive to minimise the negative effects of processes on the environment. In addition to guidelines for industry, it was acknowledged that the public should participate in the debate on sustainability. It was emphasised that society should be well-informed on science-related social issues, *i.e.*, the public should be scientifically literate and more aware of sustainability.

After the introduction of sustainability and the guidelines for sustainability, there was a demand for tools to quantify the sustainability of a specific process or product. When the concept of sustainability was introduced, there were companies that tried to find methods to, for example, compare different products with each other on environmental impact. Aspects such as energy efficiency, pollution control and waste products were analysed in those comparisons. In the 1990s, scientific influence on such comparisons resulted in normalized methods to analyse the whole life cycle of a product (Guinée *et al.*, 2011), *i.e.*, life cycle assessment (LCA) to evaluate the environmental burden of a product, process or activity. LCA consists of four steps. In step 1, the goal and scope definition are set. In step 2, an inventory analysis of extractions and emissions is done. In this step, the complete picture, *e.g.*, "use of raw materials and energy," "emission of pollutants" and "waste streams" is obtained. Step 3 is focussed on impact assessment, *i.e.*, classification of environmental impacts and an evaluation of which ones are important for the business at hand. Step 4 is an interpretation phase, in which a check is made on the conclusions. In short, LCA is a tool to monitor the flows of materials and energy for the whole life cycle, input and output, in quantitative measures. A life cycle connects all stages of a product system, starting at the production phase (starting material) and the use phase up to the disposal/recycling phase (final disposal) (Heijungs *et al.*, 2010). Other aspects, such as process costs, profit and reaction times can be closely examined with additional tools connected to LCA (Gonzalez and Smith, 2003; Finkbeiner *et al.*, 2006). These tools enable comparison of different processes, based on available quantitative data. In addition to the comparison of different processes, these quantitative data make it possible to identify points for improvement in the process, to make it more sustainable.

LCA on plastics

In chemical research and industry there is much attention for performing LCA on the production, use and re-use of plastics. Studies in which an attempt is made to compare plastics with each other are often based on multiple aspects (Harding *et al.*, 2007; Tabone *et al.*, 2010; Gironi and Piemonte, 2011; Milani *et al.*, 2011). These aspects can be subdivided into three categories, namely criteria related to LCA, physical performance of plastics and cost analysis. Criteria for LCA are, for example, the amount of emissions of certain gasses (CO_2, SO_2, NO_x), the amount of energy needed per kg product and terrestrial or marine aquatic ecotoxicity. For physical performance, criteria such as the density of the plastics, fracture toughness and/or the elastic limit can be taken into account. The cost analysis focusses on retrieving the cost structure of the process and end-products. To compare all those different aspects for multiple plastics the data is often normalized and collected in some sort of decision-making tool (*e.g.* triangle diagram, 3d bar plots or a matrix).

The study of Tabone *et al.* (2010) explicitly applies the principles of green chemistry to study the environmental impact of several

Table 1 Nine themes based on the principles of green chemistry, that can be considered with an LCA (Tabone *et al.*, 2010)

No.	Theme	Content
T1	Avoid waste	High atom economy, keep track of by-products, good mass balance.
T2	Material efficiency	Maximized mass, energy, space and time efficiency (*e.g.*, reactants in desired product, as little energy as possible). Design product that works 100% for the intended purpose. Physical characteristics.
T3	Avoid hazardous materials/ pollution	Safe chemicals, prevent pollution, prevent instead of treatment.
T4	Maximize energy efficiency	Minimizes needed utilities (energy, chemicals, re-use of output).
T5	Use of renewable sources	Use renewables.
T6	Use local sources	Use local material and energy.
T7	Design products for recycle	Products design for separation, minimize material diversity.
T8	Design to degrade	(Bio)degradability of product.
T9	Cost efficiency	Costs as low as possible.

(bio)plastics, as well as conducting an LCA. Tabone *et al.* (2010) combined three sets of principles: 12 Principles of Green Chemistry, 12 Additional Principles of Green Chemistry and 12 Principles of Green Engineering (Anastas and Warner, 1998; Winterton, 2001; Anastas and Zimmerman, 2003). From the three different sets they derived nine themes (or metrics) that could be measured to obtain quantitative data. Table 1 elaborates briefly the nine different themes that were introduced by Tabone *et al.* (2010).

The more starting material that ends up in the desired product, the more sustainable the product is (T1). The more product meets the necessary physical characteristics, the more sustainable the product is (T2). The prevention of the amount of hazardous materials and pollution (T3) is part of the ecotoxicity and human health, *e.g.*, the less hazardous material, the better the ecotoxicity impacts. The use and re-use of all the energy and chemicals (T4) related to a product indicates the effect on the environment, and with it the sustainability of the product. The more the plastic is based on renewable sources (T5), the more sustainable a product is. Another relevant item is the use of local sources (T6); the further away raw materials are extracted, the less sustainable the product becomes due to transportation. The amount of material that is recovered from the product indicates the sustainability of a product (T7). Here too, the higher the percentage, the more sustainable, because less new material is needed. The degradability of a plastic, *i.e.*, nonbiodegradable, biodegradable in artificial conditions or biodegradable in the environment, is an aspect of overall sustainability (T8). The cost of making a plastic (T9) can be a deal breaker, if a more sustainable plastic cannot compete in terms of costs with a less sustainable one. Tabone *et al.* (2010) used the themes for the production phase only, but indicated that for a proper LCA also the use and disposal scenario should be taken into account in which the same themes do play a role. The scientific paper underlines the complexity of the sustainability of plastics (or sustainability issues in general). For example, a bioplastic can score high on the green design principles by using fewer fossil fuels, but on the other hand this same plastic was obtained by growing natural material that had to be fertilized. The impact of fertilizer has some negative effects on the environment as well. From an educational point of view, the work of Tabone *et al.* (2010) is interesting because it adequately points out the themes (content knowledge) that should be considered to draw conclusions on the sustainability of plastics. Also, those themes are based on the 12 principles of green chemistry which are integrated in many chemistry curricula.

