

Into the cycle of sustainability

*Fostering students' life cycle reasoning
in secondary chemistry education*

Esther Francisca de Waard

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Freudenthal Institute



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A tree has been planted for every copy of this thesis.

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Into the cycle of sustainability

Fostering students' life cycle reasoning
in secondary chemistry education

In de cyclus van duurzaamheid

Bevorderen van het levenscyclusredeneren van leerlingen
in het secundair scheikundeonderwijs

(met een samenvatting in het Nederlands)

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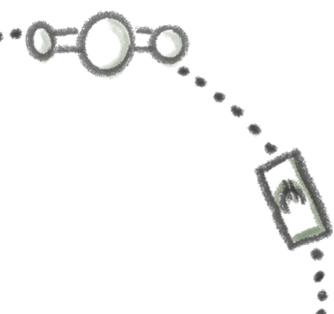
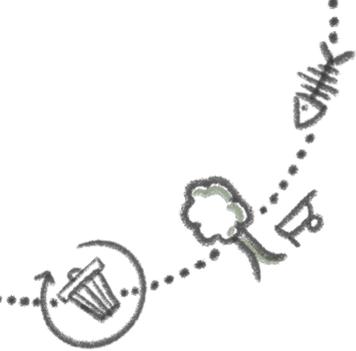
About the artwork

The cover design of this book creatively embodies the essence of the thesis through a "lab journal" style, a familiar format for Chemistry students accustomed to the rhythm of the laboratory. The interlinked spheres represent the stages of the Toulmin argumentation model, symbolizing the fluid progression of the argumentation of the students in their sustainability issue: 'which plastic is the most sustainable? A bio-based plastic or a fossil-based plastic. On the face of it an easy question, but with a complex answer. At first, there is a very distinctive separation of the green bio-based and grey fossil-based plastic, but during the process the doubt of the students becomes apparent.

Simultaneously, these interconnected forms abstractly resemble the chemical structure of a polymer, echoing the chained carbon atoms in the PLA versus PET polymers the students analyzed.

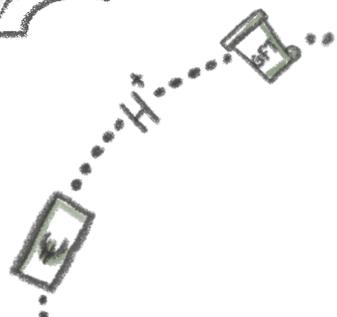
At the core of the students' work lies the Earth, symbolizing the central theme around which their arguments, warrants, backing, qualifiers and rebuttals orbit. This focus on planetary care not only unifies the design but also completes the narrative cycle, emphasizing the thesis's central message.

Further enhancing the theme of this thesis, the book has been designed and printed with a strong commitment to sustainability. On the one hand, the design was painted with non-toxic and eco-friendly materials, handmade by artist & sustainability researcher Elma Hogeboom. On the other hand, it adheres to the highest current standards, minimizing plastic use and incorporating grass-based and recycled papers, thereby closing the loop on environmental responsibility.





CHAPTER ONE
General introduction



General introduction

Every day we (un)consciously make decisions concerning sustainability issues. This can range from the choice to take the bicycle instead of the car, to eat vegetarian instead of meat, or the choice to bring your own mug from home instead of using a disposable cup. All kinds of aspects play a role in the decisions we make, for example, expenses, conveniences, and personal needs. Sometimes, we are not even aware that the choices we make relate to sustainability. However, as our decisions are increasingly influenced by considerations related to sustainability. Even seemingly simple questions may become very difficult. In my vision as a chemistry teacher, I experience responsibility to contribute by helping my students cope with such decisions by providing them with a perspective of the whole picture involved in life choices. This thesis delves into this issue: how can we support students in secondary chemistry education to reason from the chemistry perspective when making decisions related to sustainability?

1.1 Background

Sustainability

Sustainability has played an increasingly important role in recent years, due to the depletion of natural resources, global warming and the large amount of waste that is produced by the humanity. There is an increasing awareness that the (linear) way in which human society is progressing may cause problems for future generations (Harris & Briscoe-Andrews, 2008), also due to the growing world population and level of prosperity. These concerns have led to widely debated issues in multiple levels of the society, e.g., politics, industry, and science. In response to these developments, different movements arose that aim to balance the qualities of life and the environment. One of those movements is sustainable development, illustrated by the well-known definition given by the Brundtland committee (United Nations) that is mentioned in many articles and (school) textbooks.

‘Sustainable development is development that meets the needs of the present without comprising the ability of future generations to meet their own needs’ (United Nations, 1987)

Thinking in terms of sustainability requires a fundamental rethinking of the flow of resources in order to manufacture consumer products, with implications for, among others, the domains of economics, physics, and chemistry. However, the



concept of sustainability remains abstract, while it is necessary to have clearer and to-the-point guidelines to make explicit how one could live, design, produce and act sustainably. Different design philosophies emerged for the industry, e.g. The Natural Step, Biomimicry, Getting to Zero Waste, Ecological Design, Green Chemistry and Cradle-to-Cradle (García-Serna et al., 2007). All these philosophies gave science and society guidelines to act sustainably.

All actors in society, including government, industry and the public need to be well-informed on issues regarding science-related social issues, including sustainability. Especially the public needs to be literate on these issues. The industry of course has the largest footprint and the government the greatest decisiveness, however, the number of people who will be categorised as 'the public' is insanely large. In addition, the public decides who sits in the government, and they should therefore be able to make good choices so that this is reflected in the elected government. Therefore the public should be able to make well-considered choices and social debates on sustainable issues (Eilks & Rauch, 2012). And ultimately the fact remains that every little bit helps. There is no better place to educate the public than teaching sustainability to youngsters and use education as an instrument to engage the public in thinking about sustainability issues.

Science education is not intended solely as preparation for a scientific or technical career, but also to enable general understanding of science and think about scientific questions that arise from everyday experiences. Citizens should be able to search for information, discuss the obtained information, form opinions, and make considered and well-informed decisions about science-related social issues. Eventually, not only the knowledge and the ability of decision making and reasoning is important, but it is also important that citizens show behaviour that fits their knowledge. Education can form the basis in terms of, among others, knowledge and critical thinking, that youngsters can utilize with respect to sustainability issues they will come across in their lives. Besides, it also allows them in their turn to openly discuss these topics with their parents and other generations. They will be able to challenge their peers and elders in discussions and it will lift their voice.

Education for Sustainable Development

In the last decades numerous initiatives for design and incorporation of Education for Sustainable Development (ESD) have been taken. For example, the United Nations devoted a complete decade (2005-2014) to promote sustainable development in

education (UNESCO, 2014). The goal of the UN decade of ESD was to integrate principles, values, and practices of sustainable development in all aspects of education and learning; to activate people to reorient education globally in order to learn, live, and work sustainably; and to create and stimulate changes in behaviour of educators and students that create a more sustainable future, environmentally, economically, and socially, for generations to come. It stimulated in many countries pedagogical innovations and education policy, e.g., curriculum changes, in order to promote learning on sustainable development (UNESCO, 2014). And still the UN stimulates this by the Education for Sustainable Development Goals, one of which focusses on quality of education (UNESCO, 2017).

ESD serves as a bridge between science, industry, and society, which all together have an obligation to contribute to a sustainable future. A variety of skills is considered important for the future generations to have. Examples are skills related to validation and justification of claims, argumentation, morality, decision making, and the ability to discuss (Juntunen & Aksela, 2013a, 2013b; Sadler & Zeidler, 2005). It has been advocated to stimulate the integration of ESD in the chemistry curricula because it can have an important role to help future citizens to develop the above-mentioned skills (Burmeister & Eilks, 2012). It can help students to learn about sustainability but also to motivate them to act sustainably (Eilks & Rauch, 2012). Education is regarded as critical in achieving a more sustainable future. However, proper and adequate implementation of sustainability in secondary education is challenging and not straightforward. This might be due to the fact that sustainability issues tend to be complex, multidimensional by nature, and involve numerous concepts and terms that have to do with knowledge, morals, skills, and the effect of actions, all of which transcend the typical skills of secondary school students.

Sustainability in universities

At first, the development of the green chemistry curriculum was driven by the needs and interests of individual educators. Eventually, a more coordinated effort to develop green chemistry education led to more funding and therefore more opportunities (Haack & Hutchison, 2016). A prevailing view is the responsibility of universities to educate students in sustainable chemistry so that the future generation is able to deal with worldwide problems, such as climate change and exhaustion of fossil resources (Schultz, 2013). The students should be able to understand how their decisions influence sustainability.



Tasks such as 1) analysing a synthesis route with the twelve principles of green chemistry and eventually modifying the protocol to improve the greenness of a reaction (Ribeiro & Machado, 2011) or 2) the evaluation of two life cycle analyses on two reactions to determine the greenest reaction (Mercer et al., 2012), are two examples (of many more) of the incorporation of sustainability in the chemistry curriculum at universities. Universities became important in the sustainability education of future engineers and scientists in order to give them more knowledge in this field of expertise. However, tested interventions on sustainability in pre-university chemistry education are still rare, as well as insight in specific learning outcomes related to sustainability, such as life-cycle assessment, and reasoning. In addition, we lack heuristic guidelines for the design of high-quality education on sustainability.

Sustainability, argumentation, and decision-making in Dutch secondary chemistry education

In the context of this thesis, I would like to focus on the secondary chemistry education in The Netherlands. Sustainability has been included in the chemistry curriculum of Dutch upper level secondary school education since 2007. That year, a new examination program was introduced in which, among other things, reasoning in terms of sustainability (subdomain A14) and green chemistry and sustainable production processes (domain F) were added (Driessen, 2008). The end terms in the Dutch curriculum mainly focus on the principles of green chemistry from recognition (safety, renewable raw materials, use of water, recycling, and waste), to calculations (atom economy, E-factor, energy effect, efficiency), to reasoning on sustainability on multiple dimensions (social, professional, and scientific contexts) (CvTE, 2021). In addition to subject specific sustainability requirements for chemistry, broader requirements for upper-level secondary school students exist. For example, upper-level students are expected to make well substantiated judgements, which may concern chemistry-specific/sustainable matters. Students learn to distinguish between scientific arguments, normative social considerations, and personal views (CvTE, 2021). However, not only upper-level students work on argumentation and decision-making skills, the lower level students are also expected to learn how to state their opinion clearly and how to make decisions on matters of personal or general interest. It is not only understanding phenomena but also appreciating and assessing them (SLO, 2016). For many students that continue training in alpha or gamma directions, secondary school chemistry is also their final chemistry education and therefore the final opportunity to teach them about and motivate them for sustainability. It is interesting that both the knowledge of sustainability

chemistry (in upper grades) and the reasoning skills (in both lower and upper grades) are present, but in my opinion this is not yet expressed in such a capacity that the students actually can make well-considered sustainable choices. Therefore, investing in chemistry education aimed at a deeper understanding of sustainability and better control of sustainability reasoning, seems appropriate.

Life cycle assessment and reasoning in education

Life cycle assessment (LCA) is a tool for assessing the environmental impact of a product or service throughout its life cycle. This quantitative approach evaluates the material flows and energy consumption and can give students numerical/quantitative insight in the impact of a product. It is an important modelling tool in the industry but also used in many universities, typically at the graduate level. The majority of studies that used LCA in education were found in education for engineering students (Mälkki & Alanne, 2017). However, more research should be done on educating the important method of LCA, especially in secondary education for which studies appeared to be even scarcer (Tolppanen et al., 2021).

Juntunen and Aksela published multiple studies related to the incorporation of LCA in education at secondary level (Juntunen & Aksela, 2013a, 2013b, 2014). They reported the introduction of life cycle thinking into chemistry education with an inquiry-based learning approach in grade 9 of the secondary school, in which the students were asked to analyse a product of their choosing (2013a) They reported a positive impact on students' attitude towards chemistry learning and changes in environmental literacy, the importance to protect the environment and the importance to recycling. However, real changes in attitude appeared to be difficult (2013b). In another study, the argumentation skills of the students were analysed, in which the students mainly showed scientific and ecological arguments. Ethical argumentation was falling behind (2014a). Tolppanen and co-workers also reported on their intervention for lower secondary school students, 9th grade, to promote students' science career awareness. The intervention concerned LCA, and aimed to be relevant on individual, societal and vocational perspective. Eventually, LCA was shown to be a relevant topic according to the students in individual and societal perspective, and was concluded an appropriate introduction to students of scientific studies and careers in a real-life context (Tolppanen et al., 2019).

Need for LCA in secondary education

Sustainability teaching at secondary education is increasingly important for responsible



citizenship, and LCA proves an attractive topic. However, in the full curriculum of chemistry education in The Netherlands, there is little room to introduce additional subjects. Yet it is important to add a method such as LCA to chemistry education, because it gives the young generation knowledge about the impact of products on the environment. Also, it gives the opportunity to discuss environmental, economic, and societal impacts (Tolppanen et al., 2021). It potentially leads to evaluation of consumption habits, which can impact the way the youngster will behave in their adult life (Moschis, 2007). The incorporation of the LCA method into education could provide opportunities to have various discussions. Not only on environmental issues, but also health issues, economic issues, and concepts such as systems thinking and circular economy (Tolppanen et al., 2021). It also gives opportunity for a more ethical discussion in a chemistry class. The introduction of LCA provides a multidisciplinary context in science education and can be combined with multiple subjects already existing in science education, thereby easing the introduction into the already full curriculum. Finally, LCA may be one of the tools that students need in making the life choices mentioned at the beginning of this chapter.

1.2 Research aim

This dissertation explores how a contribution can be made to teach sustainability education in chemistry classes in secondary schools. We addressed the following overall research question:

How can secondary chemistry education contribute to the life cycle reasoning of students?

The answer to this research question needs 1) an evaluation of what students already naturally use in their argumentation about sustainability, 2) an intervention with a suitable sequence of activities to involve students in understanding and performing an LCA, 3) an evaluation of the outcomes of the developed intervention, and 4) an investigation which parts of the intervention are key components for a module on sustainability in order to learn and generalize to ESD in other domains. As a context, we chose the domain of plastics, as this entails many issues and controversies at a level suitable for secondary education.

Overview of the dissertation

The dissertation consists of four studies (Chapters 2-5) and a concluding chapter (Chapter 6). This concluding Chapter 6 provides an answer to the overall research

question, using the results of the four studies that have been carried out. It will end with future perspectives on possible developments that are still needed after these studies.

Study 1: Pre-university students' perceptions about the life cycle of bioplastics and fossil-based plastics - Chapter 2

Chapter 2 describes the first study in which we aim 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. *What knowledge, scientific and other, is 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 do the designed student activities make the students aware of the complexity and multi-dimensionality of the sustainability issue at hand?*

In this explorative study, qualitative data was collected in written answers and interviews from students with the subject chemistry within the age of 15-18 years old. A central question was posed to the students: What plastic do you think is the most sustainable?

Study 2: Engaging secondary students in sustainability and life cycle assessment in upper-secondary chemistry education: the case of polylactic acid (PLA) - Chapter 3

This study reflects on the design and reports on the results of the enactment of a sustainability module in classroom practice. The module aims to engage students in sustainability, plastics, and life cycle assessment. The purpose of the module 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 module consists of five parts (I-V). In part I, students are introduced to the topic. This part of the module is also used in the first study (Chapter 2). Part II-V correspond to the authentic LCA phase 1-4: *Goal & Scope, Inventory Analysis, Impact Assessment, Interpretation*. In part II, the first phase of the LCA, the students familiarize with the purpose of an LCA, what is included and excluded in an LCA



and for whom the analysis could be done. In part III, the second phase, the students walk through the complete life cycle of polylactic acid (PLA) with lab experiments and collect data. In part IV, the third phase, the information is shared and the life cycle of PLA is analysed with scientific data of experts. In part V, the fourth phase, the students investigate what part of the life cycle of PLA is the least sustainable.

Study 3: Teaching life cycle assessment in pre-university science education - Chapter 4

The aim of this study is to identify a set of guidelines for teaching LCA into secondary education. We argue that LCA is a suitable way to initiate sustainability thinking, but some guidelines for using LCA in secondary education can be helpful. This leads to a study in which two research questions are central.

1. *To what extent do students appreciate the overall structure of the module and value the teaching activities, with an emphasis on the functioning of the key activities which reflect the guidelines?*
2. *To what extent are the expected learning outcomes as formulated per part of the curriculum realized by students?*

This chapter gives an overview of the initial guidelines based on which the module was developed, and the evaluation of the students on the different parts of the module

Study 4: Pre-university students' life cycle reasoning in chemistry education - Chapter 5

The aim of the final evaluative study is to investigate whether LCA can lead students to understand the complexity of sustainability issues, and if the students would be able to substantiate/justify that with sophisticated, well-balanced and sound arguments. The following research question is addressed:

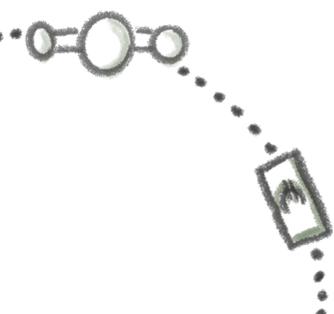
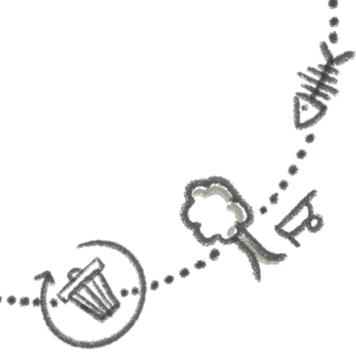
1. *How does the argumentation of pre-university students develop during a module using an LCA procedure to assess the extent of sustainability of bio- and fossil-based plastics?*

During the LCA module the students write, in small groups, two essays. The two essays, consisting of an introduction and position statement, arguments for the claim, arguments against the claim and a final summary, are written at the beginning and at the end of the module.

General discussion and main findings – Chapter 6

The final chapter provides an overview of all main findings of the studies described above. It starts with the exploration of students' perceptions on the sustainability of (bio)plastics and the knowledge they possess (chapter 2), which raised the question whether LCA could be used to identify this sustainability issue more clearly for students. It continues to the first ideas on a module on sustainability and the exploration of the suitability of the life cycle and life cycle assessment of the plastic PLA (chapter 3). Upon development of the module, it focuses on the implementation of the sustainability module and the possible guidelines that follow from it (chapter 4) and finally the development of the students' argumentation (chapter 5). An answer will be given to the overall research question and it will be discussed how further research can help the further implementation of the subject sustainability in the chemistry curriculum. Recommendations and ideas about future developments are discussed in more detail. In the end, this dissertation aims to develop and inspire further initiatives for chemistry education for a deeper understanding of sustainability in secondary education.







CHAPTER TWO

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



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

Abstract

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 use 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.

This chapter is based on: de Waard, E.F., Prins, G.T., van Joolingen, W.R. (2020) Pre-university students' perceptions about the life cycle of bioplastics and fossil-based plastics. *Chemistry Education Research and Practice*, 21(3), 908-921.

2.1 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 (Juntunen & Aksela, 2013a; Sadler & Zeidler, 2005). Future citizens need to develop these skills to help them to make well-considered choices in social debates on sustainable issues (Eilks & Rauch, 2012). Chemistry education takes a central role in teaching future generations on sustainability and to motivate them to act sustainably (Eilks & 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; Mälkki & Alanne, 2017; Ribeiro & Machado, 2013). 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 (de Goes et al., 2018; Eilks, 2015). 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 involving various stakeholders with (sometimes) conflicting ideas. Therefore, 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 a one-dimensional (i.e., politics, economics or ethics), clear solution (Sadler, 2011). Several studies have reported that using SSIs as contexts increased students' interest in science learning, creates ethical awareness and prepares students for participation in society (Juntunen & Aksela, 2014), in line with the goals of ESD. However, which sustainability issues are suitable for ESD in 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) and resulted in an increasing demand for guidelines for industry on how to behave in a more sustainable manner. Some examples of those guidelines are the well-known twelve principles of green chemistry (Anastas & Warner, 1998) and the twelve principles of green engineering (Anastas & 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 (Finkbeiner et al., 2006; Gonzalez & Smith, 2003). 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 (Gironi & Piemonte, 2011a; Harding et al., 2007; Milani et al., 2011; Tabone et al., 2010). 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 (bio)plastics, as well as conducting an LCA. Tabone et al. combined three sets of principles: 12 Principles of Green Chemistry, 12 Additional Principles of Green Chemistry and 12 Principles of Green Engineering (Anastas & Zimmerman, 2003b; Anastas & Warner, 1998; Winterton, 2001). From the three different sets they derived nine themes (or metrics) that could be measured to obtain quantitative data. Table 3.1 shows the nine different themes that were introduced in Tabone's work that will be elaborated briefly.

Table 2.1. 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.

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 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. Tabone's 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, Tabone's work 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 & Jaspersen, 2017; Boesen et al., 2019; Dilkes-Hoffman et al., 2019; Lynch et al., 2017; Steenis et al., 2017). 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 & 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 (Haider et al., 2019; Lynch et al., 2017). The study of Boesen et al. 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. 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. showed that LCA outcomes might not always match citizens' perceptions of the sustainability of a product. Steenis et al. 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. Life cycle based considerations such as production, transport and use of products were not included in their considerations (Boesen et al., 2019; Dilkes-Hoffman et al., 2019; Steenis et al., 2017).

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 findings underline the need for proper education and information about the environmental impact of (bio)plastics (Blesin & Jaspersen, 2017; Haider et al., 2019). It is interesting to investigate the perceptions of youngsters (16-17 year old) 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 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 (Mälkki & 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 conducted three studies that use LCA in secondary education (Juntunen & Aksela, 2013a, 2013b, 2014), from which only one focusses on plastics. Juntunen and Aksela (2014a) 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 (Juntunen & Aksela, 2014). The study of Juntunen and Aksela shows the potential of engaging students on sustainability issues and provide indications on how to implement LCA (on plastics) in secondary chemistry education. However, building on the results of Juntunen and Aksela, 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, Juntunen and Aksela 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 & Eilks (2012), Juntunen & Aksela (2014a). Building on the suggestion of Burmeister and Eilks (use respective practices in chemistry 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 of Toulmin's reasoning scheme 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 makes the students aware of the complexity and multi-dimensionality of the sustainability issue at hand?*

2.2 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, the subjects 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 (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 2.2 shows the outline of the student activity with the various components, function and the collected data sources. 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.



Table 2.2. 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

In the first part (A) of the student activity, the goal was to investigate the initial thinking, reasoning and initial 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 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 2.3). Written argument and interview II represent the data collected in measurement II.

Instruments

Table 2.3 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 researcher 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 researcher conducted an individual interview. Table 2.3 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

Table 2.3. The questions posed in the written answers and the protocol of Interviews I and II.

Written answers	Interview I
Production 1 (p1)	<p>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).</p> <p>What answer did you gave at the q2? - 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? Further questions for clarification were asked to obtain additional information.</p>
Production 2 (p2)	
Use 1 (u1)	
Use 2 (u2)	
Recycling 1 (r1)	
Recycling 2 (r2)	
All phases 1 (q1)	
All phases 2 (q2) (main question)	
Measurement I	
What do you know about the production process of a plastic? When is production sustainable? What requirements do you impose on the plastic that you use every day? What do you think of the compulsory fee we have to pay for a plastic bag in the shops? How would you define recycling and reusing? What do you think of the fact that China has processed our plastic waste for a while? Write down any questions that came up during the introductory film and the questions: 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
1. What plastic do you think is more sustainable? Bioplastic Fossil-based plastic Do not know	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. On which facts did you base your answer?	2. Did new information caused you to doubt? Yes: What new information has brought you to doubt?
3. Which possible doubts and/or questions do you have with your choice?	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?
Measurement II	



bio- and fossil-based plastics. Interview II was used to clarify why the students held or changed their position on this sustainable issue.

2.3 Data collection and analysis

The data were collected at two measurement points during the study. The researcher 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 and analysed with Toulmin and Tabone. 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 nine themes as identified by Tabone et al. as elaborated in the theoretical background (Table 3.1), 2) the categories of the adapted argumentation model by Toulmin 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 Tabone 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 form of Toulmin's argumentation model for the formulation of the arguments (RQ2). Based on the pilot of the student activity, we adapted the Toulmin model for the present study (Toulmin, 2003). 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 Figure 2.1, our adapted version of the Toulmin's argumentation model is presented.

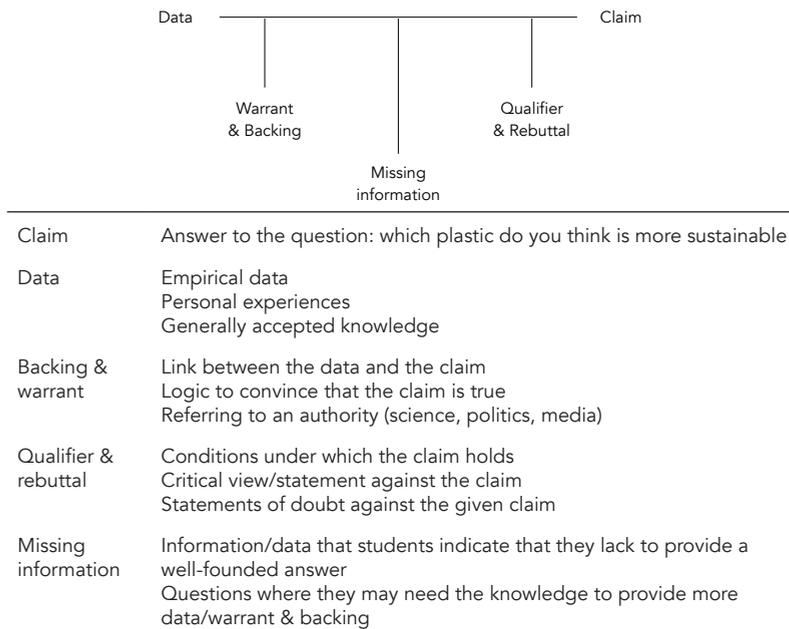


Figure 2.1. The adapted version of Toulmin's argumentation model (Toulmin, 2003).

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 structure, 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 2.4, 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. The researcher 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 & 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.