Citizens' perceptions about the sustainability of (bio)plastics

There have been a number of studies that have studied citizens' perceptions on biotechnologies and bioplastics (Blesin and Jaspersen, 2017; Lynch *et al.*, 2017; Steenis *et al.*, 2017; Boesen *et al.*, 2019; Dilkes-Hoffman *et al.*, 2019). These researches revealed that citizens from different countries (Australia, Denmark, Germany and the Netherlands) were mostly positive about bioplastics. In general, terms such as biotechnology and biodegradable evoke associations like environmentally friendly, non-toxicity, sustainability, naturalness and green feeling and reduction of waste through composting. However, also associations such as genetic modification, higher prices, improper land use, less visually appealing and short-lived products were found among citizens (Blesin and Jaspersen, 2017; Lynch *et al.*, 2017). These associations link to a number of Tabone's themes,† *e.g.*, material efficiency (T2), hazardous materials (T3), design to degrade (T8) and cost efficiency (T9). Some of the associations cannot be linked to any of Tabone's themes and have to do with socio-economic, ethical and/or ecological aspects.

Compared to conventional plastics, citizens consider bioplastics to have a more positive impact on the environment, although there was some ignorance on the proper disposal of bioplastics, degradation rates, limited biodegradability and the quality of bioplastics (Lynch *et al.*, 2017; Haider *et al.*, 2019). The study of Boesen *et al.* (2019) showed that well-educated young Danish consumers think that bio-based conclusively means that it is also biodegradable. The difference between compostable and biodegradable was not clear. The study of Dilkes-Hoffman *et al.* (2019) revealed that Australian citizens have doubts on whether the biodegradable plastics could have a negative impact on the environment. The work of Steenis *et al.* (2017) showed that LCA outcomes might not always match citizens' perceptions of the sustainability of a product. They questioned Dutch students on their perceptions of sustainability of packaging. The perceptions of these students were compared with an LCA that was performed to determine the sustainability of the different packaging materials the students could choose from. It was concluded that consumer intuitions were in some cases the opposite of the data of the LCA. In multiple research studies, it was observed that consumers perceptions were mainly based on the last phase of a product, namely the disposal phase. In particular, the influence that the consumer himself can have on this phase largely determined their considerations.

In short, the findings show that among citizens (in general) there is a positive view of bioplastics, but that there is also a serious gap in knowledge, *e.g.*, perceptions on sustainability not necessarily based on data from LCA. In addition, it was shown that there is a concern that the prefix 'bio' is used as a marketing strategy because of the positive image (Haider *et al.*, 2019). These finding underline the need for proper education and information about the environmental impact of (bio)-plastics (Blesin and Jaspersen, 2017; Haider *et al.*, 2019). It is interesting to investigate the perceptions of youngsters (age 16–17 years) related to the sustainability of (bio)plastics and the extent to which their perceptions overlap with reported perceptions of the general public. And if we are to organize education on this issue, what are the perceptions to account for, what is

† The term 'Tabone's themes' refers to the nine different themes as identified by Tabone *et al.* (2010) for performing LCA on plastics.

students' prior knowledge base and what are the possibilities to build on this to provide students with a more coherent and complete view on the sustainability of (bio)plastics?

LCA on plastics in secondary chemistry education

Research on the use of LCA in (secondary) education is scarce (Tolppanen *et al.*, 2019). In a recent review article of Mälkki and Alanne (2017), only nine studies were found to examine LCA in education, most of which were carried out in higher, undergraduate education with engineering students. To our knowledge, only Juntunen and Aksela (2013a, 2013b, 2014) conducted three studies investigating the use of LCA in secondary chemistry education, from which only one focusses on plastics. Juntunen and Aksela (2014) describe a project aimed to develop socio-scientific argumentation skills in students. In their project, the students had to choose a product and needed to collect data on the raw materials and the production, usage and recycling phase. This was finalized with a role-playing debate and a final essay in which students had to write down their thoughts on their chosen product's life cycle. The arguments used by the students were categorized in socio-economic (costs or benefits), ethical (opinion related to values, aesthetics or the future), ecological (effect on ecosystems, eco-friendlier products and lifestyle) and scientific arguments (natural resources, technologies, energy, materials and pollution). With the use of LCA of a product combined with debates and essay writing, they found that the quality of the argumentation became more varied after students have attended a rather substantial intervention. The students' reasoning skills on scientific and ecological grounds were fostered. The study of Juntunen and Aksela (2014) shows the potential of engaging students on sustainability issues and provide indications on how to implement LCA (on plastics) in secondary chemistry education. However, it is interesting to gain in-depth insight in the scientific arguments students come up with initially when confronted with LCA on plastics. In addition, they did not elaborate the structure and content of the scientific arguments put forward by students related to the production, use and re-use of (bio)plastics.

Aim and research questions

This study investigates students' reasoning on the life cycle of plastics, inspired by the work of Burmeister and Eilks (2012) and Juntunen and Aksela (2014). Building on the suggestion of Prins, Bulte and Pilot (2018) to use authentic scientific practices as contexts for science education, we used the scientific approach as applied by Tabone *et al.* (2010) as source of inspiration for engaging students in LCA on (bio)plastics. The goal was to gain insight into students' perceptions on the sustainability of (bio)plastics by revealing their arguments and the type of scientific knowledge (themes) they use. The subject of plastics is chosen because (1) students encounter plastics in daily life, (2) plastics are part of many chemistry curricula and (3) the waste management of plastics is a well-known issue in society. Three research questions are addressed:

1. Which knowledge, scientific and other, are used by students in reasoning about the sustainability of plastics?
2. Which components are present in students' reasoning, that is, which claims, backing, rebuttals and qualifiers can be identified?
3. To what extent does the designed student activity make the students aware of the complexity and multi-dimensionality of the sustainability issue at hand?

Method

This study essentially is an explorative study. The collected data is qualitative in nature and focussed on retrieving students' arguments related to the life cycle of bioplastics and fossil-based plastics. Below, we describe the participants, research design, instruments, data collection and data analysis.

Participants

The participants were 27 students from grade 10–11 (age 16–17 years) from several Dutch secondary schools from different areas in the Netherlands. The group consisted of 12 girls and 15 boys. We selected this group of students, because in the Dutch chemistry curriculum, sustainability and polymer chemistry are taught in the 10th and 11th grade. The students came from three educational levels. The students were approached by their own teacher who knew about the research through the network of the researcher. The students volunteered after they were told that the activity was about a sustainability issue and they were aware that the activity had data collection as a purpose. They were told that their opinion and knowledge were of interest and that there were no wrong answers. The study was conducted in compliance with the faculty's ethical standards. All the participants gave their informed consent, following the considerations advocated by Taber (2014). The average score of the students on chemistry was 6,7 on a scale of 1 (low) to 10 (high). The highest score was 8,5 and the lowest score was 5,0. The overall interest of the students in the school subject chemistry was 3,4 on a scale from 1 (low) to 5 (high).

Research design

The students participated in groups of three. They were introduced to the topic of the production, use and re-use of plastics by watching a video, answering questions, reading articles, interviews and group discussions (*i.e.*, all together denoted as the student activity). The set-up of the student activity, including the questions and protocols, was piloted with one group. The student activity was implemented among nine groups (in total 27 students). Data on the kind of arguments put forward by the students were collected at two moments during the student activity in order to see any development in students' reasoning.

Table 2 shows the outline of the student activity with the various components, function and the collected data sources.

Table 2 Outline of the student activity

		Activity component	Function	Collected data sources
A	1	Students watch an introductory video about a Dutch recycling company	Introduction to the subject	—
	2	Students answer a set of questions about production, use and recycling of plastics	Make explicit students' initial stance	Written answers & interview I (Table 3) Measurement I
B	3	Individual reading of 2 national news articles and making a summary of the articles with guiding questions	Confrontation with conflicting aspects related to bio and fossil-based plastics and recycling	—
	4	In a group discussion the students exchange information read in the articles and revise initial stance.	Make explicit students' final stance based on information collected	Discussion, written argument & interview II (Table 3) Measurement II

The student activity can be divided into parts A and B and was carried out in an average of 2 hours. In some cases, there was a week between part A and B. The data collected in part A of the student activity is the first measurement; this measurement consists of the data sources *written answers* and *interview I*. In part B of the student activity, the second measurement is performed with the data sources *written argument* and *interview II*. The measurements are used to investigate the development of the students' argumentation.

In the first part (A) of the student activity, the goal was to investigate the initial thinking, reasoning and opinion on production, use and recycling. The group of students watched a video about a Dutch recycling company as an introduction. In this video, the recycling company showed how they separate the various flows of waste in their factory, with a focus on plastics. To introduce the students to the subject and to activate their prior knowledge about plastics in the context of sustainability, the students individually answered some questions on paper (*written answers*) followed by a semi-structured interview (*interview I*) to collect additional data for clarification and insight on the *written answers* given. The questions were divided into questions about production, use and recycling. This was a deliberate choice to make the students think about all three phases of the life cycle of a product. The students, however, were unaware of the division into production, use and recycling questions. The final question in part A was to take a position on the issue: which plastic, bioplastic or fossil-based, do you think is the most sustainable? The answers to this question and interview I were collected as data for measurement I.

In the second part (B) of the student activity, the goal was to reveal the students' reasoning and content knowledge after they have read and talked about the topic. By using the Jigsaw method, the three students read two different news articles from Dutch national media containing positive and critical point of views related to the production, use and recycling of (bio)plastics. Through answering questions, the students were guided to understand the position of the articles (the questions posed are shown in Appendix 1). Together, the students read six news articles and discussed the content in a group discussion, which was chaired by the researcher. By sharing the (contradictory) information in the news articles, discussions were evoked among the students, which were encouraged by the chair. The answers to the guiding questions (Appendix 1) were used to keep the discussion going. The news articles were selected based on three criteria, namely (1) presence of all nine Tabone's themes, (2) the presence of all three phases of the life cycle and (3) the readability of the article from a student's perspective.

After the group discussion, the students were asked to give their final opinion on the *written argument* on the same issue as in part A: which plastic, bioplastic or fossil-based, do you think is the most sustainable? In semi-*structured interview II*, the students were asked to clarify, if needed, their answers and to get some additional information on missing information and motivation (protocol in Table 3). *Written argument* and *interview II* represent the data collected in measurement II.

Instruments

Table 3 presents all the questions asked for the written answers and the protocol for the semi-structured interview I; these represent the data for measurement I. The questions in the written answers and interview I covered all three phases in the life cycle of a plastic, *i.e.*, production, use and recycling. The material used in the student activity, as well as students' answers were in Dutch. In this paper, all exemplary questions and student responses were translated from Dutch into English. The translation was done by the first author of this paper and checked by an English language specialist, who is bilingual in English and Dutch.

The group discussion was initiated by the chair by first asking the students to clarify, explain and share the information they acquired through reading the articles. Next, the chair posed questions to the group to keep the discussion going, *e.g.*, "Tell the others the important things you have read in your articles," "Read your previous answer on p2, u2 and r2 again and indicate if you would like to change something or add something to your answer." The same procedure was followed for the answer on q2. Also, spontaneous discussions on information and opinions students shared with each other were encouraged. Finally, students individually stated a written argument and the first author conducted an individual interview. Table 3 shows the written arguments as well as the protocol for interview II. The written arguments cover the students' argumentation on the sustainable issue related to bio- and fossil-based plastics. Interview II was used to clarify why the students held or changed their position on this sustainable issue.