Table 2.4. Examples for the coding with Tabone, Toulmin and the three phases of the life cycle. The student quotes have been translated from Dutch.

	Student quotes	Tabone	Toulmin	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	Qualifier & Rebuttal	Not phase related
10.	I just believe that [fossil-based] plastic does its job very well	NT11	Backing & Warrant	Not phase related

2.4 Results

Table 2.5 presents the number of groups mentioning the different Tabone 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 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 Tabone categories.

Table 2.5. Total number of codes in measurement I and II for both Tabone (vertical) and Toulmin (horizontal).

Tabone	Number of groups	Toulmin								Total		
		Data		Backing & Warrant		Qualifier & Rebuttal		Missing Information				
		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		

Content knowledge in students' argumentations (RQ1)

Apart from the nine predefined Tabone 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 predefined Tabone 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 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., CO₂,

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 themes in more detail and give some descriptive examples of students' arguments. Quotes related to T3 are mainly focussed on CO₂ emission. The fossil-based plastics are responsible, according to the students, for the emission of CO₂ into the atmosphere, and contribute to the greenhouse effect. In addition, some students wonder what kind of substances are actually emitted apart from CO₂. 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 2.5 column 3 onwards shows the Toulmin 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 categories of Toulmin's model 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 remarkably 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 themes T3 and T5 as 'data' and aspects of T8 mainly as 'backing & warrant'. Tabone 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.

2.5 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.

2.6 Claim development

In Figure 2.2, 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.

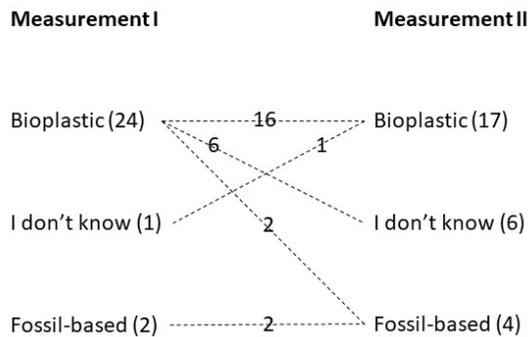


Figure 2.2. Development of the claims.

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 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.

2.7 Discussion & 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 of Toulmin's reasoning scheme 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 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 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 (2014a). 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 that students' arguments cover multiple dimensions next to a pure scientific one. This study gives insight into the content of the scientific, ethical and ecological arguments put forward by students. This 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 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 the categories of the adapted Toulmin model 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 themes were found in the Toulmin categories warrant & backing, missing information and qualifier & rebuttals. Only a few of the Tabone 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 more easier to degrade by nature/much 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 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 (Blesin & Jaspersen, 2017; Boesen et al., 2019; Dilkes-Hoffman et al., 2019; Lynch et al., 2017; Steenis et al., 2017). 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, Simon, & Osborne, 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 themes (scientific arguments) and outside the Tabone 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 & 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 themes (T2, 3, 5, 7 and 8) which might be regarded part of students' prior knowledge as well as under-represented Tabone themes in students' argumentations (T1, 4, 6 and 9). To bring the Tabone 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 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 21st century chemistry classrooms and for making society more sustainable.

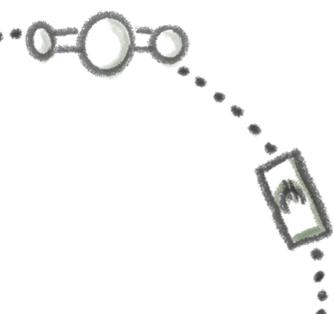
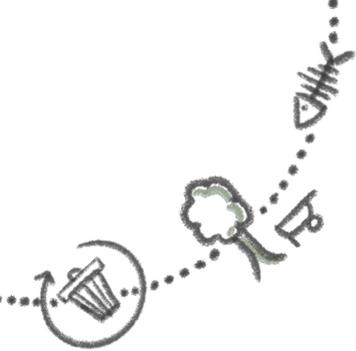
Appendix 2.1

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.

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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CHAPTER THREE

Engaging pre-university students in sustainability and life cycle assessment in upper-secondary chemistry education: The case of polylactic acid (PLA)



Engaging pre-university students in sustainability and life cycle assessment in upper-secondary chemistry education: The case of polylactic acid (PLA)

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, the qualitative part of an LCA, and might thus serve as a stepping stone towards the quantitative assessment. The preliminary results of the enactment of the lesson series are described and suggestions for future research are made.

This chapter is based on: de Waard, E.F., Prins, G.T., van Joolingen, W.R. (2022) Engaging pre-university students in sustainability and life cycle assessment in upper-secondary chemistry education: The case of polylactic acid (PLA). *Journal of Chemical Education*, 99(8), 2991-2998.

3.1 Introduction

Sustainability has become a prominent theme in society and is regarded as an integral part of scientific citizenship (Anastas & Warner, 1998; Ginzburg et al., 2019; Haack & Hutchison, 2016). 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 (Anastas & Eghbali, 2010). Numerous educational researchers and policy makers have advocated giving sustainable chemistry a prominent place in undergraduate and high school chemistry curricula (Burmeister et al., 2012; Juntunen & Aksela, 2014). 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 (Walker & Rothman, 2020). Within the goals of ESD, LCA can be both a tool for analysing 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 analysing 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.

In this article, we present a lesson series and accompanying worksheets, protocols and laboratory experiments targeting the introduction of LCA into high school



chemistry classes. We portray and reflect on the design and report the results of the enactment in classroom practice.

12 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 (Anastas & Warner, 1998). These principles do primarily apply on synthesis, but for assessing environmental impacts of complete production & 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) (Ginzburg et al., 2019). The 12 green chemistry principles and LCA are both valuable lenses that should be integrated into ESD. Whereas the 12 green chemistry principles have already found their way into many high 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 analysed 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 (ISO, 2006). 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 (Vink et al., 2003). 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 (Gironi & Piemonte, 2011b). 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) (Harding et al., 2007; Margni & Curran, 2012).

Fourth, the combined results of the LCI and LCIA are evaluated (Gironi & Piemonte, 2011b). From this, a conclusion, 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 (Walker & Rothman, 2020). 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 analysed is important. Figure 3.1 depicts the three definitions of the life cycle of a product. The cradle-to-gate

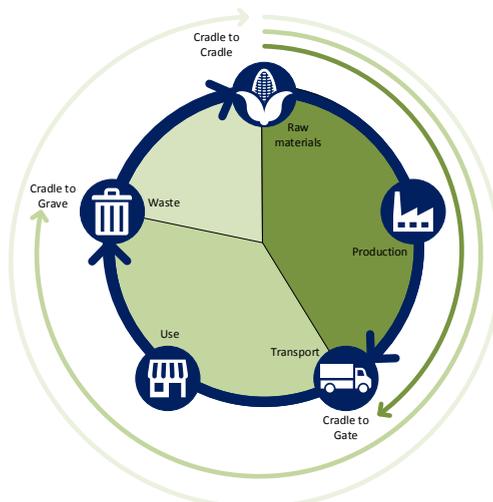


Figure 3.1. Schematic representation of three definitions of the life cycle of a product: cradle to gate (raw material–transportation), cradle to grave (raw material–waste), and cradle to cradle (raw material–raw material again).

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.

LCA of (fossil-based and bio-based) plastics

Most of the LCA studies conducted on plastics have compared fossil-based and bio-based plastics. The review by Walker and Rothman provided a comprehensive overview of the available LCA studies on this comparison (Walker & Rothman, 2020). After thorough analysis, they selected 25 articles reporting the LCA results of 39 fossil-based and 50 bio-based polymers, enabling a comparison of seven bio-based and seven fossil-based polymers across seven impact categories, namely:

1. *Energy use (MJ/kg polymer)*
2. *Ecotoxicity (CTUe/kg polymer)*
3. *Acidification (kg SO₂ eq./kg polymer)*
4. *Eutrophication (kg PO₄ eq./kg polymer)*
5. *Climate change (kg CO₂ eq./kg polymer)*
6. *Particulate matter formation (kg PM_{2.5-10} eq./kg polymer)*
7. *Ozone depletion (kg CFC11 eq./kg polymer)*

Significant variation was found between polymer types and between fossil-based and bio-based 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 bio-based plastics perform better in terms of energy use and climate change when only applying the cradle-to-gate philosophy and not considering the CO₂ 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 bio-based plastics (Walker & Rothman, 2020).

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 bio-based 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 (bio-based or fossil-based) is the most sustainable?" Based on our previous research (de Waard et al., 2020) we anticipated that the majority of the students would tend to choose bio-based plastics. An argument that is commonly put forward by students is the biological origin of bio-based 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 bio-plastics. The bio-based 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 (Aronson, 2021), 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 3.2 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 supplementary information (online). 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.

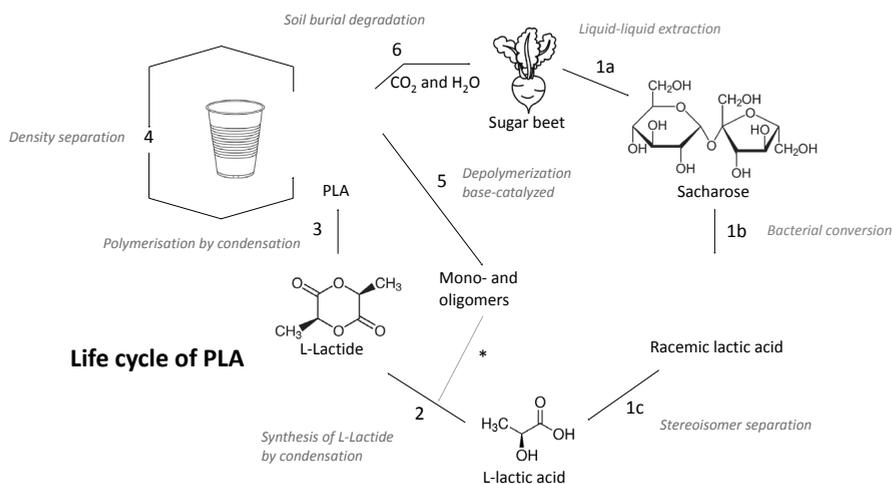


Figure 3.2 The life cycle of polylactic acid in six steps. 1a, b, c) Formation of L-lactic acid, 2) formation of L,L-lactide, 3) conversion of L,L-lactide into PLA, 4) separation of plastics and recycling, 5) depolymerization of PLA, 6) composting of PLA and *) is an additional experiment after experiment 5.

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 (Chemieleerkracht, 2020b).

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 (Garlotta, 2002; Narayanan et al., 2004; Sajewicz et al., 2008).

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. (ONTRG, 2011)

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 forming 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 set-up 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 set-up, initiation, and termination of the reaction. Commercially purchased pure *L*-lactic acid is refluxed in toluene. Next, commercially purchased catalyst SnOct₂ is added and the reflux is continued for 3 hours (Robert & Aubrecht, 2008).

Step 3 Conversion of L,L-Lactide into PLA

As step 2 takes about 5 hours in total, step 3 starts with commercially purchased *L,L*-lactide, which is refluxed in toluene together with the catalyst SnOct₂. For the conversion of *L,L*-lactide into PLA, a reflux set-up 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 one hour, 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 (Grewell et al., 2014).

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 bio-based 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 density 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 analysed through TLC (Greene, 2007). 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 (Chemieleerkracht, 2020a).

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 experiment 2 and 3. The set up should be checked before the experiment is started and chemicals such as toluene, Sn(Oct)₂, 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.

3.2 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, 2014).

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-hour class, and parts II–V were enacted in a 4.5-hour class. This set up 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, Figure 3.1) and completed the worksheet of LCA stage 1 together. Next, four expert groups (1, 2, 3 and 4, Figure 3.1) were formed, each consisting of one member of the original groups A, B, C and D according to the jigsaw method (Aronson, 2021).

Table 3.1. Distribution of students during the activities.

		Expert group			
Main group		1 (exp. 1a–c)	2 (exp. 2, 3, 4)	3 (exp. 5, 4)	4 (exp. 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

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

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).

Assessment of the lesson series

At the end of part I, a written pre-test 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 supplementary materials (online). For each question, two researchers 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.

- 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*

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 supplementary materials (online). The interviews lasted for approximately 25 minutes. 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 set-up of the entire lesson series.

3.3 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 3.2 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.

Table 3.2. Results data analysis.

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

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.

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 pre-test. 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 bio-based 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 pre-test, 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 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. And 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.

Remarkable was the lack of reflection of the content of the four stages of the LCA. 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 datasets are needed.

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

3.4 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 set-up 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 set up like Jigsaw. The students reported having limited time or support to share their outcomes with each other. The experiments in 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 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.

But 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.

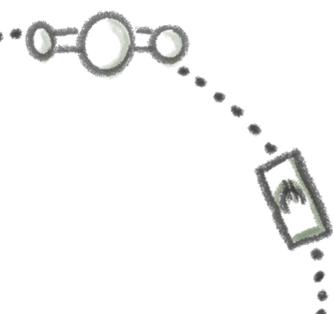
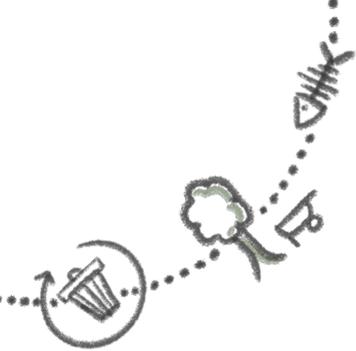
This lesson series has been designed having in mind the constraints of secondary school environment. More in-depth chemical explanations of the processes that are done in the experiments could provide opportunities to even better illustrate green chemistry in addition to sustainability. For example, students could focus on liquid-liquid extraction, which often requires high volumes of solvent and require 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 university level. We hope and expect this work will provide a starting point for redesigning the lesson series for use in undergraduate chemistry courses.

3.5 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 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 pre-test, 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 pre-university 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?





CHAPTER FOUR
Teaching life cycle assessment in pre-university science education



Teaching life cycle assessment in pre-university science education

Abstract

This study reports on the design of a module on sustainability focussed on the life cycle assessment (LCA) of bio- and fossil-based plastics. We developed guidelines for teaching sustainability using LCA to stimulate students reasoning about the life cycle of plastics, intended for use in chemistry classrooms targeting 11th grade pre-university students. A literature review provided a list of initial guidelines for the module, which were related to (1) guided inquiry-based learning and active guidance by teacher, (2) the four phases of LCA as a backbone for the module, (3) laboratory work on LCA, and (4) expert data. The module was enacted in two schools and evaluated with focus on the functioning of the initial guidelines and identification of new ones. Students' appreciation of the different teaching activities and learning outcomes were mapped out through questionnaires, submitted worksheets and interviews. The findings revealed three additional guidelines next to the four initial ones: (5) let students work in groups, (6) make sure that students understand the product life cycle, and (7) give students a clear overview of the complete module. This complete set of guidelines aims to provide educational designers, practitioners, and teachers with useful heuristics for teaching sustainability using LCA in upper secondary science education.

4.1 Introduction

Life cycle assessment (LCA) is an important modelling tool for assessing sustainability that is taught at universities, typically at the graduate level (Mälkki & Alanne, 2017). LCA is a methodology for analysing the impact of products and/or processes on the environment; it provides a context for integrating science, technology, society, and the environment and for dealing with socio-scientific issues. Incorporating LCA in pre-university classes may equip youngsters with the ability to make environmentally friendly and healthy consumption choices or could provide students with the basic LCA skills they might need in many occupations (de Haan, 2010; Eilks & Rauch, 2012). Despite its relevance, a review study (Mälkki & Alanne, 2017) found only nine studies on the use of LCA in education, the majority of which targeted undergraduate engineering students. To our knowledge only Juntunen and Aksela (2013a, 2013b, 2014a) and Tolppanen et al. (2019) have examined the use of LCA at the pre-university level. The participants in these studies were students aged 14–16 years. One reason why LCA is still in the early stages of implementation in secondary education is the technical nature and complexity of the method. Further investigation is needed into how to organise LCA teaching to suit the prior knowledge and capabilities of the target audience to allow proper implementation in secondary education.

In this article, we report on the design and testing of a module focussed on performing an LCA in secondary-level chemistry class, for Grade 11, applied to the production, use, and recycling of bio- and fossil-based plastics. We developed guidelines for the design of modules on LCA teaching so learners grasp the purpose and value of the methodology for sustainability issues. We started from a preliminary list of initial guidelines distilled from the literature, which formed a starting point for appropriately implementing the LCA methodology in a module. Based on the initial guidelines, a set of teaching activities (TAs) was designed, from which some of them were considered as key activities. The module was put into practice in several chemistry classes at two different schools, which was followed by an in-depth analysis of the learning outcomes among the learners. The results were used to evaluate the initial guidelines and to add new guidelines.

4.2 Theoretical background

The theoretical basis for this study builds on the authentic LCA methodology, as well as on pedagogical approaches and initial guidelines for teaching LCA as reported in the literature. Both bodies of knowledge are described below.



Authentic LCA methodology

LCA is a methodology for analysing the impact of products and/or processes on the environment; it consists of qualitative and quantitative components. The methodology consists of four phases: (1) definition of goal and scope, (2) inventory analysis of the complete input and output of the life cycle, (3) impact assessment on the environment, and (4) interpretation (ISO, 2006). Phases 1 and 2 can be considered its qualitative part, while Phases 3 and 4 embody the quantitative part.

In the first phase, major aspects include setting goal(s), defining the scope and boundaries, and setting the functional unit for fair comparison under consideration. The goal could be the comparison of two (or more) products or processes in terms of sustainability. Setting the goal(s) implies establishing system boundaries to define which aspects are considered, in what part of the life cycle of the product (cradle-to-gate [C2Gate], cradle-to-grave [C2Grave], cradle-to-cradle [C2C]).

In the second phase, a life cycle inventory (LCI) is performed. In this phase, actual data 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 (Gironi & Piemonte, 2011b). Next, all material flows and energy used in the various steps are categorized into impact categories with suitable indicators.

In the third phase, a life cycle impact assessment (LCIA) is performed, in which the possible environmental impacts (magnitude and significance) are evaluated quantitatively. The impact categories are calculated in their corresponding unit of measurement (Harding et al., 2007; Margni & Curran, 2012).

In the fourth and final phase, the combined results of the LCI and LCIA are evaluated. The major contributions are analysed, and sensitivity and uncertainty analyses are performed. From this, a conclusion, advice, or answer can be obtained to achieve the goal(s) of the LCA.

Pedagogical approaches and initial guidelines for teaching LCA

We argue that LCA is a suitable way to initiate sustainability thinking in students. An LCA visualizes the life cycle of a product or process using a purely scientific technical approach and calculations (e.g. quantity of raw materials needed, quantity of harmful substances formed) and measures multiple sides of the matter. However, more than scientific aspects play a role in complex sustainability issues: Economic,

ethical, and ecological aspects play their part, too, in choices that are made in sustainability issues. We thus regard LCA as a suitable case for teaching young adults about sustainability, because it shows substantiations for arguments that ultimately can have a scientific, economic, ethical, or ecological background. How, then, can students be engaged in performing an LCA, which is complex in nature, such that it supports and helps their thinking and arguing about sustainability?

Several examples of LCA instruction have been reported in the literature for curricula at the university level. These examples describe several characteristics to account for, from which we derive four initial guidelines: (1) use a guided inquiry-based learning approach, (2) use the four phases of the LCA as a backbone for the module, (3) perform laboratory work, and (4) use expert data. Each initial guideline is briefly elaborated below and underpinned by the literature.

1. Guided inquiry-based learning

The studies of Juntunen and Aksela (2013a, 2013b, 2014a) used inquiry-based learning as a pedagogical approach in LCA education. Students were allowed to investigate the life cycle of a product of their choice and had to consider the pros and cons present in the life cycle of that product. It appeared to be an example of motivating and creating a positive attitude towards learning about chemistry, and changes were observed in the students' environmental literacy. An open inquiry approach was used in the LCA intervention by Tolppanen (2019), which started with a scenario phase in which students were introduced to LCA. Students had to prepare a presentation on LCA to explain, for example, the main feature of chemical processes, describing products life cycles and to discuss evidence about environmental burden of processes. Reflecting on the findings, the authors concluded that an open-ended inquiry approach lacks the rigour and direction needed to examine LCA holistically (Tolppanen et al., 2021). They recommended a teacher-led, guided inquiry process, in which students are guided to find and collect information from several sources.

2. Four phases of LCA as backbone

Crossin et al. (2011) emphasized teaching students the authentic LCA framework and developing its documentation. Many best practices describe a variety of instructional methods to scaffold the four phases of LCA, such as lectures, weekly short tutorials, and 'minor and major' projects with a broad scope. Riley and Tech (2015) showed that teaching the LCA framework can be done in a stand-alone course but can also be integrated in suitable existing curriculum modules.

3. *Laboratory work*

Savelski et al. (2013) and Farell and Cavanagh (2014) described the integration of LCA into laboratory work across the whole chemistry engineering curriculum. In their studies, students learn and design biodiesel processes in an experimental setting, but also assess their environmental impacts and compare their results with fossil fuels. The learning outcomes reach beyond technical skills (e.g. LCA framework, development of inventory data from laboratory experience, learning LCA software) to include non-technical aspects, such as communication skills (oral and writing) and teamwork.

4. *Use of expert data*

The use of prior publications as a resource is highlighted by Belboom and Leonard (2016) and Meo et al. (2014), who gave their students published LCA papers, specifically those with detailed available inventories, to promote learning, understanding, and practicalities related to LCA, and at the same time, to promote the development of reviewing skills.

In addition to these four guidelines, we decided to let students work in groups. In previous studies we have seen that working in groups naturally evokes discussions. In addition to this, there was also a practical reason for working in groups, namely that the lab work can be divided among group members (de Waard et al., 2020, 2022).

4.3 Designed module for LCA teaching

The present study evaluates the designed module for LCA teaching. Parts of the module were tested with the target audience (Grade 11, pre-university) in our previous research studies (de Waard et al., 2020, 2022). Below, we briefly describe the incorporation of the initial guidelines, the sustainability topic at hand, and the overall structure of the module with emphasis on the parts (i.e. highlighting major design decisions as well as expected learning outcomes).

Incorporation of initial guidelines

We used the four initial guidelines to integrate LCA in a module on a topical issue. This resulted in a series of TAs in which a number of key activities were identified. These key activities are TAs which we believe play a crucial role in the module. These TAs were partly designated based on knowledge from the literature, partly based on experiences from previous studies and partly due estimates as designers. Table

4.1 provides an overview of the TAs, the key activities, and the expected learning outcomes. Following the first initial guideline, the module was based on guided inquiry-based pedagogy, including theory lectures, laboratory work, guided (group and classroom) discussions, reading and assessment of LCA papers, and reflective essays written by a group of students. The second initial guideline is implemented in Parts III–VI, which represent the four phases of an authentic LCA. The laboratory experiments, the third initial guideline, are included in Part IV of the module, which represents the second phase of the LCA. The use of expert data, the fourth initial guideline, is applied in Part V.

Bio- and fossil-based plastics as sustainability topic

This module focuses on the sustainability of bio- and fossil-based plastics, inspired by the review study by Walker et al. (2020), which presents a comprehensive overview of the available LCA studies on bio- and fossil-based plastics. Significant variation was found between polymer types and between fossil- and bio-based polymers. This means that it was not possible to declare any polymer type conclusively to have the smallest environmental impact in any category. Burmeister and Eilks (2012) have shown that plastics are a suitable topic for education for sustainable development in chemistry education. In our previous study, we found that the extent of the sustainability of bio- and fossil-based plastics can initiate students' life cycle reasoning and engage them in arguing about a well-known sustainability issue in the domain of chemistry (de Waard et al., 2020).

Overall module structure

The module consists of six parts. More details on the activities, as well as all learning outcomes, are shown in Table 4.1 and Appendix 4.1. In Part I, the teacher introduces the students to the subject of sustainability and plastics in our society, with a focus on the production, use, and re-use of bio- and fossil-based plastics. This part consists of six TAs, of which the reading of news articles followed by a group discussion (TA 5) was expected to be a key activity. Previous research (de Waard et al., 2020) has shown that this activity generated doubt, curiosity, and a more critical attitude towards the extent of sustainability of bio- versus fossil-based plastics.

Part II provides students with theoretical (background) knowledge about LCA, which they will need for later parts of the module, and positions sustainability in a broader context. First, the students were introduced to the principle of a life cycle of a product (production, use, recycling) and the possible parts of the life cycle you can

Table 4.1 Overview of teaching activities, key activities, and expected learning outcomes.

Part of the module	Teaching activities	Expected learning outcomes
Part 1 Introduction	TA1–TA3 introductory questions on sustainability TA4 position statement: sustainable plastic TA5 reading news articles and group discussion TA6.1 position statement: sustainable plastic TA6.2 writing an essay	<ol style="list-style-type: none"> 1. Awareness: sustainability & plastics 2. Awareness: bio- and fossil-based plastics 3. Contributions of yourself and industry
Part II: Theory block	Lectures and class discussion (LC, LCA, PLA)	
Part III LCA Phase I: Goal and Scope	TA7 Goal of the LCA TA8 organisations with interest TA9 Boundaries of the LCA TA10 other interesting aspects to analyse	<ol style="list-style-type: none"> 4. Able to describe purpose of LCA 5. Able to describe scope and boundaries of LCA 6. Insight into the chain of events in the LC of PLA
Part IV LCA Phase II: Life cycle inventory	Set of laboratory experiments	<ol style="list-style-type: none"> 7. Insight into material & energy flows (LCA of PLA) and understanding of impact categories: match substances to categories 8. Match impact categories to relevant stages in life cycle, production, use, recycling
Part V LCA Phase III: Impact assessment	TA11–TA13 Impact LCA of PLA TA14 choice of plastics TA15 C2C or C2Grave TA16–T18 Working with expert data TA19 determination ranking of plastics TA20 pricing of plastics	<ol style="list-style-type: none"> 9. Understanding C2Gate, C2Grave, and C2C philosophies 10. Comparing impact categories 11. Insight in environmental and health impact of different plastics
Part VI LCA Phase IV: Interpretation	TA21 Final position statement (with reference to conducted TA4, TA5 & TA6) TA22 writing an essay	<ol style="list-style-type: none"> 12. Argued position statement regarding ‘most sustainable plastic’ based on: <ul style="list-style-type: none"> • Environmental and health impact • Priorities for impact categories • Economic arguments 13. Reflect on generic applicability and benefit of LCA (for other processes and products)

look in to (C2Gate, C2Grave, and C2C). Followed by the theory on the four phases of LCA, and environmental and health impact categories, as well as comparison using normalisation techniques. The final theoretical part introduces the life cycle of polylactic acid (PLA), the plastic investigated in the module. The students' acquired knowledge in Part II is expected to become visible in the remaining TAs in Parts III–VI.