Table 3 The questions posed in the written answers and the protocol of Interviews in measurement I and II

	Written answers		Interview I
Measurement I	Production 1 (p1)	What do you know about the production process of a plastic?	*After reading the answers of the students, the researcher asked clarifying questions on the given answers, with specific attention for main questions (last question written answers).*
	Production 2 (P2)	When is production sustainable?	
	Use 1 (u1)	What requirements do you impose on the plastic that you use every day?	
	Use 2 (u2)	What do you think of the compulsory fee we have to pay for a plastic bag in the shops?	What answer did you gave at the q2?
	Recycling 1 (r1)	How would you define recycling and reusing?	– What arguments did you use?
	Recycling 2 (r2)	What do you think of the fact that China has processed our plastic waste for a while?	– On which facts did you base your answer?
			– Which possible doubts and/or questions do you have with your answer?
	All phases 1 (q1)	Write down any questions that came up during the introductory film and the questions:	*Further questions for clarification were asked to obtain additional information.*
	All phases 2 (q2) (main question)	– What plastic do you think is more sustainable? Options are (1) fossil-based plastic, (2) bioplastics or (3) do not know. – What arguments did you use? – On which facts did you base your answer? – Which possible doubts and/or questions do you have with your answer?	

	Written argument	Interview II
Measurement II	1. What plastic do you think is more sustainable? Bioplastic Fossil-based plastic Do not know 2. On which facts did you base your answer? 3. Which possible doubts and/or questions do you have with your choice?	1. Did you change your stance, or do you hold to your previous one? Yes: What information supports your stance? No: What information caused the change of opinion? 2. Did new information caused you to doubt? Yes: What new information has brought you to doubt? 3. If you have any doubts about making a choice, what would you like to know as information to make a more confident choice? 4. Would you be motivated to investigate this in a chemistry lesson?

Data collection and analysis

The data were collected at two measurement points during the study. The first author of this manuscript conducted the semi-structured single-participant interviews (I & II) for both part A and B of the activity with all the 27 participants, which lasted between 5 and 10 minutes, as well as the group discussion that lasted between 30–40 minutes. All the interviews were audio-recorded and transcribed in full. Next, relevant statements were extracted in which students substantiated their choice of a certain plastic.

The first data collection was to capture students' initial reasoning, with the least influence from others (measurement I). Statements in the *written answers* and *interview I* in which students substantiated their choice of the most sustainable plastic were selected by the first author. The total number of relevant statements from interview I and the written answers was 106.

To capture the final, more influenced, reasoning, the second data collection was done from the *written argument*, *group discussion* and *interview II.* The topics plastics and sustainability were discussed throughout the complete group discussion. However, only the parts of the groups discussion in which the students discussed their choice of plastic, substantiated their choice of plastic and/or put forward counter-arguments for not choosing their plastic, have been selected and transcribed. These selections varied from 7 to 20 minutes in total per group. The total number of relevant statements, from the *written argument, interview II*, *group discussion and interview II* was 136.

The data were analysed using a qualitative content analysis strategy (Schreier, 2013). First, a coding scheme was developed containing (1) the Tabone's themes as elaborated in the theoretical background (Table 1), (2) the categories of an adapted version of the argumentation model of Toulmin (2003) and (3) the phases in the cycle, *i.e.*, production, use and recycling. Second, six additional non-Tabone themes were added to the original nine Tabone's themes. Third, the quotes were coded on three different levels, namely the appropriate theme, Toulmin's category and appropriate phase in the life cycle.

Tabone. First, the statements were analysed using Tabone's themes for the content of the arguments of the students (RQ1). During the process of coding according to the Tabone's themes, we employed a deductive and inductive approach, *i.e.*, we maintained an open view to identify any new content related themes that might emerge from the data. We regarded a new theme as substantial if it was mentioned several times by different students. The theme was added to the coding scheme if the new theme was mentioned in at least 10% of all the non-Tabone statements. Next, all quotes with the same code were counted, merged and summarized in descriptive statements. In a last step, all codes were checked against the adapted coding scheme to ensure all data fit the coding scheme.

Toulmin. Second, the data were analysed using an adapted version of Toulmin's model (Toulmin, 2003) for the formulation of the arguments (RQ2). Based on the pilot of the student activity, we adapted the model for the present study. The categories warrant and the backing were combined, as well as the qualifier and the rebuttal. The collected data in the pilot presented difficulties in distinguishing the warrants from the backings and the rebuttals from the qualifiers. The students produced their arguments over a short period of time; therefore, the data were not sophisticated enough to analyse in much detail. In addition, it was observed that the students also asked questions to underpin their arguments. Ultimately, it was decided to see these questions as part of their argumentation. The students realised that the questions they put forward were somehow connected to their choice, and had they known the answers to their questions, they would probably have used them in their argument. In Fig. 1, our adapted version of the argumentation model is presented.

Claim	Answer to the question: which plastic do you think is more sustainable
Data	Empirical data Personal experiences Generally accepted knowledge
Backing & warrant	Link between the data and the claim Logic to convince that the claim is true Referring to an authority (science, politics, media)
Qualifier & rebuttal	Conditions under which the claim holds Critical view/statement against the claim Statements of doubt against the given claim
Missing information	Information/data that students indicate that they lack to provide a well-founded answer Questions where they may need the knowledge to provide more data/warrant & backing

Fig. 1 An adapted version of Toulmin's argumentation model (Toulmin, 2003).

Table 4 Examples of the coding with Tabone's themes, Toulmin's categories and the three phases of the life cycle. The student quotes have been translated from Dutch

	Student quotes	Tabone's themes	Toulmin's categories	Phase
1.	Fossil-based plastics last longer and can be reused better, they stay in the 'use' phase longer [description of own experience]	T2	Data	Use & recycling
2.	Whether the production [of bioplastics] creates much less CO_2 emission and is less environmentally polluting.	T3	Missing information	Production
3.	Fossil-based costs a lot of energy because of the drilling	T4	Backing & warrant	Production
4.	Fossil raw materials can run out	T5	Data	Production
5.	And the transport of all raw materials is also very important	T6	Qualifier & rebuttal	Production
6.	I think it is better if there are fewer types of plastics, so that it can be sorted more easily. This way more can be recycled.	T7	Qualifier & rebuttal	Recycling
7.	Are the bioplastics easily degradable in nature?	T8	Missing information	Recycling
8.	How expensive are bioplastics?	T9	Missing information	Not phase related
9.	This is actually under one condition. There must be campaigns from the government or non-profit organizations that make people more aware of what biological plastic means (claim: bioplastic)	NT10e behaviour society	Qualifier & rebuttal	Not phase related
10.	I just believe that [fossil-based] plastic does its job very well	NT11	Backing & warrant	Not phase related