The backbone of the four phases of LCA (guideline 2) are implemented in part III–VI. Part III corresponds to the first phase of LCA: setting the goal, scope, and boundaries. The key activity in Part III is TA 9, in which students reason on the boundaries of the LCA on plastics. This activity was considered important because it is good to realise the limitations of an LCA and to remain critical, as some things are not considered. Part IV embodies the second phase of LCA, in which students conduct an LCI of the production, use, and recycling of the bioplastic PLA. In Part IV, students study the complete life cycle and conduct laboratory experiments (guideline 3) covering the production, use, and recycling of PLA, guided by detailed protocols and worksheets. This part of the module has been studied previously (de Waard et al., 2022). The results showed that the experiments predominantly evoked life cycle thinking related to PLA in students – that is, the qualitative part of an LCA.

In Part V, the students continue with an impact assessment, corresponding to the third phase of the LCA. The students are expected to make an analysis of the sustainability of four different plastics using an Excel file with expert data, which was expected to function as key activity (TA16-19). This data (guideline 4), originating from scientific LCA articles on plastics, is given to students in a user-friendly way.

The final part, Part VI, relates to the fourth phase of an LCA, students interpret the results and conclude which plastic is the most sustainable, using all of their gained knowledge and experience collected in previous parts. This expected key activity (TA22) challenged the students to write an essay with a well-substantiated opinion.

Ethical statement

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). All participant were informed about the use of their data and all data was anonymized after collection of the workbooks and transcription of the interviews.



4.4 Research aims and questions

This study took place in the context of Education for Sustainable Development (ESD) in chemistry. In recent decades, there has been growing recognition that sustainability is not a straightforward concept to be learned. 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; such issues also tend to involve various stakeholders with (sometimes) conflicting ideas. Sustainability issues might be regarded as socio-scientific issues (SSI), which are (also) defined as rather open-ended problems that do not have a one-dimensional (i.e. politics, economics, or ethics), clear solution (Sadler, 2011). This research study, aims to identify guidelines for teaching LCA in secondary education. Two research questions were addressed, both giving a perspective on the students' perception of coherency between TAs, content, and tools in the module.

1. *To what extent do students appreciate the overall structure of the module and value its teaching activities, with an emphasis on the functioning of the key activities which reflect the guidelines?*
2. *To what extent are the expected learning outcomes, as formulated for each part of the curriculum, realized by students?*

4.5 Method

In the current study, we investigated whether the performance of the module took place as envisioned. We were interested in students' perceptions of the module and of indications of student learning processes.

Participants

The participants were 167 students from seven classes in two different schools, and five teachers. All teachers participated voluntarily. The students were in Grade 11 and had chosen chemistry as their topic. Both schools can be characterised as typical Dutch public secondary schools, teaching all levels of education, and situated in a medium-sized Dutch city. One of the classes was taught by the researcher, who also guided the other teachers in teaching the module. The teachers had a teacher's manual at their disposal, and short meetings were arranged during the implementation of the module, so that teachers could ask for additional explanations. Table 4.2 shows some characteristics of the teachers and the classes.

During the module, the students individually filled in workbooks that provided assignments related to the expected learning outcomes of the module. The workbooks were collected to analyse students' answers as a group; some of the groups completed the last part of the workbook as a group. Only the workbooks of School A (4 classes) are analysed.

At the end of the module, 41 students were asked about their experiences with the module in group interviews. Two groups of three students each were randomly selected from each class, except for one class where only one group was interviewed. An attempt was made to make as many new combinations of students as possible in the interview groups, so that the groups during the interview corresponded as little as possible to the groups during the module. A total of 13 interviews were conducted, 2–3 weeks after completion of the module. Prior to the interview, the students briefly browsed through the module with the interviewer, only mentioning the activities they had done. In the interviews, the students were asked what they thought of the TAs, which activity they liked or disliked, or if a specific activity got them thinking. Appendix 4.3 shows the interview protocol.

Data analysis

The results of the questionnaires acquired in the seven classes in the two schools were pooled. The questionnaires were collected digitally and anonymised with an individual number. The students rated all activities (except for TA 22 essay) on the aspects interest, usefulness, instructiveness, and fun on a 4-point scale. For the analysis, the opinions have been converted to the corresponding numbers 1–4, for which absolute values and averages have been calculated. On the questionnaire, the students were also asked to name their favourite and least favourite activities. The students could mention more than one activity. Every time a student mentioned an activity, this was added to the total number of times that an activity was mentioned as favourite or not favourite.

For the workbooks, the answers of the 26 groups (School A) were collected for each question. Preceding the actual data analysis, two researchers developed and agreed upon a coding scheme. This coding scheme consisted of a set of expected learning outcomes, building on Table 4.1 and further described in Appendix 4.2. The students' answers were checked to determine the extent to which they were in line with the expected learning outcomes using a 3-point scale. Ranging from good (students show expected outcomes and/or insight) to not met (no completion,

expected outcome and/or insight largely absent or not accessible. In the case of individual questions, the outcomes were scored individually for each student, and finally the overall score of the group was examined. If 50% or more of the students in the group met the outcome in their own workbook, the group was scored as meeting the learning outcome. In case of a group answer (mainly Parts V–VI), the joint answer was scored on meeting the learning outcome.

A total of 13 groups were interviewed. The interviews were used as data source for the appreciation of the TAs and for expected learning Outcome 6 (*insight into the chain of events in the LC of PLA*) and 13 (*generic applicability of LCA for other processes and products*). The students were scored individually for the two learning outcomes based on whether the learning outcome was present, not complete, or absent. Ultimately, the entire group received the score of the majority of the students.

A second researcher analysed three workbooks and three interviews, an intercoder agreement of respectively 91% and 86% was found. The analysis of the questionnaires was only done by the researcher.

4.6 Results

Students' assessment of the overall module structure and TAs

Table 4.4 presents the results of the questionnaire on the students' appreciation of four aspects of the TAs: interest, relevance, instructiveness, and fun. The results indicate an overall positive appreciation for all four aspects for all TAs. Scores varied from a minimum average of 2.31 (TA7) to a maximum average of 2.67 (TA21) on a scale from 1 to 4. The key activities (TA6, 9, 16–18, 19) were not rated higher than the other TAs. The response rate of the questionnaires was, for most parts, above 81.4%, which corresponds to a response from at least 136 of the 167 students. However, the response rate for Part III was significantly lower than for the other parts. With responses from only 103 of the 167 students (61.7%).

Table 4.4. Results of student questionnaire responses. Numbers correspond to how often a specific score was chosen. 1 = strongly disagree, 4 = strongly agree. Green bars represent the mean.

Part	Response	Activity	Interesting				Relevance				Instructiveness				Fun			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
I	81.4%	TA1	6	51	76	3	5	45	68	18	7	68	55	6	7	53	67	9
		TA2	2	49	70	15	4	31	81	20	11	58	61	6	5	55	66	10
		TA3	2	34	77	23	1	21	87	27	1	40	76	19	3	53	69	11
		TA4	3	35	79	19	3	30	81	22	1	30	85	20	3	57	72	4
		TA5	7	38	73	18	4	23	86	23	4	35	71	26	13	53	58	12
		TA6	4	50	71	11	6	32	78	20	3	52	62	19	10	63	57	6
II	61.7%	TA7	5	43	50	5	2	30	62	9	8	33	53	9	9	54	37	3
		TA8	6	38	50	9	2	28	64	9	4	34	58	7	8	47	44	4
		TA9	3	52	45	3	0	26	65	12	2	32	65	4	4	57	39	3
		TA10	5	46	46	6	2	36	59	6	1	46	54	2	7	58	37	1
V	83.8%	TA13	2	38	89	11	1	28	90	21	1	35	86	18	5	70	62	3
		TA14	4	45	83	8	5	32	84	19	5	45	76	14	4	61	72	3
		TA15	4	51	75	10	1	37	80	22	3	50	70	17	6	66	63	5
		TA19.1	2	43	74	21	2	30	85	23	2	46	75	17	5	54	69	12
		TA19.2	5	39	80	16	1	33	92	14	1	32	92	15	5	63	66	6
		TA20	3	37	77	23	1	35	86	18	2	33	84	21	7	51	71	11
VI	83.8%	TA21	4	33	80	23	1	27	87	25	4	34	76	26	5	48	75	12

The students also indicated which activities they valued over other activities in the surveyed part of the module, as well as which activities they valued lower. The combined results are depicted in Figure 4.1, where a positive and negative value is shown for each TA. The results indicate that all key activities (TA5, 9, 16–19, 22) have a positive average, which means that most students appreciated the key activities.

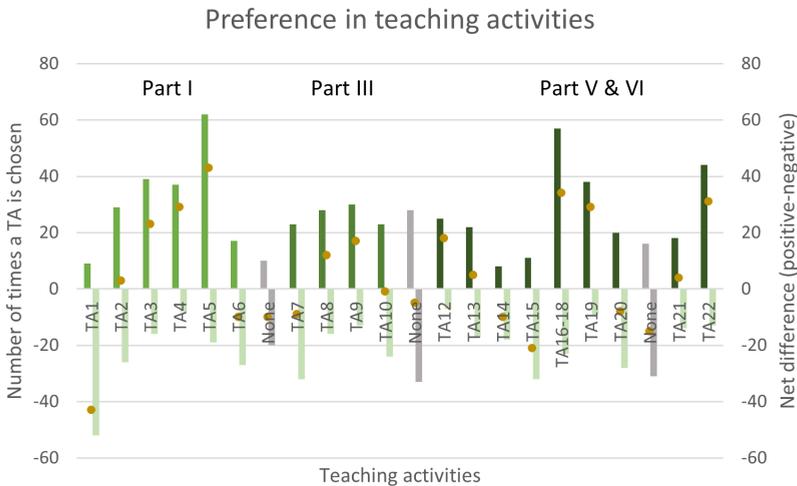


Figure 4.1. Number of times students chose an activity as the best (positive, 203 times) or one that should be deleted (negative, 168 times). Dots indicate net difference between positive and negative.

Below, the key activities TA5, TA9, TA16–19, and TA22 are discussed, based on the data from the questionnaires and group interview. Reading news articles and group discussion, TA5, was said to be interesting and instructive, but also that they learned from each other's opinions and that it made them think more critically about their own opinion. This activity was particularly highly valued by students in the questionnaires (46 times). Arguments regarding TA5 put forward by students supporting their rating in the questionnaire were: *it was educational (18/46), it was interesting (7/46), opinions of others and discussion were informative (7/46), fun (6/46), interactive (4/46), and makes you (more critically) think about it (4/46)*. In the interviews, the students rated this activity 19 times, of which 11 times it was mentioned it activity was instructive; of these it was indicated 7 times that this activity was particularly instructive for acquiring new knowledge and highlighting other views.

I also found the group discussion that preceded the essay useful, because then you could hear each other's thoughts. (Student 108)

Substantiation in the questionnaire for key activity TA9, boundaries of the LCA, was given 43 times. Most times (18/43) no explanation was given, but it was mentioned as important and/or useful for the module (6/43) and that it really made students think (2/43). During the interviews, this key activity was not discussed at all. It was expected that the students learned about the limitations and possibilities of LCA, however, this is not observed in the opinions of the students.

Key activities TA16–19 in Part V, working with expert data, was scored higher in relation to the other activities from the same part of the module. In the interviews, the students expressed their appreciation of working with expert data to compare the plastics (44 times). The terms interesting (16/44) and instructive (13/44) were mentioned the most. Students thought it was interesting that bio- and fossil-based plastics did not differ that much from each other, and that, in some cases, fossil-based plastics emerged as the more sustainable plastic variant.

And I also think it was surprising that there were still so many differences between fossil-based plastics and bioplastics within their own groups. So that you actually had quite good fossil-based plastics, but also really bad fossil-based plastics. (Student 82)

Students thought it was instructive, because it made them conscious about the central aim of their LCA project and brought all the activities in the module together (3/13). Students also expressed that, with help of TA16–19 and the expert data, they were really able to answer the sustainability issue at hand (2/13).

When I really started thinking about sustainability, it was with the table with the different impact categories [expert data]. (Student 147)

Besides being instructive and interesting, some students also indicated TA16-19 was fun to do (5/7). On the downside, a few students regarded TA16-19 as not instructive because it was too simple (1/1) or too difficult (2/2).

Key activity TA22, writing the final essay, in Part VI was often mentioned positively in the questionnaire as the best teaching activity in that specific part of the module, and this rating was supported with words like: *instructive (9/44), fun (3/44), interesting (3/44), makes you think (2/44), is more in-depth (1/44), original (1/44), or important for the goal(1/44)*. In the interviews, TA22 was often mentioned (22/42 times) as being an *instructive activity*. In particular, this activity appeared to help students to understand the material and to bring it all together (9/22).

I think the final essay was important. We had to summarise everything we have learned and really apply what you have learned to actually be able to find a sustainable plastic. (Student 34)

Other explanations that were given include that it was instructive, that the development of the opinion can be seen in the course of the module (2/22), and that it was a more in-depth part of the module (2/22). The students also mentioned that they were confronted with LCA results that they did not expect, which triggered curiosity and the realization that more in-depth information was needed about plastics. On the negative side, some students judged TA22 as not being fun to do. Writing an essay was not regarded as a part of chemistry classes. However, the students did ultimately realise that it was educational.

No, the essay was indeed not really scientific. Well, but you learn from it. But I did not like it. (Student 60)

During the interviews, it was mentioned relatively often that the students lost the overview of the module as a whole. Students commented 26 times on the overview and course of the module. A good structure was mentioned three times, but lack of clarity was mentioned seven times. Students gave several reasons: it did not feel like a whole, the practical assignments were between other activities, lessons alternated with the textbook, or the structure of the whole module was simply not perceptible. Three students also indicated that they sometimes did not see the purpose of certain activities. For example, they wondered in the moment why they should read the news articles, but it turned out in later stages of the module that they could use the articles. Several students explained that, when performing Parts V–VI, they did see the overall picture and connection between the parts and the TAs in the module. Six students indicated that the last two parts of the module caused them to make links between all the activities, bringing the module together and providing closure.

But now that I look back on it, I think there was a lot of logic in the way the module was structured. Where you start and where you worked towards. (Student 83)

4.7 Realisation of expected learning outcomes

Table 4.5 presents an overview of the extent the set learning outcomes were realised per part in the module, based on students' workbooks. If 70% of the groups met a learning outcome, we regarded the learning outcome as realised sufficiently. The results showed that most learning outcomes were sufficiently realised. The expected outcomes in Part IV, corresponding to LCA phase 2 (LCIA), were least met, followed by those in Part III, corresponding to the first phase of LCA (goal, boundaries).

The students provided answers in which three outcomes were clearly recognisable: Outcomes 1, *awareness of the sustainability & plastics*; 2, *awareness of bio- and fossil-based plastic*; and 3 *contribution of yourself and the industry*. All three expected learning outcomes showed a score of 100%, as shown in Table 4.5. Both Outcomes 4 (*ability to describe purpose of LCA*) and 5 (*ability to describe scope and boundaries of LCA*) were sufficiently observed in the workbooks of the students, with scores of 81% and 77% respectively. In case of *the purpose of LCA*, for 5 of the 26 groups, there was doubt whether the learning outcomes were met sufficiently. Three groups indicated that the goal of an LCA is to produce as little waste as possible, which is correct, but there was no explanation that LCA is an instrument

CHAPTER FOUR

Table 4.5. Results of the workbook scores for expected learning outcome. v = outcome present, o = outcome not fully (correct), n = outcome not present.

Part	Learning outcome	TA	Group																								Summary						
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	v	o	n		
I	1. Awareness sustainability & plastics	4 & 5	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	26	100%	0	0	0	0%
	2. Awareness bio- and fossil-based plastics	4 & 5	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	26	100%	0	0	0	0%
	3. Contributions of yourself and industry	4 & 5	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	26	100%	0	0	0
III	4. Able to describe purpose of LCA	7	v	o	v	o	v	v	o	v	v	o	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	21	81%	5	19%	0	0%
	5. Able to describe scope and boundaries of LCA	9 & 10	v	o	v	v	v	o	v	v	o	v	v	o	v	v	o	v	v	v	v	v	v	v	v	v	v	20	77%	6	23%	0	0%
IV	7. Insight in material & energy flows (LCA of PLA) and understanding of impact categories: match substances to categories	13	o	v	v	v	v	v	o	v	v	o	v	o	v	o	v	o	v	o	v	v	v	v	v	v	v	18	69%	7	27%	1	4%
	8. Match impact categories to relevant stages in life cycle, production, use, recycling	11	v	v	v	v	v	n	v	v	v	v	o	v	v	v	v	v	v	n	v	v	v	v	n	v	v	21	81%	2	8%	3	12%
V	9. Understanding C2G(ate), C2G(ave) and C2C philosophies	15	v	v	v	v	v	v	o	v	v	v	v	v	v	o	v	v	o	v	v	o	v	v	v	v	v	21	81%	4	15%	1	4%
	10. Comparing impact categories	16 & 17 & 18	v	v	v	v	v	n	o	n	v	v	v	v	n	v	v	v	v	n	v	v	v	v	v	n	v	20	77%	1	4%	5	19%
	11. Insight in environmental and health impact of different plastics	19	v	v	v	v	v	v	v	n	v	o	v	v	v	v	v	v	v	v	n	v	v	v	v	v	v	23	88%	1	4%	2	8%
VI	12. Argued position statement regarding 'most sustainable plastic'	4 & 5 & 21	v	v	v	v	v	v	o	v	o	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	v	23	88%	3	12%	0	0%

for making this visible. Two groups only indicated that the purpose was to analyse or display the life cycle of a product, but there was a lack of deeper insight into *why* an analysis was being carried out. In 6 of the 26 groups, there was doubt whether they could *indicate boundaries of an LCA*. Students mentioned things that seemed irrelevant, vague, or (partly) incorrect, or just named impact categories without further explanation. This showed no evidence of real understanding of the boundaries of an LCA. The learning outcome was achieved by most groups, but at the lower limit in our opinion. It may be possible that through more guidance from the teacher, students could achieve this learning outcome more easily. A well-structured group discussion could ensure that students understand the limitations and possibilities of LCA better. Compared to the other expected learning outcomes, this one scored relatively low (see Table 4.5).

Outcome 7 (*insight in material & energy flows and understanding of impact categories: match substances to categories*) was expected to achieve 100%, because this is just filling in the supplied data in the right place. The assignment was not understood by seven groups and resulted in a disappointing 69% of the groups meeting the learning outcome. For Outcome 8 (*match impact categories to relevant stages in LC*), a satisfying percentage of 81% was achieved. During the lab experiments, the students looked at part of the life cycle in practice. They looked at the practical implementation of experiments but also at the impact of that part of the life cycle on nature. Most groups were able to show that different impact categories played a role in different parts of the LC of PLA.

Four learning outcomes remain to be discussed for the last two parts of the module. The key activities of these parts involved working with expert data, determination ranking of plastics, and final position statement. The majority of the students can be said to have mastered these four expected learning outcomes. For Outcome 9 (*understanding C2G(ate), C2G(rave) and C2C philosophies*), 81% of the groups were able to give a correct answer. For 10 (*comparing impact categories*), 77% of the groups were able to demonstrate sufficiently that this was controlled. For both 11 (*insight into environmental and health impact of different plastics*) and 12 (*argued position statement regarding 'most sustainable plastic'*) a satisfying score of 88% was achieved. In the closing group interviews, the final two learning outcomes were discussed. The results of the analysis for Outcomes 6 and 13 are shown in Table 4.6.

Table 4.6. Results of the expected outcomes: (6) Insight into the chain of events in the LC of PLA & (13) reflect on generic applicability and benefit of LCA. v = outcome present, o = outcome not fully (correct), n = outcome not present.

Insight into the chain of events in the LC of PLA		
v	2	15%
o	4	31%
n	7	54%
Reflect on generic applicability and benefit of LCA (for other processes and products)		
v	7	54%
o	5	38%
n	1	8%

Learning Outcome 6 was only understood by two groups. The results show that the majority of the students showed no *insight into the chain of events in the LC of PLA*. They indicated that they enjoyed doing the experiments, but they could not always transfer their knowledge to the complete picture.

...I could not place it [experiments done by the student] properly in the complete life cycle. (Student 31)

Some students mentioned that TA 6 made them realise that the LC of a plastic, such as PLA, contains many steps.

You saw how complicated the whole process is. (Student 49)

The expectation was that although the students would not do all the experiments themselves, they would still have enough of an overview regarding the various steps in the LC and their respective role. In the interviews, half of the students do not show that they had gained this overview.

Learning Outcome 13 scored better, with just over half the groups interviewed showing that group members could demonstrate an understanding of the generic applicability of LCA. The students answered the question of whether they understood the purpose of an LCA, and usually one student started to give an explanation, after which the other students added or explained things further. The students were able to make statements about a) viewing input and output, b) improving and comparing processes, c) content issues related to an LCA (impact categories, scope), d) the complete production chain.

4.8 Conclusion and Discussion

This article evaluated a module in which eleventh-grade students are engaged in performing an LCA to gain insight into the relative sustainability of bio- versus fossil-based plastics. The goal was to identify guidelines for teaching sustainability using LCA in secondary education. Two research questions were addressed, one focused on students' appreciation of the overall structure of the module and rating of the TAs, the second on the extent the expected learning outcomes were realised. Both research questions give a perspective on the students' perception of the coherency between TAs, content, and tools in the module.

The overall results indicate that it is possible to integrate LCA into secondary science (chemistry) education. The analysis of student appreciation (RQ1) showed that key activities were valued and positively scored (compared to other TAs) and most of them appeared to have achieved their goal. For example, TA5, reading new articles and group discussion, was said to be interesting because they learned from each other's opinion and it made them think more critically about their own opinion. This induced curiosity about the actual answer to the question of which plastic is the most sustainable.

The students indicated that working with expert data (TA16-19) let them to questions they did not have before. However in case of TA9, scope and boundaries of LCA, more guidance from a teacher or a well-structured group discussion could ensure that students understand the limitation and possibility of LCA better. The teacher can help the students by taking an active role, not merely to support students only when they need help but, rather, constantly asking the students questions that help them gain further insight into the LCA methodology.

The analysis of the expected learning outcomes (RQ2) showed that most of them were achieved, but three were not fulfilled satisfactory: 7 (*insight in material and energy flows and understanding of impact categories: match substances to categories*); 6 (*insight into the chains of events in the LC of PLA*), and 13 (*reflect on generic applicability and benefit of LCA generic applicability of LCA*). These learning outcomes will therefore be briefly discussed.

The question (TA12) used to score Outcome 7 allowed for multiple interpretations, the lack of clarity in the question might have caused the lower score for this learning outcome. More urgent is the low score for Outcome 6; earlier research (de Waard et

al., 2022) had already shown that students had difficulty fully understanding the life cycle concept. By using the jigsaw expert method, the students only performed part of the whole life cycle, but it remained difficult for them to see the complete system. The possibilities to share information was not guided enough, therefore, more guidance is needed from the teacher or another (additional) TA. In case of Outcome 13, the students found it hard to transfer their knowledge to a different situation and did not show interest in another LCA. Reflections on metaknowledge is challenging for students (Schwarz et al., 2009), therefore more investigation of this reflection is interesting. Besides, we found indication that students perceived reflection as not meaningful. They were aware that they would not encounter a similar LCA task in their school career. On the other hand, the LCA in itself was not a learning goal: the LCA was a case with which sustainability could be examined in detail.

Reflections on the design

To conclude, the module taught learners more about LCA and sustainability in the context of plastics. It is important to get students to think carefully about sustainability, and this module succeeded in doing that – from actual change in opinion and behaviour, being critical of new information as opinion of others, to showing a possible way to analyse the currently so important concept of sustainability in a chemical way. Most of the key activities of the module were also appreciated by the learners and achieved their goals. Clarifying some of the questions, more guidance from the teacher, and a clearer structure and end goal could raise the effectiveness of the module. However, the goal of the first and last parts of the module were achieved. The first part allowed students to get acquainted with the subject easily. It activated existing knowledge and added some new information by sharing news articles and new insights through the group discussion. With the authentic phases of LCA, an attempt was made to do a realistic analysis with available scientific data. The work to be done was scientific and more challenging, which was then converted into an essay with proper argumentation and understandable language. By doing this in groups, each student can contribute, be it more on the more social questions or in the scientific activities. This seemed to be a promising structure for a module on LCA.

Guidelines for teaching LCA

The first four guidelines were also mentioned in the literature and formed the starting point for development of the module. Guidelines 5–7 are new and based on the empirical findings collected in a precious studies and this study. Together with the recommendations expressed in the literature on LCA in education, we

determined the following set of guidelines for teaching sustainability using LCA secondary science education.

No.	Guideline
1	Guided inquiry-based learning approach, active guidance by the teacher Our research showed that active guidance is important so students share information correctly with each other at crucial moments.
2	Four phases of the LCA as module backbone The authentic four steps of the LCA forms the backbone of a module for pre-university students. In a simplified form, the phases appear to be understandable and a suitable starting point for a module on sustainability.
3	Laboratory work Working on the experiments of the life cycle increases students' understanding of the actual life cycle of a product. This is possible in an expert group setting; however, it is important that the feedback loop is well organized. It is also a motivating, fun, and stimulating component.
4	Use expert data Give students the opportunity to substantiate the problem with real data, from real experts. This helps them to understand the urgency and complexity of the issue. However, the best way to work with expert data is to simplify it so students can work with it easily.
5	Students working together in groups Based on earlier studies (de Waard et al., 2020, 2022), group work facilitates low-threshold discussions between students. This promotes the exchange of opinions and reflection on own/ other point of views. It also enhances curiosity, which leads to intrinsic interest in the answer, which leads to willingness to find an answer.
6	Understanding the life cycle, in this case of a plastic, and its complexity Let students discover the complete life cycle of a product. This realization also helps raise awareness of the complexity of the sustainability issue, as the processes to get from raw materials to waste, and back again to raw materials, is quite complex and so is the impact on nature.
7	Make sure students have a clear view of the module's overall goal and setup The data showed that it is important that students maintain an overview of the module and can enter the LCA in a guided manner. The ultimate goal of the module can be found in the third and fourth phases of the LCA, which attempt to answer the central question of which plastic is the most sustainable. The goal must be clear, and all other activities should have a clear function in achieving this goal.

To implement guideline 6, we propose to have guidance from the teacher. The teacher can ask questions before/after the feedback loop of the expert groups. Guided questions can be offered to the students to structure their feedback loop. Taken to the extreme, the teacher could also discuss the complete LC of the plastic with the whole class. In case of guideline 7, we advise clearly discussing the ultimate goal at the start of the module, and look ahead to what is to come during the module. To these seven guidelines, we would like to add that a module on sustainability is preferably integrated in already existing subjects in the chemistry curriculum, which should be relevant for the students, which is in line with the literature (Riley & Tech, 2015). The integration of the module into an existing topic could help overcome the problem of a crowded chemistry curriculum.



4.9 Limitations

Two case studies at two schools ultimately provided the data on which the conclusions were drawn. The data collected in this study were mainly at the group level. It could be interesting to realise a more in-depth research to investigate students' individual progress. The availability of in-depth information on sustainability aspects of plastics is also an important prerequisite. The LCA data were well-documented and had already been judged feasible for use in chemistry education (de Waard et al., 2020, 2022). The module could be used in a different context, but for this a teacher would also have access to expert LCA data, because such data are an essential part of the module and provide good substantiation in terms of content. This requires skill on the part of the teacher to put this data together to form a new module on sustainability in a different context. The module is mainly scientific in nature due to the use of LCA. It is therefore not an unexpected outcome that the students' arguments mainly have a scientific or ecological background. Ethical arguments were seldom found in the essays. There could be more focus on the more moral side in the module; for example, behavioural changes are noted in the interviews but not really deepened in a teaching activity.

4.10 Further research

This study focused on a complete trial of a module teaching sustainability using LCA in upper secondary education, which was explicitly aligned with the authentic LCA procedure. We advocate further empirical research to investigate the prescriptive value and quality of the provided guidelines. The results obtained here support the design strategy of transforming authentic LCA practices into learning trajectories. Further elaboration of this design strategy is warranted to indicate to what extent they are ready for use in LCA education with other products or processes. More subjects and modules are needed to teach young students about sustainability and to prepare them for possible choices and decisions they will make in their future life. This also reveals an interesting topic for more research – namely, to what extent does a module on sustainability also create behaviour changes. A disadvantage of a module like this is that it is a time-consuming process due to the numerous activities, such as an introduction, the four phases of LCA, practical work, and making a product in which the learning outcome can be tested. Time is often scarce and can therefore have a deterrent effect for teachers who consider using it. It could thus be interesting to investigate what parts of the module could be more

compact to reduce class time spent on the module that may limit time spent on all other subjects that a teacher has to cover.

To conclude, because sustainability is a prominent theme in society, it is also important that it be included in subjects such as chemistry to teach students about broader aspects of sustainability. Students in secondary school must learn to talk, think about, and discuss sustainability. LCA in secondary chemistry education can equip students with skills that will make them think more about sustainability and allow them to understand the complexity of sustainability issues. Chemistry can thus contribute to move society towards a more sustainable way of thinking.



Appendix 4.1

Part of the module, teaching activities, key activities and questions (Q.I. = individual question, Q.G. = group question, A = activity as a group)	Purpose of key activities
<p>Part I: Introduction</p> <p>Introduction to the central question: which plastic is the most sustainable? A bio- or a fossil-based plastic.</p> <p>Introductory questions, watching a video, reading news article, group discussion, writing an essay</p> <p>TA 1. Q.I. What words come to mind when you think of sustainability? Write down at least five.</p> <p>TA 2. Q.I. a. What do you do in your daily life to contribute to a sustainable world? b. What would you have to do to call yourself sustainable?</p> <p>TA 3. Q.I. What do you think industry should do to be able to call itself sustainable?</p> <p>TA 4. Q.I. Indicate below which of the two types of plastics you think is the most sustainable. Explain this in two sentences. Also explain in two sentences why you think the other group of plastics is less sustainable. [Table with examples of bio-based and fossil-based plastics].</p> <p>TA 5. A. Individually reading news articles and group discussion of the content</p> <p>TA 6.1 Q.I. Take a look back at your answer to TA 4. Do you still agree with the choice you made? If so, have you heard any new arguments that further substantiate your choice? If not, explain why you changed your mind.</p> <p>TA 6.2 A. Write an essay (first essay) with your group about the choice made for the most sustainable type of plastic: bio-based or fossil-based plastics. The essay should have a maximum of 500 words. Provide at least two arguments that support your opinion, a counterargument, and a refutation of the counterargument.</p>	<p>Supplementing existing knowledge, possibly questioning existing knowledge, and introducing other point of views (from the articles and from fellow students)</p>
<p>Part II: Theory</p> <p>Theory on life cycle in general: use, produce and recycling, (the four phases of life cycle assessment (LCA), the life cycle of poly lactic acid (PLA).</p> <p>Part III: The first phase of LCA</p> <p>Group discussion led by the teacher followed by group (3-5 students) assignments related to the goal, scope and boundaries of LCA on the production, use, and recycling of bio- and fossil-based plastics.</p> <p>TA 7. Q.G. Describe in your own words what the purpose of an LCA is.</p> <p>TA 8. Q.G. Which organisations (companies/government/knowledge institutes, etc.) have an interest in an LCA being carried out for the plastic PLA. Also note what purpose they have with the output of the LCA. Multiple answers are possible.</p> <p>TA 9. Q.G. For an LCA, a number of aspects will not be included in the analysis. Can you think of aspects we cannot take into account. (production, use and recycling phases)</p> <p>TA 10. Q.G. Note below any aspects that you think are also important to include in an LCA of PLA</p>	<p>Show students the limitations of the LCA for analysing a process/product</p>

Part IV: The second phase of LCA Introduction to the life cycle of PLA. In expert groups, all the experiments of the life cycle of poly lactic acid are performed. And let the students experience for themselves the materials and energy flows involved as a stepping stone to summarise these input and output resources into relevant impact categories. The aim was for students to demonstrate that they were aware that the impact categories actually played a role over the entire life cycle. See Figure 4.2

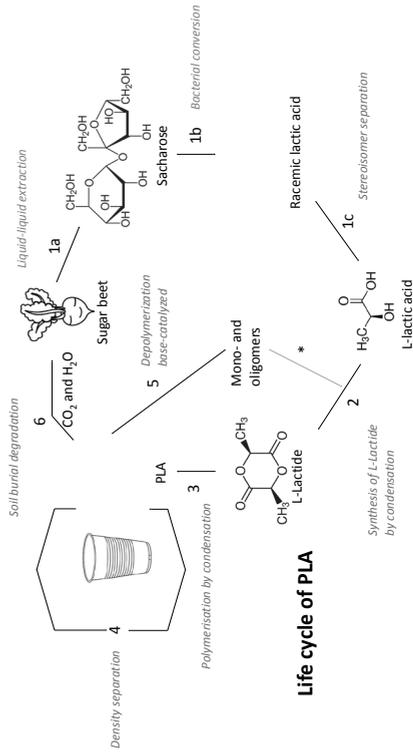


Figure 4.2. Life cycle of PLA

Part V: The third phase of LCA

- TA 11. Q.G. Fill in the table and indicate which steps of the life cycle have an impact on the environment. Decide that for the 7 impact categories (energy use, ecotoxicity, acidification, eutrophication, climate change, particulate matter emissions, ozone depletion)
- TA 12. Q.G. Fill in the Excel sheet with the LCA matrix
- TA 13. Q.G. Which step in the life cycle of PLA has, according to you, the largest impact on the environment?
- TA 14. Q.G. Write down which of the plastics you are going to compare. Explain why you chose these plastics.
- TA 15. Q.G. Explain why you chose C2Gate or C2Grave studies.
- TA 16 – TA 19. Q.G. Working with expert data (Figure 4.3)
 TA 16. Fill in the table with all the values for the four plastics you have chosen.
 TA 17. Determine which of the plastics has the largest impact on the environment for every impact category. Write down these rankings in the LCA matrix Excel sheet (Figure 4.4).
- TA 18. Q.G. Prioritise the impact categories.
- TA 19. Q.G. What is the ranking of the four plastics. Do you agree with this ranking? Think of an aspect in which the plastic at ranking 2 can be improved.

Letting students look at a sustainability issue using real scientific data. Introduce an authentic working method and let them try to reach a conclusion.

	Energy MJ/kg polymer	Ecotoxicity CTUe/kg polymer	Acidification kg SO ₂ eq/kg polymer	Eutrophication kg PO ₄ eq/kg polymer	Climate change kg CO ₂ eq/kg polymer	Particulate matter formation kg PM _{2.5} -10eq/kg polymer	Ozone depletion kg CFC-11 eq / kg polymer x 10 ⁻⁶	Costs* €/kg polymer
Fossil HDPE	78-80	-	0.07 - 0.022	0.001-0.003	1.8-2.6	-	0.80	500
Fossil LDPE	-	-	0.028	0	1.9-3.05	-	1.80	500
Fossil PET	12-82	12	0.009 - 0.018	-	2.3-5	0.002	0.10	1000
Fossil PP	74-79	-	0.049	0.001-0.006	1.5-3.6	0.007	0.02-0.8	500
Fossil PS	88	-	-	-	3	-	-	900
Fossil PVC	50	0	0.004	0.0005	1.5-2.3	0.002	0.00	500
Bio PBS	64	-	-	0.009	2.2	-	0.30	2000 - 5000
Bio PET	8-11	25-34	0.013 - 0.03	0.001	2.0-5.6	0.01	0.00	2000 - 5000
Bio PHB	2-58	-	0.013 - 0.025	0.002 - 0.005	-1.7-4	0.014	0.10	> 3500
Bio PLA	40-87	-	0.008 - 0.021	0.002 - 0.005	0.5-2.9	-	0.0 - 5.3	<2000
Bio TPS	-	-	-	-	-	-	-	<2000
Bio PVC	72-99	3-4	0.013 - 0.019	0.002 - 0.0025	0.02-2.7	0.0055	0.01	2000 - 5000

* values are averages

Figure 4.3 Part of the Excel sheet with the expert data

Impact category	weighing factor	BioPLA	BioPET	FossilPP	FossilPET
Energy	0.05				
Ecotoxicity	0.40	1	2	4	3
Acidification	0.00	4	1	2	2
Eutrophication	0.00	4	2	3	1
Climate change	0.50	3	1	1	2
Particulate matter formation	0.05	1	4	3	2
Ozone depletion potential	0.00	2	1	4	3
Weighting factor complete?	YES	3	1	4	2
Points earned per plastic					
Ranking plastics					
		17	12	21	15
		3	1	4	2

Figure 4.4. Matrix in which the students do their analysis, using the expert data

TA 20. Q.G. Look at the pricelist for the production of the plastics. What do you notice?

Part VI: The fourth phase of LCA

TA 21. Q.I. What is the most sustainable plastic?

TA 22. Q.G. Write an essay (second essay) about the question: Which plastic is the most sustainable: bioplastic or fossil-based plastic?

Letting students with limited word count try to look at a sustainable issue from different angles. Let them argue concisely and substantiate the answer to a sustainability issue.

Appendix 4.2: Coding scheme

Expected outcomes are briefly described below. In some cases, examples are given (not the only possible answers).

Part	Expected outcome	Description	Data sources	
			Written answers of students	Interview questions
Part I Introduction	1. Awareness of sustainability and plastics	In the answer, the students explain why a plastic can be or is not sustainable. Examples: (no) renewable source, remains a long/short time in nature, emission of (harmful) substances.	TA 4, 6 (individual)	
	2. Awareness bio- and fossil-based plastics	In the answer, a distinction is made between two types of plastics (difference(s) based on own presumptions, not necessarily truthful). Distinctions can be made based on raw material, durability, degradability, obtain raw material/extraction, short or long carbon cycle. If a student indicates that a type of plastic (fossil or bio) is more easily degradable or easier to recycle, this is seen as sufficient awareness of two types of plastics as long as there is a comparative word (e.g., easier, better).	TA 4, 6 (individual)	
	3. Own and industry contributions	Identifying both things the student can do to be sustainable and identifying things the industry should/could do. Examples, student contribution: take short showers, eat less meat, second-hand clothing. Examples, industry: emit fewer toxic substances, use green energy, reuse.	TA 2, 3 (individual)	
Part II phase of LCA	4. Able to describe purpose of LCA	Student should give a good example of a possible goal of an LCA. Examples: improving/sustaining a process, mapping the in/output of a process/product on the environment, environmental impact, mentioning examples of an impact category (e.g., climate change, energy use, acidification).	TA 7 (group)	
	5. Able to describe scope and boundaries of LCA	The student must give at least one example of a boundary for one of the phases (production, use, recycling). Examples: not including production of the needed equipment (machinery, factory, vehicles), transportation, the use phase/consumer use, production/extraction of raw materials, completely exclude part of the LC (use or recycling) e.g., with C2Gate use and recycling will be omitted.	TA 8, 9 (group)	
Part III First phase of LCA	6. Insight into the chain of events in the LC of PLA	The students should be able to retrieve details of the LC of PLA. This can be in the form of details from their own experiments, but also in the realisation that the LC of PLA consists of many different steps. Both show that there is insight into the chain of events that take place in the LC.		All questions



CHAPTER FOUR

Part	Expected outcome	Description	Data sources	
			Written answers of students	Interview questions
Part IV Second Phase of LCA	7. Insight into material and energy flows (LCA of PLA) and understanding of impact categories (i.c.): match substances to categories	Answer to the question is production. This follows from correctly viewing/entering the data. However, it is possible that recycling is also mentioned because it was close to the scores of the production phase.	TA 13 (group)	
	8. Match impact categories (i.c.) to relevant stages in LC (production, use, recycling)	Indicate where a specific i.c. can have influence: from data or from own assessment. In TA11, the students must write 'yes' at least 5 times to show that they realise that more than one i.c. has an impact and sometimes the same i.c. in more parts of the LC.	TA 11 (group)	
Part V Third phase of LCA	9. Understanding C2G(ate), C2G(rave), and C2C philosophies	Student must give a correct argument for choosing the scope (cradle-to-gate or cradle-to-grave). Examples for C2Gate: Only interested in the production, more data available, not much information available from the use phase (that makes cradle-to-grave) less truthful. Examples for C2Grave: interest in entire process, especially interested in recycling, most complete picture, concerns bigger part of the life cycle.	TA 15 (group)	
	10. Comparing impact categories (i.c.)	Students must give an i.c. weighting factor in their excel sheet, prioritize the i.c., substantiate the hierarchy.	TA 16, 17 (group)	
Part VI Fourth phase of LCA	11. Insight into environmental and health impact of different plastics	The students have to show their order of plastics in terms of sustainability based on their own findings for their chosen plastics.	TA 19 (group)	
	12. Argued position statement regarding 'most sustainable plastic' based on: (* environmental and health impact * priorities to * economic arguments * human behaviour	During the module the students has to update their statements. This happens between TA4/TA6 and between TA6/TA21. One of these times the answer must be refreshed. Examples: arguments from the news articles can be recognized, change of opinion, expression of doubt.	TA 4, 6, 21 (individual)	
Part VI Fourth phase of LCA	13. Reflect on generic applicability and benefit of LCA (for other processes and products)	The students should be able to explain what an LCA is or should be able to indicate why there could also be interest in the LCA of a completely different product (with an example).		Q 2, 4, 5, 8, 9

Appendix 4.3: Interview protocol

Evaluation module

1. What activities did you find the most important/instructive/fun?
 2. How useful did you find the module?
 3. How much did you enjoy doing the module?
-

Sustainability, LCA, and plastics

4. You have now learned and heard a lot about plastics and sustainability and LCA. Were there any surprising things you learned?
 5. Is LCA a suitable tool for saying things about sustainability?
 6. Do you think more attention should be paid to sustainability in science classes?
 7. Would you be curious about another LCA and analysing it?
-

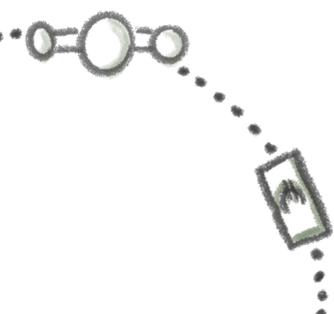
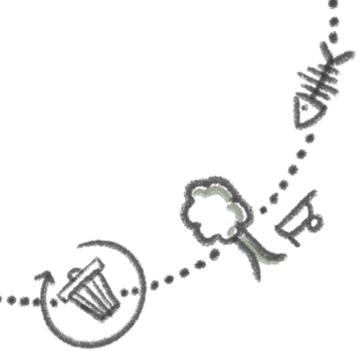
Knowledge gained

8. Can you explain why LCA is often used in sustainability issues?
 9. Do you feel you have more depth/tools to think about sustainability issues?
-

Conclusion

10. Do you have any comments/suggestions regarding the module?
-







CHAPTER FIVE

Pre-university students' life cycle reasoning in chemistry education



Pre-university students' life cycle reasoning in chemistry education

Abstract

This study reports on the development of the argumentation of secondary chemistry students while working on a module focussed on the life cycle assessment (LCA) of bio- and fossil-based plastics. At the beginning and end of the module, students, grouped in teams, wrote essays. The central question in the essays was: "Which plastic is more sustainable, a bio-based plastic or a fossil-based plastic?" The quality of the arguments in students' essays was analysed on the structure of the argument by means of the Toulmin argumentation model (claim, ground, warrant, backing, qualifier and rebuttal), the background of the argumentation (ecological, ethical, scientific and socio-economic), and the soundness of the arguments (weak or debatable). Toulmin's argumentation components and the soundness led to a combined score, dubbed the level of argumentation. In addition, the LCA content (impact categories) used by students was mapped. For most groups, an increased level of argumentation was determined and the number of debatable arguments decreased. A Wilcoxon signed-rank test showed a statistically significant change in mean argumentation level from 3.15 ± 1.16 to 3.96 ± 0.87 $z=-3.571$ (corrected for ties), $p<.001$, with an effect size of 0.70. The dominant background of the argumentation is scientific in nature and the most commonly used impact categories were climate change and energy use. This study shows and concludes that a positive development of argumentation is achieved in a module on a subject in sustainability in secondary chemistry education.

5.1 Introduction

Since the final decades of the 20th century, sustainability has become a prominent theme in society. The sustainability concept was introduced in 1987, as a means to stimulate the current generation to live in such a way that future generations would be able to live in similar quality of life (United Nations, 1987). The overall goal of sustainable development is to create an equilibrium between the economy and the environment, for the short term but especially for the long term (Emas, 2015). Sustainability is an important theme both at the levels of politics, industry, and science, and at an individual level. Citizens need to take responsibility and make sustainable choices in their everyday life to achieve a good balance between the comfort of living, economy, and the environment. Making sustainable choices starts with understanding the science behind sustainability as well as developing skills that are relevant for sustainable choices. This set of knowledge and skills goes beyond cognitive aspects and includes morals, values and insight into the long term effect of actions. The skill of such *environmental literacy* refers to the ability to become actively involved in balancing the qualities of life and the environment with the knowledge on solutions for environmental problems (Juntunen & Aksela, 2013b). For citizens, environmental literacy is essential for making well-considered choices in sustainability issues (Eilks & Rauch, 2012). For education, especially science education, it is important to provide students with opportunities to become involved in sustainability issues with an aim to develop their environmental literacy (de Haan, 2010). Currently, many studies in science education stress the importance of implementing sustainability issues in school science. In response to this call, many national curricula have incorporated the concepts of green chemistry and sustainable chemistry, that share goals that are similar to those stated by national and international bodies, such as IUPAC (Martinez, 2013) and the United Nations sustainable development goals (United Nations, 2023). This has led to the idea of Education for Sustainable Development (ESD). The field of ESD encompasses numerous interdisciplinary concepts and terms that have to do with knowledge, morals, skills and the effects of actions (Nichols, 2010). A challenge for teachers is how to cover all dimensions of sustainability and how to choose pedagogies that are suitable for ESD.

A possible approach to ESD is to acquaint students with methods used in the practice of sustainable chemistry and so help them understand both the complexity of sustainability issues and the solutions to tackle this complexity. In this article, we focus on a well-known method, called life cycle assessment (LCA) (de Waard et al.,



2020, 2022; Juntunen & Aksela, 2013a, 2013b, 2014; Tolppanen et al., 2021). LCA is used to assess the environmental burden and health impact of a product and/or process, throughout its complete life cycle, from acquisition of raw materials to utilizing waste (Blackburn & Payne, 2004; Vervaeke, 2012; Walker & Rothman, 2020). The value of teaching LCA has already been demonstrated in higher education. Studies have claimed that teaching LCA supports scientific development (Masanet et al., 2014), increases students' understanding and awareness of environmental issues (Weber et al., 2014), motivates students (Balan & Manickam, 2013), and increases interest towards science (Meo et al., 2014). In addition, LCA can help students to get a broader sense of sustainability and to help them to develop relevant skills, as it can also be used to discuss issues, such as values or human rights, and how psychology, norms, and marketing may affect our consumption (Mälkki & Alanne, 2017; Tolppanen et al., 2021).

LCA can be characterised as a scientific method that fuels critical thinking and reviewing sustainability issues from multiple perspectives. To our knowledge, only Juntunen and Aksela (Juntunen & Aksela, 2013a, 2013b, 2014) and Tolppanen et al. (2021) have examined the use of LCA in education in secondary science education. These studies found that LCA fostered students' scientific and ecological argumentations skills, and to a lesser extent arguments in the ethical and socio-economic category. The authors indicate that their analysis was focussed on mapping the structure of students' arguments according to Toulmin's model of argumentation, which is only one lens through which argument quality may be viewed. The authors advocate to design and evaluate pedagogical approaches that support students to develop sophisticated arguments in sustainability issues. This study builds on and extends the studies of Juntunen et al. by investigating the quality of students' arguments about the sustainability of bio- and fossil-based plastics through engaging them in LCA on the production of plastics.

5.2 Background

In this section we describe the structure of the LCA with its four phases, followed by a brief literature review about critical thinking and argumentation, and the different types of lenses that can be used for the analysis of the students' argumentation.

Life cycle assessment

Life cycle assessment (LCA) is a method that helps making the level of sustainability of products and processes measurable to some extent. The method consists of

four phases (International Organization for Standardization, 2006), in which the first phase is the determination of the goal and scope. This phase leads to a decision on what the desired outcome will be and in what kind of system. The scope should be defined to establish what part of the life cycle will be considered and which peripheral matters are included or not. In the second phase, the inventory analysis of the life cycle is performed. Actual data and models are used to determine the input (e.g., raw materials, water use, and energy) and the output (e.g., emission of pollutants and waste streams) of a certain part of a product's life cycle (Gironi & Piemonte, 2011b). This data is categorized into impact categories with suitable indicators. The third phase is an impact assessment, in which the environmental impact of every aspect of the life cycle is evaluated on magnitude and significance (Harding et al., 2007; Margni & Curran, 2012). The fourth and final phase summarizes the results of the second and third phase leading to a conclusion in line with the intended goal(s) set in the first phase. From a chemistry perspective, LCA is a unifying approach (Juntunen & Aksela, 2013a): it combines green chemistry (Anastas & Lankey, 2000; Poliakoff et al., 2002), sustainable chemistry (Böschchen et al., 2003) and sustainable engineering (Eissen, 2012) – all of which include aspects of science ethics and moral awareness (Burmeister et al., 2012; Zeidler et al., 2005).

Critical thinking & argumentation

In responding to calls to improve *environmental literacy* in school science, there is an increasing emphasis on ensuring that young people are able to use their scientific knowledge to construct and critique arguments about socio-scientific issues (SSI) which impact society now and in the future. Thinking about SSI involves a consideration of, among others, scientific, economical, legal, societal, religious and ethical aspects. Students engaging with SSI need to be able to understand the underlying science and sources of evidence, and weigh up appropriate evidence, ask relevant questions and consider the perspectives of different stakeholders (Sadler & Dawson, 2012). Students need regular opportunities to develop and practice their argumentation skills about SSI alongside the relevant scientific concepts at hand. The process of argumentation is considered a central component of critical thinking (Ennis, 1985) and an essential scientific process (Newton et al., 1999). As a result, considerable effort has gone into promoting the development of students' argumentation skills in school science, as well as measuring argumentation skills. In general, students tend to make claims without adequate justifications and they do not pay enough attention to opposing positions in the form of counter positions or rebuttals (Sadler, 2004). It has been advocated that if more scientific argumentation is asked for, students need

considerable time to become familiar with the topic first (Osborne et al., 2004). This puts constraints on the SSI to be studied; it should be complex, but not too broad in scope for students to engage with (Hancock et al., 2019). In a previous study (de Waard et al., 2020), we used the sustainability of bio- versus fossil-based plastics as SSI and elaborated and mapped students' initial arguments. This study showed that the students are sensible to the complexity of the issue and are able to argue on the level of sustainability.

Lenses of argumentation analysis

Ways of measuring the quality of arguments have been hotly debated (Erduran, 2007; Sampson & Clark, 2008), which gave rise to the emergence of different methods of measuring argumentation quality. In this study, we employ three lenses of analysis. The argumentation of the students is analysed on 1) argumentation components, 2) background, and 3) soundness. In turn, this gave input for further analysis of the level of argumentation and the LCA impact categories (LCA content).