Phase of the life cycle. Third, all students' statements (in total 242) were categorized into one or more phases, *i.e.*, production, use and/or recycling (RQ3). Statements related to raw materials (transport, growth process) and specific references to the production process were assigned to the production phase. The moment students discussed functions, chemical structures, use or quality of plastics, it was coded as a statement in the use phase. Discussion of the circumstances that plastic breaks down (in nature), or specific issues concerning recycling, separating waste and the behaviour of people with the waste, were all coded as the recycling phase. When elements from multiple phases were discussed, that statement was assigned to more than one phase. Typical terms such as cycle and ecological footprint were seen as a statement that discussed all phases. When it was not clear which phase the student was talking about, it was coded as *not phase related*. This included matters such as research into plastics, biologically as a misleading term, general remarks about advantages and disadvantages.

In Table 4, some examples of the coding of the statements are presented. The inter coder agreement was tested by calculating the percentage of statements coded equally by two researchers (first and second author of this paper). The first author selected eleven statements for each group, five from measurement I (from written answers and interview I) and six from measurement II (from written argument, group discussion and interview II). In total, 99 statements were coded independently by two researchers. This is 41% of the total data set. The inter coder agreement for Tabone's themes was 80% and 74% for Toulmin's categories.‡ Taken together, the inter coder agreement was 78%. In literature, 70 percent is regarded as the lower limit for a sufficient level of agreement, and 80 percent for a substantial level (Miles and Huberman, 1984). In the present case, we regarded 78% as a sufficient level of agreement, taking into account that the Tabone's themes are rather broadly formulated and do show overlap. We also analysed the statements coded as 'non-Tabone' in more detail to reveal new themes that emerged from the data. Five new themes were identified which were labelled as (1) direct comparison of bio vs fossil (NT10a), (2) bio as misleading term (NT10b), (3) agricultural land (NT10c), (4) pros and cons (NT10d3) and (5) behaviour society (NT10e). Any remaining statements were coded as miscellaneous (NT11). Next, the complete research team discussed the results to identify major trends and findings.

‡ The term 'Toulmin's categories' refers to the categories in the adapted version of Toulmin's argumentation model (Toulmin, 2003) as portrayed in Fig. 1.

Results

Table 5 presents the number of groups mentioning the different Tabone's themes in their collective arguments. The results of measurement I and II are presented separately from each other. The total number of statements that include the different Tabone's themes are summarized in the last two columns. In the first row of Table 5, Toulmin's categories are presented (except the claim). Two bottom rows show (1) the total number of data, backing & warrants, qualifier & rebuttals and missing information and (2) the total number of groups that use the different Toulmin's categories.

Content knowledge in students' argumentations (RQ1)

Apart from the nine predefined Tabone's themes, five new themes were identified. Category NT10a, *comparison*, concerns correctness and completeness of the data about the different phases of both bioplastics and fossil-based plastics in order to make a proper comparison. NT10b, *prefix 'bio'*, is focussed on the misleading image of the prefix bio. NT10c, *agricultural*, concerns the production of organic raw materials and the use of agricultural land. The theme NT10d, *pros and cons*, is used for arguments concerning the prioritizing and valuing of advantages and disadvantages of both plastics. Finally, in NT10e, *society*, relates to the behaviour of humans that matters for the sustainability of a product. Statements that did not fit in any of the aforementioned five new themes, nor in the nine

Table 5 Total number of codes in measurement I and II for both Tabone's themes (vertical) and Toulmin's categories (horizontal)

			Toulmin's categories									
			Data		Backing & warrant		Qualifier & rebuttal		Missing information		Total	
Tabone's themes		Number of groups	I	II	I	II	I	II	I	II	I	II
T1	Waste	0/9	0	0	0	0	0	0	0	0	0	0
T2	Efficiency	9/9	3	1	5	5	0	0	3	3	11	9
T3	Pollution	8/9	6	10	5	5	0	1	3	5	14	21
T4	Energy	3/9	0	0	1	0	0	1	1	1	2	2
T5	Renewable	8/9	19	10	2	3	0	2	2	1	23	16
T6	Local sources	1/9	0	0	0	0	0	1	0	0	0	1
T7	Design recycle	8/9	0	0	4	7	0	10	4	6	8	23
T8	Design degrade	9/9	0	0	9	9	0	3	3	6	12	18
T9	Costs	4/9	0	0	1	5	0	1	0	1	1	7
NT10a	Comparison	8/9	0	0	5	3	0	1	7	5	12	9
NT10b	Prefix 'bio'	7/9	0	0	10	5	1	3	0	0	11	8
NT10c	Agricultural	4/9	1	0	0	2	0	2	4	0	5	4
NT10d	Pros & cons	5/9	0	0	0	7	0	1	0	0	0	8
NT10e	Society	6/9	0	0	2	3	0	5	1	0	3	8
NT11	Miscellaneous	4/9	1	0	2	2	0	0	1	0	4	2
		Total	30	21	46	56	1	31	29	28	106	136
		Number of groups	9/9	9/9	9/9	9/9	1/9	8/9	9/9	9/9		

predefined Tabone's themes, were coded as miscellaneous (NT11).