The first lens is to examine the presence or absence of the argumentation components of an argument, based on Toulmin's argumentation model. This model illustrates the structure of an argument in terms of an interconnected set of a claim; grounds that support that claim; warrants that provide a link between the grounds and the claim; backings that strengthen the grounds; qualifiers that state under which conditions the claim is true and finally, rebuttals which point to the circumstances under which the claim would not hold true (Toulmin, 2003).

Although Toulmin's model is a flexible and valuable tool for assessing the structure of argumentation, it assesses only one aspect of the quality of arguments (Zohar & Nemet, 2002). Lunsford (2002) mentions that gauging the quality of arguments is, in Toulmin's terms, a 'field-dependent' matter. In the field of sustainability, arguments are commonly considered in terms of socio-economic, ethical, ecological and scientific background (Liu et al., 2010), which were also used in the study of Juntunen and Aksela (2014). The second lens in this study is therefore the background of the students' arguments. Ecological statements will, among other things, include comments on ecosystems, biodiversity and effects on ecosystems. Ethical statements contain, for example, opinions related to values, aesthetics, environmental ethics and scientific statements describe resources, technologies, materials, and safety. The final background, socio-economic, contain comments on costs or benefits and economic development.

The third lens we used is the assessment of the soundness of the statements, i.e., whether there is a case of erroneous reasoning. In scientific contexts, the use of scientific evidence to support a claim is used to convince others of the claim's validity. The correct use of scientific evidence is knowledge that is in a certain way ratified by the scientific community (theories, models, concepts, empirical findings). However, this knowledge should be used in the correct context (Klopp & Stark, 2020). Erroneous reasoning can be observed as 1) no justification or support for claims at all (Sadler, 2004), 2) the justification of claims by inappropriate use of scientific theories, models or concepts, 3) by the use of non-scientific knowledge that originates from everyday observations, experiences, beliefs or implicit theories (Klopp & Stark, 2020). This can result in hasty generalizations, jumping to conclusions and the use of information without a suitable authority. The content soundness of the argument becomes questionable if a form of erroneous reasoning is used. A list has been compiled from literature with forms of erroneous reasoning that could be taken into account during the analysis of the content soundness of the arguments: 1) making false generalizations, 2) using incorrect facts, 3) jumping to conclusions, 4) using information without a suitable authority, 5) drawing the wrong conclusion and, 6) concluding causality from correlation only.

The first and third lens (argumentation components and soundness) can be used in further analysis of the student's argumentation. Erduran, Simon and Osborne (2004) have illustrated that Toulmin's model can be used to judge the enhanced quality of argumentation. They developed a framework on quality in terms of five levels of argumentation. The first level includes arguments that only consist of (counter-) claims. The second level adds either data, warrants or backings to the arguments. The third level adds an occasional weak rebuttal; the fourth levels show a clearly identifiable rebuttal. In the fifth and final level, the argumentation displays an extended argument with more than one rebuttal. (Erduran et al., 2004)

The second lens (background) provides an entry point to look more substantively at the students' arguments. Since the students are following an LCA module, it is also interesting to see to what extent LCA content (LCA impact categories) is reflected in the students' arguments. For the analysis, seven impact categories are distinguished: 1) energy use, 2) ecotoxicity, 3) acidification, 4) eutrophication, 5) climate change, 6) particulate matter emission, and 7) ozone depletion.

5.3 Research aim and questions

The aim of this study is to investigate to what extent explicit LCA teaching improves students' understanding of the complexity of sustainability issues, evidenced by sophisticated, well-balanced and sound arguments. We analysed students' arguments as put forward in their essays made during and after a lesson series on LCA on argument components, background and soundness. Furthermore, the essays of the students received a level of argumentation and their argumentation was examined for the use of the LCA impact categories. The following research question is addressed:

How does the argumentation of pre-university students develop during a module using an LCA procedure to assess the extent of sustainability of bio- and fossil-based plastics?

5.4 Method

In this study, we evaluated a chemistry module on LCA. We start with introducing the module, followed by the description of the participants, data collection and analysis.

Outline of the module

Table 5.1 and Appendix 5.1 provide an overview of the module. It starts with introductory questions about sustainability and plastics (teaching activity, TA 1-4) in Part 1. In these introductory questions, the central sustainability theme in this module is stated: what plastic do you think is the most sustainable, fossil-based, or bio-based plastic? The students read news articles and have a group discussion (TA 5), write down their own opinion on the central sustainability theme and write an essay on the same theme in a group (TA 6). This continues in Part 2, consisting of a series of lectures about the life cycle of a product, life cycle assessment and the specific life cycle of the plastic polylactic acid. In Part 3, students perform the first phase of the LCA; with guiding questions, the students will determine a goal and scope for their LCA (TA 7-10). In the second phase of the LCA, they will perform the experiments of the life cycle of polylactic acid (PLA). All the students become experts in a selection of the experiments. After this, the third phase of the LCA is enacted, in which the students analyse which part of the life cycle of PLA has the largest impact on the environment (TA 11-13), using expert data. The students continue with the comparison of four plastics, again with use of expert data, to determine which of the plastics is the most sustainable (TA 11-20). This is concluded in the fourth and final phase of the LCA. The students return again the central sustainability theme (TA 21) and write the final essay in groups (TA22).

Table 5.1. Overview of the module.

Part of the module	Teaching activities	Collected data
1. Introduction	TA 1-6	First essay (TA 6.2)
2. Theory	No teaching activities	
3. First phase of LCA	TA 7-10	
4. Second phase of LCA	Experiments	
5. Third phase of LCA	TA 11-20	
6. Fourth phase of LCA	TA 21-22	Second essay (TA 22)

During the module, the students write two essays in groups, both of which with a word limit of 400-500 words. The first essay is written directly after the introductory activities and the second essay is written at the end of the module after having conducted an LCA.

Participants

Three chemistry teachers participated with their chemistry classes on a voluntary basis. Four upper secondary chemistry classes from one school (grade 11) participated, with 99 students (aged 16-17 years) in total. One of the classes was taught by the researcher. The researcher also informed the other teachers about the module in short meetings, wrote a teacher's manual, and was available for further explanations and questions. All students completed a short questionnaire in which some characteristics of the group were collected.

Students were grouped in groups of three to five students each. TA 1-10 were performed in these groups. For the experiments in Part 4 of the module, the groups were split up and formed expert groups, each participating in a specific experiment illustrating part of the cycle of production and re-use of PLA. The remaining parts of the module (TA 11-22) were performed in the original groups, completing a "jigsaw" design (Aronson, 1978). The study was conducted in compliance with the faculty's ethical standards. All participants gave informed consent, following the considerations advocated by Taber (2014).

Data collection & analysis

The main data source consists of the essays written in TAs 6 and 22. A total of 26 groups submitted their two essays, and these 52 essays were analysed. The essays were split into individual quotes, i.e., sentences, parts of sentences or two or more



related sentences that contain a single statement. The quotes were scored using the lenses described above: first on the presence of argumentation components based on Toulmin's argumentation model (claim, ground, warrant, backing, qualifier and rebuttal). Second, each of the argumentation components were assessed in terms of background (ecological, ethical, scientific, socio-economic). In the third step, the quotes were assessed for soundness (sound or debatable).

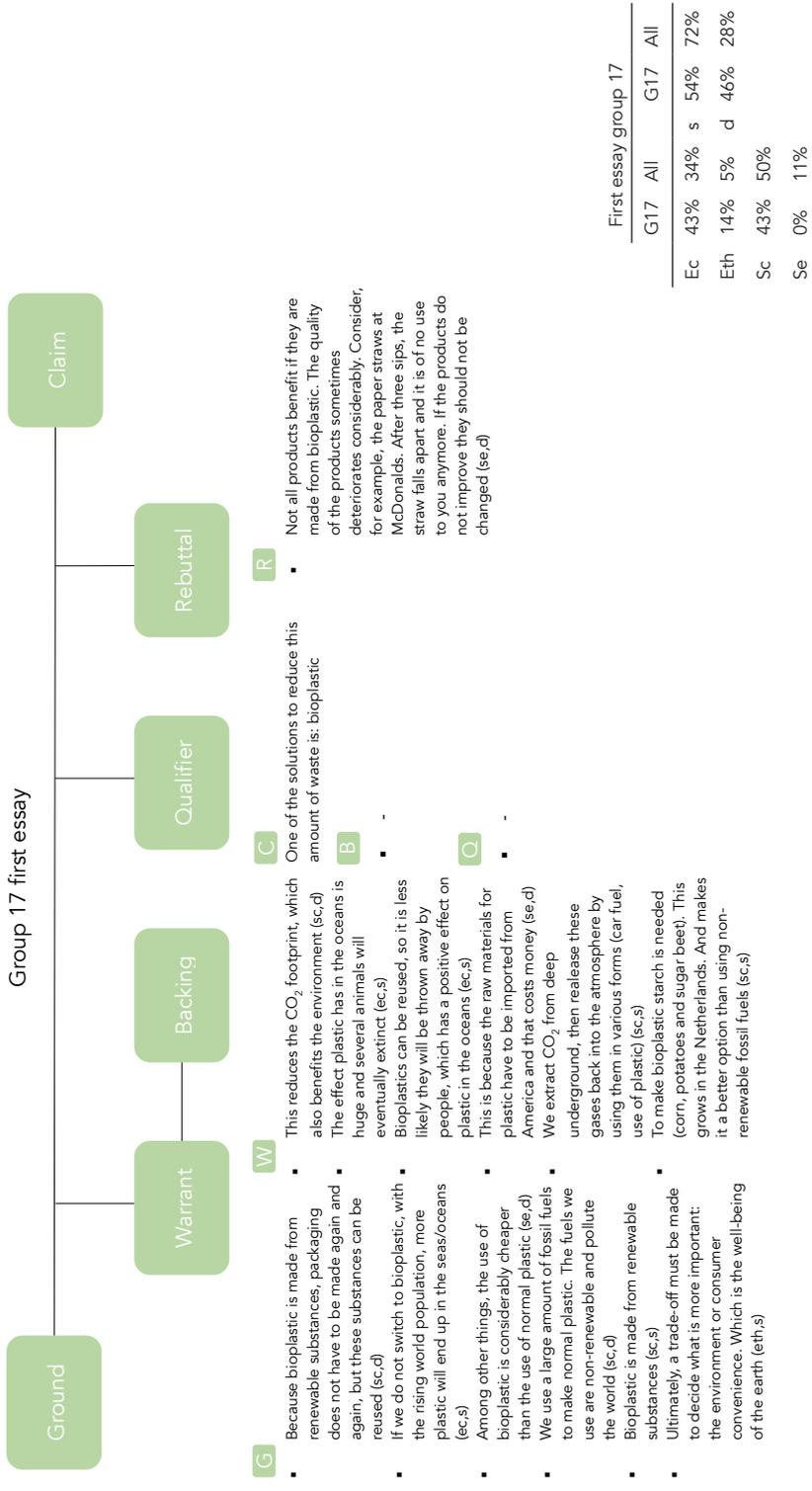
To obtain consistent and reliable scoring, two researchers jointly developed a codebook for the three rounds of coding. The resulting codebook was tested and updated by the two researchers independently by coding a third essay and comparing the results. Next, all essays were coded by the researcher and 10 essays from 5 different groups were coded by a second researcher to check for inter-coder reliability. An agreement of 87% was found between the two coders. Table 5.2 displays a summary of the codebook.

Table 5.2. Short description of the coding categories. * in case of soundness s = strong, d = debatable

First lens		Second lens		Third lens	
Argumentation component		Background		Soundness*	
Claim	Position of the argument in the essay	Ecological	Effects on the environment and species	S	Content of the quote is correct
Ground	Evidence that supports the claim	Ethical	Values, personal opinions	D	Content of the quote is debatable due to erroneous reasoning:
Warrant	Link between ground and claim	Scientific	Generally accepted facts, empirical data		- False generalizations
Backing	Substantiation of the warrant	Socio-economic	Cost, economics and waste		- Use of incorrect facts
Qualifier	Validity clause in which the claim is tenable				- Jumping to conclusions
Rebuttal	Statements of doubt, counterargument and other point of views				- Use of information without a suitable authority
					- Draw the wrong conclusion
					- Correlation does not imply causality

An example of the work of one of the groups is given below (Figure 5.1a & b). This group is selected because it contains examples of all possible codes. Both the analysis of the first essay and the second essay are presented. For readability, the students' texts are shortened and translated to English.

Figure 5.1a. Example of quotes coded for one of the groups, in this figure the first essay of group 17. In the table a comparison is made between this group (G17) and the average of all groups (All). The percentages show the share of codes (background and soundness) in the quotes. ec = ecological, eth = ethical, sc = scientific, se = socio-economic, s = strong, d = debatable



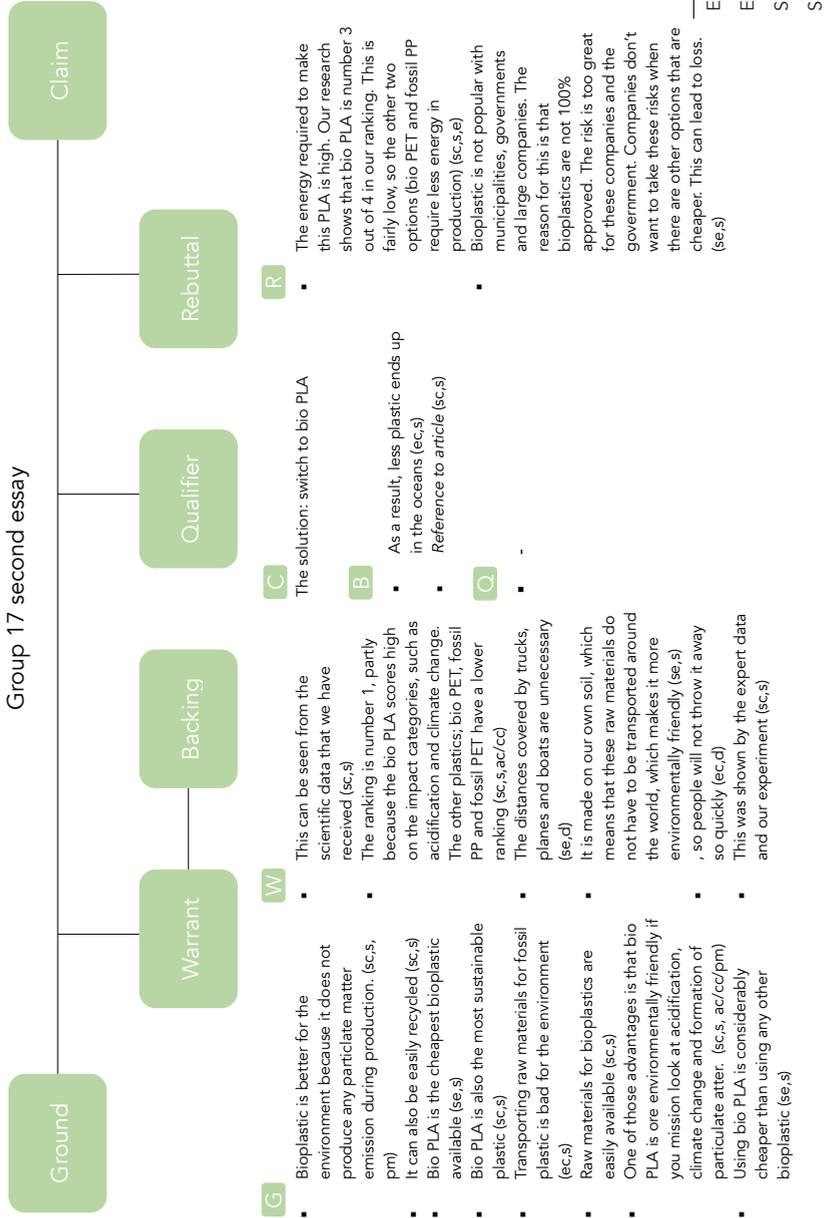


Figure 5.1b. Example of quotes coded for one of the groups. In this figure the second essay of group 17. ec = ecological, eth = ethical, sc = scientific, se = socio-economic, s = strong, d = debatable, w = weak. In this second essay also impact categories present: pm = particulate matter, cc = climate change, ac = acidification, e = energy

After the quality analysis of the arguments based on argumentation components, background and soundness, a level of argumentation was determined using a slightly adapted version of the levels of Erduran et al. (2004) presented in Table 5.3.

As the study of Erduran et al. (2004) used class discussions as data, in contrast to the essays used in this study, small adaptations were made. Whereas Erduran includes codes for counter-claims, which can occur in a class discussion, they will not be part of essays. Instead, we look at rebuttals within the essays. Only sound argumentation components were taken into consideration in determining the level.

Table 5.3. Description of the levels of argumentation based on the five levels of Erduran (2004).

Level	Description level
0	Argumentation that consists of a claim
1	Argumentation that consists of a claim & ground
2	Argumentation that consists of a claim, ground and either one warrant, backing, qualifier or rebuttal
3	Argumentation that consists of a claim, ground, warrant and one of: backing, qualifier or rebuttal
4	Argumentation that consists of a claim, ground, warrant and two of: backing, qualifier or rebuttal
5	Complete argumentation that consists of a claim, ground, warrant, backing, qualifier and rebuttal(s)



Level zero starts with only the presence of a claim; level five, the highest level, is defined as a complete argument according to Toulmin with the basic elements (claim, ground, warrants) together with one or more sound rebuttals and a more extended argument with both backings and qualifiers to make a more persuasive text.

The argumentation levels and the number of types of background before and after the LCA teaching, i.e., in the first and the final essays were compared using a Wilcoxon signed rank test.

Impact categories

As LCA includes impact categories, the aspects of the product's life cycle that is affected, Table 5.4 provides short definitions for several impact categories. All the quotes with background ecological and/or scientific were analysed for LCA impact categories as a subcode. If the students mentioned the impact category by name or gave descriptions that fit one of the impact categories, the quotes were coded with the corresponding impact category.

Table 5.4. Short definition of the impact categories.

Impact category	Definition
Energy use	Indicator for the amount of energy that is needed for processes
Ecotoxicity	Indicator for the harmful effect on the environment
Acidification	Indicator for the contribution to the acidification of soil
Eutrophication	Impact on atmosphere, water and earth by excess nutrients and phosphorus
Climate change	Indicator for the possible contribution to climate change by the emission of greenhouse gases
Particulate matter emission	Indicator for possible air pollution by particulate matter
Ozone depletion	Indicator for the impact on the depletion of the ozone layer

5.5 Results

Structural analysis of the argumentation

Table 5.5 gives an overview of the codes given to all 598 quotes that were found in the 52 essays.

Table 5.5. The scoring from all 52 (26 first and 26 second) essays. Each quote was scored as a specific argumentation component, as having a specific background and whether it was sound or debatable.

First essay												
Argumentation component	Background								Soundness			
	Ecological		Ethical		Scientific		Socio-Economic		Total	%	sound	debetable
	Sound	Debatable	Sound	Debatable	Sound	Debatable	Sound	Debatable				
Ground	23	6	5	1	47	21	7	5	115	43%	82	33
Warrant	24	10	2	0	34	16	6	1	93	35%	66	27
Backing	3	2	0	0	7	4	1	0	17	6%	11	6
Qualifier	2	1	2	0	3	1	3	1	13	5%	10	3
Rebuttal	12	1	1	0	4	1	5	4	28	11%	22	6
Total	64	20	10	1	95	43	22	11	266	100%	191	75
%	24%	8%	4%	0%	36%	16%	8%	4%	100%		72%	28%

Second essay												
Argumentation component	Background								Soundness			
	Ecological		Ethical		Scientific		Socio-Economic		Total	%	sound	debetable
	Sound	Debatable	Sound	Debatable	Sound	Debatable	Sound	Debatable				
Ground	22	0	4	0	70	1	17	0	114	35%	113	8
Warrant	27	0	6	0	72	0	19	0	124	38%	124	10
Backing	1	1	0	0	16	0	1	0	19	6%	18	1
Qualifier	2	0	1	0	5	0	7	0	15	5%	15	0
Rebuttal	8	6	2	0	15	12	12	2	57	17%	37	1
Total	60	7	13	0	178	13	56	2	329	100%	307	20
%	18%	2%	4%	0%	54%	4%	17%	1%	100%		93%	6,1%

In the first essay, 191 of 266 quotes were regarded as sound (71.8%) and 75 were judged as debatable (28.2%). In the second essay, 307 of the 327 quotes were judged as sound (93.3%) and 20 were judged as debatable (6.1%). In both essays, about 77% of the argumentation components were grounds and warrants and 23% were rebuttals, backings and qualifiers.

Looking at the background, most quotes were either scientific or ecological. In the first essays, 49.7% of the sound quotes is assessed as scientific, and in the second essays, this increased to 58.0% of the quotes. The picture of ecological quotes is different; their number decreased from 33.5% in the first essay to 19.5% in the second. The socio-economic quotes show an increase from 11.5% to 18.2%. Finally, ethical arguments are relatively rare with only 5.2% and 4.2% of the quotes for both the first and second essay. A Wilcoxon signed-rank test showed that the increase of scientific and socio-economic backgrounds in students' arguments in the second essays were significant. For scientific from 3.65 ± 1.94 to 6.85 ± 2.56 $z=-4.022$ (corrected for ties), $p<.001$, with an effect size of 0.79, and for socio-economic from 0.85 ± 0.73 to 2.12 ± 1.70 $z=-3.216$ (corrected for ties), $p<.001$, with an effect size of 0.63.

Table 5.6 shows a cross-tabulation of the levels of the first and second essays. In total, the second essays of 11 groups (42,3%) were at the same level as their first essay. For 15 groups, the second essays (57,7%) were at a higher level. No group decreased in level.

Table 5.6. Number of groups, cross-tabulated according to the level of their first and second essays

		Number of second essays in level						Totals
		0	1	2	3	4	5	
Number of first essays in level	0				1			1
	1							0
	2			1	3	2	1	7
	3				3	3	1	7
	4					5	4	9
	5						2	2
Totals		0	0	1	7	10	8	26

A Wilcoxon signed-rank test showed that the second essays were of a significantly higher level, 3.15 ± 1.16 to 3.96 ± 0.87 $z=-3.571$ (corrected for ties), $p<.001$, with an effect size of 0.70.

LCA impact categories

All seven impact categories (energy, ecotoxicity, acidification, eutrophication, climate change, particulate matter emission, ozone depletion) were observed in multiple final essays. Table 5.7 provides the number of essays that included a certain impact category in the substantiation, together with a general description of how the impact categories were used.

Table 5.7. Number of groups that mention the impact categories in their essays, and a general description how the impact categories are used in the argumentation.

Impact category	Number of groups (out of 26)	General description
Climate change	26	The impact of CO ₂ on the greenhouse effect was mentioned, or the values of the expert data was used to make the comparison between plastics.
Energy	24	More pollutants are released to the environment if more energy was needed, or the expert data was used for the comparison.
Acidification	16	The negative effect of acidification on biodiversity (less diverse) was mentioned or expert data were used.
Particulate matter emission	13	Descriptions of the effect and consequences of particulate matter on human health or the expert data were used.
Ecotoxicity	13	Harmful substances are released during the life cycle of a plastic, which has a negative effect on ecosystems, or the expert data were used
Eutrophication	11	The effect on biodiversity (less diverse) in lakes and ponds was mentioned or the expert data were used.
Ozone depletion	11	The comparison of plastics was based on the results of the LCA/expert data.

5.6 Conclusion & Discussion

This study investigated to what extent the argumentation of the students improved as a consequence of performing a module on sustainability built around Life Cycle Assessment (LCA). The quality of the argumentation was measured in terms of: argumentation components, background, soundness, level of argumentation and LCA impact categories.

In terms of soundness and level of argumentation, we observe an improvement from the first to the second essay for most students. The students' arguments during the module on plastics and sustainability became more structured and sound. The increase in number of argumentation components shows that the students' arguments improved in completeness and richness. It should be noted that the students had to write both their essays within certain word limits, so the increase in argumentation can be ascribed to a better structure of the arguments and not to lengthier essays. The decrease in debatable quotes shows that the content of the essays has improved as the students provide better substantiation for their statements and are also able to note more sound facts and matters.

The determined level of argumentation for the first and second essays indicates a positive development in the level of argumentation for most groups: 15 out of 26 groups improved their essays, while no group decreased in level.

An important aspect of this study is the way we assessed the outcomes. Using essays for assessing students' argumentation is not directly connected to LCA, i.e., we did not test students' knowledge about the LCA method. This could be interpreted as that immersing students in a primarily scientific methodology such as LCA has a positive effect on their way of thinking, resulting in better argumentation. Possible contributions to this improvement can be exposure to expert data and the reasoning needed at each step of the LCA method.

Regarding the seven impact categories (energy, ecotoxicity, acidification, eutrophication, climate change, particulate matter emission, ozone depletion), we found that climate change and energy were mentioned most often. This could be explained by these two being the best known to students, for instance due to their occurrence in the media. Yet, all impact categories were mentioned by the students, with ozone depletion and eutrophication being the least-mentioned categories. This may of course be due to these categories being less affected by the plastics the students had chosen.

The background of the arguments was mainly scientific and ecological, with a notable shift to scientific in the second essay. It is not surprising that arguments with a scientific background will dominate in the context of a chemistry class. The influence of the module can be seen in the increase of socio-economic arguments. Also, socio-economic aspects were treated explicitly in the module, resulting in an

increase in socio-economic arguments. We therefore conclude tentatively that the information processed by the students during working on the LCA made its way to their final argumentation.

It is appropriate to comment on the small number of ethical quotes found in the essays. Juntunen et al. (2014) also found few ethical arguments in the debates in their study. Teachers observed informally that the students thought it was strange to write an essay in a chemistry class and that some of the questions about sustainability were not really chemistry. Feierabend et al. (2011) indicated that it is important that students do not see chemistry as just a collection of facts and theory; instead, chemistry education allows students to learn about sustainability and the discussions surrounding it. However, in our case, students might have thought that scientific substantiation would be preferred by their chemistry teacher, leading them to also favour scientific arguments over ethical ones.

Overall, the module we evaluated in this article shows potential to help students to improve their reasoning; however, more focus on rebuttals and ethical substantiation could help them even more. It would be good to pay more attention to ethical issues in chemistry courses, as that is part of sustainable reasoning.

5.7 Limitations

The units of analysis in this study were groups of three to five students. The development of the argumentation by individuals was not analysed. While the essays were written in a setting where talking and discussing were stimulated, we cannot be sure that all students benefitted from the activity. Group dynamics may have influenced the results. However, we see the group work in writing the essays as a positive experience for the students. Overall, our assessment method does provide a good impression of students' argumentations, although it would not be a proper summative evaluation of student knowledge.

As the data in this study were collected at a single school, the results may be typical for that specific set of students. However, based on grades and students' expressed interest in sustainability and chemistry, we can still argue that we had a group with a wide range of interest and aptitude for chemistry and/or sustainability.

5.8 Future research

In this study, we showed the potential of LCA to provide the students the possibility to look at a sustainability issue from multiple perspectives. In our case, the scientific perspective was prominent, with other aspects being less represented in student reasoning. We can see the current study as a first case study for applying LCA as a teaching mechanism to direct students' attention to sustainability aspects that go beyond the ones central in our module; especially ethical arguments could be stimulated.

This can be achieved by providing contexts other than plastics. Possibilities are batteries, energy transition, packaging materials, etc. An interesting challenge is to combine teaching of the chemical content with the complexity of the sustainability aspects and teaching and learning about the methods of chemistry and sustainability such as LCA.

In our study, we focussed on students' argumentation. Apart from this, it might also be interesting to analyse whether the students show some changes in behaviour when looking at different processes/products with LCA data. Do the LCA and the scientific data used also have an impact on insight into the sustainability of, for example, using packaging material?

During the analysis, only the sound quotes were used. We still kept track of the number of debatable quotes; however, it could be interesting to look more carefully into the debatable quotes: what are the kinds of incorrect reasoning students apply?

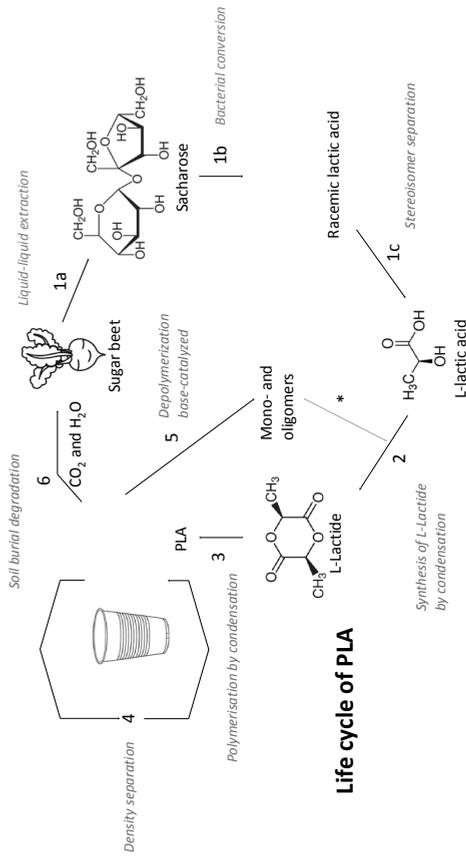
The module shows that the use of an LCA is an adequate method to get students to reason about sustainability. We advocate that teaching scientific methodologies can provide excellent routes to bring the theme of sustainability into chemistry classes.



Appendix 5.1

Description of the module, teaching activities, key activities and questions (Q.I. = individual question, Q.G. = group question, A = activity as a group)	Purpose of key activities
<p>Part I: Introduction</p> <p>Introduction to the central question: which plastic is the most sustainable? A bio- or a fossil-based plastic.</p> <p>Introductory questions, watching a video, reading news article, group discussion, writing an essay</p> <p>TA 1. Q.I. What words come to mind when you think of sustainability? Write down at least five.</p> <p>TA 2. Q.I. a. What do you do in your daily life to contribute to a sustainable world? b. What would you have to do to call yourself sustainable?</p> <p>TA 3. Q.I. What you think industry should do to be able to call itself sustainable?</p> <p>TA 4. Q.I. Indicate below which of the two types of plastics you think is the most sustainable. Explain this in two sentences. Also explain in two sentences why you think the other group of plastics is less sustainable. [table with examples of bio-based and fossil-based plastics].</p> <p>TA 5. A. Individually reading news articles and group discussion of the content</p> <p>TA 6.1 Q.I. Take a look back at your answer to TA 4. Do you still agree with the choice you made? If so, have you heard any new arguments that further substantiate your choice? If not, explain why you changed your mind.</p> <p>TA 6.2 A. Write an essay (first essay) with your group about the choice made for the most sustainable type of plastic: bio-based or fossil-based plastics. The essay should have a maximum of 500 words. Provide at least two arguments that support your opinion, a counterargument, and a refutation of the counterargument.</p>	<p>Supplementing existing knowledge, possibly questioning existing knowledge, and introducing other point of views (from the articles and from fellow students)</p>
<p>Part II: Theory</p> <p>Theory on life cycle in general: use, produce and recycling, (the four phases of) life cycle assessment (LCA), the life cycle of poly lactic acid (PLA).</p> <p>Part III: The first phase of LCA</p> <p>Group discussion led by the teacher followed by group (3-5 students) assignments related to the goal, scope and boundaries of LCA on the production, use, and recycling of bio- and fossil-based plastics.</p> <p>TA 7. Q.G. Describe in your own words what the purpose of an LCA is.</p> <p>TA 8. Q.G. Which organisations (companies/government/knowledge institutes, etc.) have an interest in an LCA being carried out for the plastic PLA. Also note what purpose they have with the output of the LCA. Multiple answers are possible.</p> <p>TA 9. Q.G. For an LCA, a number of aspects will not be included in the analysis. Can you think of aspects we cannot take into account. (production, use and recycling phases)</p> <p>TA 10. Q.G. Note below any aspects that you think are also important to include in an LCA of PLA</p>	<p>Show students the limitations of the LCA for analysing a process/product</p>

Part IV: The second phase of LCA Introduction to the life cycle of PLA. In expert groups, all the experiments of the life cycle of poly lactic acid are performed. And let the students experience for themselves the materials and energy flows involved as a stepping stone to summarise these input and output resources into relevant impact categories. The aim was for students to demonstrate that they were aware that the impact categories actually played a role over the entire life cycle. See Figure 5.2.



Life cycle of PLA

Figure 5.2. Life cycle of PLA

Part V: The third phase of LCA

TA 11. Q.G.

TA 12. Q.G.

TA 13. Q.G.

TA 14. Q.G.

TA 15. Q.G.

TA 16 – TA 19. Q.G.

TA 17. Q.G.

TA 18. Q.G.

TA 19. Q.G.

Fill in the table and indicate which steps of the life cycle have an impact on the environment. Decide that for the 7 impact categories (energy use, ecotoxicity, acidification, eutrophication, climate change, particulate matter emissions, ozone depletion)

Fill in the Excel sheet with the LCA matrix

Which step in the life cycle of PLA has, according to you, the largest impact on the environment?

Write down which of the plastics you are going to compare. Explain why you chose these plastics.

Explain why you chose C2Gate or C2Grave studies.

Working with expert data (Table 5.8)

Fill in the table with all the values for the four plastics you have chosen.

Determine which of the plastics has the largest impact on the environment for every impact category. Write down these rankings in the LCA matrix Excel sheet (Table 5.9).

Prioritise the impact categories.

What is the ranking of the four plastics. Do you agree with this ranking? Think of an aspect in which the plastic at ranking 2 can be improved.

Letting

students look at a sustainability issue using

real scientific data. Introduce

an authentic working

method and let them try

to reach a conclusion.



Table 5.8. Part of the Excel sheet with expert data

	Energy	Ecotoxicity	Acidification	Eutrophication	Climate change	Particulate matter formation	Ozone depletion	Costs*
	MJ/kg polymer	CTUe/kg polymer	kg SO ₂ eq/kg polymer	kg PO ₄ eq/kg polymer	Kg CO ₂ eq/kg polymer	kg PM2.5-10eq/kg polymer	kg CFC-11 eq / Kg polymer x 10 ⁶	€/kg polymer
Fossil HDPE	78-80	-	0.07 - 0.022	0.001-0.003	1,8-2,6	-	0,80	500
Fossil LDPE	-	-	0.028	0	1,9-3,05	-	1,80	500
Fossil PET	12-82	12	0.009 - 0.018	-	2,3-5	0.002	0,10	1000
Fossil PP	74-79	-	0.049	0.001-0.006	1,5-3,6	0.007	0,02-0,8	500
Fossil PS	88	-	-	-	3	-	-	900
Fossil PVC	50	0	0.004	0.0005	1,5-2,3	0.002	0,00	500
Bio PBS	64	-	-	0.009	2,2	-	0,30	2000 - 5000
Bio PET	8-11	25-34	0.013 - 0.03	0.001	2,0-5,6	0.01	0,00	2000 - 5000
Bio PHB	2-58	-	0.013 - 0.025	0.002 - 0.005	-1,7,4	0.014	0,10	> 3500
Bio PLA	40-87	-	0.008 - 0.021	0.002 - 0.005	0,5-2,9	-	0,0 - 5,3	< 2000
Bio TPS	-	-	-	-	-	-	-	< 2000
Bio PVC	72-99	3-4	0.013 - 0.019	0.002 - 0.0025	0,02-2,7	0.0055	0,01	2000 - 5000

* values are averages

Table 5.9. Matrix in which the students do their analysis, using the expert data

Impact category	weighing factor	BioPLA	BioPET	FossilPP	FossilPET
Energy	0.05	1	2	4	3
Ecotoxicity	0.40	4	1	2	2
Acidification	0.00	4	2	3	1
Eutrophication	0.00	3	1	1	2
Climate change	0.50	1	4	3	2
Particulate matter formation	0.05	2	1	4	3
Ozone depletion potential	0.00	3	1	4	2
Weighting factor complete?	YES				
Points earned per plastic		17	12	21	15
Ranking plastics		3	1	4	2

TA 20. Q.G. Look at the pricelist for the production of the plastics. What do you notice?

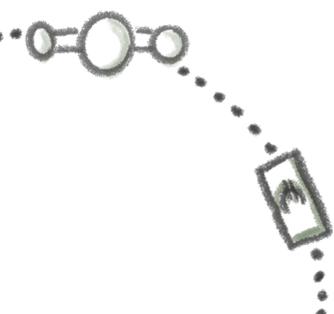
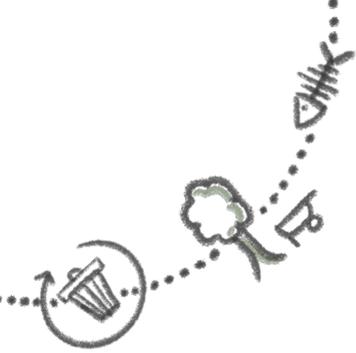
Part VI: The fourth phase of LCA

TA 21. Q.I. What is the most sustainable plastic?

TA 22. Q.G. Write an essay (second essay) about the question: Which plastic is the most sustainable: bioplastic or fossil-based plastic?

Letting students with limited word count try to look at a sustainable issue from different angles. Let them argue concisely and substantiate the answer to a sustainability issue.







CHAPTER SIX
General conclusion and discussion



General conclusion and discussion

The main aim of this dissertation was to explore how to teach sustainability education in chemistry classes in secondary schools. The previous chapters described the steps taken that focussed on teaching students about sustainability and on letting them discuss sustainability issues. These steps include evaluating the suitability of plastics as sustainability context, bringing the four phases of life cycle assessment (LCA) into chemistry classes, formulating guidelines and analysing the argumentation of the students.

The recurring question posed to students throughout all studies in this dissertation was:

What plastic do you think is the most sustainable? A fossil-based plastic or a bio-based plastic?

First, in the study in Chapter 2, we evaluate whether students in Grade 11 were able to reason about sustainability in the context of plastics with the information they received. We analysed the structure of students' arguments in terms of Toulmin's argumentation model (Toulmin, 2003). Students' awareness of the complexity and multidimensionality of the sustainability issue at hand was investigated based on the doubts, critical views and questions put forward by students. In the following study, described in Chapter 3, the four phases of the LCA were added to the activities of the first study. The students followed the life cycle of the bioplastic polylactic acid (PLA) and performed an LCA. Students were prompted to determine the goal and scope of the LCA, to perform an inventory analysis including lab experiments, to structure the data into LCA impact categories and finally to interpret the findings, to assess the overall impact and to answer the predetermined goal of the LCA. In Chapter 4, we describe and evaluated a teaching module in which the fourth and last phase of the LCA was extended by letting students analyse the impact of four different plastics, two bio-based and two fossil-based. Students were challenged to make a choice, using scientific expert data (Walker & Rothman, 2020), which plastic was most sustainable. From the development of the module and students' reactions we identified guidelines for modules on sustainability with the LCA as a method. Finally, in Chapter 5, we analyse the given argumentation of the students in terms of structure, background, soundness, and use of LCA impact categories, before and after performing the module.

In Section 6.1, the main findings and the conclusions of the four studies are presented. Sections 6.2 and 6.3 will reflect on main findings and conclusions, as well as on the methodology. Sections 6.4 and 6.5 discuss the limitations and give an outlook on future research. Sections 6.6 and 6.7 will discuss the enrichment of education and the considerations for textbook writers. This will be concluded with section 6.8 with a personal reflection.

6.1 Main findings and conclusions

In this section the major findings of the four studies (Chapters 2-5) will be described and discussed.

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

The aim of the first study is to investigate students' reasoning on the life cycle of plastics. Three research questions were formulated to investigate students' reasoning:

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

Knowledge in argumentation

This study focussed on the initial reasoning of the students and on the appropriateness of the context of plastics to induce discussions on sustainability. The analysis of the content of the argumentation showed that some of the twelve principles of green chemistry (Anastas & Warner, 1998) occur naturally in the argumentation of the students. Students often mentioned issues related to the efficiency of processes in terms of mass, energy, space, and time. They also mentioned issues related to pollution, design of a product, and the recycling or degrading in nature. However, some principles were barely mentioned in the argumentation of the students, such as those related to waste, energy and utilities, local sources for material and energy. Apparently, these principles are not within students' initial thoughts and need more attention in education to direct students toward incorporating these matters in their argumentation.



Structure of the argument

The students were given limited time to think about which plastic is the most sustainable. However, despite the very short period of time, we noticed that the students' argumentation was fairly complete. An adapted version of Toulmin's argumentation model, see Figure 6.1, turned out to be appropriate to analyse the students' argumentation. The number of qualifiers and rebuttals increased between the two moments of measurement. This finding was interpreted as an indication that students were starting to think more critically about their own claim. Also, in literature, an increase in rebuttals is regarded as an indication of an increasing and deepening level of reasoning (Erduran et al., 2004).



Figure 6.1. An adapted version of Toulmin's argumentation model. Original work: (Toulmin, 2003)

Complexity of the sustainability issue

The awareness of the students of the complexity and the multi-dimensionality of the sustainability issue was observed in the raised number of doubts in their argumentation, as also evidenced by an increasing number of qualifiers and rebuttals and by the statements that students were missing information to take position. Also, the students showed they were able to reflect critically on their claim, and some adjusted their claim based on other arguments or opinions that were brought in during the activities. This showed that the students are sensible to the complexity of the issue of sustainable plastic and underpins the suitability of the plastics context for reasoning about sustainability.

Key findings

- The prior content knowledge of secondary chemistry students was enough to build on and to elaborate on the sustainability issue at hand.
- The sequence of activities raised the number of doubts and questions among students, a need-to-know was triggered.
- The use of an adapted version of Toulmin's argumentation model proved to be adequate for the analysis of rudimentary, at this stage not very sophisticated, arguments.

- *Students showed awareness of the complexity of this sustainability issue at hand, evidenced by the adjustments of claims, notions of missing information, expression of doubts, and the increasing number of qualifier & rebuttals.*

Implication for education about sustainability

- *Introducing students into the sustainability issue can be organised through introductory questions, watching a video, reading new articles, and group discussions.*
- *The development of argumentation can be initiated through posing a central question, in the present case which plastic is the most sustainable.*

Engaging pre-university students in sustainability and life cycle assessment in upper-secondary chemistry education: the case of polylactic acid

The aim of the second study was to investigate to what extent LCA teaching fostered students' involvement in sustainability issues of the plastic PLA. By performing the four phases of an LCA, including phase 2, doing experiments, it was examined whether the students understand what a life cycle of a plastic looks like, and whether they understand the purpose and benefits of conducting an LCA.

Awareness of the life cycle and life cycle assessment

The students conducted an LCA on PLA. The lesson series proved to evoke in students a critical view on the life cycle of plastics. Progress in students' critical view of the data was noticed. The students showed that they were aware of the complexity of the issue at hand. They showed increasing awareness of lacking information and knowledge on the LCA data of fossil-based and bio-based plastics. However, it was observed that the students showed mainly life cycle reasoning and not really life cycle assessment. More time and proper instruction were needed for the students in order to show the ability to perform the life cycle assessment, i.e., to analyse which reaction step, in this case, is the most sustainable or, conversely, the least sustainable.

In this study, the students were able to perform the entire life cycle of the plastic PLA in lab experiments, but the students indicated that due to the jigsaw expert method that we employed in the design, they lacked insight into the complete life cycle of the plastic. But they were, for example, more aware of issues surrounding the reaction steps in the life cycle, exemplified by being able to talk about details from the experiments or whether the experiments could be used in the data collection of an LCA. It was observed that understanding of the concepts of biodegradation, renewability, and/or energy costs was improved.



Key findings

- *Engaging students in LCA proved effective in evoking life cycle thinking among students.*
- *LCA teaching predominantly evoked life cycle thinking in students, the qualitative part of an LCA, and might thus serve as a stepping stone towards the quantitative assessment.*

Implications for education on LCA

- *A brief introduction to the life cycle of PLA and the theory behind life cycle assessment should be clearly presented.*
- *Specific attention to the LCA phases in which the assessment takes places should be given.*
- *All students need a complete picture of the life cycle of the plastic PLA through, for example, visualisation.*

Teaching life cycle assessment in pre-university education

The aim of the third study was to identify guidelines for teaching sustainability using LCA in secondary education. To this end, we identified guidelines from literature for designing such a module, created a module and executed it with 167 students spread over 7 classes in 2 schools. For this study, we looked at the amount to which students appreciate participating, as well as the learning outcomes for each of the teaching activities in the module. Two research questions were posed:

1. *To what extent do students appreciate the overall structure of the module and value its teaching activities (TA), with an emphasis on the functioning of the key activities which reflect the guidelines?*
2. *To what extent are the expected learning outcomes, as formulated for each part of the module, achieved by students?*

Appreciation

The appreciation of the students towards the teaching activities was generally positive. The module consist of 6 parts. A short description of these 6 parts will follow. In addition, examples of key activities will be given. Part 1 was the introduction to the subject with, among other things, reading new articles followed with a group discussion. In Part 2, a theoretical background is given on the life cycle of PLA and the content of an LCA. Part 3-6 correspond to the content of the four phases of the LCA. In Part 3 (i.e., first phase of the LCA) the determination of the goal and scope

was one of the activities. Part 4 focussed on the second phase of the LCA, and therefore lab experiments were conducted corresponding to the different steps in the life cycle of PLA. Part 5 (i.e., third phase of the LCA) included working with expert data with which the students made an analysis of four different plastics and how well these plastics scored on the different impact categories of the LCA. Part 6 dealt with the fourth phase of the LCA and there the students tried to give an answer in an essay to the established goal from the first phase of the LCA (Part 3).

The results showed that the key activities mentioned above were also appreciated by the students, in both the questionnaires and the interviews. These activities were valued more positively compared to other activities in the corresponding part of the module. These key activities therefore appear to be rightly designated for both the appreciation of the students and for the learning outcomes.

Achieved learning outcomes

For each part of the module, it has been determined in advance what the desired learning outcome should be. In general, most of the learning outcomes were achieved. Below, a list of desired learning outcomes with a short description of the content of the learning outcome.

1. *Awareness of bio- and fossil-based plastic: The students should realise that these two types of plastics exist.*
2. *Awareness of sustainability and plastic: The students can explain why a plastic is (not) sustainable.*
3. *Contribution of yourself and industry: The students can give examples how sustainable choices can be made at home and in the industry.*
4. *Ability to describe purpose of LCA: The students can give good examples of goals of an LCA.*
5. *Ability to describe scope and boundaries of LCA: The students can give examples of boundaries.*
6. *Insight into the chain of events in the LC of PLA: The students can retrieve details of the life cycle of PLA*
7. *Being able to indicate which stage has the most impact on the environment: The students can determine from their data which stage of PLA (production, use, recycling) has the most impact.*
8. *Match impact categories to relevant stages in life cycle: The students can identify what steps in the life cycle of PLA score in an impact category.*



9. *Being able to argue the choice of scope cradle-to-grave, cradle-to-gate, cradle-to-cradle: The students can distinguish the three scopes.*
10. *Comparing impact categories: The students can give a weighting factor to the impact categories so that they distinguish between important and less important impact categories.*
11. *Awareness of environmental impact of different plastics: The students can draw conclusions from the order in which the plastics appear in their sustainability comparison.*
12. *Refreshing position statement on learning experience: the students can refresh and update their point of views during the module.*
13. *Generic applicability of LCA (for other processes and products): The students can explain what an LCA is.*

The learning outcomes were achieved except for two that were not satisfactorily achieved. The students were not sufficiently able to indicate which stages have the most impact on the environment. This learning outcome depended on only one activity from the module, which turned out to be multi-interpretable. The students were not sufficiently able to show a proper insight into the chain of events in the life cycle of PLA. The understanding of the chain of events should follow from the practical part of the module. However, due to the jigsaw method, the students did not perform the complete life cycle on their own. Therefore, they depend on information from other students, and apparently this transfer of information was not yet done properly. This was also observed in the second study.

Guidelines

From our experience with the module, we revisited the guidelines that we used as a start to underpin the design of the module. The purpose of these guidelines is to provide educational designers, practitioners, and teachers with useful heuristics for teaching LCA in upper secondary science education. The combination of the initial guidelines from the literature (1-4) together with the guidelines deduced from the analyses (5-7) formed a list of seven guidelines, which have a positive effect on the smooth running of an LCA module in secondary education.

1. *Guided inquiry-based learning approach, active guidance by the teacher*
Teachers are advised to give active guidance, so students can correctly share information with each other at crucial moments (information transfer after expert groups, guidance in group discussions)

2. *Four phase of the LCA as module backbone*
Authentic four steps of LCA in a simplified form appear to be understandable and a suitable starting point for a module on sustainability
3. *Laboratory work*
Increases students' understanding of the life cycle of a product
4. *Use expert data*
Students are able to substantiate their arguments with real data. In addition, this gives an opportunity to enhance understanding of the complexity of the sustainability issue. However, the expert data should be simplified, so students can work with it.
5. *Students working together in groups*
Facilitates low-threshold discussions between students, promotes exchange of opinions and enhances reflections of point of views, and inspires curiosity.
6. *Understanding the life cycle and its complexity*
Gives the realisation of the many steps in a life cycle and therefore helps to raise awareness of the complexity of the sustainability issue.
7. *Clear view of the module*
All the activities should have a clear function in achieving the goal of the module. Students should be aware of the function of every activity.

Key findings

- *A list of seven guidelines (guided inquiry-based learning, LCA as backbone, laboratory work, use expert data, working in groups, understanding of LC, clear view of module) aims to provide educational designers, practitioners, and teachers with useful heuristics for teaching LCA in upper secondary science education.*
- *The life cycle of the plastic of interest (PLA) was practically carried out with lab experiments using the jigsaw method, however, the students still do not feel that they have the complete overview of the life cycle.*

Pre-university students' life cycle reasoning in chemistry education

The aim of the fourth study was to investigate whether LCA can lead students to life cycle reasoning, that is, to understand the complexity of sustainability issues as evidenced by sophisticated, well-balanced and sound arguments. For this, we returned to the method used in the first study. For a subset of the students who performed our module in Study 3, we collected essays before and after performing the main parts of the module. The arguments were analysed both on structure, e.g., the aspects in Toulmin's argumentation model (Toulmin, 2003) as well as on



background, e.g., ecological, ethical, scientific, and socio-economic (Juntunen & Aksela, 2014), and on soundness. In addition, students' arguments were analysed on the use of LCA impact categories. Combining these aspects, a level of argumentation was determined (Erduran et al., 2004). The following research question was addressed:

How does the argumentation of pre-university students develop during a module using an LCA procedure to assess the extent of sustainability of bio- and fossil-based plastics?

Students' argumentation

Students' arguments during the module on plastics and sustainability developed towards a more structured and sound argument. The arguments in the final essays contained more structural components of Toulmin's argumentation model. For example, there was an increase in grounds, warrants, and rebuttals. Also, less debatable items were observed, which showed that the quality of the essays also improved. The level of argumentation increased for more than half of the groups with a statistically significant ($p < 0.01$) change in mean argumentation level with an effect size of 0,70. This could be explained by the increase in number of rebuttals and the decrease of debatable argumentation. This shows that the students provide a better substantiation for their statements and are also able to use and distinguish truthful facts and matters.

The background of the students' argumentation was mainly scientific. Ethical statements were scarcely used. The mostly scientific nature of the argumentations was a logical consequence of a module that employed a rather scientific approach. Especially the LCA data the students used in the module were very often also cited in their substantiation of their claim or for contradicting the claim.

Ethical argumentation which contained personal values or opinions was employed less. This was in line with previous research of Juntunen and co-workers (2014) Possibly the scientific subject, here chemistry, did not encourage the students to write an ethical substantiation. The expectation of the students might have been that the teacher expected them to write a scientifically written text with a limited amount of ethical substantiation. The students should be encouraged more to express themselves in a more ethical manner.

Key findings

- *In general, there was a statistically significant increase in the students' level of argumentation with a median effect size of 0,70 ($p < .001$).*
- *The background of the argumentation of the students was mainly scientific.*
- *The soundness of the arguments became stronger over the course of the module.*
- *The most mentioned impact categories were climate change, energy use, and acidification.*

6.2 Reflection on main findings and conclusions

Argumentation

The arguments of the students were examined in several ways, from the somewhat rudimentary arguments of the students in the beginning (Study 1 – Chapter 2) to the further developed essays with more sophisticated argumentation (Study 4 – Chapter 5). In both studies, the argumentation was analysed with Toulmin's argumentation model. The first study was used as an explorative study to analyse the initial argumentation of the students, while the fourth study was a more in-depth analysis.