The total number of statements that were coded as a non-Tabone subcategory were 35 and 39 for measurement I and II respectively. Below, we elaborate on the two most often mentioned themes NT10a and NT10b, in which the students discuss (1) the comparison between fossil-based plastics and bioplastics and (2) the influence of the prefix bio. In the NT10a category, questions were raised about the ecological footprint of both plastics. In most cases, students did not compare the complete cycle of bio- and fossil-based plastics, but zoomed in on a single step or instance in the cycle for which they lacked information. For example, students claim that the impact on the environment is comparable both for the production and the recycling of bioplastics and fossil-based plastics and stress the need for more information regarding the use phase and its impact on nature. As for NT10b, students admit that they think that bioplastics are the most sustainable due to the stereotype 'bio is environmentally friendly'. Students mention that media and social media play a role in this, because most of the time the fossil-based products/materials are portrayed poorly and the biological products/processes are portrayed as good. Students themselves, at some point, raised the question whether it is misleading to use the prefix bio, as typified by the following statement:

'It is better for the environment, but the word is misleading.' – student 16 written argument

Considering the original Tabone's themes, it can be concluded that T2, 3, 5, 7 and 8 were the most frequently mentioned by the majority of the groups (8 or 9). These categories describe matters related to efficiency (materials), pollution (*e.g.*, CO_2, greenhouse effect) and design of products with the possibility of recycling or (bio)degradability. In contrast, T1, 4, 6 and 9 were mentioned the least, respectively by 0, 3, 1 and 4 groups. The latter themes include matters related to avoiding waste, energy efficiency, the origin of energy and materials, and costs. Statements related to costs were predominantly mentioned in measurement II.

Below, we portray the four frequently used Tabone's themes in more detail and give some descriptive examples of students' arguments. Quotes related to T3 are mainly focussed on CO_2 emission. The fossil-based plastics are responsible, according to the students, for the emission of CO_2 into the atmosphere, and contribute to the greenhouse effect. In addition, some students wonder what kind of substances are actually emitted apart from CO_2. In general, many students just state that fossil-based plastics are the most polluting for the environment, or *vice versa*, that bioplastics are the least polluting, without further substantiation. In the T5 category, the students mentioned that fossil resources are running out, evoking a need for alternatives for fossil-based plastics. A frequently mentioned argument is that society needs to become more efficient in the use of fossil raw materials and/or alternatives are needed. Other statements in the theme are focussed on the biological raw materials and the fact that they are renewable. As for theme T7, what becomes evident from the students' arguments is that they perceive that the recycling process of bio-organic materials is easier. Students often posed questions related to the recyclability of fossil-based plastics. Notably, students made connection between T2 and T7, *e.g.*, they argued that since fossil-based plastics are much stronger (T2) it is much harder to break them down and to recycle them, as typified by the statement below:

'I may be completely wrong, but fossil-based products are generally stronger than bio-based products, which makes them less likely to break down and less easily to recycle' – student 25 Interview I

During measurement II, students indicated the complexity of the recycling process, based on one article that described the difficulties encountered by recycling companies dealing with many different types of plastics. They started to question the recycling of both fossil-based plastics and bioplastics and indicated that the choice of the most sustainable plastic does depend on how easily a plastic can be recycled. Students expressed a need for more information/data for this aspect. Related to T8, many students argued that bioplastics are easily absorbed and digested by nature. For those last two discussed categories (T7 and T8), it was observed that some students faced difficulties distinguishing between recycling and degradation. In most cases, it was possible to separate the statement into two statements. An example is given below, in which the student discussed T8 in the first part of the statement and T7 in the last part.

'Bioplastics are biodegradable, so if you leave them behind [in nature] it just goes away and that is not the case with fossil-based plastics, so that is more recyclable.' – student 26 interview I

Comparing measurement, I to II, the results show an increase in students arguments related to recycling (from 8 to 23) and pollution (from 14 to 21). A possible reason for this increase might be that four articles zoom in on the concept of recycling and that pollution was a recurring theme in the group discussions.

Toulminian components in students' argumentations (RQ2)

Table 5 column 3 onwards shows the Toulmin's categories present in students' argumentations to substantiate their claim(s). It can be concluded that all the Toulmin's categories occurred in the students' argumentation for both measurement I and measurement II. For eight groups, the 4 different Toulmin's categories could be assigned to the statements. Only one group did not mention any qualifier and/or rebuttals. This finding is interpreted as an indication that this specific sustainability issue is suitable for students to argue about. The number of Toulmin's categories remained more or less at the same level between measurement I & II (see column Total). However, the number of qualifier & rebuttals increased remarkedly from measurement I to II (from 1 to 31). This finding is interpreted as an indication that students started to think more critically about their claim. In addition, students mainly use Tabone's themes T3 and T5 as 'data' and aspects of T8 mainly as 'backing & warrant'. Tabone's theme T7 is used many times as 'qualifier & rebuttals' and T8 and T9 are mentioned mainly by students as 'missing information'. Finally, students use the non-Tabone themes (NT10 and NT11) in all categories except for the 'data'.

The development of students' awareness (RQ3)

To answer the third research question ('To what extent does the designed student activity makes the students aware of the complexity and multi-dimensionality of the sustainability issue at hand?'), we analysed whether students were able to reason about all three phases in the life cycle of a plastic and monitored students' claim development.

Phases of life cycle present in students' argumentation. It was observed that all three phases are considered by students in their argumentation. However, the phases production and recycling were mentioned more often than the use phase. Some of the statements by the students covered multiple phases of the life cycle. In total, seven groups were able to discuss all three phases in their collective argumentation; the other two groups did not reflect on the use phase.

Some statements could not be assigned to any of the phases, since it was (1) unclear what phase(s) the students were talking about and/or (2) the statements reflected the image of society about the sustainability of plastics influenced by the media or campaigns. In these cases, the focus is on peripheral matters that do play a role in a sustainable issue.

Claim development. In Fig. 2, the development of the claims is presented. It can be observed that there is a shift in claims during the student activity. In measurement I, most students believed that a bioplastic would be the most sustainable, one student indicated that it was uncertain and stated *do not know*, and two students claimed that the fossil-based plastic would be the most sustainable.

In measurement II, nine students altered their claim about the most sustainable plastic. Those nine students came from five different groups. Two groups completely changed their claim. In one of those groups, all three students claimed *bioplastic* in measurement I; after the student activity all students changed their claim to *do not know*. In the other group, two students claimed *bioplastic* and one student *do not know*. After the student activity, they changed their claim to *fossil-based* and bioplastic respectively. Three students from three different groups changed their claim from *bioplastic* to *do not know*. Two of them came from a group that chose only *bioplastic* and one of them came from a group in which one of the other students chose *fossil-based* and the third student chose *bioplastic*.

So, after the student activity, a shift in the distribution of the claims was seen. Several students indicated that they strongly doubted their earlier claim, resulting in changing their claim to *do not know*. The students that changed their claim to *do not know* expressed their doubts by mentioning the information they read in the articles or what they heard from the other students during the group discussion (*e.g.*, difficulties in the degradation process of bioplastics, the use of agricultural land and the competition with food, and the influence of the behaviour/knowledge of society). The students also made statements about the advantages and disadvantages for both types of plastics, however, this was limited by the students indicating that they missed information. According to the students

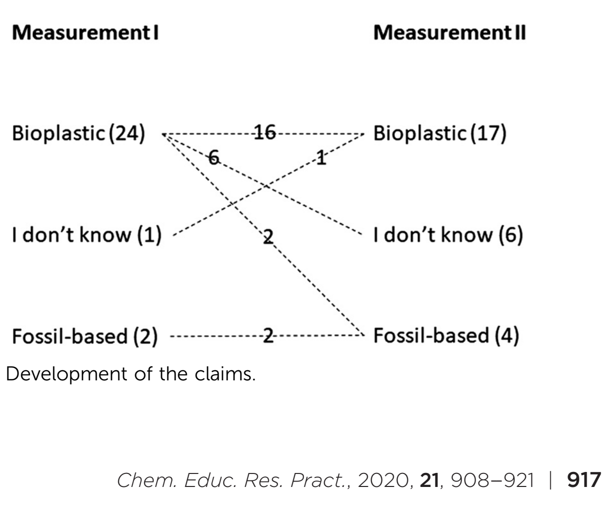

Fig. 2 Development of the claims.

themselves, they could not make a proper comparison, resulting in becoming indecisive about the most sustainable plastic.

Two students changed their claim from *bioplastic* to *fossil-based* plastic. For these students, who came from the same group, the argument was mainly that if we as society were to use a single type of plastic, we as society would have less problems in the recycling process. One of the two students who hold the claim *fossil-based* plastic also explained that there is no problem with the use of the strong fossil-based plastics, but we have to handle them more neatly and recycle 100%. There was also a student who changed the claim from *do not know* to *bioplastics*. For this student, the fact that bioplastics are produced from a material that is an inexhaustible source was a valid and important argument to be sure about their choice for bioplastics as the most sustainable.

In total, sixteen students stuck to their claim that *bioplastic* is the most sustainable plastic. However, ten of these students expressed (small) doubts or said that they felt more uncertain about their claim because of the student activity. Their doubts were in some cases phrased as a qualifier and rebuttal, but despite their doubts they kept their claim (*bioplastics*) because the advantages outweigh the disadvantages. These ten students came from five of the nine groups. The other six students that held their claim on *bioplastics* indicated that they were more certain or said that they had no doubt after the student activity. These students came from five different groups.

Discussion and conclusion

This study investigated to what extent the production, use and re-use of (bio)plastics forms a suitable topic to initiate students' reasoning and to engage them in arguing on a well-known sustainability issue in the domain of chemistry. We posed three research questions, namely 'Which knowledge, scientific and other, are used by students in reasoning about the sustainability of plastics?', 'Which components are present in students' reasoning, that is, which claims, backing, rebuttals and qualifiers can be identified?' and 'To what extent does the designed student activity makes the students aware of the complexity and multi-dimensionality of the sustainability issue at hand?'.

The focus of the first question was mainly on the use of the 12 principles of green chemistry as embodied in the Tabone's themes. The results of our research have shown that a number of Tabone's themes are not spontaneously used in the reasoning of the students (T1, 4, 6 and 9), and some of the themes are mentioned regularly (T2, 3, 5, 7 and 8). This indicates that T2, 3, 5, 7 and 8 are part of students' prior knowledge. However, T1, 4, 6 and 9 require more attention to familiarize the students so that these themes also become part of their knowledge and reasoning. In addition to the predefined Tabone's themes, we identified a number of additional themes in the statements of the students. These statements, overall, portrayed a more general approach or had to do with society related matters. These non-Tabone themes were mentioned in measurement I as well as II, so these non-Tabone themes are part of students' prior knowledge. We regard students' comments regarding the misleading image of the prefix 'bio' as remarkable. In our opinion, this testifies to a critical view of the term that is frequently used for many products. The mentioned non-Tabone themes by students do comply to large extent with the ethical and ecological categories as defined by Juntunen and Aksela (2014). The non-Tabone themes NT10a and NT10e fall within the ecological category, whereas the themes NT10b, NT10c and NT10d relate to the ethical category. Our study supports the findings of Juntunen and Aksela (2014) that students' arguments cover multiple dimensions next to a pure scientific one. Our study gives insight into the content of the scientific, ethical and ecological arguments put forward by students. In addition, our study shows some similarities between the perceptions of the citizens (the elderly) surveyed and youngsters in secondary school. Studies into citizens' perceptions of bioplastics have shown that the image of bioplastic is generally positive and generates positive associations, such as more environmentally friendly and more sustainable. From the literature, it is known that T2, 3, 8 and 9 occurred in the argumentation of the citizens. In our study, T2, 3 and 8 were also part of the most-mentioned themes in the students' argumentation. Also, ignorance and more negative aspects found in citizens, such as land use and more short-lived products, were broadly in line with the perceptions found in students. In short, the results in this study indicate which content knowledge students bring in when confronted with the sustainability issues regarding plastics, as well as which content knowledge is absent or hardly used by students using Tabone's themes as frame of reference. This information is of valuable use when designing education in which students are engaged in LCA on plastics. It reveals the prior content knowledge of students to build on and elaborate and clearly shows content knowledge to account for.