Structure of argumentation – Toulmin's argumentation model

Toulmin's argumentation model proved successful in analysing the structure of the students' argumentation in both studies. Students, in general, tend to state their claims without an adequate justification and with primarily sociocultural arguments, as they touch upon their own opinion and world as experienced (Juntunen & Aksela, 2014). Moreover, for students to bring scientific arguments, they need time to search for information or learn more about the topic (Osborne et al., 2004). The quality of students' arguments in Study 4 significantly exceeded the quality of argumentation in Study 1. In Study 4, students completed a module in which they were given time to develop their arguments. The richness of the argumentation, focused on Toulmin's categories, is noteworthy. The fact that the number of rebuttals is increasing showed that the students' argumentation is deepening (Erduran et al., 2004). However, the quality of arguments cannot be assessed solely on the presence of Toulmin's structural components. Therefore, more lenses to assess the quality of students' argumentation are needed. In the first study, it was already indicated that no distinction was made between substantively correct statements and substantively incorrect statements.

In Study 4 to assess the development of the structure of the students' argumentation during the module, levels of argumentation were used in Study 4. These levels were



inspired by the work of Erduran (2004), who based the levels of argumentation on the presence of certain components of Toulmin's argumentation model. Flexibility was a positive feature in the analysis with the levels, because the levels could be adjusted at your own discretion. In our case, we mainly followed Erduran's levels, but we converted this approach to a minor extent to fit our purposes and the data collected. Since our students had to write an essay, students would not use counter claims, because the essay is based on one claim that is further elaborated. In addition, a slightly different distribution was made when analysing the rebuttals. In our case, the number of rebuttals does not define a level of argumentation, but only the soundness of the rebuttals. In this way, it was possible to follow the development of the structure of the students' arguments. To conclude, Toulmin's argumentation model showed to be a suitable and flexible method to analyse the structure of arguments as well as the argumentation levels of Erduran.

Content of argumentation

Where Toulmin is useful to evaluate the structure of an argument, we also need to assess the content of the arguments. For that purpose, the combination of structural components, background, and soundness seems adequate to grasp the overall quality of argumentation.

In the field of sustainability, arguments are commonly considered in terms of socio-economic, ethical, ecological and scientific aspects (Liu et al., 2010). These backgrounds were also successfully used in the work of Juntunen et al. (2014) to analyse students' argumentation in essays and debates. In our work, it was shown that it was a suitable method to map out more clearly in which direction the students are thinking. When defining scientific and ecological aspects, it was important to make a clear distinction. In our analysis, during the intercoder agreement, we noticed some overlap between these backgrounds. The students' statements could all be captured under one of the four categories. Increasing the number of categories could cloud the bigger picture and was therefore not desired. In our case, all students' statements could be mapped to one of these four categories, so changes in categories were not needed.

As for soundness, the assessment could use some improvement. In Study 1, the statements made by students that were not entirely sound were considered just as valuable as sound statements. Eventually, students must also be able to assess whether a statement by a peer was sound. This is one of the skills that ESD stands for,

namely the validation and justification of claims (Sadler & Zeidler, 2005). Therefore, the importance of assessing the distinction between strong and debatable statements also increased. In study four, we made that distinction, but we also concluded that the definition for strong and debatable statements is somewhat vague and should be documented very clearly.

Because the module focused on the LCA, it was relevant to analyse the students' argumentation regarding the use of specific LCA knowledge, basically the impact categories in the present case. The analysis was appropriate for the essays because it was possible to look more closely at the LCA knowledge used by students. On the other hand, there was also some criticism to be made on this judgement, because only the ecological and scientific statements were examined. This analysis could not be done for the socio-economic and ethical statements because they did not overlap with the impact categories. If a student had a mainly ethical and/or socio-ecological essay, the analysis of LCA content would not be high. However, this could be a good essay as well. It is important that even in chemistry classes ethical and socio-economic statements are as valuable as the scientific and ecological statements. As in the work of Juntunen et al. (2014), in our work the ethical category was mentioned less often. It is desirable that a subject such as chemistry explores a sustainability issue in a scientific way, but it is debatable whether the lack of ethical backgrounds is a great loss. The fact that the students can provide the arguments in a scientific way is to be applauded for a subject such as chemistry, but is it also good to explore alternative argumentations. The students needed skills for their whole life and if chemistry in secondary school were the final moment to learn about sustainability it would be a great loss if ethics were not discussed. At least, the students were able to express some moral arguments, but due to the fact that ethics are not often talked about in chemistry lessons, students need a bit more encouragement to express moral considerations in chemistry classes. Additionally, ethical arguments are the most personal of all, therefore the environment should be safe enough to share those personal expressions. It was clear that the students needed more encouragement to include the ethical arguments to their argumentation.

6.3 Reflection on methodology

Having a researcher design an educational module has advantages and disadvantages. In our case, the researcher was also a secondary school chemistry teacher, which gave realistic expectations of how certain activities would work in the classroom. It resulted



in a design of activities building on previous findings (Chapter 2-5), according to the ideas of educational design research. The structure of the module was designed with iterating sequences, which could be observed in the development and expansion of the module across the four studies. The activities used in the first study were included in the design of the module used in the second study and so on. This provided the necessary evaluations for further adjustments and extensions that followed from the conclusions drawn from the collected data. During the development of the module, it was challenging to gain complete understanding and expertise of the subject matter of sustainability and the LCA. A lesson study might have been a good alternative for the development of the module, but would also have meant that the teachers involved had to familiarize themselves with the LCA methodology.

6.4 Limitations

Sustainability as a context is relatively new. Most of the chemistry teachers have been taught about sustainability only to a limited extent. Only since 2007 has there been greater emphasis on sustainability in the curriculum of secondary school chemistry education. Since then, sustainability has been slowly increasingly emphasized in the national central exams. However, the central exams focus more on measurable sustainability methods (e.g. atom economy, efficiency) than on reasoning on sustainability. Textbooks used in secondary schools show a minimal amount of material to discuss the context of sustainability. Combined, the task for a chemistry teacher to support the students' development in the field of reasoning on sustainability is a challenging one.

In these studies, we have been able to demonstrate that implementing LCA in secondary chemistry education is possible. This proof of principle showed a successful final run on two secondary schools, however, the implementation of LCA teaching is not straightforward and/or easy at any school. Possible hindering factors are, for example, the absence of appropriate lab equipment, competences of the teachers, or the time pressure teachers feel because of the already dense curriculum. In Study 3 (Chapter 4), a few key activities and guidelines were found that work for the students or for the learning outcome. This can be used in further research and in further development of sustainability modules (with LCA) for secondary education. Here, the implementation of LCA has been shown successfully for secondary school students at the two level of the Dutch school system (pre-university level), but the question for The Netherlands remains to what extent the module would work on the havo and vmbo levels. These

havo and vmbo students spend 1 or 2 years less in secondary school, respectively, and also take fewer chemistry lessons and acquire less chemistry knowledge compared to the vwo students who participated in our studies. An interested chemistry teacher raised the question of whether the module was not better suited for undergraduates at university. Although university undergraduate education could be an appropriate place as well, we do strongly believe in the importance of teaching students about sustainability as early as possible. Unfortunately, limited material is available for that purpose outside of the work presented here.

6.5 Further research

In the last two studies, we reported various areas that show success, from a positive appreciation of activities in the module to the development of students' argumentation. However, an even more important question is the ability of the students to retain the knowledge they acquired during the module. To emphasize the importance of this, we will illustrate this through case reports of students who stated that a change in behaviour was observed in their life. A first example was a student who preferred not to buy food in plastic anymore. A second example was a student who no longer bought plastic bottles but had purchased a sustainable plastic bottle. These were desirable developments, following the continuation of the module, but to what extent did the behaviour continue to change? Another example is the interest of some students in an LCA on another subject, for example, electric cars or wind turbines. These comments are valuable because the students understand that there are other processes within complex sustainability issues. This intrinsic interest was noticed directly after completing the module, and the students showed some insight in the value of an LCA. However, after extended time, do they still think of LCA as a useful method to investigate sustainable issues? It is also interesting to see what the retention is of the behaviour and knowledge they have now acquired. And is it ultimately possible to increase this retention by offering an annual project on sustainability? One could consider using an LCA and reasoning about sustainability over a number of consecutive years. From a very simplified version in the lower grades to a complex form in the final year. On the other hand, student statements during the interviews also included comments that doing an LCA was fine, however, another LCA on other subjects would be boring. Lastly, that comment indicates an interesting area of research: to what extent can the guidelines put forward as a result of Study 3 (Chapter 4) be used in other sustainability issues while preventing boredom. Further research is necessary



to incorporate these guidelines into other modules with, for example, redox, acid-base reactions or biochemistry as a subject.

6.6 Enrichment of education

In the developed module, only one subject, plastics, was combined with sustainability. However, it could also be said that sustainability should really become part of the whole profession. At this point, teaching sustainability means teaching a measurable way of sustainability. Consider, for example, atom economy, E-factor, efficiency. Real reasoning, however, lags behind, while in the Netherlands this is certainly one of the points included in the chemistry exam program (CvTE, 2021; Driessen, 2008; SLO, 2016). Merely making sustainability measurable is not enough for students to reason about it, this requires context and supportive education. Though tempting, it is too easy to think that following one module on sustainability would be enough to actually make students more resilient to sustainability issues. In this case, we only considered chemistry as a subject in secondary school that is suitable and obligated to teach sustainability, but it is certainly also useful for cross-curricular subjects. In the Netherlands, for example, there is a subject NLT (Nature Life and Technology) in which a number of subjects are represented (e.g., biology, physics, chemistry, geography, mathematics). A cross-curricular subject such as NLT could be very suitable to offer a module on sustainability, or collaborations between two subjects to integrate it even further.

6.7 Recommendations for the curriculum

In order to obtain a more sustainable generation, it is very important that chemistry textbooks respond to this and take their chance to improve sustainability reasoning in secondary school (chemistry) students. However, choices will have to be made, because the chemistry curriculum is already crowded. Yet it is important to offer multiple moments in which sustainability reasoning is stimulated. Calculations such as the atom economy, E-factor or efficiency are tools that students will not use in their everyday life. However, talking and forming opinions about sustainability issues, on the other hand, can actually enrich the skill set that students learn in secondary school education. Therefore, we should let them reason more about sustainability. The power in discussing a sustainability issue with secondary school students in an educational environment, is that they will encounter a dilemma for which there is no single, one-dimensional yes or no answer. They can learn how to deal with issues like this, so we should provide situations to let them practice in sustainability

issues. Using a method, such as LCA, to look at a sustainability issue seems a good strategy. The expert data are data without any opinion of the authors. They are objective data compared to subjective data that we can obtain from for instance news articles, in which the author has interpreted the pure data that were used as a source. The expert data are pure data on which the students ultimately form their own opinion. There is so much LCA data available, which can also be used in a simplified way by the students. The students seem to be sensitive to discussions to develop their opinion and self-awareness of sustainability. A consumer can make choices, but not all choices are the responsibility of the consumer. There are certain places where decisions are made, in the industry, in politics, in the supermarket or at our homes. Make the students consciously curious about the answers of the central (sustainability) questions, for the students to have an intrinsic need to look for an answer to the complex sustainability issue at hand. This can be done by giving the students some additional information, e.g., in the form of news articles, and letting them discuss the problem. Perhaps this results in a form of frustration because there is no simple answer to give. For the students, it is almost incomprehensible that a teacher does not actually believe that there is a right or wrong. However, this can also result in a motivation to understand the sustainable issue. It is good to give the students self-awareness of sustainability. But more important is to prepare them for sustainable choices they will make in their personal life or professional life, through incorporation of tasks with the LCA as a backbone, e.g., in exercises in textbooks or practical assignments, to make the sustainable development in students more sustainable. This could be a way to make sustainability part of the subject chemistry.



6.8 Final statement

What I have learned from this research is that it is good and enjoyable to work on sustainability with students. I see the importance of it even more, and I also see that there is still a lot to teach to our future generations. When you, as a teacher, express enthusiasm about such an important topic like sustainability, it is also possible to have incredibly wonderful and interesting conversations with the young people that are in your classroom. Obviously not every student will share your enthusiasm about sustainability, but the discussions or conversations that you can have after a module about sustainability are priceless. For example, the normally very shy student who now asks with genuine interest what you, as a teacher, think about which plastic is the most sustainable, and argues with you about it. Or the student who normally does not do anything in class, who now encourages his fellow group members to further refine their

opinion in the essay because it can be better. Or the surprised looks or the realisations during the module. That makes your teacher's heart skip a beat. But also, as a researcher it was special to see that the module could teach the students something and that some of them really grew in the subject I sometimes asked myself whether what we were doing was really important, or whether it could make a difference. I believe that every module in which a student is concerned with sustainability prepares another person for the choices we have to make in our lives. The module, which was used in its entirety for the first time in 2021, is still being developed, minor adjustments are being made to achieve an even better learning outcome and possible collaborations with other subjects are discussed. With just one module, it is not possible to prepare all students for these choices, and not everyone will be really open for learning about sustainability. However, every subject at (secondary) school has the responsibility to teach students about sustainability. If we do this as researchers and teachers, we give a little more hope for the future of the earth.



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Summary

General introduction

Sustainability has played an increasingly important role in recent years, due to the depletion of natural resources, global warming and the large amount of waste that is produced by the humanity. There is an increasing awareness that the (linear) way in which human society is progressing may cause problems for future generations, also due to the growing world population and level of prosperity. These concerns have led to widely debated issues in multiple levels of the society, e.g., politics, industry and science. In response to these developments, different movements arose that aim to balance the qualities of life and the environment.

All actors in society, including government, industry and the public need to be well-informed on issues regarding science-related social issues, including sustainability. Especially the public needs to be literate on these issues. There is no better place to educate the public than teaching sustainability to youngsters and use education as an instrument to engage the public in thinking about sustainability issues. Education can form the basis in terms of, among others, knowledge and critical thinking, that youngsters can utilize with respect to sustainability issues they will come across in their lives. Besides, it also allows them in their turn to openly discuss these topics with their parents and other generations.

A variety of skills is considered important for the future generations to deal with sustainability issues. Examples are skills related to validation and justification of claims, argumentation, morality, decision making, and the ability to discuss. Chemistry education plays an important role, as it can help future citizens to develop these types of skills. However, proper and adequate implementation of sustainability in secondary education is challenging and not straightforward. This might be due to the fact that sustainability issues tend to be complex, multidimensional by nature, and involve numerous concepts and terms that have to do with knowledge, morals, skills, and the effect of actions, all of which transcend the typical skills of secondary school students.

One way to turn the extent of sustainability measurable and negotiable is to conduct life cycle assessment. Life cycle assessment (LCA) is a tool for assessing the environmental impact of a product or service throughout its life cycle. This

quantitative approach evaluates the material flows and energy consumption, and can give students numerical/quantitative insight in the impact of a product.

The incorporation of the LCA method into education could provide opportunities to have various discussions. Not only on environmental issues, but also health issues, economic issues, and concepts such as systems thinking and circular economy. It also gives opportunity for a more ethical discussion in a chemistry class.

This thesis delves into this issue: how can we support students in secondary chemistry education to reason from the chemistry perspective when making decisions related to sustainability? The overall research question addressed is:

How can secondary chemistry education contribute to the life cycle reasoning of students?

To answer the overall research question four studies have been conducted. As a context, we chose the domain of plastics 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. The recurring question posed to students throughout all studies in this dissertation was:

What plastic do you think is the most sustainable? A fossil-based plastic or a bio-based plastic?

Chapter 2 - Pre-university students' perceptions about the life cycle of bioplastics and fossil-based plastics

In the first study we evaluated whether students from grade 11 were able to reason about sustainability in the context of plastics with the information they received. This study focussed on the initial reasoning of the students and on the appropriateness of the context of plastics to induce discussions on sustainability. The analysis of the content of the argumentation showed that some of the twelve principles of green chemistry naturally occur in the argumentation of the students. Matters that were often mentioned by the students were related to the efficiency of processes in terms of mass, energy, space and time. Students also mentioned issues related to pollution, design of a product, and the recycling or degrading in nature. However, matters related to waste, energy and utilities, local sources for material and energy

were not well represented in the argumentation of the students. We noticed that the students' argumentation was fairly complete. An adapted version of Toulmin's argumentation model showed to be appropriate to analyse the students' argumentation. The number of qualifiers and rebuttals increased between the two moments of measurement. This finding was interpreted as an indication that students started to think more critically about their own claim. The awareness of the students of the complexity and the multi-dimensionality of the sustainability issue was observed in the raised number of doubts in their argumentation, as also evidenced by an increasing number of qualifiers and rebuttals and by the statements that students miss information to take position. Besides, the students showed to be able to reflect critically on their claim, and some adjusted their claim based on other arguments or opinions that were brought in during the activities.

Chapter 3 - Engaging pre-university students in sustainability and life cycle assessment in upper-secondary chemistry education: The case of polylactic acid

The aim of the second study was to investigate to what extent LCA teaching fostered students' involvement in sustainability issues of the plastic PLA. By performing the four phases of an LCA, including phase 2, doing experiments, it was examined whether the students understand what a life cycle of a plastic looks like, and whether they understand the purpose and benefits of conducting an LCA.

The lesson series proved to evoke in students a critical view on the life cycle of plastics. However, the study also showed that more time and proper instruction was needed for the students in order to really perform an life cycle assessment, i.e. to analyse which reaction step, in this case, is the most sustainable or, conversely, the least sustainable. The students indicated that due to the jigsaw expert method, they lacked insight into the complete life cycle of the plastic.

Chapter 4 - Teaching life cycle assessment in pre-university education

The aim of the third study is to identify a set of guidelines for teaching sustainability using LCA into secondary education. Based on study 1 and 2, a complete module was designed in which students conducted an LCA of PLA, worked with expert data to examine the LCA of different plastics, and argued on the level of sustainability of bio- versus fossil-based plastics. The module consisted of 6 parts which included an introduction, theoretical lessons on the life cycle of PLA and theory on LCA and 4 parts that were dedicated to the authentic four phases of the LCA.

The appreciation of the students towards the teaching activities was generally positive, according to the data from both the questionnaires and the interviews. Activities, such as, reading news articles and a groups discussion, performing lab experiments, working with expert data and writing an essay were valued more positive compared to other activities in the corresponding part of the module.

For each part of the module, it has been determined in advance what the desired learning outcome should be. In general, most of the learning notions are achieved in sufficient extent:

- *Awareness of bio- and fossil-based plastics*
- *Awareness of sustainability and plastic*
- *Contribution of yourself and industry*
- *Ability to describe purpose of LCA*
- *Ability to describe scope and boundaries of LCA*
- *Match impact categories to relevant stages in life cycle*
- *Being able to argue the choice of scope cradle-to-grave, cradle-to-gate, cradle-to-cradle*
- *Comparing impact categories*
- *Awareness of environmental impact of different plastics*
- *Refreshing position statement on learning experience*
- *Generic applicability of LCA (for other processes and products)*

A set of guidelines was distilled, both based on literature and the practical implementation of the module. The guidelines aim to provide educational designers, practitioners, and teachers with useful heuristics for teaching LCA in upper secondary science education.



1. *Guided inquiry-based learning approach, active guidance by the teacher*
Teacher are advised to give active guidance, so students can correctly share information with each other at crucial moments (information transfer after expert groups, guidance in group discussions)
2. *Four phase of the LCA as module backbone*
Authentic four steps of LCA in a simplified form appear to be understandable and a suitable starting point for a module on sustainability
3. *Laboratory work*
Increases students' understanding of the life cycle of a product
4. *Use expert data*
Students are able to substantiate their arguments with real data. In addition, this gives an opportunity to enhance understanding of the complexity of the sustainability issue. However, the expert data should be simplified, so students can work with it.
5. *Students working together in groups*
Facilitates low-threshold discussions between students, promotes exchange of opinions and enhances reflections of point of views, and inspires curiosity.
6. *Understanding the life cycle and its complexity*
Gives the realisation of the many steps in a life cycle and therefore helps to raise awareness of the complexity of the sustainability issue.
7. *Clear view of the module*
All the activities should have a clear function in achieving the goal of the module. Students should be aware of the function of every activity.

Chapter 5 - Pre-university students' life cycle reasoning in chemistry education

The aim of the fourth study was to investigate whether LCA can lead students to life cycle reasoning, that is, to understand the complexity of sustainability issues as evidenced by sophisticated, well-balanced, and sound arguments. The arguments are analysed both on structure, e.g., the aspects in Toulmin's argumentation model, as well as on background, e.g., the ecological, ethical, scientific, and socio-economic, and on soundness. The combination of the argumentation components (Toulmin) and the soundness gave also input to determine a level of argumentation. In addition, students' arguments, with the backgrounds scientific and ecological, were analysed on the use of LCA impact categories.

Students' arguments, during the module on plastics and sustainability, developed towards a more structured and sound argument. The arguments in the final essays contained more structural components of Toulmin's argumentation model. For example, there was an increase in grounds, warrants, and rebuttals. Besides, less debatable items were observed, which showed that the content of the essays also has improved.

The level of argumentation increased for more than half of the groups with a statistically significant change in mean argumentation level from 3.15 ± 1.16 to 3.96 ± 0.87 $z=-3.571$ (corrected for ties), $p<.001$, with an effect size of 0.70. This shows that the students provide a better substantiation for their statements and are also able to use and distinguish truthful facts and matters.

The background of the students' argumentation was mainly scientific. Ethical statements were scarcely used. The mostly scientific nature of the argumentation was a logical consequence of a module that employed a rather scientific approach. Especially the LCA data that the students used in the module was very often also cited in their substantiation of their claim or for contradicting the claim. Ethical argumentation which contained personal values or opinions was employed less. Possibly the scientific subject, here chemistry, did not encourage the students to write an ethical substantiation. The expectation of the students might have been that the teacher expected them to write a scientifically written text with a limited amount of ethical substantiations. The students should be encouraged more to express themselves in a more ethical manner.

Limitations

In these four studies, we have been able to demonstrate that implementing LCA in secondary chemistry education is possible. This proof of principle showed a successful final run on two secondary schools, however, the implementation of LCA teaching is not straightforward and/or easy at any school. Possible hindering factors are, for example, the absence of appropriate lab equipment, competences of the teachers, or the time pressure the teachers feel because of the already dense curriculum.

Further research

This research has delivered some activities and guidelines for teachers and educational designers that can be used for development of other sustainability modules (with LCA) for secondary education. An interesting area of research is to investigate to what extent can the guidelines (chapter 4) be used in other sustainability issues. Further research is necessary to incorporate these guidelines in other modules with, for example, redox, acid-base reactions or biochemistry as a subject.

This study has shown that the implementation of LCA can be successful for secondary school students at the vwo level of the Dutch school system (pre-university level), but the question for The Netherlands context remains to what extent the activities and guidelines work on the havo and vmbo levels.

We reported a positive appreciation of activities in the module as well as an increase of the overall quality of students' argumentation around sustainability issue of plastics. However, an even more important question is the ability of the students to retain the acquired knowledge they developed during the module. It is interesting to see what the retention is of the behaviour and knowledge they have now acquired. And is it ultimately possible to increase this retention by offering an annual project on sustainability. One could consider using an LCA and/or reasoning about sustainability over a number of consecutive years. From a very simplified version in the lower grades to a complex form in the final year.

Recommendations for the curriculum

In order to obtain a more sustainable generation it is very important that the chemistry textbooks respond to this and take their chance to improve sustainability reasoning in secondary school (chemistry) students. Choices have to be made, because the chemistry curriculum is crowded. However, it is important to offer multiple moments in which sustainability reasoning is stimulated. Talking and forming opinions about sustainability issues can actually enrich the skill set that students learn in secondary school education. One way for achieving this is incorporation of tasks with the LCA as a backbone in chemistry text books used in secondary schools, e.g. in exercises or practical assignments, to make the sustainable development in students more tangible and visible.

Final statement

The module, which was used in its entirety for the first time in 2021, is still being developed further, minor adjustments are being made to achieve an even better learning outcome and possible collaboration with other subjects are discussed. With just one module, it is not possible to prepare all students for the sustainability choices they will encounter during life, and not everyone will be really open for learning about sustainability. However, every subject at (secondary) school has the responsibility to teach students about sustainability. If we do this as researchers and teachers, we give a little more hope for the future of the earth.



Samenvatting

Duurzaamheid is de laatste jaren een steeds belangrijker rol gaan spelen, door de uitputting van natuurlijke hulpbronnen, de opwarming van de aarde en de grote hoeveelheid afval die door de mensheid wordt geproduceerd. Er is een toenemend besef dat de (lineaire) manier waarop de menselijke samenleving zich ontwikkelt, problemen kan opleveren voor toekomstige generaties, mede door de groeiende wereldbevolking en het stijgende welvaartsniveau. De zorgen hierover worden op verschillende plekken in de samenleving veelvuldig besproken, zoals in de politiek, het bedrijfsleven en de wetenschap. Als reactie op deze ontwikkelingen zijn verschillende bewegingen ontstaan die als doel hebben om de kwaliteit van het leven en van het milieu in balans te brengen.

Alle actoren in de samenleving, waaronder de overheid, het bedrijfsleven en het publiek, moeten goed worden geïnformeerd over onderwerpen die verbonden zijn met aan de wetenschap gerelateerde maatschappelijke kwesties, waaronder duurzaamheid. Vooral het publiek moet hiervan kennis hebben. En waar kun je beter beginnen met het voorlichten van het publiek dan in het onderwijs? Via het onderwijs kun je het publiek van jongs af aan betrekken bij het nadenken over duurzaamheidskwesties. Onderwijs kan de basis vormen voor onder andere kennis en kritisch denken; iets wat jongeren kunnen gebruiken bij de duurzaamheidskwesties die ze in hun leven zullen tegenkomen. Bijvoorbeeld om deze onderwerpen openlijk te bespreken met hun ouders en andere generaties.