The second question was focussed on the structure of students' arguments, *i.e.*, are the students able to provide a well-founded argument with enough support for their statement? In general, the arguments of the students appeared to be fairly complete. All of the Toulmin's categories could be assigned multiple times. The students proved able to discuss this subject at a fairly complete level. The adapted Toulmin's model proved appropriate to analyse the (at this stage) still rudimentary students' argumentation. The students did not have not much time to think about their claim in this relatively short student activity. In addition, the students were not trained in giving a complete argument on LCA of plastics. This adaptation follows some critics in literature on Toulmin's model claiming that it is difficult to distinguish the different categories (Erduran *et al.*, 2004). Also, the context in which the student express their argumentation matters (Kelly *et al.*, 2007). The addition of the category *missing information* made it possible to include the questions of the students in their arguments, related to the context of production, use and re-use of plastics. We regarded the lack of knowledge as expressed by students as a valuable component of student argumentation. Most of the Tabone's themes were found in the Toulmin's categories warrant & backing, missing information and qualifier & rebuttals. Only a few of the Tabone's themes were assigned to data (T3 and T5). This, however, could be a consequence of our rather strict definition of Toulmin's category *data*, *i.e.*, empirical data, experience and/or generally accepted knowledge. It is possible that a number of students' statements did not fit this definition of category *data* and ended up in other categories.

Regarding research question 1 and 2, in this study we did not analyse the quality of students' arguments and focussed only on the structural components in their arguments. This complies with the goal of this study, as we were interested in the kind of argumentations students put forward initially, including the content knowledge they use. Examples of (partially) incorrect statements are, for example, claims that bioplastics are easier to degrade by nature, easier to recycle, that bioplastics are easier to produce and/or that bioplastics thrown in nature will soon disappear. These statements surely require more substantiation and more scientific underpinning. However, these kinds of (partly) incorrect or less underpinned statements will also pop up during chemistry classes and thus offer opportunities to use as starting point for discussion with students. However, if students come up with more sophisticated arguments, other models for analysis of arguments are needed.

The third research question was focussed on the awareness of the students of the complexity and the multi-dimensionality of the sustainability issue. It was observed that the students were able to reason on this sustainable issue. All phases of the life cycle were present in the students' argumentation. From this, it can be concluded that the student activity was successful in guiding students to reflect on all phases of the life cycle. In our opinion, this is a remarkable finding because earlier studies have revealed that the last recycling phase in particular is considered when thinking about life cycles (Steenis *et al.*, 2017; Boesen *et al.*, 2019; Dilkes-Hoffman *et al.*, 2019). During the student activity, the students discovered that the easy-looking question was more complex than they initially thought. Doubts were raised during the student activity, as identified by the increasing number of qualifier & rebuttals. In literature, the increase of rebuttals is regarded as an indication of an increasing and deepening level of reasoning (Erduran *et al.*, 2004). The shift in claims during the student activity shows that the students start to think more critically about their claim, particularly evidenced by the increase in the number of claims *do not know* from measurement I to II. Apparently, some students are unable to make a good choice between the bioplastics on the one hand and the fossil-based plastics on the other. The expressed doubts, to a lesser extent, were also visible in the statements of the students who nevertheless maintained their claim.

This explorative study provides indications and guidelines for the design of an intervention aimed at fully engaging students in LCA on plastics. The students' arguments, in general, are rich with aspects both falling within the Tabone's themes (scientific arguments) and outside the Tabone's themes (socio-cultural arguments). The students showed to be able to reflect critically on their claim, and some adjusted their claim based on other arguments or opinions brought in. These findings show that the students are sensible to the complexity of the issue of sustainable plastics and underline the suitability of this context for reasoning about sustainability. Previous studies have revealed that students, in general, have a tendency to make their claims without adequate justifications and put forward primarily socio-cultural arguments as they touch upon their own opinion and world as experienced (Juntunen and Aksela, 2014). In addition, Osborne *et al.* (2004) claims that students need time to search for information or learn the topic first in order to bring in scientific arguments. The results in our study, however, show that students are using scientific arguments in their argumentations relatively short after introduction of the sustainability topic. In our opinion, this is an indication that the student activity was well designed and functioned adequately. The essence of the student activity was the comparison of two plastics on sustainability. Comparing two arguments helps students to realise the importance of justifying their claims (Simon, 2008). The student activity presented and tested in this study seems to be suitable to use as an introduction in a larger curriculum unit on sustainability issues related to plastics.

Although the results are based on a relatively small test group, the findings provide relevant input for design of interventions focussed on engaging students in LCA on plastics. In this respect, it is needed to account for the Tabone's themes (T2, 3, 5, 7 and 8) which might be regarded part of students' prior knowledge as well as under-represented Tabone's themes in students' argumentations (T1, 4, 6 and 9). To bring the Tabone's themes into focus, both theoretical and practical (lab)work might be considered. For example, calculating the amount of waste produced during the practical assignments might contribute to the meaning of the production of waste (T1), including the impact it has on the sustainability of a product. In addition, doing practical (lab)work also offers opportunities to make students aware of the efficiency of utilities (T4), *e.g.*, students can research the origin of the raw materials. While the Tabone's themes mainly offer a scientific perspective on sustainability issues related to plastics, the non-Tabone themes mentioned by students give input for organizing class discussion about the broader socio-cultural aspects.

Generally in ESD, students tend to exclude scientific knowledge from their personal knowledge (Sadler, 2004). This study indicates that students are able to bring in relevant scientific knowledge when confronted with a suitable SSI context. However, there is still a need for creating science education that fosters students' content knowledge in performing LCA. Future studies should aim to find effective means to incorporate LCA in chemistry education. It is worthwhile that students, as future citizens, are aware of and practice skills that come with performing LCA on products and processes. Having well-documented examples, as well as more understanding of the effectiveness of teaching approaches on conducting LCA in chemistry education, is crucial for improving ESD in 21th century chemistry classrooms and for making society more sustainable.

Conflicts of interest

There are no conflicts to declare.

Appendix 1

The following questions were asked to help the students obtain the important information from the articles and to summarize the content. The answers were collected but not used for further analysis. The students were allowed to have these questions and answers in the group discussion. This is part B3 from the student activity (Table 2).

Guiding question for reading articles

1. From which two perspectives have you read the two articles (positive or negative point of view)?
2. What is the central claim of each of the two articles?
3. What do the two articles agree on?
4. What do the two articles disagree on?
5. For each article, write down the most important arguments according to you.
6. Which article matches best with your own opinion? What does this say about your position?
7. Do you think the organizations that give the information in the article are reliable sources?

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