Verschiedende vaardigheden worden belangrijk geacht voor de toekomstige generaties om met duurzaamheidsvraagstukken om te gaan. Voorbeelden zijn vaardigheden met betrekking tot validatie en rechtvaardiging van claims, argumentatie, moraliteit, besluitvorming en het vermogen om te discussiëren. Scheikundeonderwijs speelt een belangrijke rol, omdat het toekomstige generaties kan helpen dit soort vaardigheden te ontwikkelen. Het goed en adequaat implementeren van duurzaamheid in het voortgezet onderwijs is echter uitdagend en niet eenvoudig. Dit kan te wijten zijn aan het feit dat duurzaamheidsvraagstukken vaak complex en multidimensionaal van aard zijn en te maken hebben met kennis, moraal, vaardigheden en het effect van acties. Dit overstijgt allemaal de typische vaardigheden van middelbare scholieren.

Een manier om de mate van duurzaamheid meetbaar en bespreekbaar te maken, is het uitvoeren van een levenscyclusanalyse. Een levenscyclusanalyse (LCA) is

een instrument om de milieu-impact van een product of dienst gedurende de hele levenscyclus te beoordelen. Deze kwantitatieve benadering evalueert de materiaalstromen en het energieverbruik, en kan leerlingen numeriek/kwantitatief inzicht geven in de impact van een product.

De integratie van de LCA-methode in het onderwijs zou mogelijkheden kunnen bieden om verschillende discussies te voeren. Niet alleen op het gebied van milieu, maar ook op het gebied van gezondheid, economie en concepten als systeemdenken en circulaire economie. Het geeft ook de mogelijkheid voor een meer ethische discussie in een scheikundeles.

Dit proefschrift gaat in op deze vraag: hoe kunnen we leerlingen in het voortgezet scheikundeonderwijs ondersteunen om vanuit het scheikundeperspectief te redeneren bij het nemen van beslissingen op het gebied van duurzaamheid? De algemene onderzoeksvraag die aan bod komt is:

Hoe kan het voortgezet scheikundeonderwijs bijdragen aan het levenscyclusredeneren van leerlingen?

Om de algemene onderzoeksvraag te beantwoorden, zijn vier onderzoeken uitgevoerd. Als context hebben we gekozen voor het domein plastics omdat 1) leerlingen in aanraking komen met plastics in het dagelijks leven, 2) plastics deel uitmaken van veel scheikundecurricula en 3) het afvalbeheer van plastics een bekend probleem is in de samenleving. De terugkerende vraag die tijdens alle studies in dit proefschrift aan leerlingen werd gesteld, was:

Welk plastic is volgens jou het meest duurzaam? Een fossiel plastic of een bioplastic?

Hoofdstuk 2 - Percepties van vwo-leerlingen over de levenscyclus van bioplastics en fossiele plastics

In het eerste onderzoek evalueerden we of leerlingen uit klas 5 in staat waren om met de informatie die ze kregen te redeneren over duurzaamheid in de context van plastics. Dit onderzoek richtte zich op de initiële redenering van de leerlingen en op de geschiktheid van de context van plastics om discussies over duurzaamheid op gang te brengen.



Uit de inhoudelijke analyse van de argumentatie bleek dat een aantal van de twaalf principes van de groene chemie van nature terugkomen in de argumentatie van de leerlingen. Zaken die vaak door de leerlingen werden genoemd, hadden te maken met de efficiëntie van processen in termen van massa, energie, ruimte en tijd. Leerlingen noemden ook kwesties met betrekking tot vervuiling, ontwerp van een product en de recycling of afbraak in de natuur. Zaken met betrekking tot afval, energie en nutsvoorzieningen, lokale bronnen voor materiaal en energie, waren echter niet goed vertegenwoordigd in de argumentatie van de leerlingen.

Het viel ons op dat de argumentatie van de leerlingen redelijk compleet was. Een aangepaste versie van het argumentatiemodel van Toulmin bleek geschikt om de argumentatie van de leerlingen te analyseren. Het aantal qualifiers en rebuttals nam toe tussen de twee meetmomenten. Deze bevinding werd geïnterpreteerd als een indicatie dat leerlingen kritischer gingen nadenken over hun eigen bewering.

Het bewustzijn van de leerlingen van de complexiteit en de multidimensionaliteit van het duurzaamheidsvraagstuk werd waargenomen in het aantal geuite twijfels in hun argumentatie, zoals ook blijkt uit een toenemend aantal qualifiers (voorwaardes) en rebuttals (weerleggingen) en uit de stellingen dat leerlingen informatie missen om een standpunt in te nemen. Daarnaast toonden de leerlingen kritisch te kunnen reflecteren op hun bewering, en sommigen pasten hun bewering aan op basis van andere argumenten of meningen die tijdens de activiteiten werden ingebracht.

Hoofdstuk 3 - Betrekken van vwo-leerlingen bij duurzaamheid en levenscyclusanalyse in de bovenbouw van het voortgezet scheikundeonderwijs: de casus van polymelkzuur

Het doel van de tweede studie was om te onderzoeken in hoeverre LCA-onderwijs de betrokkenheid van leerlingen bij een duurzaamheidskwesties zoals die van de plastic PLA bevorderde. Door het uitvoeren van de vier fasen van een LCA, waaronder fase 2, het doen van experimenten, werd onderzocht of de leerlingen begrijpen hoe een levenscyclus van een plastic eruitziet, en of ze het doel en de voordelen van het uitvoeren van een LCA begrijpen.

De lessenreeks bleek bij leerlingen een kritische blik op de levenscyclus van plastics op te leveren. Uit het onderzoek bleek echter ook dat er meer tijd en een goede instructie nodig waren voor de leerlingen om echt een levenscyclusanalyse uit te

voeren, dus om te analyseren welke reactiestap in dit geval het meest of juist het minst duurzaam is. De leerlingen gaven aan dat ze door de expertmethode geen inzicht hadden in de volledige levenscyclus van het plastic.

Hoofdstuk 4 – Onderwijzen van levenscyclusanalyse in het vwo

Het doel van het derde onderzoek was om een set richtlijnen op te stellen voor het onderwijzen van duurzaamheid met behulp van LCA in het voortgezet onderwijs. Op basis van studie 1 en 2 werd een complete module ontworpen waarin leerlingen een LCA van PLA uitvoerden, met expertdata werkten om de LCA van verschillende plastics te onderzoeken en argumenteerden over de mate van duurzaamheid van bio- versus fossiele plastics. De module bestond uit zes delen met een inleiding, theoretische lessen over de levenscyclus van PLA en theorie over LCA en vier delen die gewijd waren aan de authentieke vier fasen van de LCA.

De waardering van de leerlingen voor de onderwijsactiviteiten was over het algemeen positief, zo bleek uit de gegevens van zowel de vragenlijsten als de interviews. Activiteiten zoals het lezen van nieuwsartikelen, het voeren van een groepsdiscussie, het uitvoeren van labexperimenten, het werken met expertdata en het schrijven van een essay werden positiever gewaardeerd in vergelijking met andere activiteiten in de overeenkomstige delen van de module.

Per onderdeel van de module was vooraf bepaald wat de gewenste leeruitkomst moest zijn. Over het algemeen werden de meeste leerbegrippen in voldoende mate bereikt:

- *je bewust worden van bio- en fossiele plastics;*
- *je bewust worden van duurzaamheid en plastic;*
- *je bewust worden van de bijdrage van jezelf en de industrie;*
- *kunnen beschrijven van het doel van LCA;*
- *kunnen beschrijven van de reikwijdte en grenzen van een LCA;*
- *kunnen afstemmen van de impactcategorieën op relevante fasen in de levenscyclus;*
- *kunnen discussiëren over de keuze van scope: cradle-to-grave, cradle-to-gate, cradle-to-cradle;*
- *kunnen vergelijken van impactcategorieën;*
- *je bewust worden van de milieu-impact van verschillende plastics;*
- *kunnen herzien van standpunt;*
- *je bewust worden van de generieke toepasbaarheid van LCA (voor andere processen en producten).*

Er werd een set richtlijnen gedestilleerd, op basis van zowel de literatuur als de praktische implementatie van de module. Deze richtlijnen zijn bedoeld om onderwijsontwerpers, praktijkmensen en leraren nuttige handvatten te bieden voor het onderwijzen van LCA in het voortgezet onderwijs.

1. *Guided inquiry-based learning approach (begeleid onderzoekende leren), actieve begeleiding door de leerkracht*
Aan docenten wordt geadviseerd om actieve begeleiding te geven, zodat leerlingen op cruciale momenten op de juiste manier informatie met elkaar kunnen delen (informatieoverdracht na expertgroepen, begeleiding in groepsdiscussies).
2. *LCA als ruggengraad van de module*
De authentieke vier stappen van LCA in een vereenvoudigde vorm blijken begrijpelijk en een geschikt startpunt voor een module over duurzaamheid.
3. *Practica*
Practica vergroten het begrip van leerlingen van de levenscyclus van een product.
4. *Gebruik van expertdata*
Leerlingen zijn in staat om hun argumenten te onderbouwen met echte data. Daarnaast bieden deze de mogelijkheid om meer inzicht te krijgen in de complexiteit van het duurzaamheidsvraagstuk. De expertdata moeten echter worden vereenvoudigd, zodat leerlingen ermee kunnen werken.
5. *Leerlingen die in groepen samenwerken*
Samenwerken in groepen faciliteert laagdrempelige discussies tussen leerlingen, bevordert de uitwisseling van meningen en de reflecties op standpunten, en wekt nieuwsgierigheid op.
6. *Inzicht in de levenscyclus en de complexiteit ervan*
Kennis van een levenscyclus maakt de vele stappen ervan inzichtelijk en vergroot daarmee het bewustzijn van de complexiteit van het duurzaamheidsvraagstuk.
7. *Duidelijk overzicht van de module*
Alle activiteiten moeten een duidelijke functie hebben voor het bereiken van het doel van de module. Leerlingen moeten zich bewust zijn van de functie van elke activiteit.

Hoofdstuk 5 - Levenscyclusredenering van vwo-leerlingen in het scheikundeonderwijs

Het doel van de vierde studie was om te onderzoeken of LCA leerlingen kan aanzetten tot levenscyclusredenering, dat wil zeggen het begrijpen van de complexiteit van

duurzaamheidskwesties zoals blijkt uit geavanceerde, evenwichtige en correct onderbouwde argumenten. De argumenten werden zowel geanalyseerd op structuur, bijvoorbeeld de aspecten in het argumentatiemodel van Toulmin, als op achtergrond, bijvoorbeeld de ecologische, ethische, wetenschappelijke en sociaal-economische, en op correctheid. De combinatie van de argumentatiecomponenten (Toulmin) en de correctheid gaven ook input om het argumentatieniveau te bepalen. Daarnaast werden de argumenten met de wetenschappelijke en ecologische achtergronden, geanalyseerd op het gebruik van LCA-impactcategorieën.

De argumenten van de leerlingen ontwikkelden zich tijdens de module over plastics en duurzaamheid tot meer gestructureerde en gefundeerde argumenten. De argumenten in de uiteindelijke essays bevatten meer structurele componenten van Toulmins argumentatiemodel. Er was bijvoorbeeld een toename van grounds (data), warrants (rechtvaardigingen) en rebuttals (weerleggingen). Daarnaast werden minder discutabele onderdelen waargenomen, waaruit bleek dat ook de inhoud van de essays was verbeterd.

Het argumentatieniveau nam toe voor meer dan de helft van de groepen met een statistisch significante verandering in het gemiddelde argumentatieniveau van $3,15 \pm 1,16$ naar $3,96 \pm 0,87$ $z=-3,571$ (gecorrigeerd voor gelijkblijvende groepen), $p<.001$, met een effectgrootte van 0,70. Hieruit bleek dat de leerlingen een betere onderbouwing gaven voor hun stellingen en ook in staat waren om waarheidsgetrouwe feiten en zaken te gebruiken en te onderscheiden.

De achtergrond van de argumentatie van de leerlingen was vooral wetenschappelijk. Ethische uitspraken werden nauwelijks gebruikt. Het overwegend wetenschappelijke karakter van de argumentaties was een logisch gevolg van een module die een nogal wetenschappelijke benadering hanteerde. Vooral de LCA-gegevens die de leerlingen in de module gebruikten, werden heel vaak ook aangehaald in hun onderbouwing van hun bewering of voor het tegenspreken van de bewering. Ethische argumentatie die persoonlijke waarden of meningen bevatte, werd minder gebruikt. Mogelijk heeft het wetenschappelijke vak, scheikunde, de leerlingen niet aangemoedigd om een ethische onderbouwing te schrijven. De veronderstelling van de leerlingen kan zijn geweest dat de docent van hen verwachtte dat ze een wetenschappelijk geschreven tekst zouden schrijven met een beperkte hoeveelheid ethische onderbouwingen. De leerlingen zouden aangemoedigd moeten worden om zich op een meer ethische manier uit te drukken.

Beperkingen

In deze vier onderzoeken hebben we kunnen aantonen dat het implementeren van LCA in het voortgezet scheikundeonderwijs mogelijk is. Dit bewijs toonde een succesvolle uitvoering op twee middelbare scholen, maar de implementatie van LCA-onderwijs is niet op elke school eenvoudig. Mogelijk belemmerende factoren zijn bijvoorbeeld het ontbreken van geschikte laboratoriumapparatuur, competenties van de docenten, of de tijdsdruk die de docenten voelen vanwege het toch al volle curriculum.

Verder onderzoek

Dit onderzoek heeft een aantal activiteiten en richtlijnen opgeleverd voor docenten en onderwijsontwerpers die kunnen worden gebruikt voor de ontwikkeling van andere duurzaamheidsmodules (met LCA) voor het voortgezet onderwijs. Het is interessant om te onderzoeken in hoeverre de richtlijnen (hoofdstuk 4) kunnen worden gebruikt in andere duurzaamheidsvraagstukken. Verder onderzoek is nodig om deze richtlijnen te integreren in andere modules met bijvoorbeeld redox, zuur-basereacties of biochemie als onderwerp.

Uit dit onderzoek is gebleken dat de implementatie van LCA succesvol kan zijn voor middelbare scholieren op vwo-niveau van het Nederlandse schoolstelsel, maar de vraag voor de Nederlandse context blijft in hoeverre de activiteiten en richtlijnen werken op havo- en vmbo-niveau.

We rapporteerden een positieve waardering voor de activiteiten in de module, evenals een toename van de algehele kwaliteit van de argumentatie van leerlingen over de duurzaamheidskwestie van plastics. Een belangrijk punt is het vermogen van de leerlingen om de verworven kennis die ze tijdens de module hebben ontwikkeld, vast te houden (de zogenoemde 'retentie'). Het zou interessant zijn om te zien wat de retentie is van het gedrag en de kennis die ze nu hebben opgedaan en of het mogelijk is om deze te verhogen door jaarlijks een project over duurzaamheid aan te bieden. Denk aan het gebruik van een LCA en/of redenering over duurzaamheid tijdens een aantal opeenvolgende jaren. Van een zeer vereenvoudigde versie in de onderbouw tot een complexe vorm in het laatste jaar.

Aanbevelingen voor het curriculum

Om een duurzamere generatie op te leiden, is het van groot belang dat de scheikundeboeken hierop inspelen en hun kans grijpen om het duurzaamheidsredeneren bij middelbare scholieren te verbeteren. Er moeten keuzes gemaakt worden, want het scheikunde curriculum is overvol. Toch is het belangrijk om op verschillende momenten aandacht te besteden aan dit type redeneren. Praten en meningen vormen over duurzaamheidskwesties kan de vaardigheden die leerlingen in het voortgezet onderwijs opdoen juist verrijken. Een manier om dit te bereiken is door in de scheikundeboeken taken op te nemen met de LCA als ruggengraat. Door middelbare scholieren oefeningen en praktijkopdrachten te laten doorlopen worden duurzame ontwikkelingen tastbaarder en zichtbaarder.

Tot slot

De module, die in 2021 voor het eerst in zijn geheel werd gebruikt, wordt nog steeds doorontwikkeld. Er worden kleine aanpassingen gedaan om tot een nog beter leerresultaat te komen en er wordt gesproken over een mogelijke samenwerking met andere vakken. Met slechts één module is het niet mogelijk om alle leerlingen voor te bereiden op de duurzaamheidskwesties die ze tijdens het leven zullen tegenkomen, en niet iedereen zal echt openstaan voor het leren over duurzaamheid. Elk vak op de (middelbare) school heeft echter de verantwoordelijkheid om leerlingen iets bij te brengen over duurzaamheid. Als we dit als onderzoekers en docenten doen en stimuleren, creëren we een beetje meer hoop voor de toekomst van de aarde.



Dankwoord

Aan alles komt een eind, en ik kan het bijna niet geloven, maar aan mijn onderzoek dus ook. De afgelopen jaren stonden in het teken van mijn onderzoek, lesgeven, muziek en het ontstaan van ons mooie gezin. Het lijkt soms bijna onmogelijk hoe alle ballen in de lucht zijn gebleven en dat er nu eentje weggelegd kan worden. Ik wil dan ook heel graag een aantal mensen bedanken die er voor hebben gezorgd dat dit allemaal mogelijk was. Want helemaal alleen heb ik het zeker niet gedaan!

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Lieve Anne en Rob, mijn paranimfen. Anne, wij zijn tegelijk begonnen aan ons promotietraject. Inmiddels een tijd geleden, maar hoe bijzonder is het dat we het nu ook bijna gelijk hebben afgerond. Met zoveel trots stond ik een paar maanden geleden bij jouw verdediging, als paranimf, en hoe fijn vind ik het dat je nu ook aan mijn zijde staat. Je was mijn kamergenootje, reisgenootje, praatgenootje, luisterend oor, motivator en ook gewoon mijn maatje. Jij wist als geen ander hoe uitdagend het soms kon zijn om een baan als docent te combineren met een baan als onderzoeker. En al die leuke momenten samen: Helsinki en Jyväskylä, Bologna, vrijgezellenfeesten, diners en lunches. Rob, mijn zwager en nu ook mijn paranimf. Er waren een paar jaren dat we beiden bezig waren met ons promotieonderzoek. Hoe fijn vond ik het om af en toe even te praten over jouw of mijn werk, want het stimuleerde om door te gaan. Met veel geduld en zorgvuldigheid heb jij mijn teksten gelezen en me met kritische vragen scherp gehouden. Je gaf me ook zelfvertrouwen en rust, ik vind het zo fijn dat je aan mijn zijde staat.

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Curriculum vitae

Esther Francisca de Waard was born on 24 May 1989 in Gouda, the Netherlands. She completed her secondary education at the Johannes Fontanus College in Barneveld in 2007, after which she went to study Chemistry at Utrecht University. The desire of becoming a teacher grew during the bachelor years while tutoring and working with secondary school students. As board member of the U.S.S. Proton, the chemistry student association at Utrecht University, she was responsible for education and communication. During her bachelor's degree final year, Esther took a course that introduced her to teaching students at secondary schools. This would ultimately be the deciding factor for choosing a career in education. In 2011 she completed the bachelor Chemistry in Utrecht.

She proceeded with a Master in Chemistry: Nanomaterials - Chemistry & Physics, with a specialisation in Organic Chemistry and Catalysis. In 2014 she finished her Master in Chemistry in Utrecht. She continued in the same year with the OnderwijsTraineeship, a teacher traineeship for secondary education, with the specialty in chemistry. Esther started working as a teacher at the Corlaer College in Nijkerk, and finished her OnderwijsTraineeship after 2 years.

In 2016, Esther acquired the Promodoc Grant from the Dutch Ministry of Culture, Science and Education (OCW). This enabled her to perform her parttime PhD research at Utrecht University's Freudenthal Institute, during which she continued to also work as a chemistry teacher in secondary education. In 2018 Esther switched schools and started teaching chemistry at the Scala College in Alphen aan den Rijn, still as parttime teacher and researcher.

After obtaining her PhD, Esther will continue working as a chemistry teacher at the Scala College in Alphen aan den Rijn.



Publications and conference contributions related to this dissertation

Scientific publications

De Waard, E.F., Prins, G.T., & van Joolingen, W.R. Pre-university students' life cycle reasoning in chemistry education, *submitted*

De Waard, E.F., Prins, G.T., & van Joolingen, W.R. Teaching life cycle assessment in pre-university science education, *submitted*

De Waard, E. F., Prins, G. T., & van Joolingen, W. R. (2022). Engaging pre-university students in sustainability and life cycle assessment in upper-secondary chemistry education: The case of polylactic acid (PLA). *Journal of Chemical Education*, 99(8), 2991-2998. <https://doi.org/10.1021/acs.jchemed.2c00374>

De Waard, E. F., Prins, G. T., & van Joolingen, W. R. (2020). Pre-university students' perceptions about the life cycle of bioplastics and fossil-based plastics. *Chemistry Education Research and Practice*, 21(3), 908-921. <https://doi.org/10.1039/C9RP00293F>

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De Waard, E.F., Prins, G.T. (2022). Argumenteren over duurzaamheid van plastics in de klas. Workshop at the Woudschoten Chemie conferentie in Zeist, the Netherlands, 4 November.

De Waard, E. F., Prins, G. T., & van Joolingen, W. R. (2019). Pre-university students' life cycle reasoning related to plastics as a sustainable issue in chemistry education. Poster presentation at the European Science Education Research Association (ESERA) conference in Bologna, Italy, 26-30 August.

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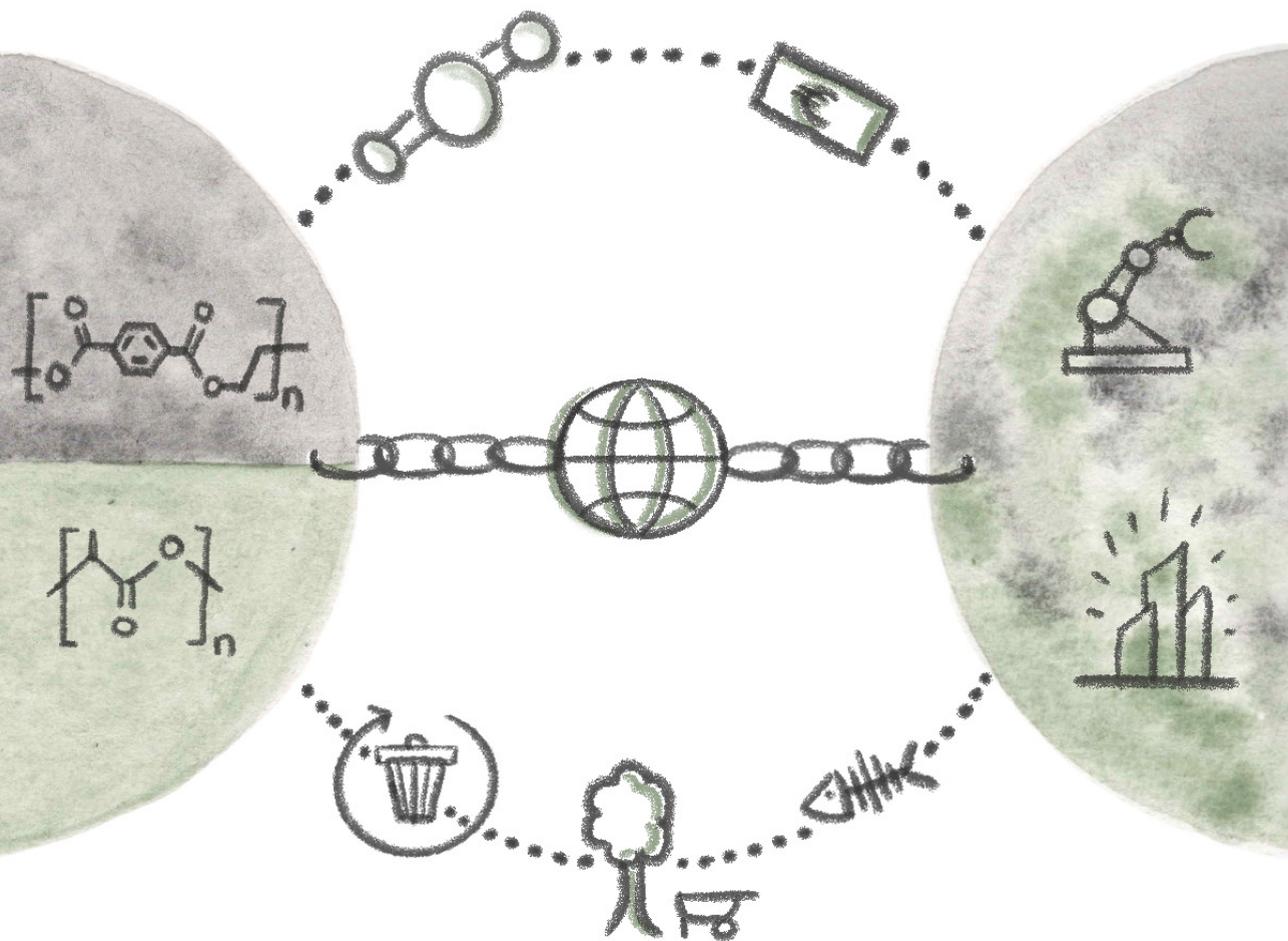
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Sustainability has played an increasingly important role in recent years, due to depletion of natural resources, global warming and the large amount of waste that is produced by the humanity. All actors in society, including government, industry and the public need to be well-informed on issues regarding science-related social issues, including sustainability. There is no better place to educate the public than teaching sustainability to youngsters and use education as an instrument to engage the public in thinking about sustainability issues. A variety of skills is considered important for the future generations to deal with sustainability issues. Examples are skills related to validation and justification of claims, argumentation, morality, decision making, and the ability to discuss.

This dissertation describes how we can support students in secondary education to reason from the chemistry perspective when making decisions related to sustainability. This dissertation describes four studies which were conducted to answer the main research question: How can secondary chemistry education contribute to the life cycle reasoning of students? Our studies demonstrate the development of (initial) reasoning of students about sustainability in the context of plastics. And based on our findings, we give a set of guidelines in order to provide educational designers, practitioners and teachers with useful heuristics for teaching LCA in upper secondary science education.